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1980 Annual Report of the Coolidge Solar Irrigation Project

Leroy Torkelson, Sandia National Laboratories
Dennis L. Larson, The University of Arizona

Prepared by Sandia National Laboratories, Albuquerque, New Mexico 87185
and Livermore, California 94550 for the United States Department
of Energy under Contract DE-AC04-76DP00789

Printed February 1981

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Price: Printed Copy $11.00; Microfiche: A01

SAND80-2378
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1980
ANNUAL REPORT OF THE COOLIDGE SOLAR IRRIGATION PROJECT

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ABSTRACT

The Coolidge Solar Irrigation Facility at Coolidge, Arizona, consists of a 2136.8-m^2 (23,000-ft^2) line-focus collector subsystem, a 113.55-m^3 (30,000-gallon) thermal storage subsystem, and a 150-kW_e (142.2-Btu/s) power generation unit. The purpose of this document is to report the performance of the facility and its operational and maintenance requirements. This document covers the period of time from the facility's initial operation in October 1979 to 31 August 1980.

ACKNOWLEDGMENT

The authors acknowledge the following contributions:

The section "Solar Collector Subsystem Performance Predictions" was contributed by L. L. Lukens.

The section "Examples of Thermosiphoning at the Coolidge, Arizona, Solar Irrigation Facility" was contributed by R. W. Harrigan.

The section "Construction Costs for the Coolidge, Arizona, Solar Irrigation Facility" was contributed by Marx Matteo, Acurex Corporation.

Jack Hoopes, Lee Ballard, and Ruben Wood were responsible for operating and maintaining the Coolidge Solar Irrigation Facility.

The facility performance data were processed by Tim Clark of the University of Arizona.

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INTRODUCTION

This document is composed of a collection of reports written on the performance of the Coolidge, Arizona, Solar Irrigation Facility during its first year of operation.

The facility is the world's largest solar thermal power plant. The site, which is the Dalton Cole farm south of Coolidge, Arizona, was selected in February 1977. A preliminary design study of the facility was undertaken early in 1977 by three contractors and completed in August 1977. On the basis of the conceptual design competition, Acurex Corporation was selected as the prime contractor for this project as well as the supplier of the solar collectors. The major subcontractors to Acurex are Sundstrand Corporation and Sullivan and Masson Consulting Engineers. Sundstrand is the supplier of the Organic Rankine Cycle (ORC) power generation unit. The team of Sullivan and Masson and Acurex was responsible for the detailed design task.

The collector field is made up of 2140.49 m^2 (23,040 ft^2) of Acurex-supplied line-focusing parabolic trough collectors arranged in eight loops having a north-south orientation. The system is designed around three heat transfer loops. One loop extracts warm heat-transfer oil from the bottom of a thermal storage tank, circulates the oil through the collector field, and returns it hot to the top of the thermal storage tank. The second loop extracts hot oil from the top of the storage tank, circulates the oil through a vaporizer heat exchange unit, and returns it to the bottom of the storage tank or directly to the collector field inlet. The third loop circulates liquid toluene through the vaporizer heat exchange unit to vaporize it and then expands the vapor through the turbine in the power conversion module to extract the energy for electrical power generation. The cycle is completed by condensing the expanded low-enthalpy vapor and pumping the condensate back to the vaporizer. The system flow diagram is shown in Figure 1.

The solar energy is converted to electrical energy by means of an ORC power conversion module, using toluene as the working fluid. The unit is complete with gear reduction and a 440-volt ac, 60-hertz, high-efficiency generator. Supporting equipment includes a vapor condenser for condensing the toluene and a vaporizer assembly consisting of a preheater, an evaporator, and a superheater for vaporizing the toluene.

Energy is stored in a 113.55-m^3 (30,000-gallon) insulated tank 4.1666 metres (13.67 feet) in diameter and 14.9 metres (49 feet) high. Various pumps, valves, and auxiliary tanks are included, and an underground tank is provided for the makeup heat transfer oil.

The control subsystem monitors and controls the collection and storage of solar energy and the generation and supply of electric power. In addition, the subsystem protects against system-related anomalies such as high temperatures in the collector field as well as natural events such as high gusty winds.

The main control functions are

- Collector tracking
- Field flow
- Collector loop flow
- Thermal storage
- ORC system
- Overtemperature protection
- High-wind protection

These control functions are largely independent, i.e., not cascaded, have built-in fail-safe action or directly acting limiting devices, and are based primarily on closed loop control and analog signal transmission.

The data acquisition subsystem monitors the performance of the system and measures the auxiliary power consumed by the system.

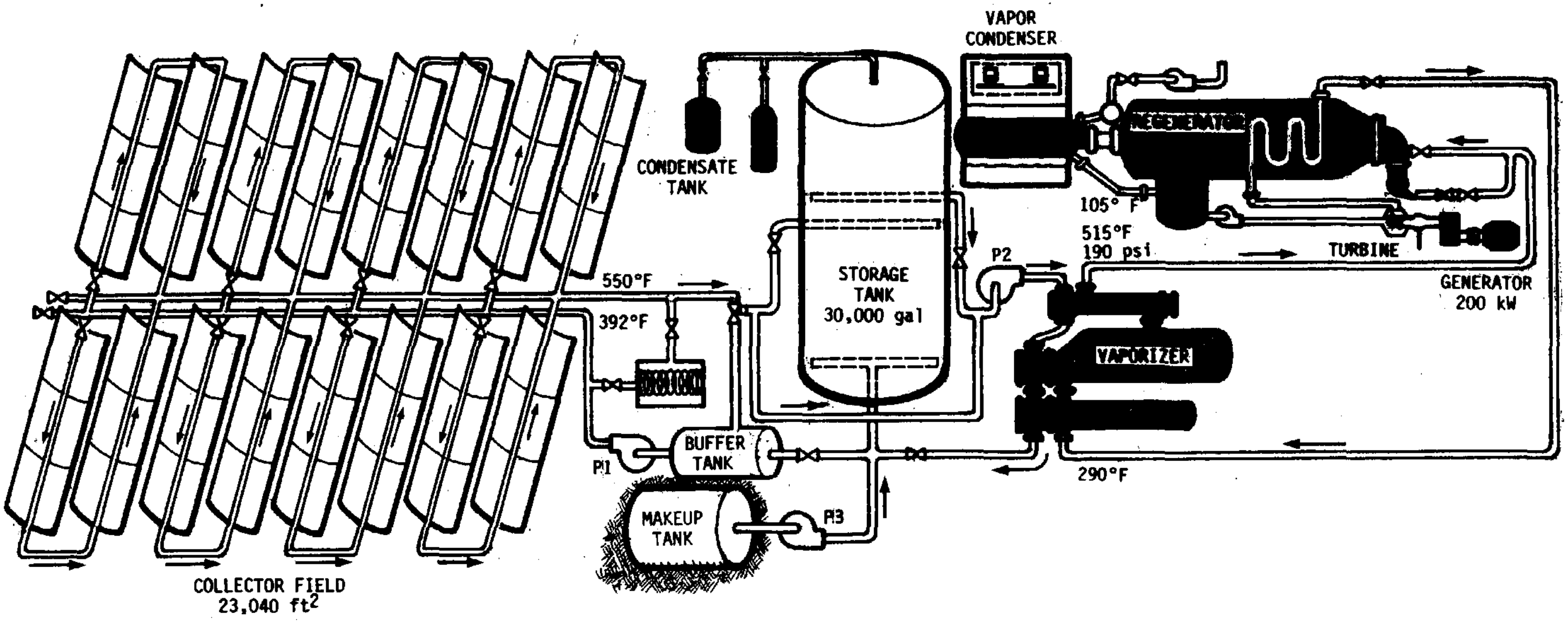

Figure 1. 150-kW$_e$ Solar-Powered Irrigation Facility Flow Diagram

The data acquired are used for plant control and for the performance analysis of main plant components. Data are derived from

- Weather conditions
- Collector fields
- Storage tank
- ORC unit
- Plant electrical output

Most of the data collected consist of conventional temperature, pressure, flow rate, and power measurements. A summary of the major system elements is given in Table 1.

Table 1 indicates a collector field subsystem efficiency of 38.6% at summer solstice. This field of Acurex solar collectors utilizes Coilzak for its reflective material. The reflectivity of the Coilzak has been found to be 60% as measured by a portable reflectometer. The performance of this subsystem can be substantially improved by the use of better reflector materials.

For a more complete description of the facility, refer to the following report:

D. Duffy, M. Matteo, and D. Rafinejad, Design, Construction, and Operation of a 150 kW Solar-Powered Irrigation Facility, ALO/4159-1.

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During 1980, the facility was operated, tested, and evaluated in accordance with the following report:

L. E. Torkelson, 150 kWe Solar Irrigation Project Test and Evaluation Plan, SAND80-1568.

Table 1

Subsystem Description

Collector Field	
Size:	48 Acurex collector groups with N-S axis orientation = 23,040 ft^2
Fluid:	Caloria HT-43
Temperatures:	Inlet 392°F, outlet 550°F
Design conditions:	q_i = 190 $Btu/ft^2 \cdot h$ $\dot{m}$ = 15,800 lb/h Subsystem efficiency at summer solstice = 38.6%
Thermal Storage	
Type:	Stratified liquid (thermocline)
Tank size:	50,000 gal -- 13.67-ft diameter by 49-ft length (30,000 gal usable storage)
Storage temperature:	392°F to 550°F
Storage medium:	Caloria HT-43
Insulation:	12-in.-thick fiberglass
Cooling System	
Type:	Vapor condenser
Water (makeup):	10 gal/min
Condensing temperature:	105°F
Power Generation	
Type:	Organic Rankine Cycle
Working fluid:	Toluene
Gross efficiency:	20%

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OVERALL SUMMARY

System Performance

The final product of the facility is the electrical power it feeds into the grid network of the local utility. The monthly electrical energy generation for January through August 1980 is shown in Figure 1.

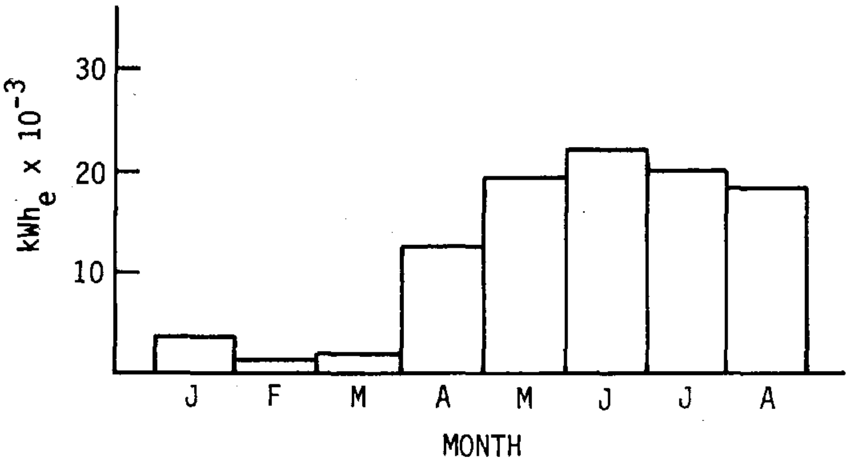


Figure 1. Electrical Energy Generated by the Plant from January through August 1980

The line-focus solar collectors were oriented in the north-south direction to maximize the amount of energy collected in the summer when irrigation demands are the highest. This orientation results in reduced energy collection in the winter. The present use of Coilzak as the reflector material for the solar collectors contributes to the poor winter performance due to the material's low reflectivity. Year-round system performance can be improved by the use of better reflector materials. Most of the electrical energy generated in January and

February resulted from operation of the gas-fired heater. Energy production in February and March was abnormally low due to problems with the pump seals in the collector field pump and turbine pump.

Operation and Recurring Maintenance Costs

The operation and recurring maintenance costs have been broken down into weekly costs for summer and winter. The costs assume the facility is operated a full 7 days a week.

The operational costs include the man-hours required to initiate facility operation daily and to monitor the operation in order to assure all is normal. The power conversion system has required operator attention during startup and some manual control. Direct operational costs have included cooling water for the turbine's condenser, nitrogen for the expansion volume on top of the thermal storage tank, CO_2 for cooling the pump seals, and electricity for air conditioning the control room.

The labor for operation amounted to 30 hours per week. The direct costs are itemized below.

Weekly Costs of Plant Operation

Operation Components	Summer	Winter
Water (municipal)	$20	$ 5
Water treatment	35	10
N_2	5	5
CO_2	8	6
Electricity (air conditioning)	10	--
Total cost per week	$78	$26

The recurring maintenance costs include labor and the cost of supplies and replacement materials for those efforts. Below is a summary of the average weekly costs over the year broken down for the various subsystems.

Weekly Costs of Recurring Maintenance

Subsystem	Man-Hours	Materials
Solar collector	8.0	$15.20
Fluid loops	4.8	1.60
Power conversion	4.8	15.90
Total cost per week	17.6	$32.70

Experiences and Insights

Summarized below are the lessons learned from the construction and operation of the facility.

Construction:

- Piping joints will tend to leak, with threaded joints being the worst, followed by flanges, then swagelock fittings, then welded joints.
- Conventional arc welding of plumbing joints is satisfactory in most cases. Tungsten inert gas (TIG) welding is necessary for stainless-steel attachments and swagelock thermocouple fittings.
- Thermocouples with swagelock fittings are best for measuring fluid temperatures.
- All valve bodies should be welded into their pipelines.
- Insulation should be installed in multilayers with lapped joints.
- Valve stems should point downward to prevent leakage from getting into insulation.
- Manholes on the side of a thermal storage tank are undesirable since they will leak fluid and are a source of heat loss.
- Leak tests should be performed on the pipelines with the lines filled with fluid and at temperature prior to insulating them.
- Operating personnel should be onsite during final construction and checkout.

Operation:

- Decomposition of the Caloria HT-43 has been very slight.
- The automatic fill system for the storage tank has not been needed since fluid decomposition was slight.
- Eighty percent of nonrecurring maintenance work has been on the power generation subsystem.
- A rain switch has been installed to allow the operators to point the collectors upward during a rainstorm.
- To prevent thermosiphoning, plumb downward away from heat sources.
- Provide an automatic closure valve in the pipeline to the base of the thermal storage tank to prevent a large oil spill.
- Provide easy, year-round access to all subsystems.
- Provide an evacuation route from potential oil spill areas.
- Construct an earth berm around the thermal storage tank.
- Provide a well-marked, accessible "kill button" to deactivate valves, collectors, flow, etc., in event of an emergency.
- Use water--not CO_2 or chemicals--on oil fires.
- Repair oil leaks on a priority basis.
- Avoid overheating oil seals on pumps, etc.
- Label all fluid containers carefully and maintain tight control.
- Provide a backup electrical power source to allow the collectors to be defocused in the event of a commercial power outage.
- Forbid the bypassing of safety devices.
- Set up extensive, periodic, preventive inspection and maintenance.
- Maintain a good spare-parts inventory.
- Periodically tighten flanges.

- Clean receiver tubes weekly.
- A collector field temperature-control system which senses collector outlet oil temperature at only one point works well.
- Collector field startup in cold weather using warm weather techniques has proven to be no problem.

Future Plans

During the coming year, system performance will continue to be monitored. In addition, the remaining specific tests in the test plan will be conducted. Some changes will be made to the facility to upgrade its performance and eliminate some of its problems. These changes will include the installation of FEK-244 reflective surfaces on the collectors and modifications to the plumbing system. The replacement of the present Coilzak reflector material with FEK-244 will improve the reflectivity of the collector surfaces from 60% for the Coilzak to 85% for the FEK-244 when the surfaces are clean. A significant improvement in system performance is anticipated with the FEK-244.

The plumbing modifications will include (1) the elimination of the buffer tank at the inlet to the collector field pump, (2) the replacement of the present three-way butterfly-type diverter valve with a conventional spool-type three-way diverting valve, and (3) the plumbing of the gas-fired heater in series with the collector field. The elimination of the 1.89-m^3 (500-gallon) buffer tank will eliminate a source of heat loss and should shorten the warmup time of the collector field. The new three-way valve will eliminate the leakage problems experienced with the old valve. The old valve was allowing about 0.6 ℓ/s (10 gal/min) of oil to be diverted to the top of the storage tank during warmup, when the oil is being circulated through the collector field. With the gas-fired heater operating in series with the collector field, it will be possible to generate electrical power throughout the winter season, and plans are being made to do so. In this mode, the collector field will be used to preheat the Caloria.

Operation and recurring maintenance costs will be watched during the coming year with an eye toward minimizing them. With cost minimization in mind, further steps will be taken toward complete automation of the facility.

Grain alcohol production processes and hardware are being studied to determine the feasibility of installing a facility onsite for producing alcohol to fuel farm machinery; the alcohol would be produced utilizing a portion of the energy collected by the the solar collectors.

ENERGY COLLECTION AND PRODUCTION OF THE COOLIDGE, ARIZONA, SOLAR IRRIGATION FACILITY FOR THE PERIOD 1 JANUARY 1980 THROUGH 31 AUGUST 1980

The amounts of available solar energy, collected thermal energy, and generated electrical energy have been compiled for January through August 1980. Solar energy data for intensities greater than 300 W/m^2 (946 Btu/ft•h) integrated over the whole day have been compiled. That portion of the total direct radiation received during collector system operation is listed as solar energy available during operation. The collected solar energy is the daily thermal energy output of the solar collector subsystem. Electrical energy and natural gas usage for plant operation and tests have also been recorded. For comparison with plant production, the quantity of electricity used by three irrigation pumps on the Dalton Cole farm has been obtained. The three pumps require approximately 150 kW (200 hp).

Energy data for the 8 months are attached. When unavailable due to data gathering problems, the information has been estimated and is noted. Footnotes explain the estimation methods. Monthly totals for available solar energy and collected thermal energy are presented graphically in Figure 1. Total electrical energy generated monthly is shown in Figure 2.

A relatively small amount of thermal energy was collected in January, February, and March. The plant was not operated on 1 January, and 15 other days received little direct solar radiation. Much of the energy collected between the first of January and the middle of February was too low in temperature for power production. The reason for this was the lower solar collector efficiency at this time of the year, which was caused by the low sun angle. This seasonal low efficiency is a characteristic common to all collector arrays oriented in the north-south direction. Collector field pump repair caused the February energy collection to be very low and greatly reduced the March operation. The long downtime was caused by heavy rains which resulted in deep mud around the pump. Because of the mud, a boom truck could not be driven in to remove the heavy pump for repair. To avoid long downtimes due to pump failures in the future, a portable hoist is kept onsite along with a spare pump impeller, shaft, bearing, and seal assembly for quick repair. After March, thermal energy collection gradually increased, peaking in May and June. May generally has less cloudy weather than June. Energy collection decreased in July and August; the decline was accentuated by the number of days receiving reduced amounts of direct solar radiation during those months.

The amount of collected thermal energy as a percentage of available direct radiation received during collector system operation increased from 7.5% in January to 20.6% in March to 32.5% in June.

Percent of Available Solar Radiation During Operation
Collected as Thermal Energy

January	7.5	May	30.6
February	9.7	June	32.5
March	20.6	July	32.3
April	28.2	August	29.6

Electrical energy production averaged about 815 kWh (2.78 x 10^6 Btu) per operating day in June. Power plant electrical energy use averaged about 260 kWh (8.87 x 10^5 Btu) on those same days. The ratio of net to gross energy production increases with increased operating hours. Natural gas was used for winter operation and specific power plant tests. Spring and summer usage occurred during periodic boiler tests.

Irrigation pumps were operated periodically during the early part of the year. However, almost continuous pump operation was recorded during some periods of the spring and summer seasons.

Plant performance and data gathering efforts improved during the year. Energy budgets will be compiled during 1980-81 to provide better data for use in analysis of performance.

Conclusions

This section has presented the energy production records for the facility to date. These records illustrate how energy production varies from season to season with a parabolic trough collector system displaying the collectors in the north-south orientation. Had the collectors been oriented in the east-west direction, electrical power production would have been possible year-round; however, production in the summer would have been significantly less. The north-south orientation was chosen to maximize electrical power production in the summer when power consumption by the irrigation pumps is at its peak.

150 kWe SOLAR PROJECT MONTHLY ENERGY BALANCE

January, 1980

Day	OPERATING TIME, hr.			THERMAL ENERGY, kWh					ELECTRICAL ENERGY, kWh		Irrigation Pump Energy Usage, kWh
				SOLAR ENERGY							
	Solar Energy Available[a]	Collector System	Generator System	Total Direct[a]	Available During Operation[b]	Collected	Natural Gas Use[h]	Total Input[i]	Generator Output	Plant Usage	
1	7.0	---	---	6500[c]	6240[d]	----	-----	-----	---	60	----
2	7.3	0.8	---	6600[c]	-----	----	7028	7028	---	90	----
3	7.5	7.5	---	6675	6511	456[e]	-----	456	---	100	----
4	7.5	7.5	---	7122	6956	487[e]	666	1153	---	120	----
5	7.5	5.5	---	5185	4906	319[e]	-----	319	---	90	----
6	0	---	---	2497	-----	----	6664	6664	---	80	----
7	0	---	---	1942	-----	----	10117	10117	---	100	----
8	0	---	---	3216	-----	----	7149	7149	---	90	----
9	0	---	---	68	-----	----	5695	5695	---	90	----
10	0	---	---	33	-----	----	-----	-----	---	70	----
11	0	---	2.3	226	-----	----	-----	-----	360	140	----
12	3.0	3.0	---	6453	5994	----	-----	-----	---	80	----
13	7.0	7.0	---	13128	12669	511	-----	511	---	90	----
14	0.8	0.8	2.2	3793	1807	----	4483	4483	256	160	----
15	7.0	7.0	---	11823	11110	644	-----	644	---	90	----
16	7.5	7.5	---	15279	14758	1353	-----	1353	---	100	----
17	3.5	3.5	---	8617	8157	641	-----	641	---	80	----
18	0	---	1.5	6752	-----	----	7149	7149	224	140	----
19	3.2	3.2	---	4063	3075	128	-----	128	---	90	----
20	7.5	7.5	---	14374	13620	1587	-----	1587	---	90	----
21	0	---	3.2	1252	-----	----	5271	5271	576	180	----
22	7.5	7.5	---	8691	5824	338	-----	338	---	100	----
23	7.5	7.5	---	8700[c]	8352[d]	668[e]	-----	668	---	90	----
24	7.7	7.7	---	12500[c]	12000[d]	1080[e]	-----	1080	---	100	----
25	8.1	8.1	0.7	15000[c]	14400[d]	1440[e]	-----	1440	96	120	----
26	8.0	8.0	---	14000[c]	13440[d]	1344[e]	-----	1344	---	90	----
27	7.8	7.8	---	13500[c]	12960[d]	1231[e]	-----	1231	---	90	----
28	0	---	---	2000[c]	-----	----	8210	8210	---	90	1140
29	0	---	3.8	3000[c]	-----	----	8906	8906	736	210	1140
30	2.5	2.5	4.4	5000[c]	4800[d]	360[e]	9754	10114	640	230	1140
31	6.0	3.5	2.3	10000[c]	9600[d]	768[e]	2484	3252	384	160	1140
TOTAL	124.4	113.4	20.4	217989	177179	13355	83576	96931	3272	3410[f]	4560[g]

Note: See page 32 for footnotes.

150 kWe SOLAR PROJECT

MONTHLY ENERGY BALANCE

February, 1980

Day	OPERATING TIME, hr.			THERMAL ENERGY, kWh					ELECTRICAL ENERGY, kWh		Irrigation Pump Energy Usage, kWh
				SOLAR ENERGY							
	Solar Energy Available[a]	Collector System	Generator System	Total Direct [a]	Available During Operation [b]	Collected	Natural Gas Use [h]	Total Input [i]	Generator Output	Plant Usage	
1	7.8	7.8	---	14000[c]	13440[d]	1344[e]	-----	1344	---	80	1140
2	7.6	7.6	---	13500[c]	12960[d]	1296[e]	-----	1296	---	80	1140
3	6.8	6.8	---	12500[c]	12000[d]	1200[e]	-----	1200	---	80	1140
4	7.8	7.8	---	7500[c]	7200[d]	684[e]	-----	684	---	80	1140
5	8.2	8.2	---	9000[c]	8640[d]	820[e]	-----	820	---	80	----
6	7.2	7.2	---	6500[c]	6240[d]	562[e]	-----	562	---	80	----
7	8.2	8.2	---	13500[c]	12960[d]	1296[e]	-----	1296	---	90	----
8	0	---	---	2500[c]	-----	----	-----	-----	---	60	----
9	8.3	8.3	---	14000[c]	13440[d]	1344[e]	-----	1344	---	90	----
10	8.5	8.5	---	12500[c]	12000[d]	1200[e]	-----	1200	---	90	----
11	8.1	8.1	4.9	10000[c]	9600[d]	768[e]	-----	768	530	240	----
12	8.0	---	---	8419	-----	----	11753	11753	---	100	----
13	0	---	2.4	33	-----	----	-----	-----	220	130	----
14	0	---	2.3	1437	-----	----	-----	-----	270	130	----
15	0	---	---	799	-----	----	-----	-----	---	60	----
16	0	---	---	1919	-----	----	-----	-----	---	60	----
17	0	---	---	1085	-----	----	-----	-----	---	60	----
18	0	---	---	40	-----	----	-----	-----	---	50	----
19	0	---	---	507	-----	----	-----	-----	---	60	----
20	2.5	---	---	9831	-----	----	-----	-----	---	60	----
21	0	---	---	561	-----	----	-----	-----	---	60	----
22	8.6	---	---	14655	-----	----	-----	-----	---	60	----
23	8.8	---	---	18394	-----	----	-----	-----	---	50	----
24	8.8	---	---	12519	-----	----	-----	-----	---	70	----
25	9.0	---	---	16454	-----	----	-----	-----	---	60	----
26	9.0	---	---	21609	-----	----	-----	-----	---	60	2182
27	9.0	---	---	18925	-----	----	-----	-----	---	60	2182
28	9.0	---	---	13307	-----	----	-----	-----	---	60	2182
29	9.0	---	---	9832	-----	----	-----	-----	---	60	2182
30											
31											
TOTAL	160.2	78.5	9.6	319826	108480	10514	11753	22267	1020	2300[f]	13288[g]

Note: See page 32 for footnotes.

150 kWe SOLAR PROJECT

MONTHLY ENERGY BALANCE

March, 1980

Day	OPERATING TIME, hr.			THERMAL ENERGY, kWh					ELECTRICAL ENERGY, kWh		Irrigation Pump Energy Usage, kWh
				SOLAR ENERGY							
	Solar Energy Available[a]	Collector System	Generator System	Total Direct[a]	Available During Operation[b]	Collected	Natural Gas Use[h]	Total Input[i]	Generator Output	Plant Usage	
1	0	---	---	5178	-----	----	-----	-----	---	70	2182
2	0	---	---	6077	-----	----	-----	-----	---	70	2182
3	0	---	---	2438	-----	----	-----	-----	---	70	2182
4	4.5	---	---	14303	-----	----	-----	-----	---	70	480
5	8.3	---	---	19224	-----	----	-----	-----	---	70	480
6	7.0	---	---	14830	-----	----	-----	-----	---	70	480
7	9.0	3.2	---	14820	-----	----	-----	-----	---	80	480
8	9.3	8.8	---	16205	-----	----	-----	-----	---	100	480
9	8.0	8.0	---	11316	-----	----	-----	-----	---	90	480
10	0	---	---	60	-----	----	-----	-----	---	70	2419
11	8.0	2.5	---	10541	9323	611	-----	611	---	80	2419
12	9.6	9.6	---	23184	15398	3724	-----	3724	---	100	2419
13	9.7	2.1	---	19316	6527	1217	-----	1217	---	80	2419
14	9.7	---	---	18450	-----	----	-----	-----	---	70	2411
15	0	---	---	7450	-----	----	-----	-----	---	70	2411
16	9.8	9.8	---	19777	12536	2152	-----	2152	---	100	2411
17	9.7	0.7	---	21026	17929	167	8603	8770	---	100	2411
18	9.1	7.8	---	15944	14858	805	-----	805	---	100	2411
19	2.3	2.3	---	10748	10340	2378	-----	2378	---	80	2411
20	9.8	9.8	---	20435	19645	5246	-----	5246	---	100	2411
21	9.7	3.6	---	13697	8470	84	-----	84	---	80	2411
22	0	---	---	15618	-----	----	-----	-----	---	70	2411
23	10.1	10.1	---	19947	17715	5525	-----	5525	---	100	2411
24	5.8	5.8	3.1	13041	5195	1231	-----	1231	220	180	2411
25	7.2	7.2	1.5	16530	12265	2575	5574	8149	240	160	5896
26	1.2	1.2	2.4	3257	-----	----	9148	9148	180	180	5896
27	8.8	8.2	2.3	16500[c]	15510[d]	4188[e]	-----	4188	290	160	5896
28	10.0	10.0	1.3	21500[c]	20855[d]	6674[e]	-----	6674	180	140	5892
29	9.8	1.6	---	20500[c]	2000[d]	480[e]	-----	480	---	80	5892
30	9.9	9.9	---	21000[c]	20370[d]	6111[e]	-----	6111	---	100	2591
31	9.7	0.5	2.7	12749	480	66	-----	66	330	150	2591
TOTAL	206.0	122.7	13.3	445661	209416	43234	23325	66559	1440	3040[f]	80373[g]

Note: See page 32 for footnotes.

150 kWe SOLAR PROJECT

MONTHLY ENERGY BALANCE

April, 1980

Day	OPERATING TIME, hr.			THERMAL ENERGY, kWh					ELECTRICAL ENERGY, kWh		Irrigation Pump Energy Usage, kWh
	Solar Energy Available[a]	Collector System	Generator System	SOLAR ENERGY Total Direct[a]	SOLAR ENERGY Available During Operation[b]	SOLAR ENERGY Collected	Natural Gas Use[h]	Total Input[i]	Generator Output	Plant Usage	
1	7.1	7.1	1.6	14421	11969	3388	-----	3388	288	140	2591
2	4.7	4.7	1.3	12765	8201	1882	-----	1882	160	120	2591
3	10.4	10.4	4.0	21417	18463	6324	-----	6324	800	100	2591
4	7.3	7.3	---	14955	12031	3294	-----	3294	---	110	2591
5	10.4	10.4	3.6	19478	17891	4817	-----	4817	736	300	3672
6	10.6	10.6	---	15735	14688	3308	-----	3308	---	90	3672
7	10.7	10.7	5.6	17877	16895	5273	-----	5273	960	200	3672
8	10.6	10.6	---	20273	18864	6429	-----	6429	---	310	3672
9	10.7	10.7	5.6	20569	19113	4048	-----	4048	1184	270	3672
10	10.7	10.7	---	20500[c]	19885[d]	6761[e]	-----	6761	---	20	3672
11	10.8	10.8	6.3	17500[c]	13125[d]	4069[e]	-----	4069	1216	210	3672
12	11.0	8.5	5.7	16000[c]	12000[d]	3360[e]	3817	7177	1024	190	3672
13	10.8	9.8	---	16500[c]	15675[d]	4546[e]	-----	4546	---	180	3846
14	10.8	10.8	5.3	19000[c]	18240[d]	5837[e]	-----	5837	1280	320	3846
15	10.8	1.5	---	4000[c]	3960[d]	870[e]	5937	6807	---	180	3846
16	11.0	10.3	5.0	16395	16204	4481	666	5147	704	230	3846
17	10.8	7.3	2.5	11748	11730	3450	-----	3450	320	150	3846
18	10.9	10.9	2.7	17018	16273	5320	-----	5320	416	160	3846
19	10.9	10.9	2.9	16754	15814	5240	-----	5240	480	190	3846
20	4.0	4.0	---	8531	7364	1630	-----	1630	---	130	3846
21	11.0	9.6	---	18233	17276	4800	-----	4800	---	130	3846
22	9.5	9.5	5.3	15101	13970	3900	-----	3900	864	260	3054
23	4.0	4.0	---	5616	3784	20	-----	20	---	70	3054
24	6.1	6.1	---	11410	9341	1400	8906	10306	---	110	3054
25	11.1	11.1	5.3	18359	17155	6440	-----	6440	800	260	3054
26	10.7	10.7	1.7	16377	14936	4560	-----	4560	320	240	3054
27	6.5	6.5	---	7353	4812	710	-----	710	---	90	3054
28	7.5	7.5	6.3	16538	15032	4710	-----	4710	928	190	3054
29	3.8	3.8	---	9503	9007	890	-----	890	---	80	3054
30	5.2	5.2	---	4603	3683	110	-----	110	---	90	3054
31											
TOTAL	270.4	252.0	70.7	450529	397381	111867	19326	131193	12480	5030	101840[g]

Note: See page 32 for footnotes.

150 kWe SOLAR PROJECT

MONTHLY ENERGY BALANCE

May, 1980

Day	OPERATING TIME, hr.			THERMAL ENERGY, kWh					ELECTRICAL ENERGY, kWh		Irrigation Pump Energy Usage, kWh
				SOLAR ENERGY							
	Solar Energy Available[a]	Collector System	Generator System	Total Direct[a]	Available During Operation[b]	Collected	Natural Gas Use [h]	Total Input [i]	Generator Output	Plant Usage	
1	9.1	9.1	---	15704	15339	2160	----	2160	----	100	3054
2	7.4	7.4	---	10432	10016	2730	----	2730	----	100	3931
3	11.1	11.1	7.4	20207	19237	6570	----	6570	1184	290	3931
4	10.3	9.0	2.7	17358	14497	4610	848	5458	384	140	3931
5	9.1	9.1	3.1	13498	12217	3550	----	3550	416	190	3931
6	11.2	11.2	2.8	18455	17533	5780	----	5780	512	170	3931
7	10.3	10.3	3.9	15824	15316	4340	----	4340	512	210	3931
8	11.4	11.4	4.0	22383	20632	6590	----	6590	704	140	3931
9	9.6	9.6	2.9	17248	14218	3730	----	3730	640	200	3931
10	11.2	11.2	3.8	20487	18853	6700	----	6700	544	190	139
11	5.2	5.2	2.5	11310	9163	1890	----	1890	128	140	139
12	11.7	11.7	4.9	21864	19711	6900	----	6900	1024	180	139
13	10.1	10.1	---	9064	5758	1990	----	1990	----	100	139
14	8.8	4.1	5.2	15901	-----	----	5210	5210	832	250	139
15	5.5	5.5	3.5	14278	6307	570	----	570	288	140	139
16	11.7	11.7	---	19857	17643	4570	----	4570	----	180	----
17	5.5	5.5	4.8	9808	7152	1450	----	1450	864	200	----
18	11.8	11.8	5.2	19500[c]	18720[d]	6180[e]	----	6180	960	200	----
19	9.0	9.0	4.3	17322	15719	5190	----	5190	672	220	----
20	11.8	11.8	5.3	21183	19630	5950	----	5950	992	270	----
21	11.7	11.7	4.1	20942	20010	6650	----	6650	864	210	----
22	11.7	11.7	5.1	22668	20985	5810	----	5810	896	270	----
23	11.8	11.8	5.9	21014	19950	6570	----	6570	1010	260	2212
24	12.0	12.0	5.5	22047	21107	6260	363	6623	1024	250	2212
25	12.0	11.3	4.7	20500[c]	19680[d]	6690[e]	----	6690	832	200	2212
26	12.1	12.1	4.7	22000[c]	20900[d]	7740[e]	----	7740	864	200	2212
27	12.1	12.1	4.7	22000[c]	20900[d]	7740[e]	----	7740	896	260	2212
28	11.9	10.2	---	21855	20791	7080	----	7080	----	160	2212
29	12.0	5.0	4.5	21172	20137	3370	----	3370	768	220	2212
30	12.0	12.0	2.5	22910	20718	7500	----	7500	448	200	2212
31	12.0	11.0	5.5	22974	21356	7470	----	7470	992	280	1422
TOTAL	323.1	306.7	109.5	571765	504195	154330	6421	160751	19250	6120	54465[g]

Note: See page 32 for footnotes.

150 kWe SOLAR PROJECT MONTHLY ENERGY BALANCE

June, 1980

	OPERATING TIME, hr.			THERMAL ENERGY, kWh					ELECTRICAL ENERGY, kWh		
				SOLAR ENERGY							
Day	Solar Energy Available[a]	Collector System	Generator System	Total Direct[a]	Available During Operation[b]	Collected	Natural Gas Use[h]	Total Input[i]	Generator Output	Plant Usage	Irrigation Pump Energy Usage, kWh
1	12.2	11.0	7.0	22273	21101	6830	-----	6830	1100	300	1422
2	12.2	12.2	5.1	20900	19381	7670	-----	7670	1000	210	1422
3	12.0	11.0	4.8	22427	20896	6660	-----	6660	900	240	1422
4	11.3	10.5	5.2	21684	19520	7640	-----	7640	1010	250	1422
5	7.0	12.0	1.0	16563	15058	5320	-----	5320	180	200	1422
6	12.2	12.2	3.4	17280	16303	7260	-----	7260	630	280	1422
7	11.0	11.0	7.0	16477	15305	5850	-----	5850	1290	220	1422
8	5.5	5.5	---	9839	8163	1950	-----	1950	----	90	1422
9	11.0	11.0	3.4	16770	15078	6330	-----	6330	640	210	1422
10	12.3	7.0.	3.7	21325	16380	4400	-----	4400	700	260	1422
11	12.0	8.3	---	22020	20951	5268	-----	5268	----	200	808
12	12.3	8.5	4.2	21131	14911	6009	-----	6009	830	280	808
13	12.1	11.9	8.9	21933	20206	1990	-----	1990	1740	320	808
14	11.2	11.2	3.6	17707	16941	5130	-----	5130	530	200	808
15	12.1	12.1	4.2	22630	21694	7150	-----	7150	990	270	808
16	12.0	12.0	6.5	19622	18175	7410	-----	7410	1240	330	808
17	12.0	12.0	5.1	18938	17742	5770	-----	5770	830	200	808
18	12.0	12.0	4.6	17280	16180	5935	-----	5935	660	380	808
19	9.9	7.5	3.6	18273	15005	3393	2787	6180	240	240	3673
20	12.1	11.8	5.9	18516	17430	5718	-----	5718	990	290	3673
21	11.9	11.9	4.8	19927	18900	5912	-----	5912	700	270	3673
22	12.3	10.5	---	18417	15694	2847	-----	2847	----	260	3673
23	12.5	12.5	10.7	21452	20604	6357	-----	6357	1140	320	3673
24	12.3	6.4	1.9	21552	20426	7106	-----	7106	290	320	3673
25	12.0	12.0	5.6	21453	20020	7510	-----	7510	1180	280	3673
26	11.5	11.5	4.5	19916	19151	6534	-----	6534	940	220	2569
27	12.0	12.0	1.0	17398	11375	2614	-----	2614	250	250	2569
28	11.9	11.9	3.3	14540	13255	4471	-----	4471	520	250	2569
29	11.2	11.1	5.6	14000[c]	13200[d]	4620[e]	-----	4620	1030	280	2569
30	10.0	9.8	3.5	15155	14602	5370	-----	5370	450	220	2569
31											
TOTAL	348.2	323.3	128.7	567198	513649	167024	2787	169811	22000	7640	59240

Note: See page 32 for footnotes.

150 kWe SOLAR PROJECT

MONTHLY ENERGY BALANCE

July, 1980

Day	OPERATING TIME, hr.			THERMAL ENERGY, kWh					ELECTRICAL ENERGY, kWh		Irrigation Pump Energy Usage, kWh
				SOLAR ENERGY							
	Solar Energy Available[a]	Collector System	Generator System	Total Direct[a]	Available During Operation[b]	Collected	Natural Gas Use[h]	Total Input[i]	Generator Output	Plant Usage	
1	11.0	10.0	2.0	14011	11707	1453	-----	1453	135	250	2569
2	12.4	12.4	4.5	20223	19694	6923	-----	6923	900	270	2569
3	12.4	10.7	7.9	23877	21155	7060	-----	7060	1350	380	2990
4	12.0	12.0	9.2	24543	22509	8393	-----	8393	1240	330	2990
5	11.9	11.9	5.7	20498	20131	6922	-----	6922	1050	280	2990
6	1.5	---	---	4872	-----	----	-----	-----	----	110	3853
7	7.5	7.5	3.8	17738	15246	4980	-----	4980	690	230	3853
8	12.0	12.0	6.2	22357	20748	7328	-----	7328	1080	310	3853
9	5.6	5.5	2.6	17118	4564	1283	1999	3282	330	170	3853
10	6.8	6.0	1.6	5994	4045	1371	-----	1371	280	190	3853
11	12.0	10.5	4.1	20908	19752	5857	-----	5857	810	270	3853
12	6.0	6.0	3.0	10721	8858	2734	-----	2734	400	200	3853
13	10.0	10.0	5.1	17573	16964	5772	-----	5772	820	230	3853
14	11.0	10.0	5.0	18908	17910	6002	-----	6002	950	280	3853
15	11.9	11.9	5.8	19860	18526	5978	-----	5978	910	270	3021
16	9.0	9.0	4.7	18398	16732	5089	-----	5089	730	250	3021
17	11.9	11.8	4.1	18879	17560	4506	-----	4506	700	260	3021
18	11.4	11.4	4.1	17398	15972	4782	-----	4782	660	250	3021
19	3.5	3.5	1.3	5822	4475	194	2423	2627	160	180	3021
20	8.8	8.7	3.7	15166	13481	4316	-----	4316	620	200	3021
21	10.7	10.7	4.6	17395	16476	5418	-----	5418	790	260	3366
22	4.3	4.3	---	7581	6456	2132	-----	2132	---	130	3366
23	8.2	8.2	5.3	4789	3512	1149	-----	1149	840	270	3366
24	5.0	5.0	1.9	9453	8757	2759	-----	2759	300	210	3366
25	11.5	11.5	3.6	17147	16161	5451	-----	5451	670	220	3366
26	11.5	11.5	5.1	13572	12493	4562	-----	4562	970	320	3366
27	11.1	11.1	3.6	17978	16442	5899	-----	5899	620	280	3366
28	9.2	9.2	5.1	14604	13730	4920	-----	4920	1040	330	3366
29	5.5	5.5	1.5	9919	8161	2501	-----	2501	220	230	3366
30	10.9	10.9	4.3	12007	11049	4105	-----	4105	700	250	3366
31	11.2	11.2	5.1	19172	18007	6160	-----	6160	930	310	3366
TOTAL	287.7	279.9	124.5	478481	421273	137999	4422	140421	20895	7720	103937[g]

Note: See page 32 for footnotes.

150 kWe SOLAR PROJECT

MONTHLY ENERGY BALANCE

August, 1980

	OPERATING TIME, hr.			THERMAL ENERGY, kWh					ELECTRICAL ENERGY, kWh		
				SOLAR ENERGY							
Day	Solar Energy Available[a]	Collector System	Generator System	Total Direct[a]	Available During Operation[b]	Collected	Natural Gas Use[h]	Total Input[i]	Generator Output	Plant Usage	Irrigation Pump Energy Usage, kWh
1	11.5	11.5	4.5	17412	16926	5761	----	5761	700	300	3366
2	11.0	11.0	3.4	15611	14960	5144	----	5144	590	160	3366
3	11.6	11.6	3.0	17994	17461	5657	----	5657	500	220	3366
4	7.3	7.3	2.9	14601	113100	3904	----	3365	580	240	3366
5	10.6	10.6	5.1	16686	15547	4769	----	3767	980	280	3366
6	11.1	11.1	4.7	19234	17785	5722	----	4392	680	240	3366
7	11.1	11.1	4.5	20133	18535	5836	----	4683	870	290	3366
8	6.0	6.0	2.8	11569	10316	2713	----	2055	460	240	3366
9	5.5	5.5	1.1	8378	6426	1564	----	955	150	170	3492
10	5.5	5.5	1.8	8926	7567	2098	----	1369	270	200	3492
11	9.5	9.5	3.3	11275	9219	2548	----	1871	500	260	3492
12	9.2	9.2	2.8	12987	12177	3002	----	2099	410	230	3492
13	7.5	7.5	3.1	7815	7033	1784	1860	3644	440	240	3492
14	3.4	3.4	---	8707	4702	973	----	973	----	100	3492
15	10.0	10.0	4.6	18073	16301	4360	----	4360	670	250	3492
16	11.0	11.0	4.6	22792	20105	6313	----	6313	880	260	3311
17	11.1	11.1	6.8	22418	20233	6586	----	6586	1190	310	3311
18	6.0	6.0	2.9	13969	12220	3150	----	3150	430	180	3311
19	8.5	8.5	4.6	19080	17725	4602	----	4602	680	250	3311
20	11.1	11.1	3.8	20806	19394	5373	----	5373	630	250	3311
21	11.1	11.1	6.2	20645	18911	5670	----	5670	1000	280	3311
22	11.0	11.0	3.2	8415	5890	2866	----	2866	520	250	3311
23	0	0	---	6938	-----	----	----	----	----	200	3311
24	3.9	3.9	---	8730	4929	1120	----	1120	----	120	3311
25	9.5	9.5	5.1	16601	16011	4732	----	4732	800	190	3311
26	10.8	10.8	4.7	17207	16661	4982	----	4982	790	280	3500
27	10.7	10.7	4.4	17220	16909	5088	----	5088	810	230	3500
28	9.9	9.9	4.7	15910	14030	3604	1674	5278	720	270	3500
29	10.2	10.2	3.7	16306	15232	4419	----	4419	580	210	3500
30	10.7	10.7	3.2	19830	18427	5334	----	5334	630	220	3500
31	10.8	10.8	5.3	19921	18511	5590	----	5590	1000	270	3500
TOTAL	277.1	277.1	110.8	476243	423243	125264	3534	128798	18530	7190	105482[g]

Note: See page 32 for footnotes.

Footnotes

Notations on the monthly energy balance summaries refer to the following definitions and assumptions used in the compilation of energy budget information:

a. Direct normal radiation when >300 W/m^2 (>945.7 Btu/ft•h).
b. Available solar energy during collector system operation.
c. Data unavailable; estimate based on hours of operation and seasonal data.
d. Data unavailable; estimate based on seasonal ratio and operating time.
e. Data unavailable; estimate based on seasonal efficiency and operating time.
f. Measured periodically; apportionment based on daily equipment usage.
g. Measured periodically; apportioned equally to each day.
h. Natural gas used to heat Caloria. Boiler efficiency was assumed to be 100%.
i. Collected solar energy plus natural gas usage. Since boiler efficiency was assumed to be 100%, energy gain by Caloria is overestimated.

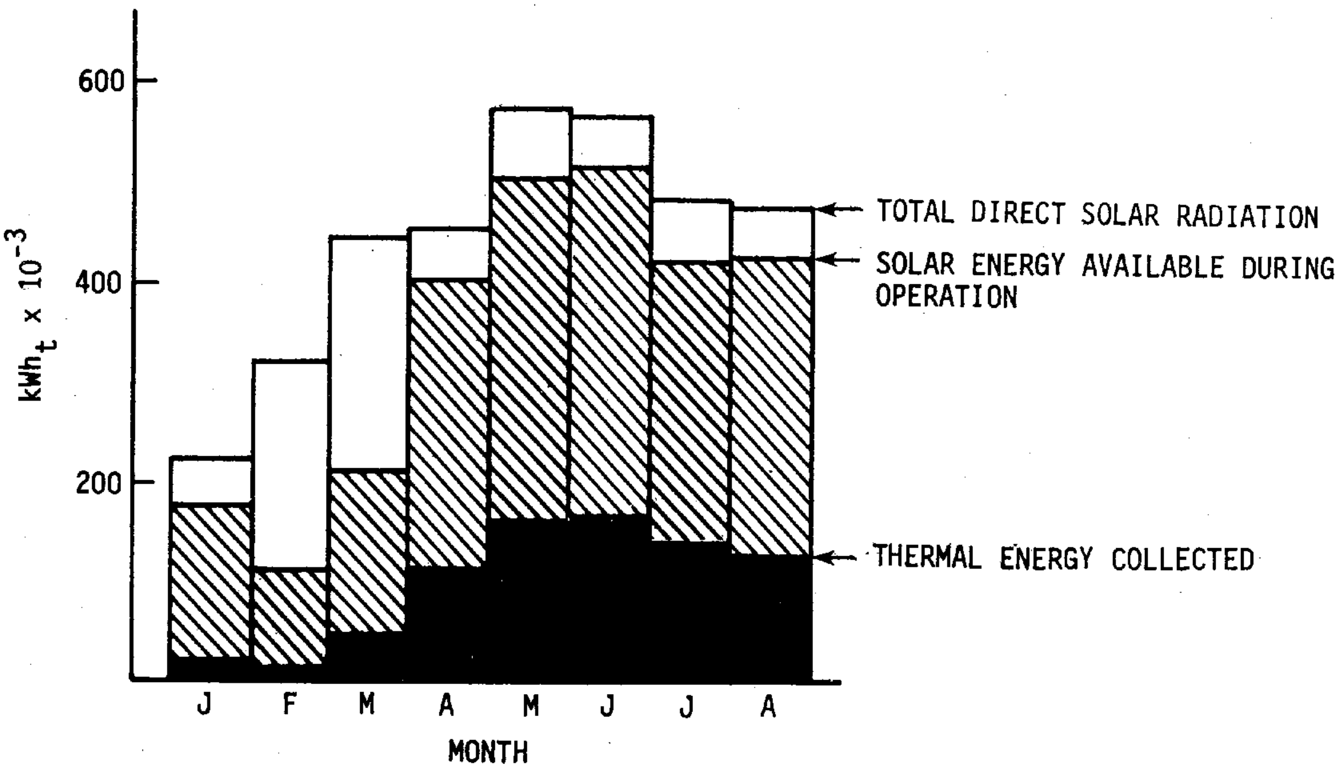


Figure 1. Solar Energy Available and Thermal Energy Collected by the Plant from January through August 1980. Low amounts of available insolation during operation in February and March are due to pump outage for repair.

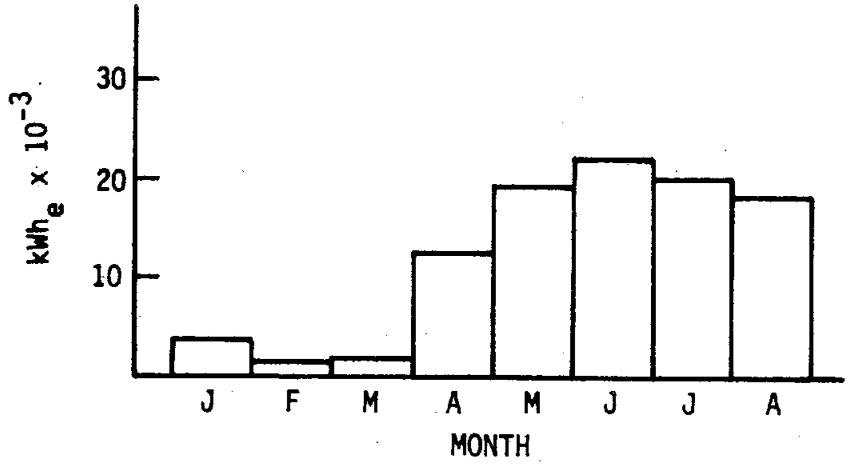


Figure 2. Electrical Energy Generated by the Plant from January through August 1980

PERFORMANCE OF THE SOLAR COLLECTOR SUBSYSTEM
AT THE
COOLIDGE SOLAR IRRIGATION FACILITY
ON
17, 18, AND 24 DECEMBER 1979

Introduction

Collector system operational data were obtained on 17, 18, and 24 December 1979 to determine performance near winter solstice. This report describes the test procedures and presents the test data.

Procedures

Collectors were rinsed with untreated water and air dried prior to the 17 December test. Some water spots remained on the reflector surface. Receiver cover tubes also were rinsed externally, but most tube interiors had some dust accumulation.

Oil in storage was preheated to approximately 200°C (392°F) on days prior to the test. Morning test operation began with minimal, 560 to 850 ℓ/min (20 to 30 gal/min), oil flow rates and with oil recirculation from the buffer tank only. The flow rate was adjusted to maintain the desired constant collector system output temperature.

When buffer tank oil temperatures reached a preset value, the primary oil storage tank was included in the flow loop. If primary tank oil temperatures were significantly lower than buffer tank oil temperatures, inclusion resulted in a dramatic change in test conditions and collector performance. In some cases, collector outlet temperatures were reduced sufficiently to cause a return to the buffer tank oil recirculation mode.

Seventeen and 18 December were mostly cloudless, but 24 December had intermittent high cloudiness. Collector outlet temperature goals were 288°, 232°, and 260°C (550°, 450°, and 500°F). Sustained operation at the desired outlet temperature was obtained only with the 232°C (450°F) test on 18 December.

Results

On 17 December, the 1.3-ℓ/s (20-gal/min) flow rate and buffer tank oil recirculation were maintained until midafternoon to attain the desired 288°C (550°F) collector system output temperature. This temperature was maintained only briefly. The inclusion of the main storage tank in the flow loop again reduced the outlet temperature. Collector efficiency was less than 10% most of the day, averaging 4.4%. The brief spike in the efficiency curve is an erroneous indication due to low inlet temperatures at the moment of tank switching while outlet temperatures were still high.

The 18 December test resulted in almost constant collector output at 232°C (450°F). The efficiency curve is U-shaped. Collector efficiency was 8.0% to 8.4% near noon, nearly 20% for a short period in midmorning, and about 30% for a moment in midafternoon. Average daily collector efficiency was 9.9%.

The data of 24 December show performance on a day of intermittent cloudiness and less direct insolation. Buffer-tank-only flow recirculation occurred, and collector outlet temperatures gradually increased to over 200°C (392°F). Midafternoon insolation improved, and efficiency increased from about 5% to more than 10%. Operation on this cloudy day was productive, but collection efficiency averaged only 3.7%.

Conclusions

Collector system efficiency ranged from about 8% at noon to nearly 20% at midmorning and midafternoon with 200°C (392°F) inlet and 232°C (450°F) outlet temperatures on 18 December. The north-south orientation of the collectors dictates that the collection efficiency shall peak in midmorning and midafternoon and dip at noon. This pattern occurs because the sun is more normal to the collectors in midmorning and midafternoon than at noon. The desired outlet temperature of 288°C (550°F) was obtained for only a short time on 17 December. Tests on 24 December yielded cloudy-weather performance data.

Collection efficiencies are low near winter solstice. Little high-temperature collection can be attained by the subsystem. The subsystem performance could be improved by changing the collector reflector material from Coilzak to a high-reflectivity material such as FEK-244. Power plant operation with solar energy can be maintained throughout the winter season through the use of a fossil fuel heater plumbed in series with the collector field. In this mode, the collector field would be used to preheat the Caloria for the fossil fuel heater.

Collection efficiency is defined as the ratio of thermal energy gained by the oil as it passes through the collector field ($\dot{m}\, C_p \Delta T$) to the direct normal insolation measurement multiplied by the collector aperture area. Oil properties are

Density = $55.06 - 0.02337T$ (Density in lb/ft^3; T in °F)

$C_p = 0.4458 + 4.796 \times 10^{-4}T$ (C_p in Btu/lb•°F; T in °F)

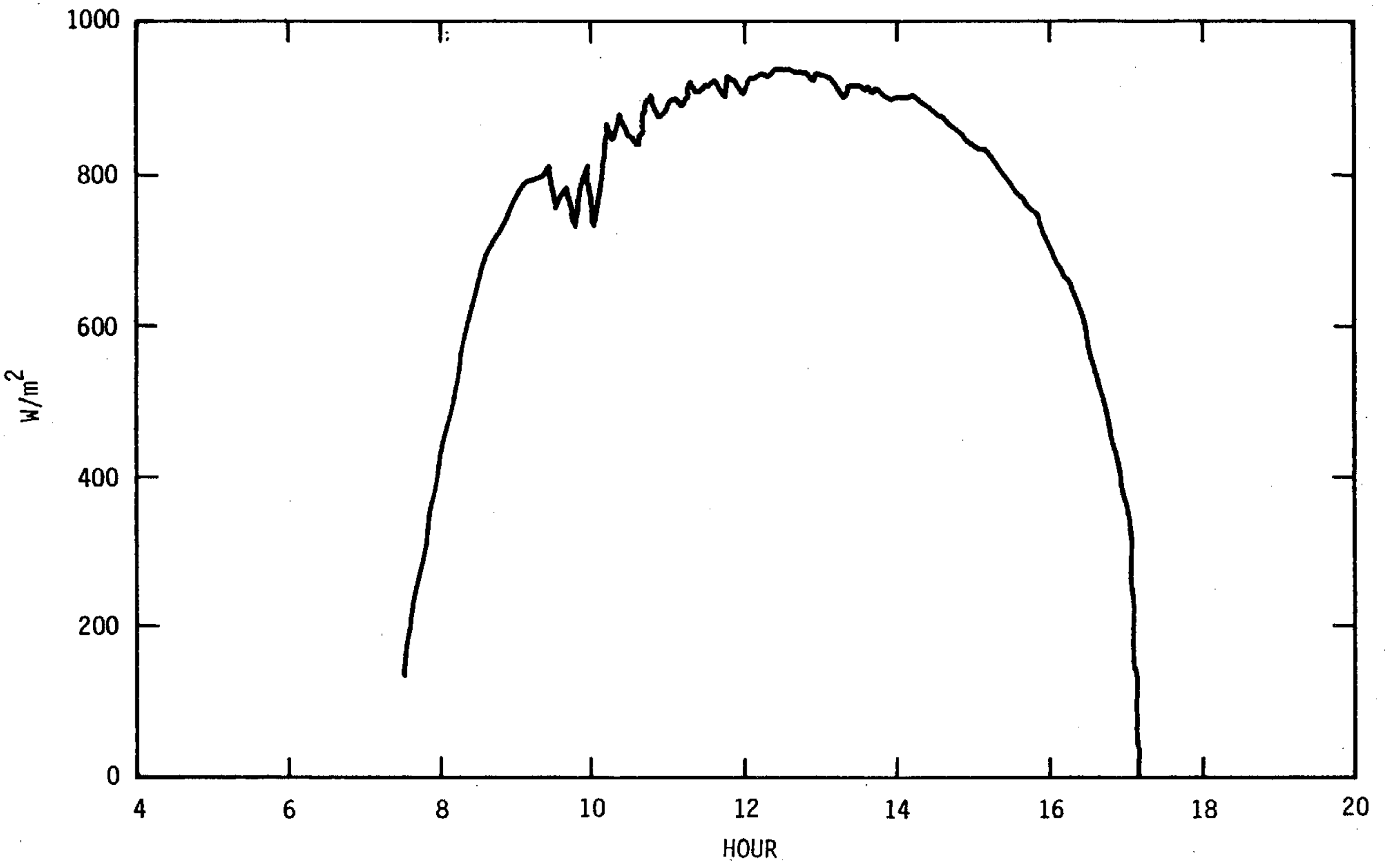


Figure 1. Insolation, 351-1979

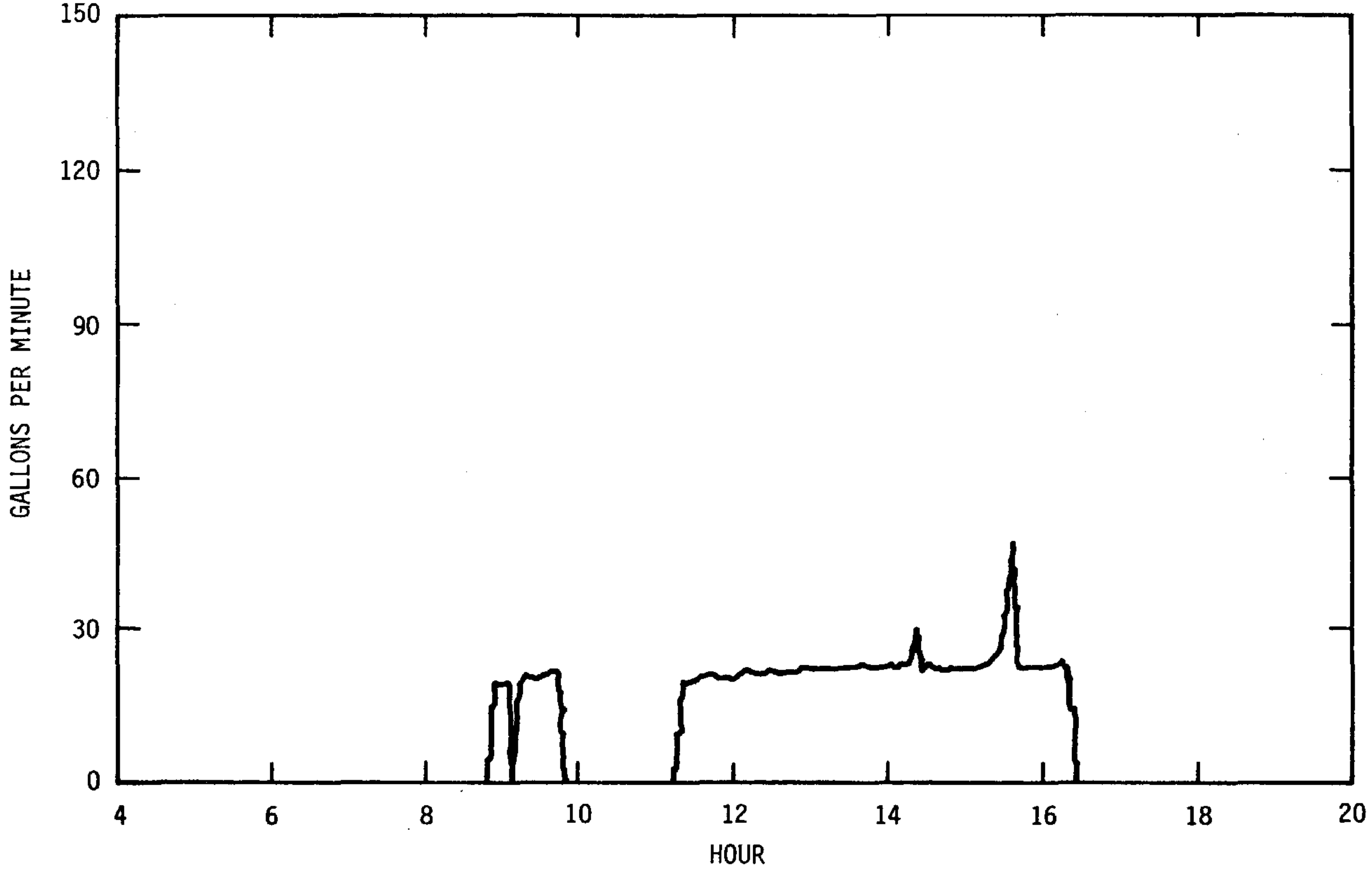


Figure 2. Flow Rate, 351-1979

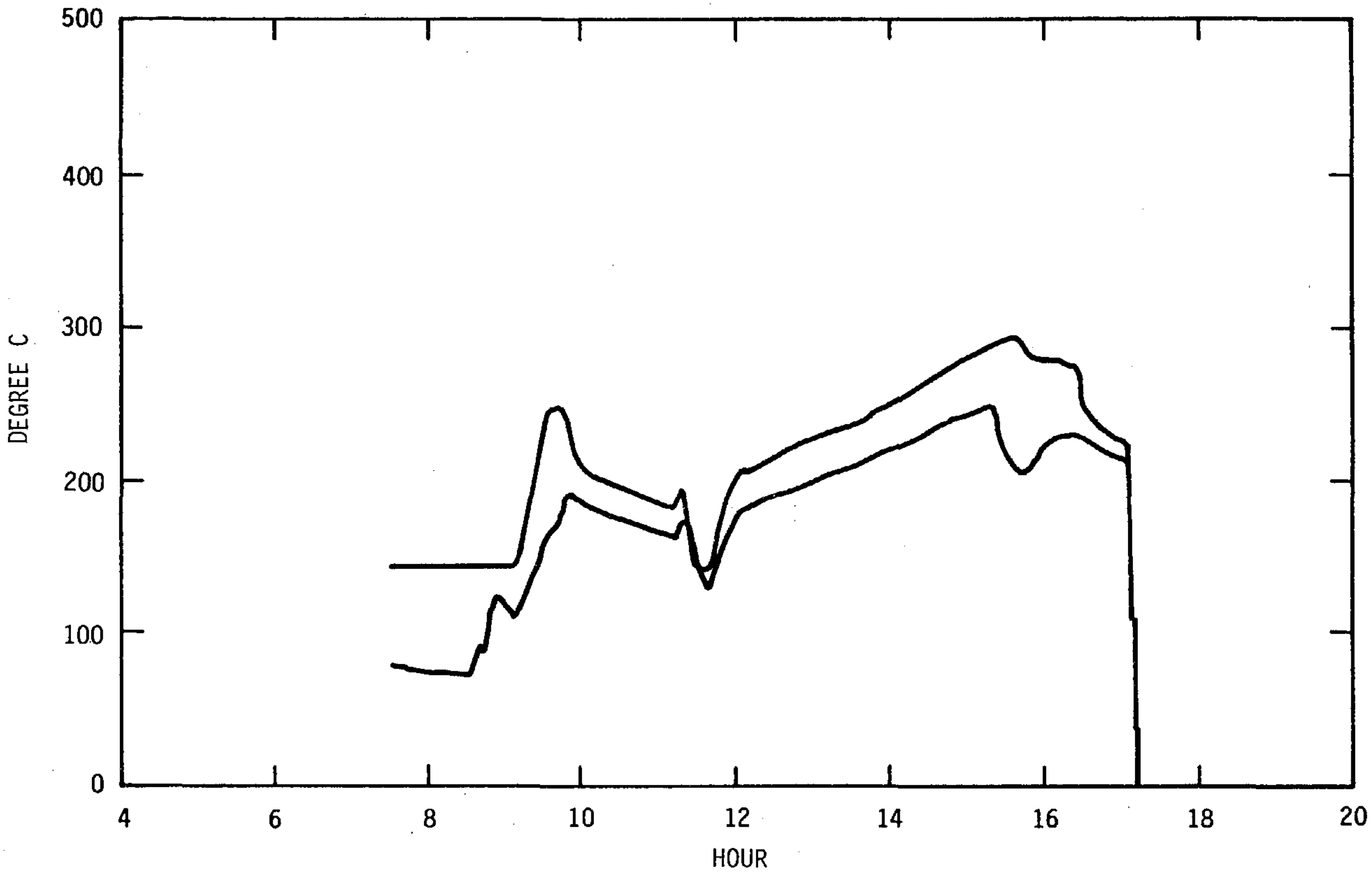


Figure 3. Inlet and Outlet Temperatures, 351-1979

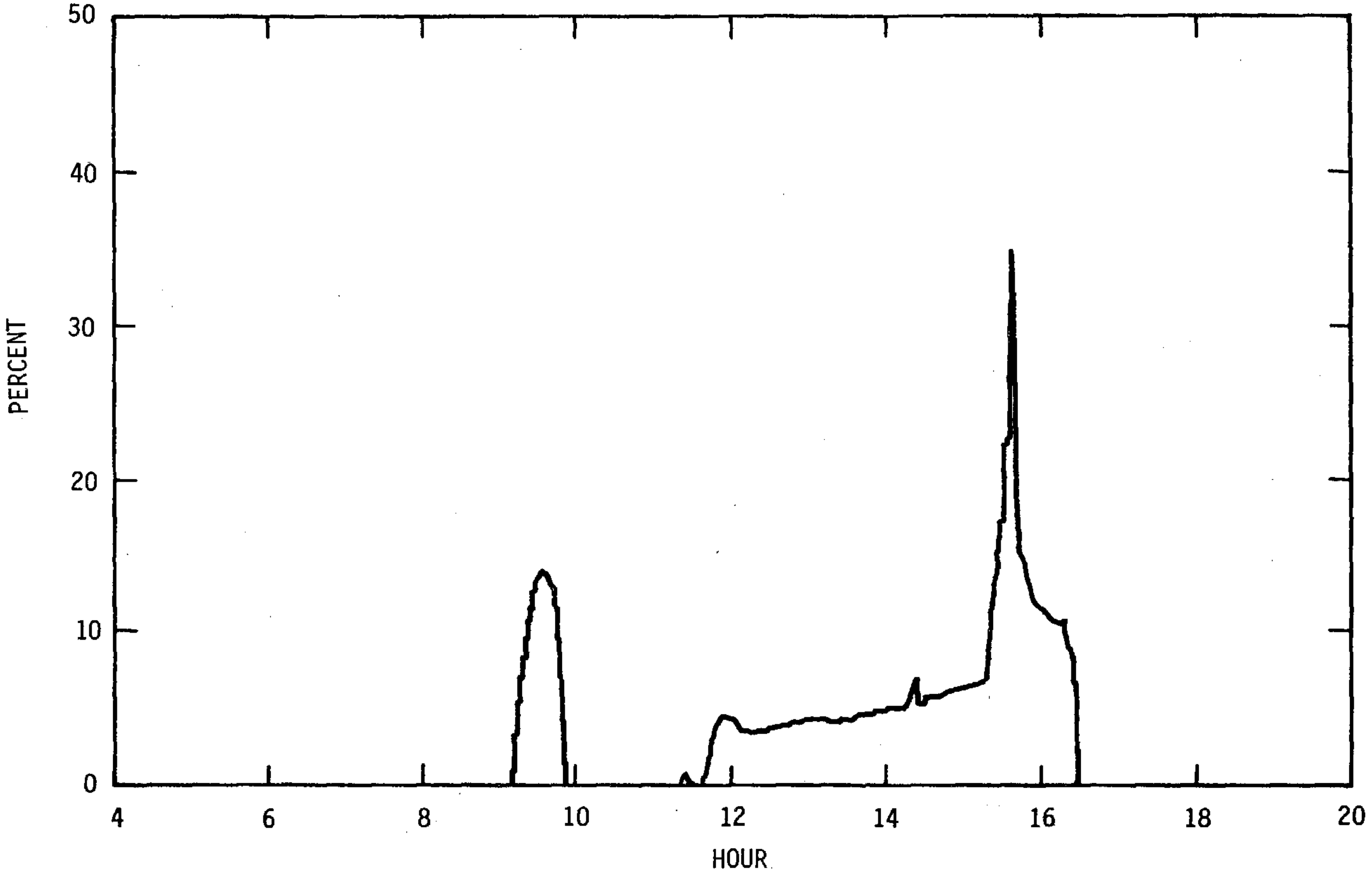


Figure 4. Efficiency, 351-1979

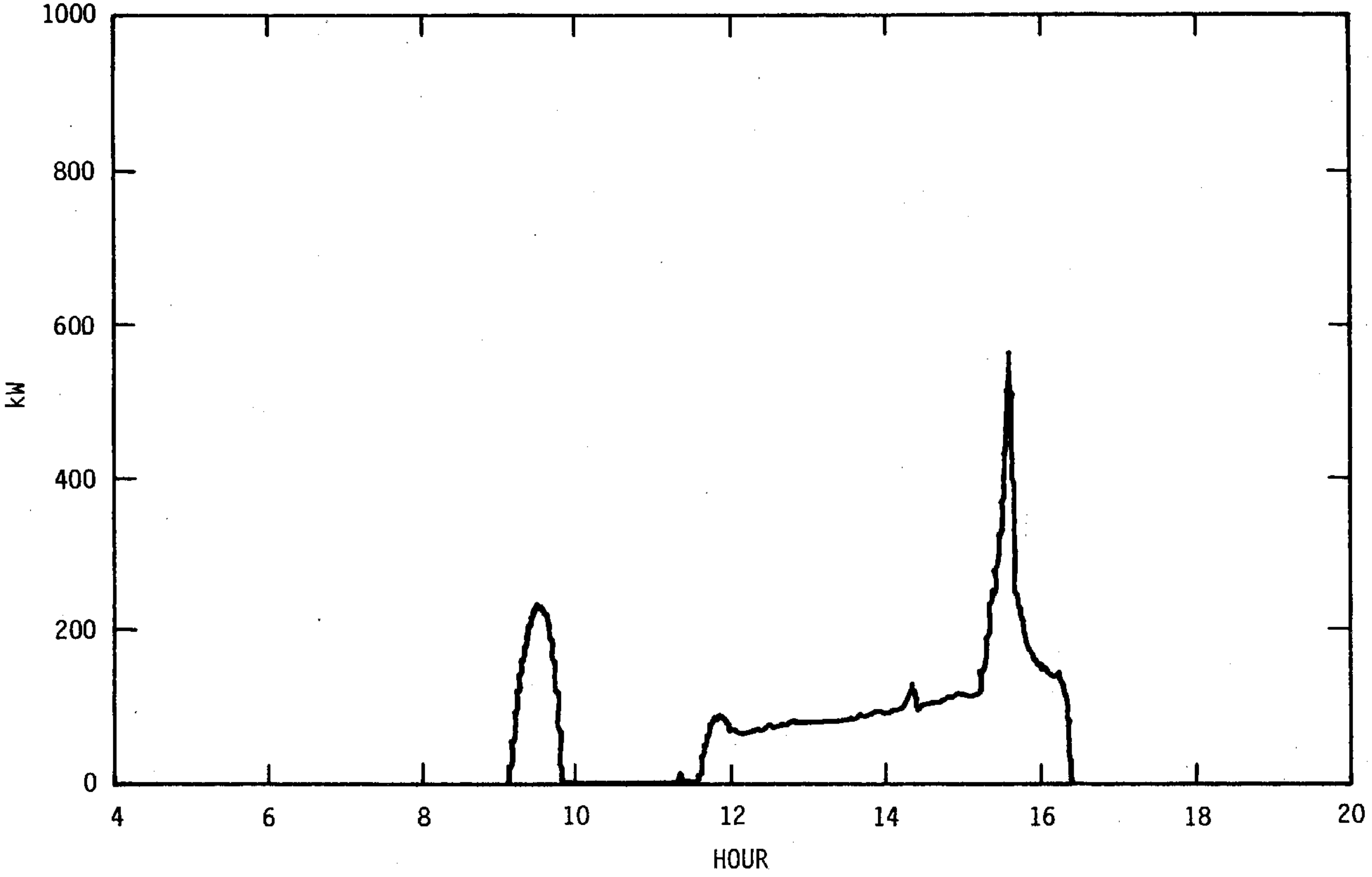


Figure 5. Collected Power, 351-1979

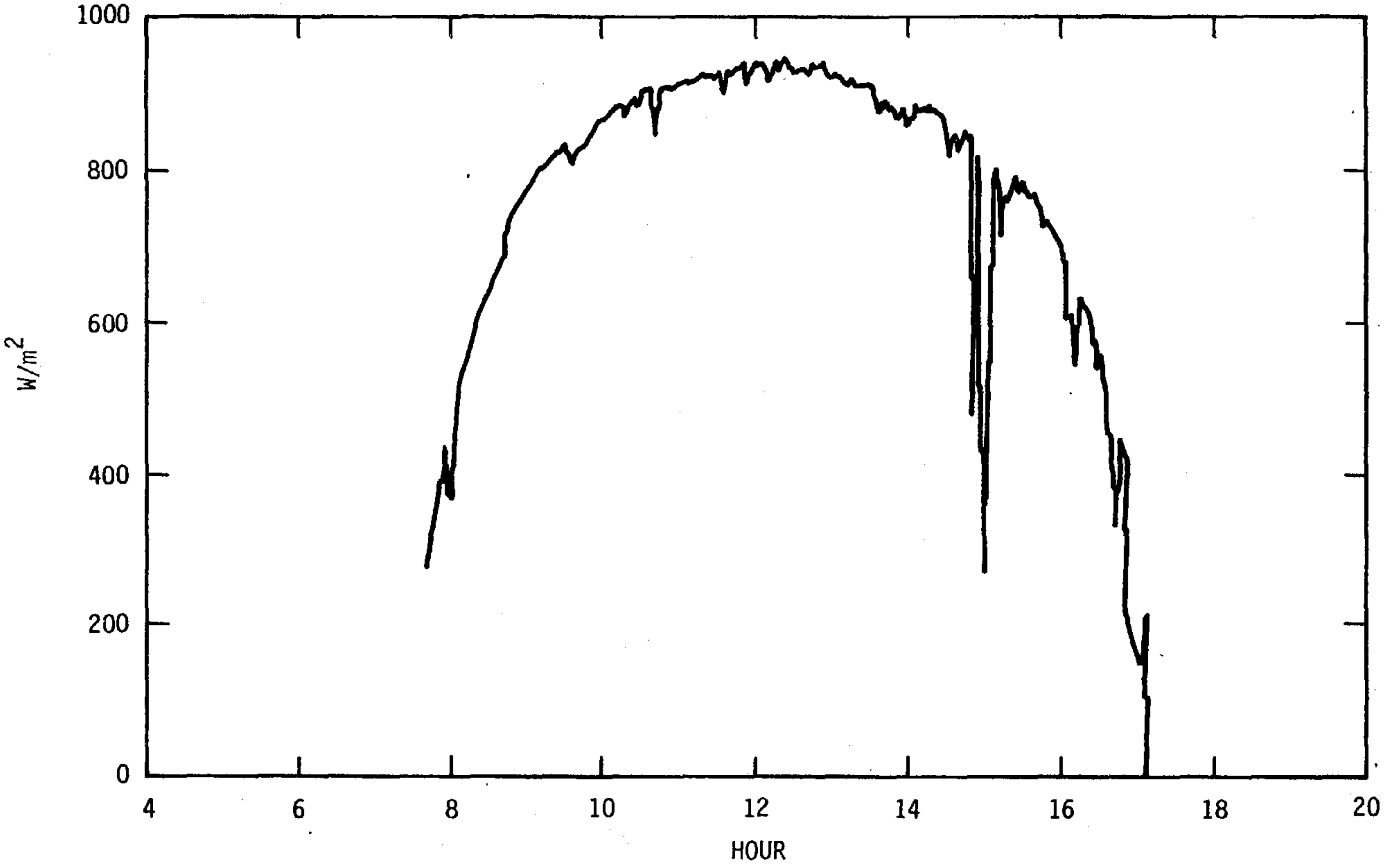


Figure 6. Insolation, 352-1979

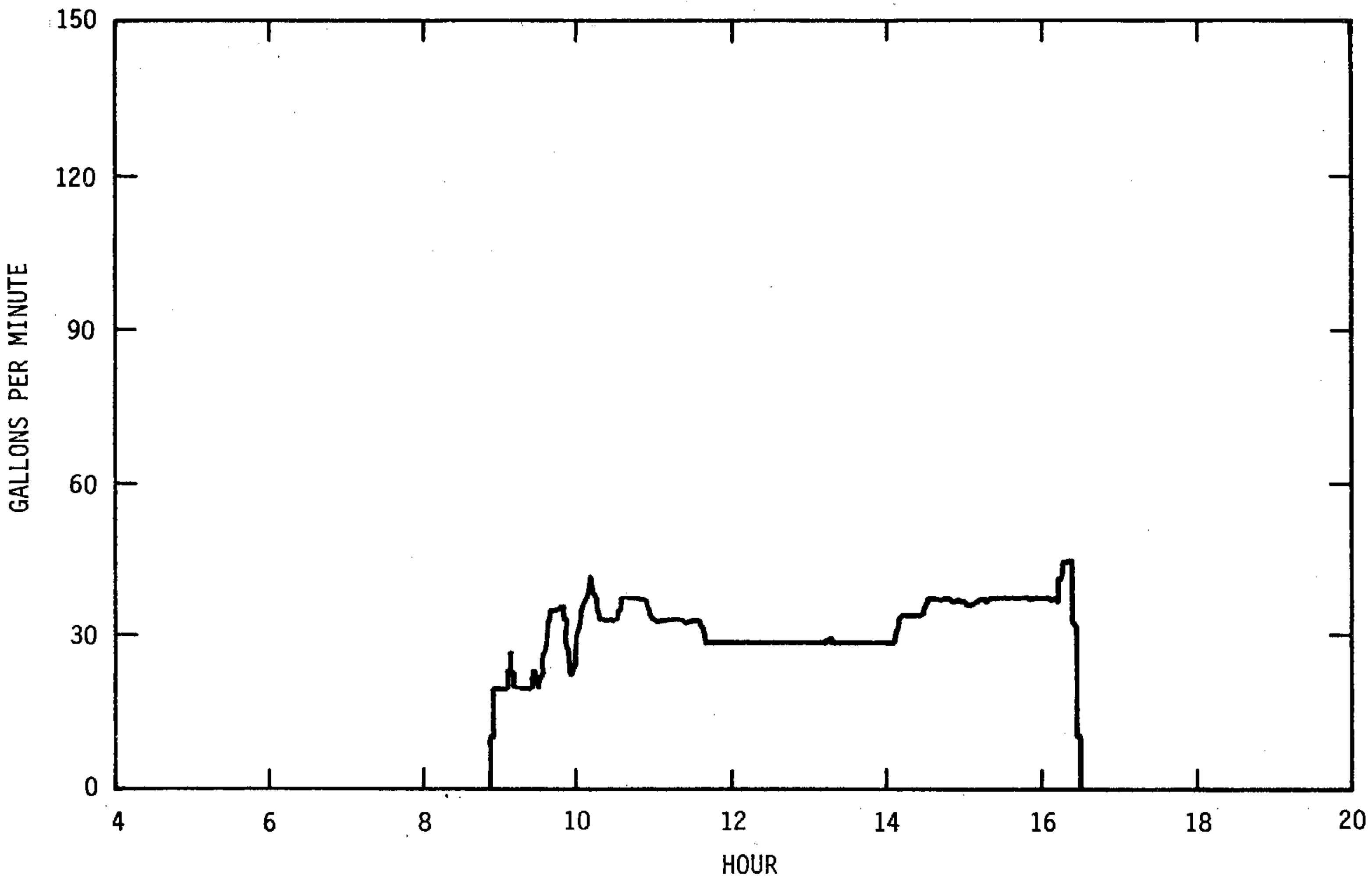


Figure 7. Flow Rate, 352-1979

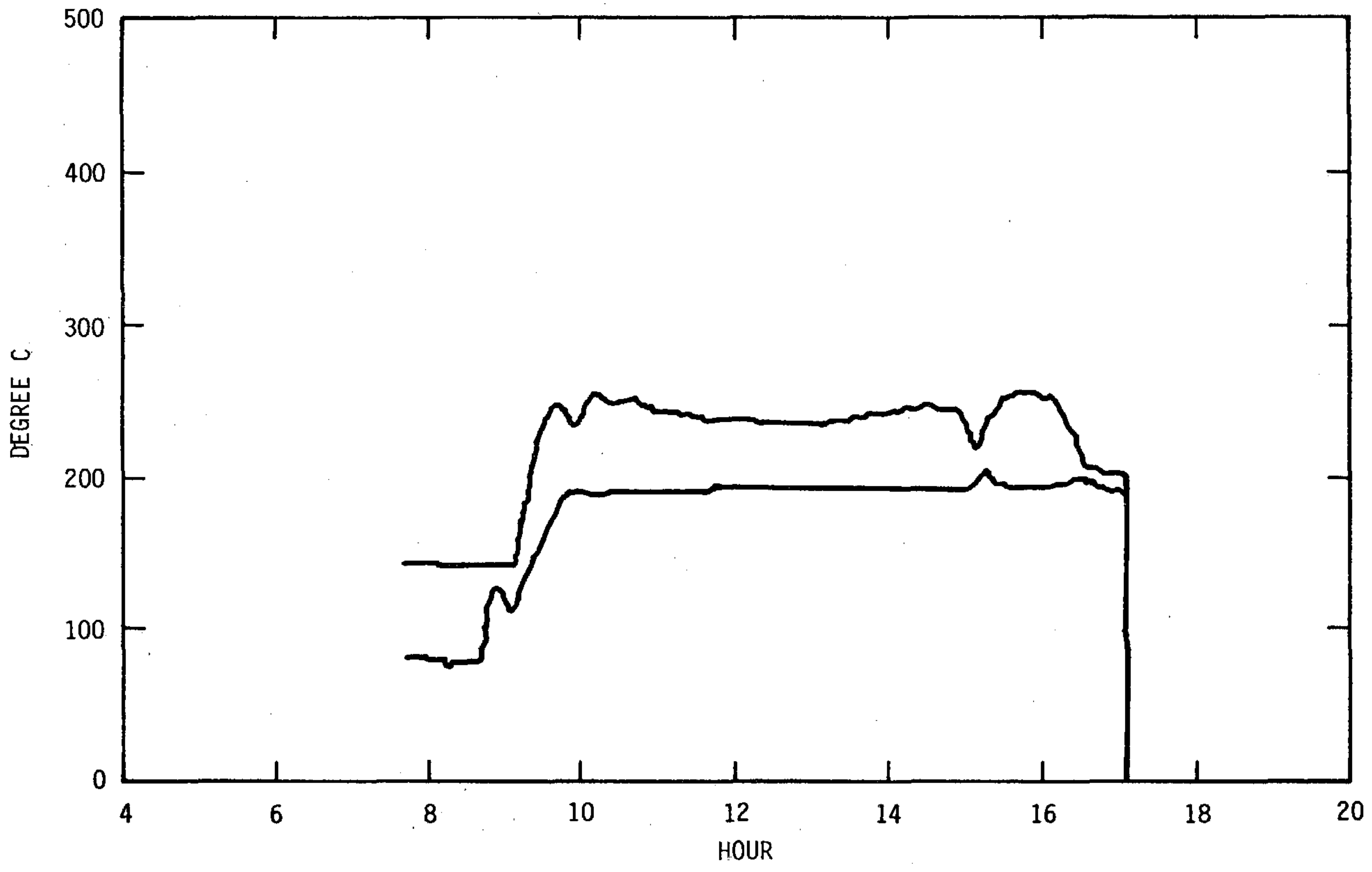


Figure 8. Inlet and Outlet Temperatures, 352-1979

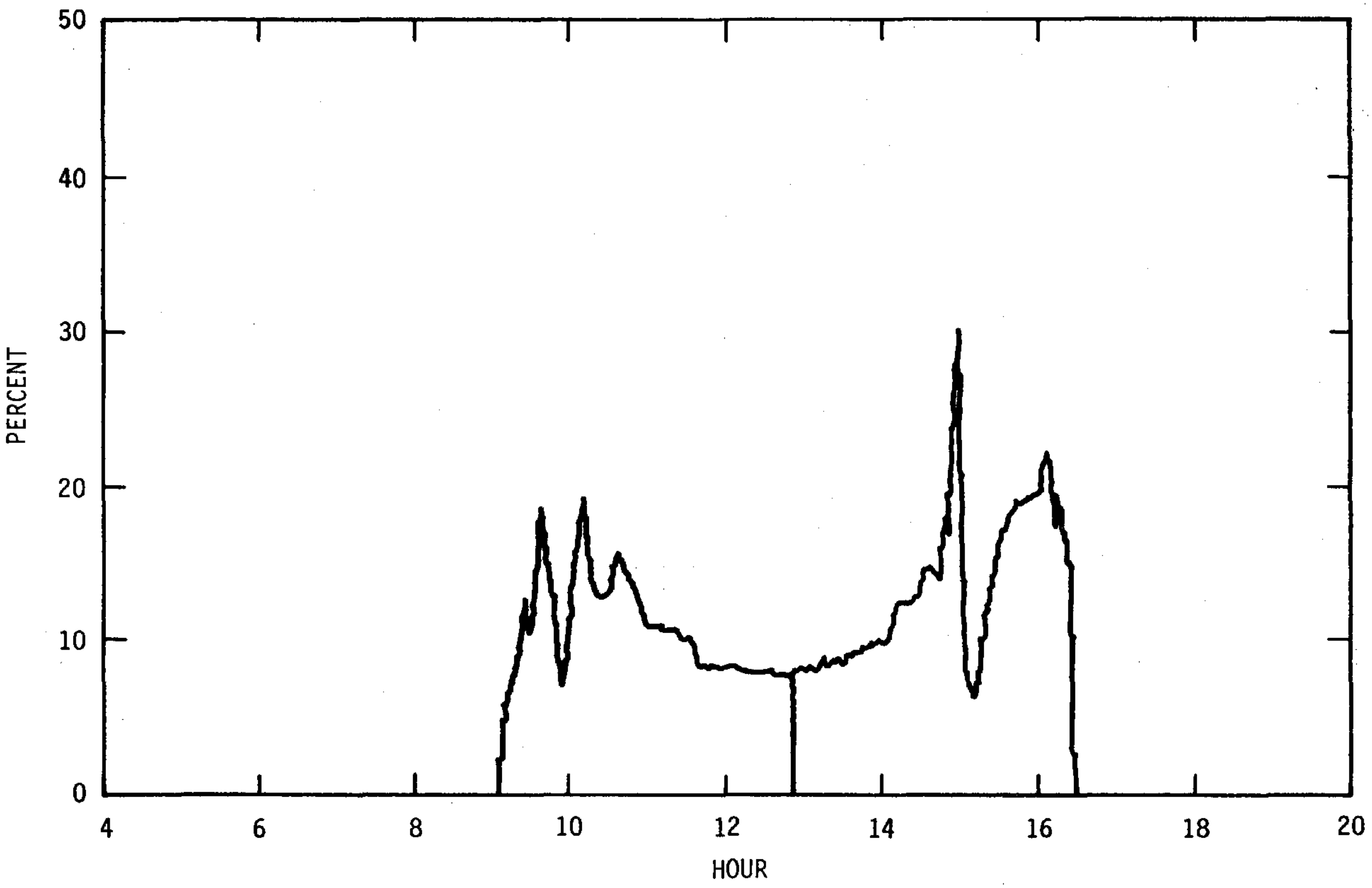


Figure 9. Efficiency, 352-1979

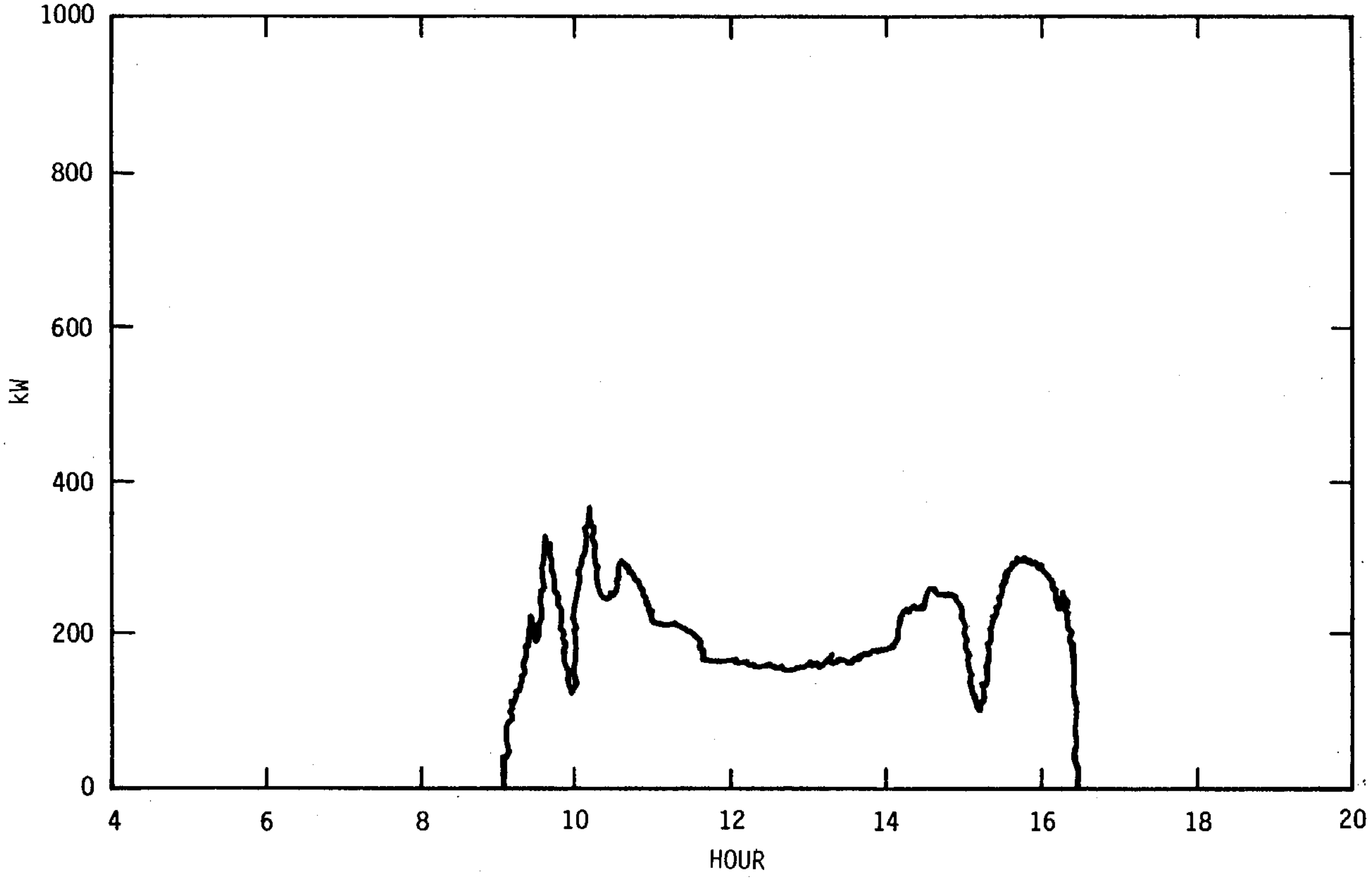


Figure 10. Collected Power, 352-1979

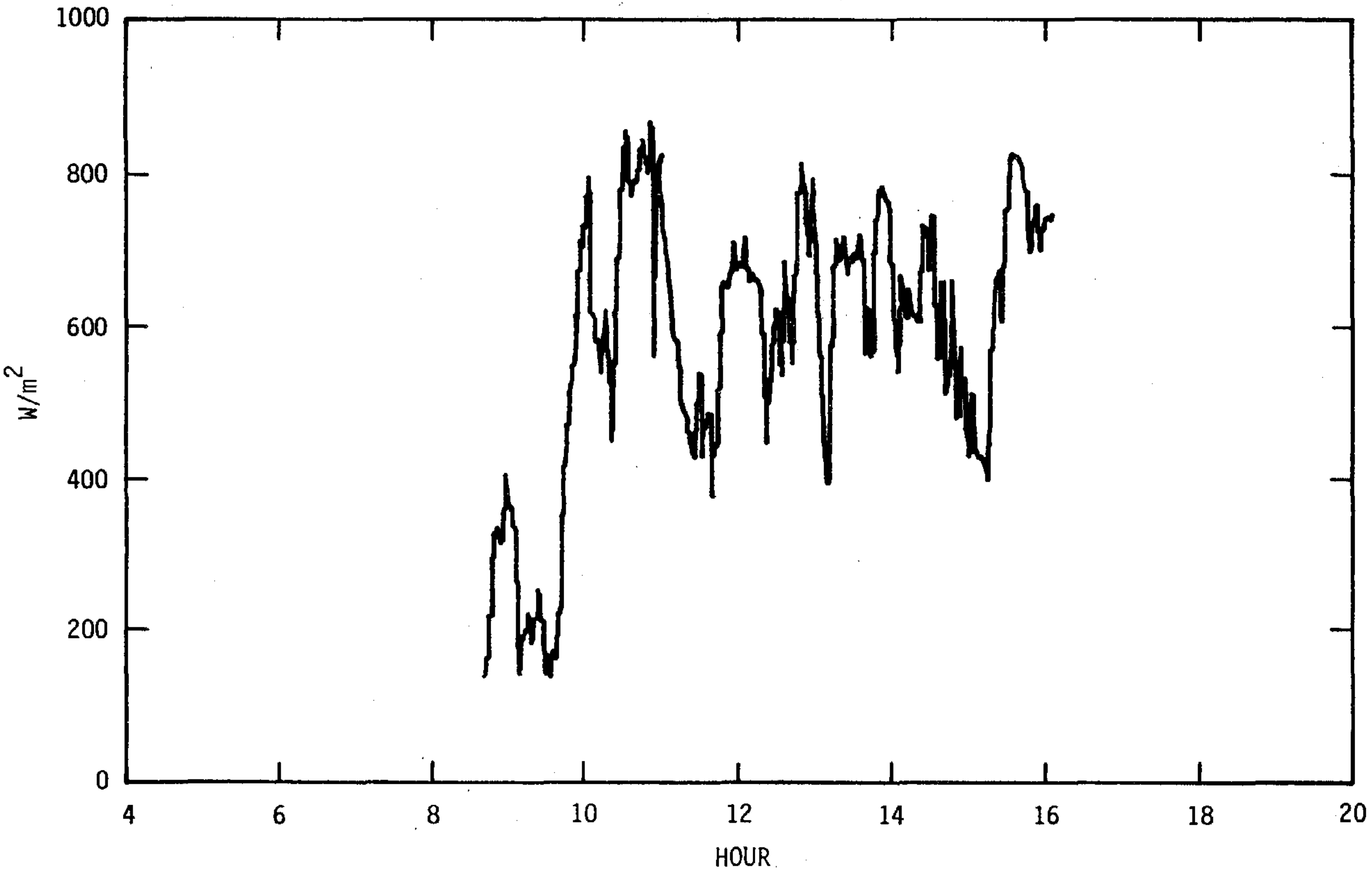


Figure 11. Insolation, 358-1979

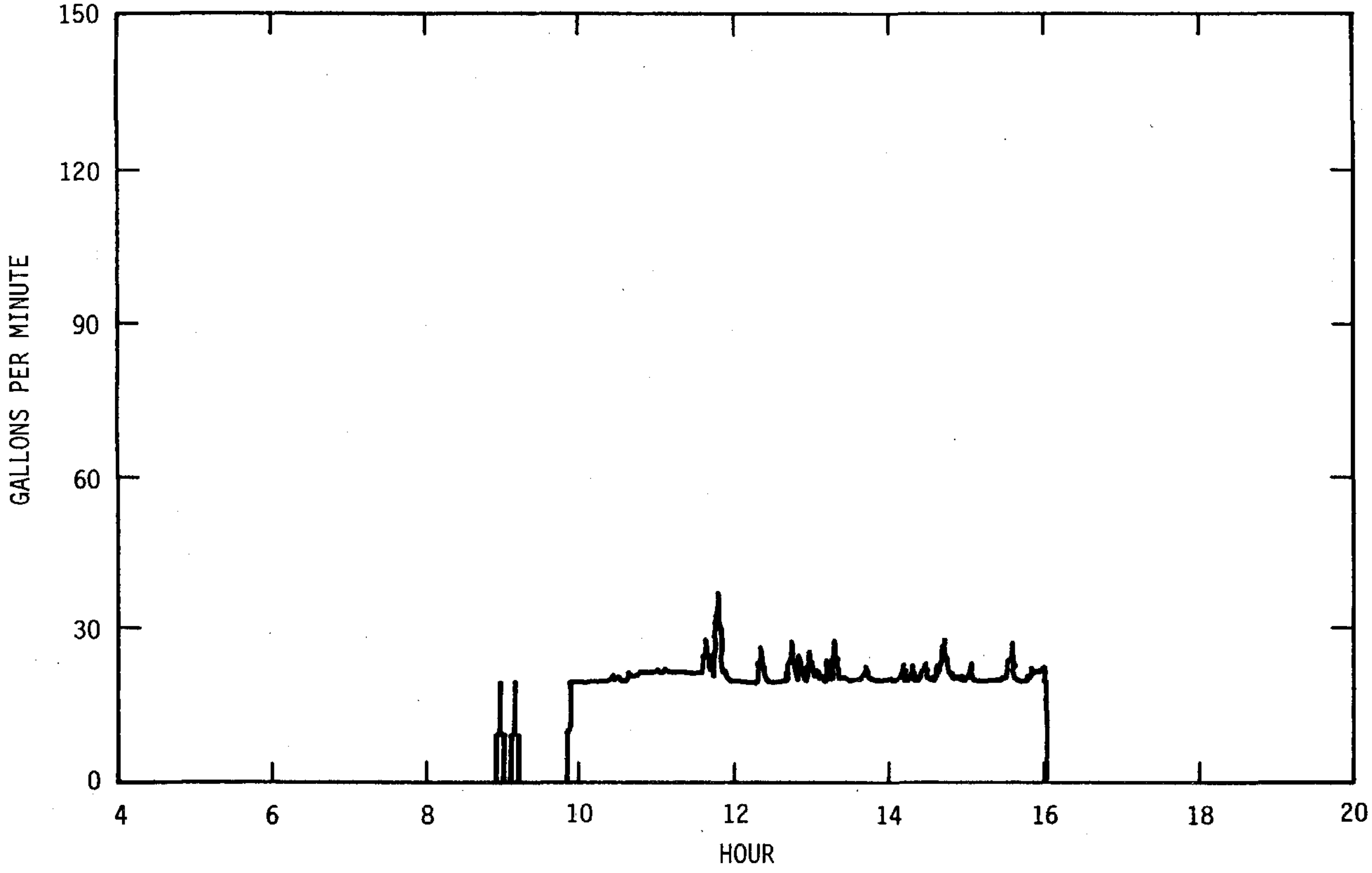


Figure 12. Flow Rate, 358-1979

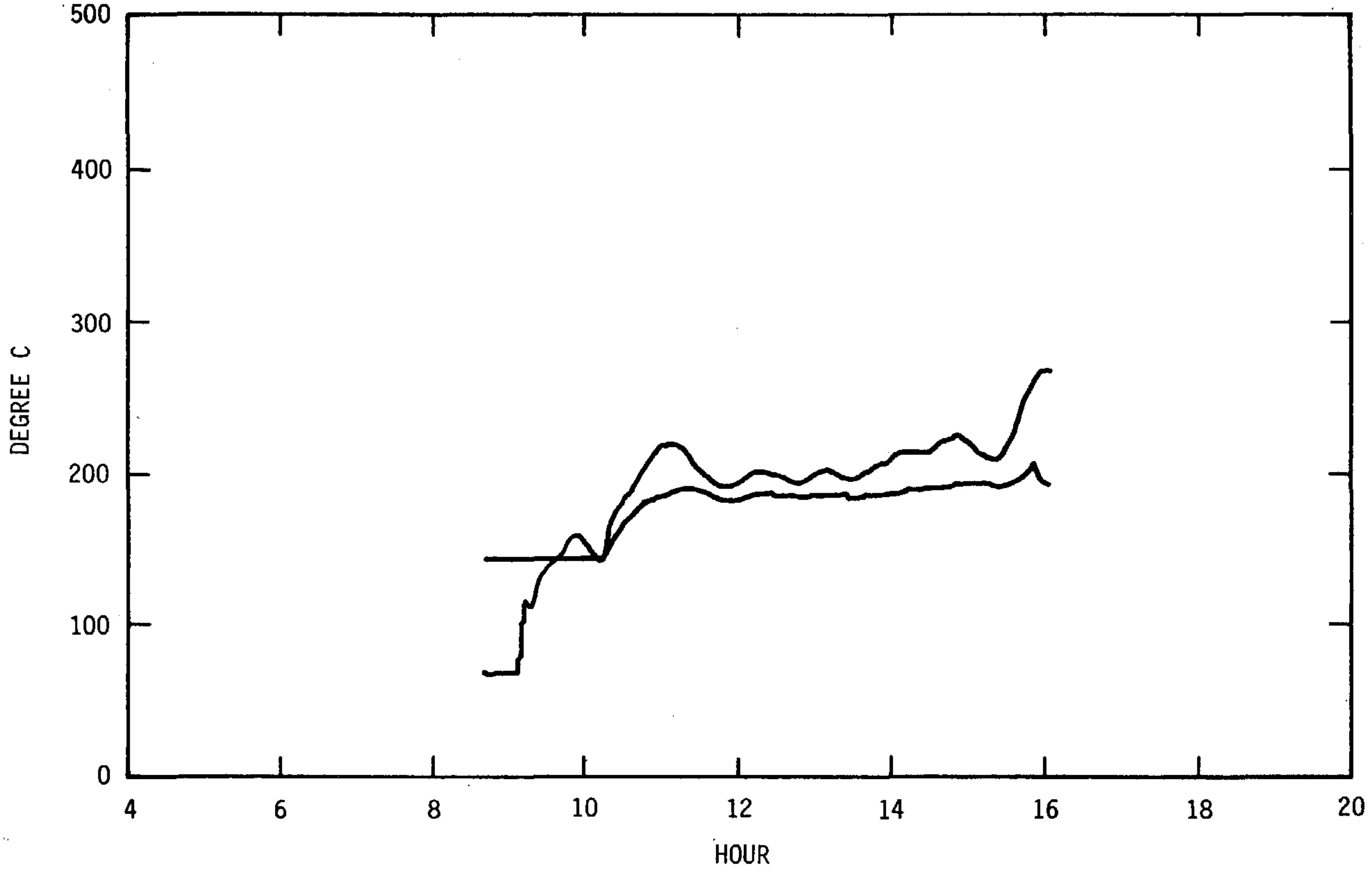


Figure 13. Inlet and Outlet Temperatures, 358-1979

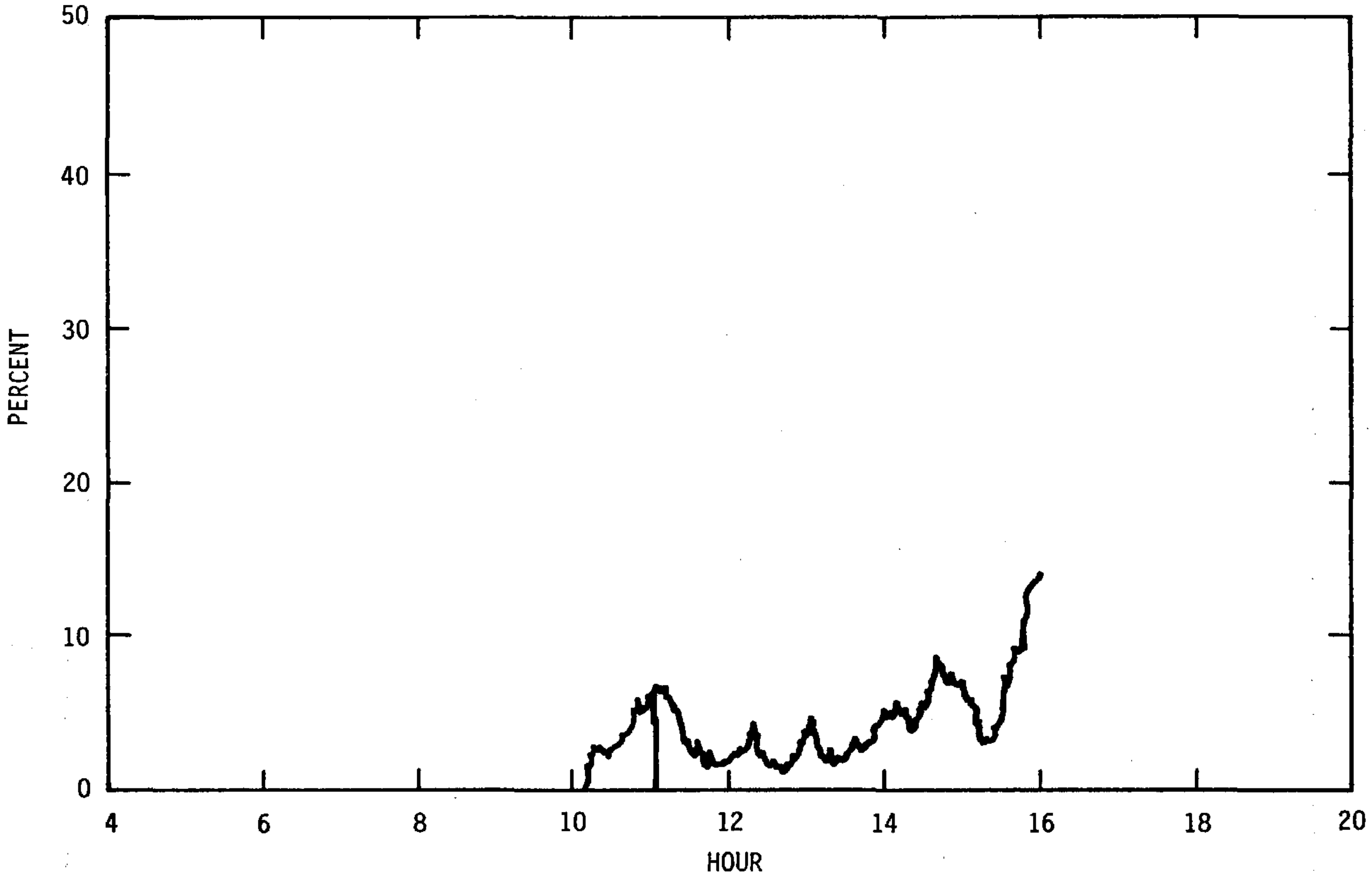


Figure 14. Efficiency, 358-1979

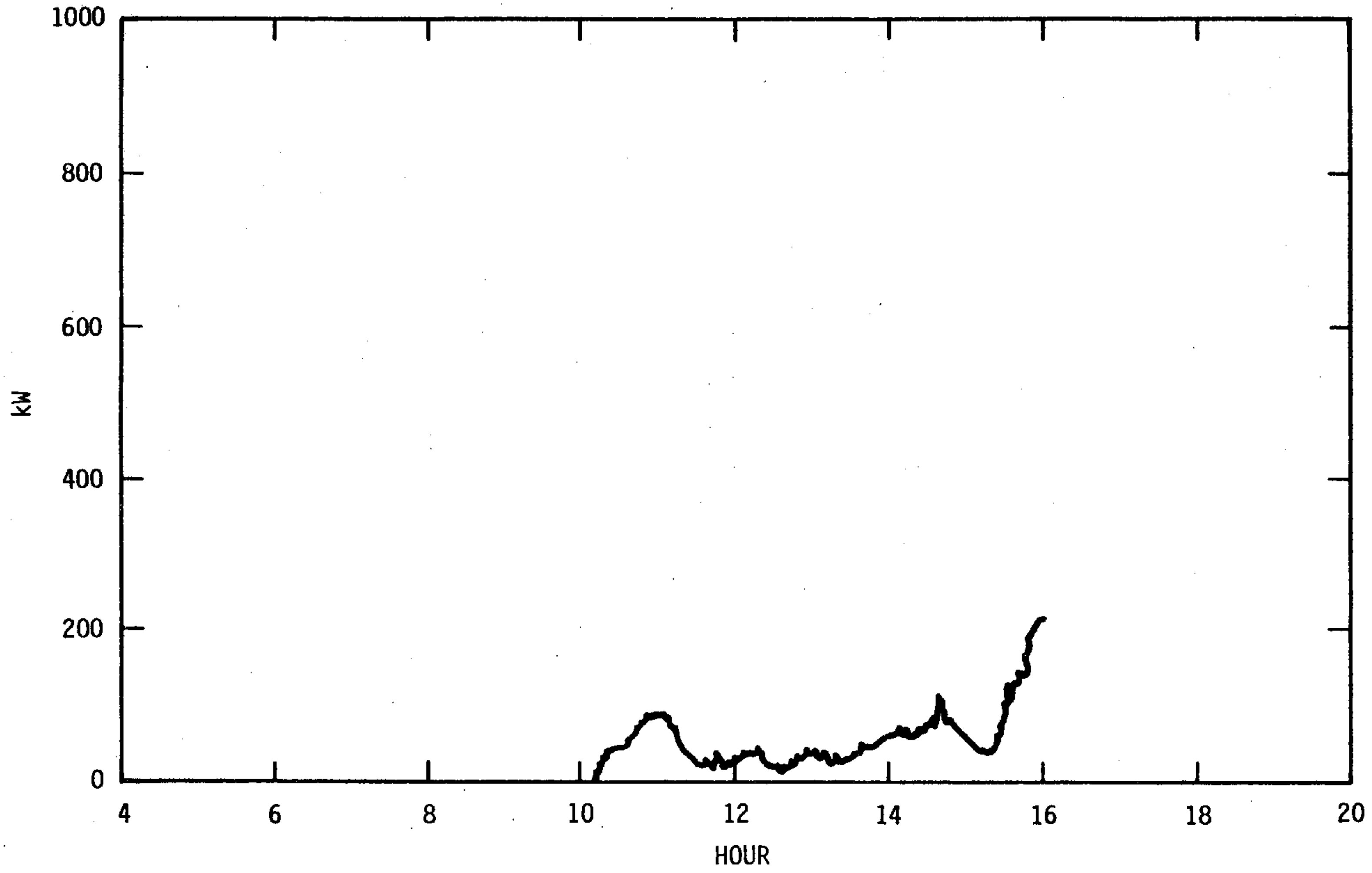


Figure 15. Collected Power, 358-1979

SOLAR COLLECTOR SYSTEM VERNAL EQUINOX PERFORMANCE, 20 AND 23 MARCH AND 3 APRIL 1980

Solar collector performance tests were conducted on 20 and 23 March and 3 April 1980 (days 80, 83, and 94) to determine solar energy collection efficiency during the period near spring equinox. Average collection efficiencies for those days were 22.9%, 26.9%, and 30.1%, respectively.

Methods

Collector reflective surfaces and receiver insulating glass tubes were washed, and tracking was adjusted to align reflection onto the receiver tubes prior to commencing the performance tests. Washing and rinsing by a commercial firm was repeated before the 3 April test.

After a lower flow rate startup period to preheat the system, Caloria was circulated from the main storage tank at a flow rate which maintained the desired collector system outlet temperature. Inlet temperature was about 200°C (392°F); outlet temperature was 260° to 288°C (500° to 550°F) during the various tasks.

All test periods had good insolation and moderate ambient temperatures and wind velocities. See Table 1 for the times recorded for the events of each test day.

Collector system flow rate was measured with a vortex-type device, temperatures with resistance temperature detector (RTD) and thermocouple sensors, and insolation with a pyrheliometer.

Table 1

Times Recorded on Days of Spring
Equinox Collector Tests

Event	March 20	March 23	April 3
Sunrise	6:28 a.m.	6:20 a.m.	6:14 a.m.
Collectors Focused	7:38 a.m.	7:34 a.m.	7:20 a.m.
Switch to Main Tank	8:58 a.m.	8:29 a.m.	8:08 a.m.
Collectors Defocused	5:45 p.m.	5:32 p.m.	5:42 p.m.
Sunset	6:35 p.m.	6:35 p.m.	6:47 p.m.

Collector system efficiency was computed as thermal energy gained by Caloria between system inlet and outlet manifold locations divided by direct normal solar radiation times the collector aperture area.

Conclusions

The collection efficiency at vernal equinox was shown to be significantly higher than at winter solstice. This was as expected, since the incidence angles between the sun and the collector apertures are much less at vernal equinox than at winter solstice. At equinox, the sun is exactly normal to the collectors at sunrise and sunset and less than normal at noon, which explains the shape of the efficiency curves.

Performance test results for days 80, 83, and 94 follow.

Day 80 Results

Solar collector system efficiency on day 80 ranged from 23% to 29% for much of the central part of the test period. The average collection efficiency for the entire day was 22.9%.

Day 80 was clear with modest winds which briefly ranged up to 10 km/h (6.2 mi/h). Ambient temperature was about 20°C (68°F) during much of the test period.

Collector system outlet temperature was maintained at about 280°C (535°F) during most of the test. Inlet temperature was about 225°C (437°F). Collector system Caloria flow rate was quite variable but was about 5 ℓ/s (79 gal/min) for much of the test period.

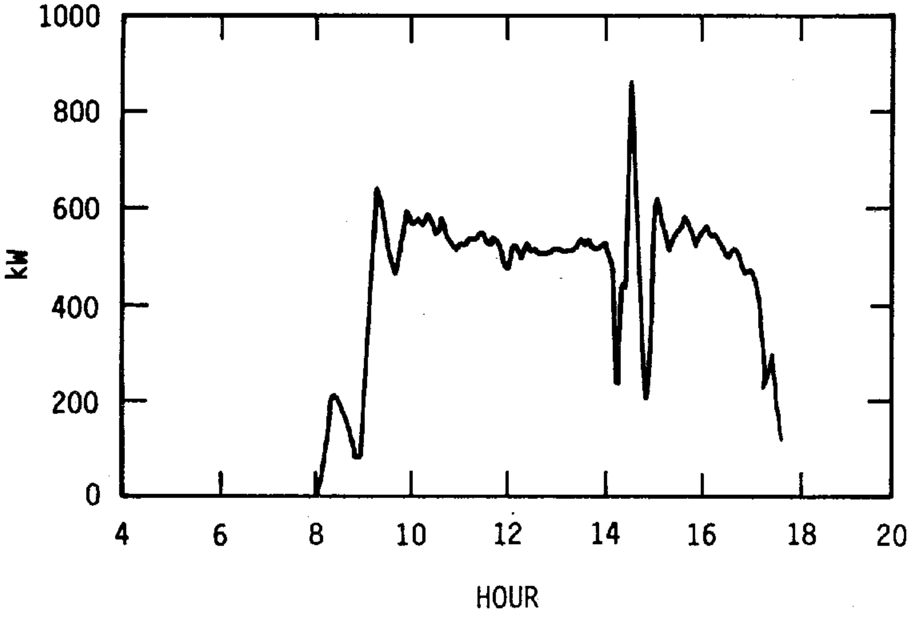


Figure 1. Collected Power, 80-1980

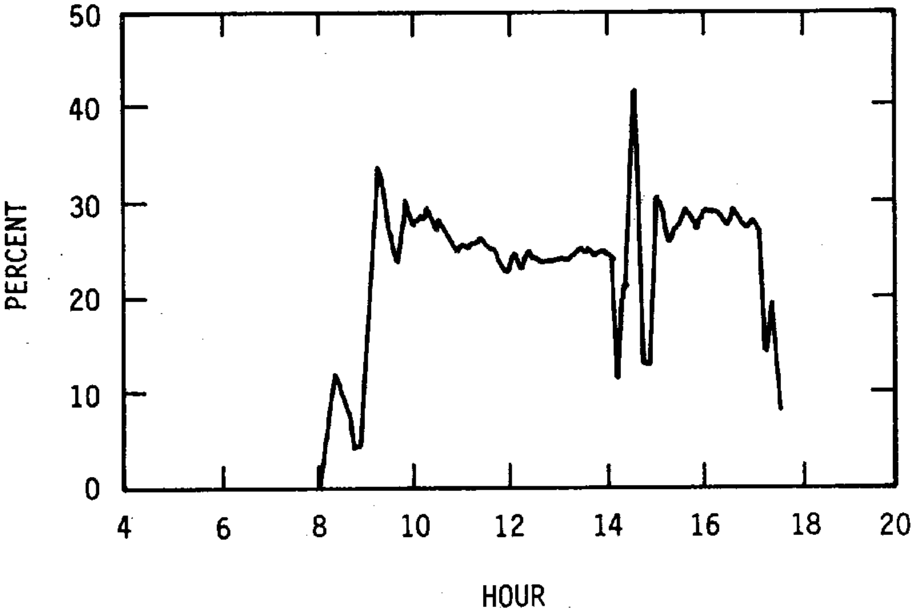


Figure 2. Efficiency, 80-1980

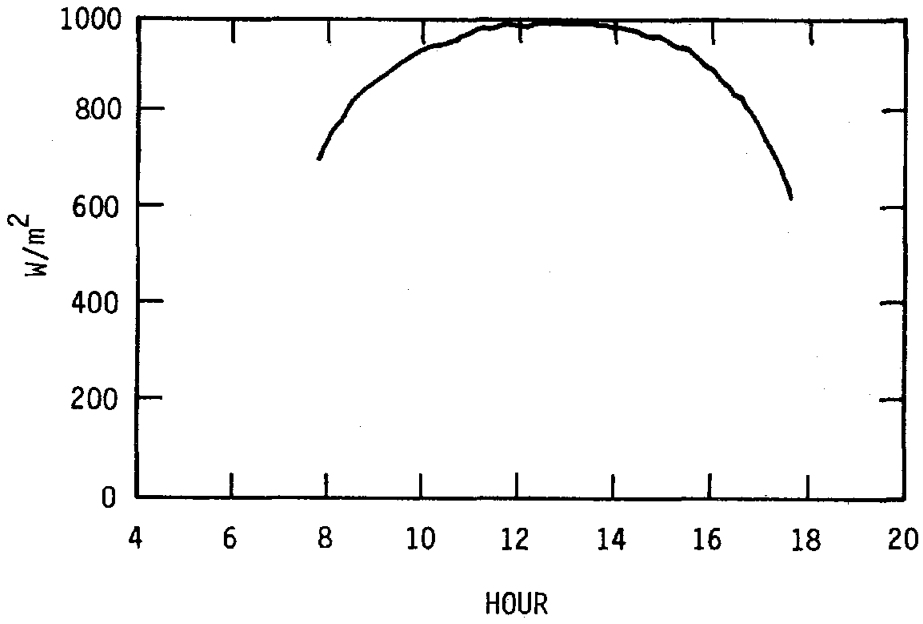


Figure 3. Insolation, 80-1980

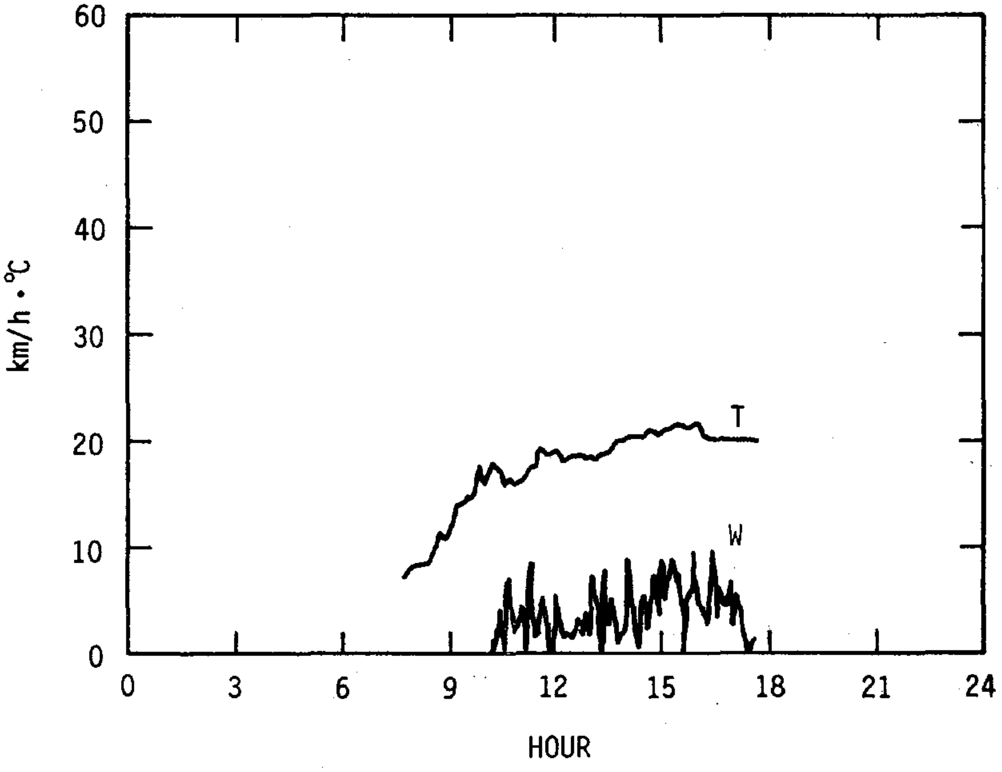


Figure 4. Wind Speed and Ambient Temperature, 80-1980

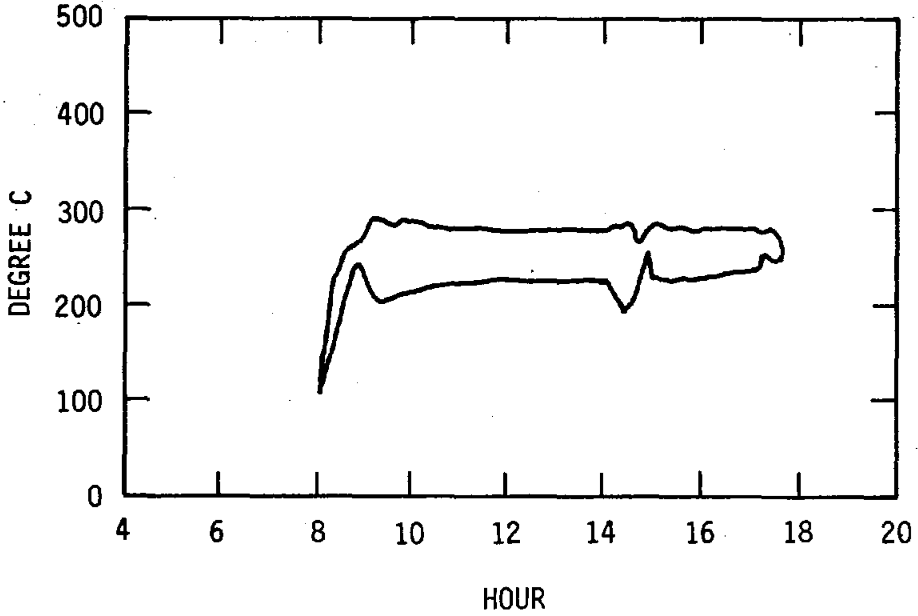


Figure 5. Inlet and Outlet Temperatures, 80-1980

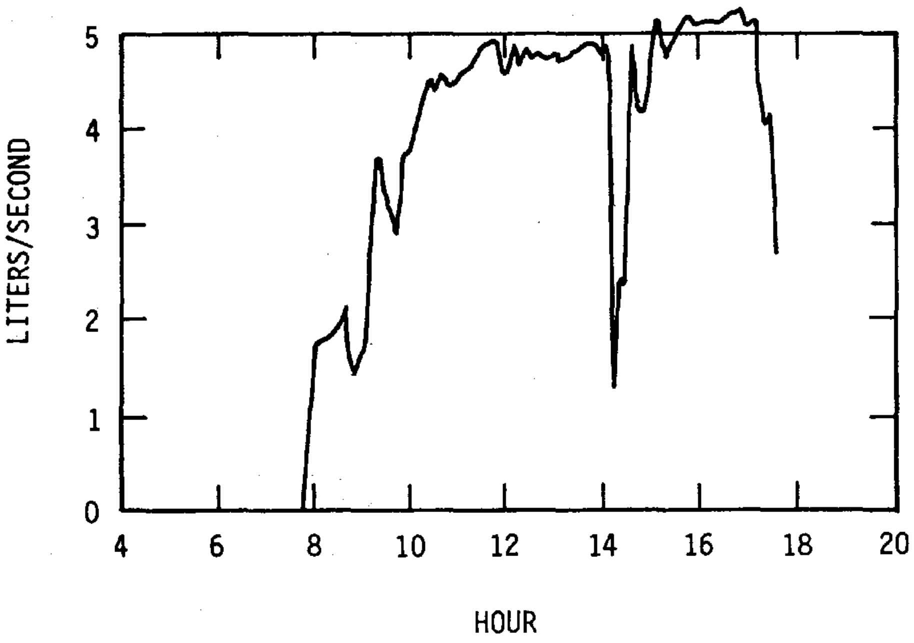


Figure 6. Flow Rate, 80-1980

Day 83 Results

On day 83, collector system efficiency ranged from 25% to 30% except for the periods immediately after startup and before shutdown. The average daily solar energy collection efficiency was 26.9%.

Day 83 was clear with essentially no wind. However, wind velocity was not recorded. Ambient temperature was 12° to 20°C (54° to 68°F).

The collector system outlet temperature was maintained at about 260°C (500°F). System flow rate was about 5 ℓ/s (79 gal/min) from 10 a.m. until 2 p.m. and then increased to nearly 6 ℓ/s (95 gal/min) for the remainder of the day to maintain the desired collector system outlet temperature.

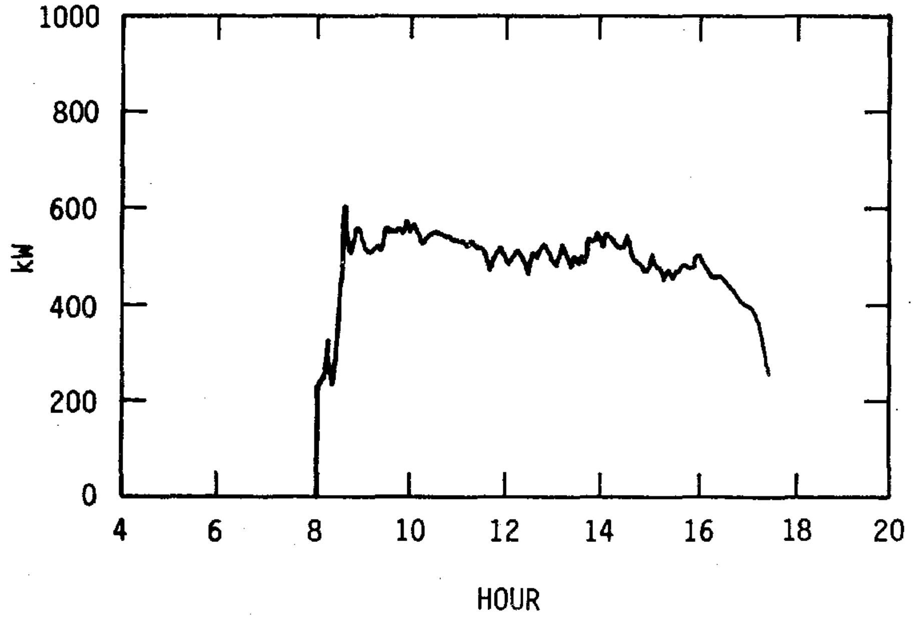


Figure 7. Collected Power, 83-1980

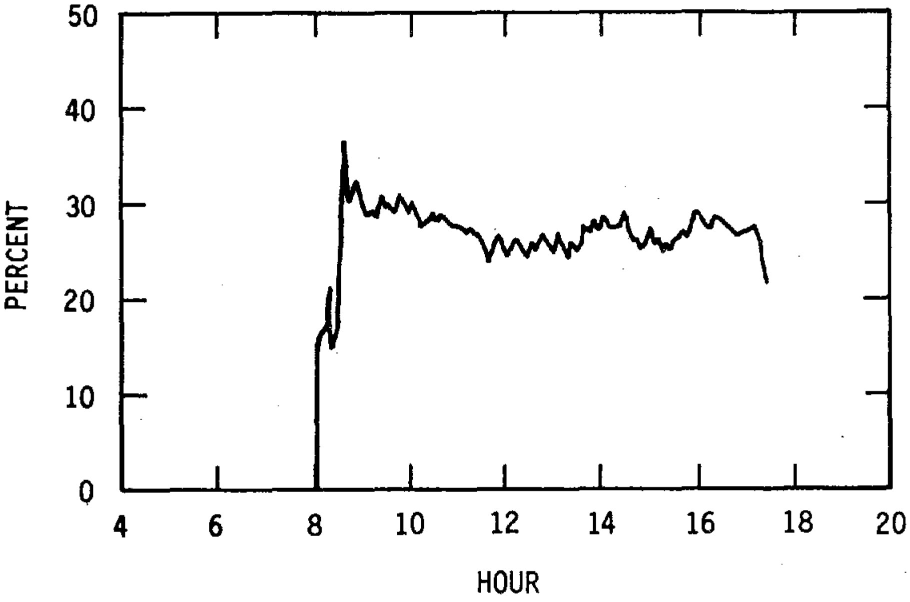


Figure 8. Efficiency, 83-1980

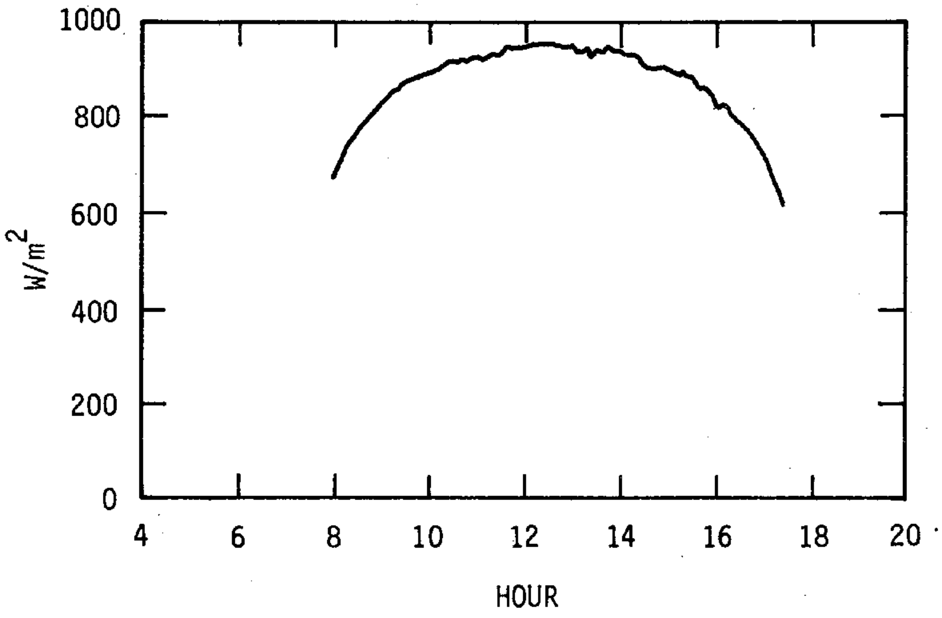


Figure 9. Insolation, 83-1980

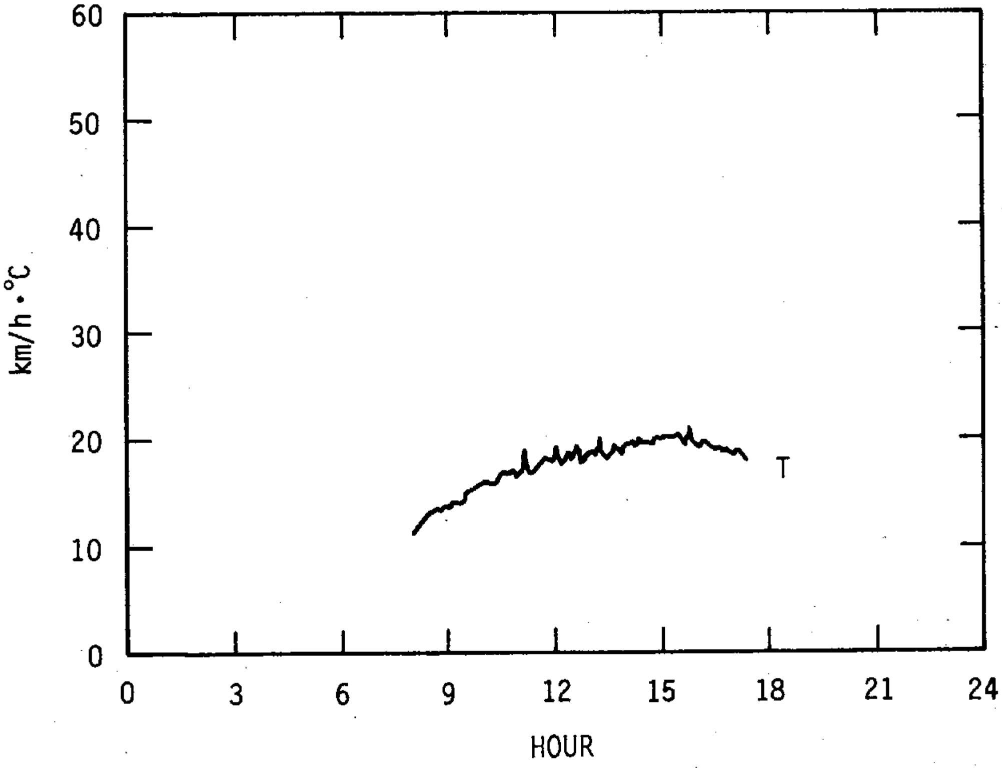


Figure 10. Wind Speed and Ambient Temperature, 83-1980

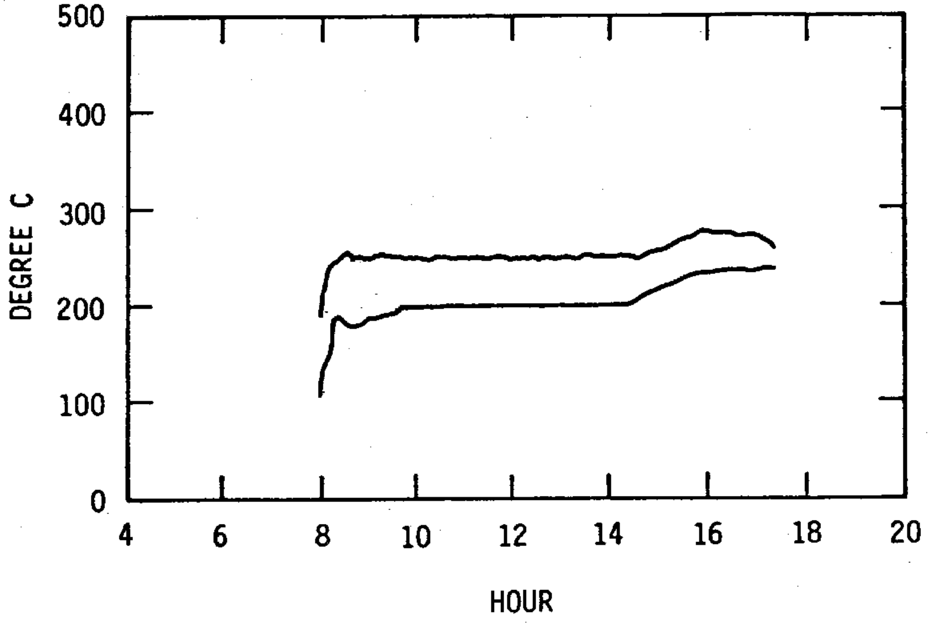


Figure 11. Inlet and Outlet Temperatures, 83-1980

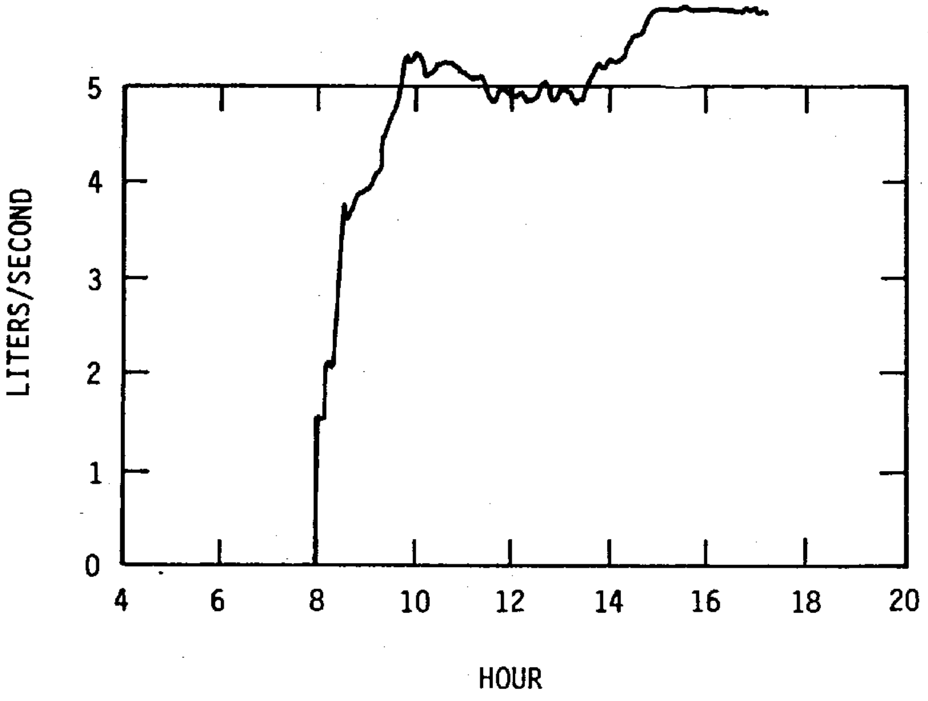


Figure 12. Flow Rate, 83-1980

Day 94 Results

Solar collector surfaces were washed and rinsed thoroughly by a commercial firm prior to the day 94 collector system performance test.

Collector system solar energy gathering efficiency ranged from 30% to 37% during the period from 9 a.m. to 3 p.m. The average collection efficiency during the day was 30.1%.

Day 94 was clear until after 4 p.m. Ambient temperature was only about 15°C (61°F) at 10 a.m. but increased to between 20° and 23°C (68° and 73°F) later in the test period. Wind velocities were highly variable, averaging about 5 km/h (3 mi/h) with brief wind bursts of over 10 km/h (6 mi/h) on four occasions.

The collector system outlet temperature was maintained at 285°C (545°F) throughout the test. Inlet temperature was about 190° to 200°C (374° to 392°F). System flow rate was about 3.4 ℓ/s (45 gal/min), but varied somewhat to maintain the desired outlet temperature.

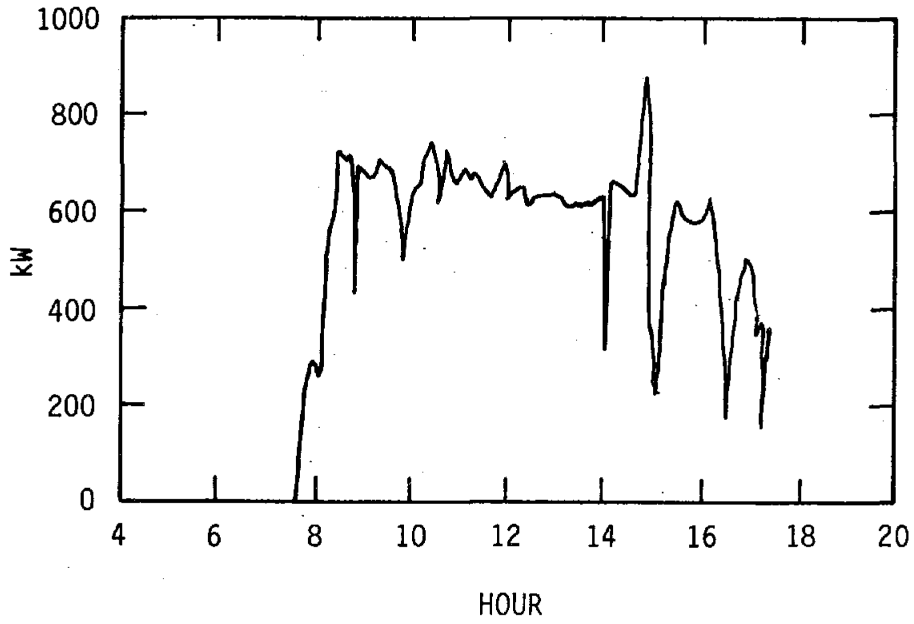


Figure 13. Collected Power, 94-1980

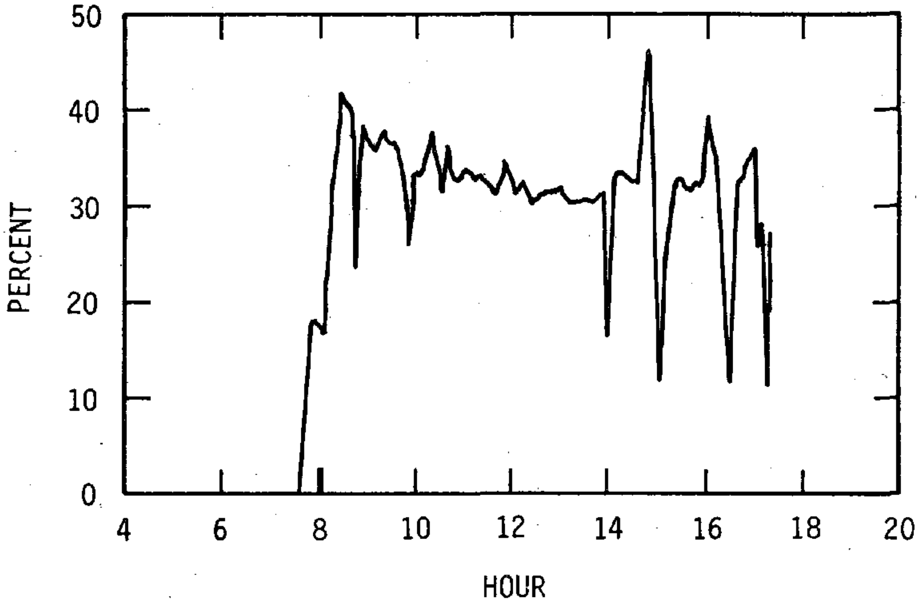


Figure 14. Efficiency, 94-1980

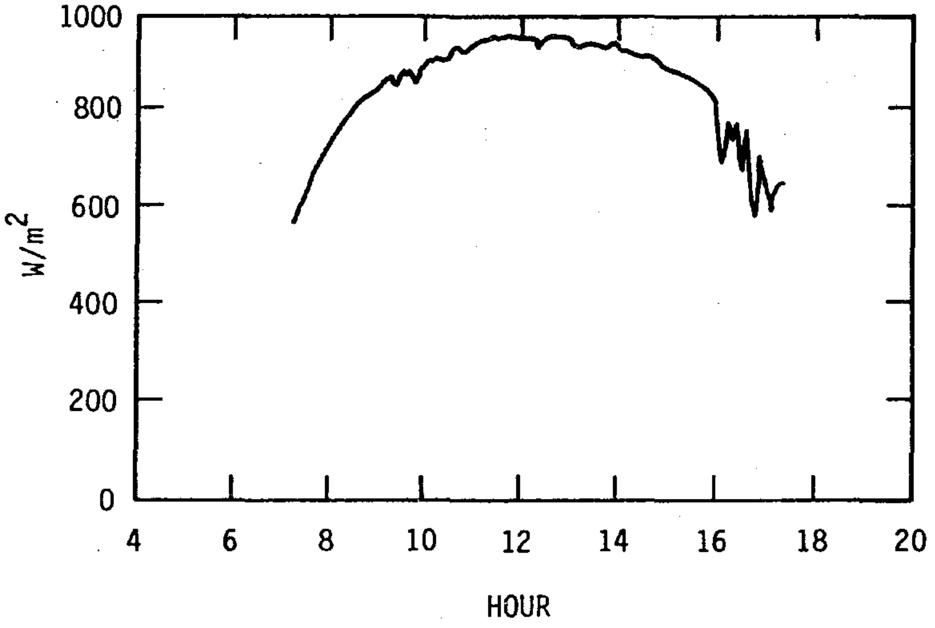


Figure 15. Insolation, 94-1980

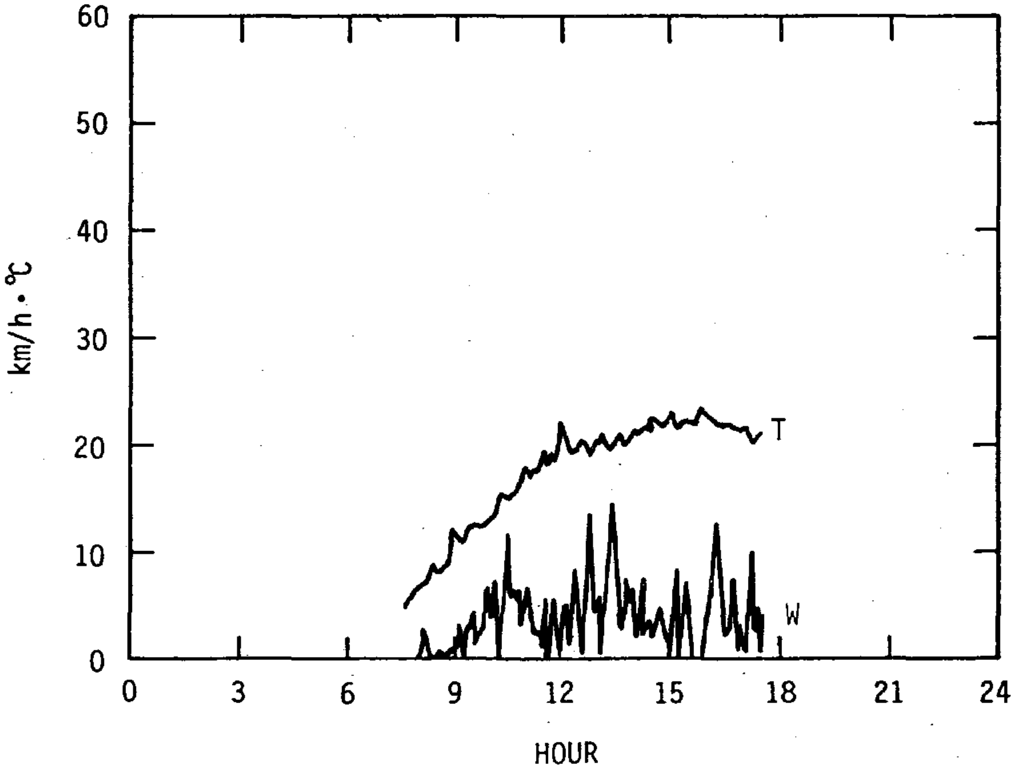


Figure 16. Wind Speed and Ambient Temperature, 94-1980

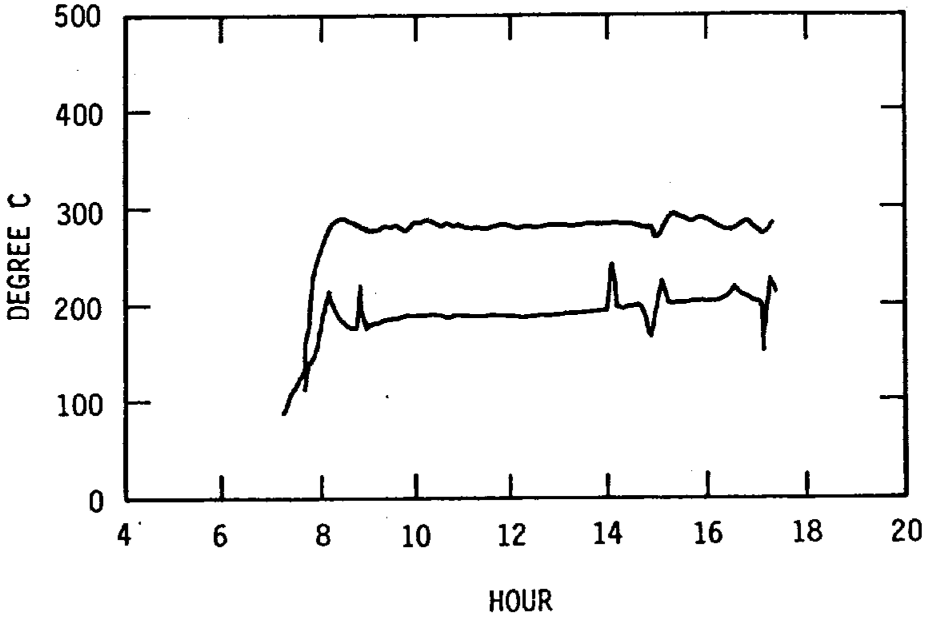


Figure 17. Inlet and Outlet Temperatures, 94-1980

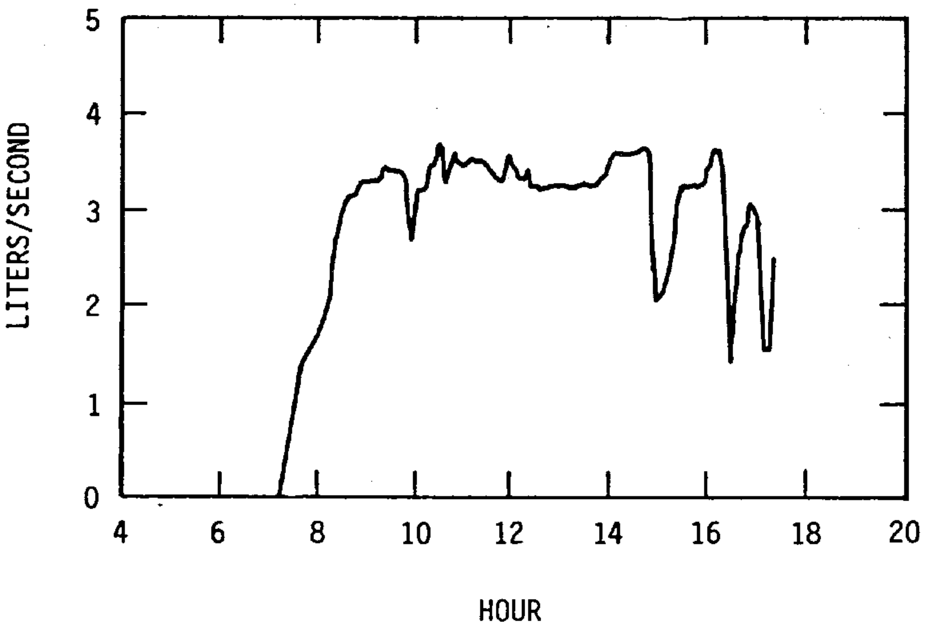


Figure 18. Flow Rate, 94-1980

PERFORMANCE OF THE SUBSYSTEM AT COOLIDGE, ARIZONA, 25 JUNE AND 4 AND 5 JULY 1980

Solar collector subsystem performance was evaluated on 25 June and 4 and 5 July 1980 (days 177, 186, and 187) to determine solar energy collection efficiency during the period near summer solstice. Average daily subsystem solar energy collection efficiencies for those days were 36.9%, 36.7%, and 34.4%, respectively. The sustained midday efficiency on the day following collector washing, 25 June, was 40% to 42%. Performance was degraded on 4 and 5 July due to intervening dust storms.

Methods

Collector reflective surfaces and receiver glass covers were washed by a commercial firm prior to commencing the tests. Collector reflector-receiver alignment was checked and adjusted as required to assure optimum performance.

After warmup, Caloria was circulated through the collector subsystem at a flow rate which was controlled to maintain the desired, constant, collector subsystem outlet temperature.

Collector system flow rate was measured with a vortex-shedding-type meter, temperatures with resistance temperature detector (RTD) sensors, and insolation with a pyrheliometer. Data were recorded at 2-minute intervals.

Collector subsystem efficiency was computed as the thermal energy gained by Caloria during passage from subsystem inlet to subsystem outlet manifold location divided by the direct normal solar radiation impinging on the collector aperture area. Total daily direct normal insolation received during operation was used in the computation of the daily average subsystem efficiency.

Test information is summarized in Table 1 and in the daily performance test presentations.

Table 1

Times Recorded for Performance Test Events

Event	June 25	July 4	July 5
Sunrise	5:20 a.m.	5:23 a.m.	5:23 a.m.
Collectors Focused	6:34 a.m.	6:37 a.m.	6:45 a.m.
Flow to Main Storage	7:26 a.m.	7:23 a.m.	7:45 a.m.
Collectors Defocused	6:36 p.m.	6:36 p.m.	6:36 p.m.
Sunset	7:43 p.m.	7:42 p.m.	7:41 p.m.

Conclusions

Days 177 and 187 can be compared to determine the effect of collector washing on collector performance since the solar input was nearly identical for the 2 days. The collectors were very clean on day 177, since they had been washed the day before. On day 187, the collectors were very dirty again due to dust storms on the preceding days. The sustained midday collection efficiency was about 41% on day 177 and 37% on day 187. The 4-percentage-points difference in collection efficiency represents the improvement that is realized by cleaning.

Day 177 Results

Solar collector receiver glass tubes and reflector surfaces were washed and rinsed by a commercial firm on the day prior to this performance test.

The solar collector subsystem gathered energy at a rate of 600 to 800 kW (2049 to 2732 Btu/h) from 8 a.m. to 5 p.m. Solar collector subsystem efficiency was about 40% during this period, with a computed efficiency of about 42% for an extended time during the period. The average collection efficiency for the entire day was 36.9%.

Day 177 was mostly clear. Winds were 5 to 15 km/h (3 to 9 mi/h) with brief gusts to 20 km/h (12.4 mi/h). The ambient temperature was over 40°C (104°F) during much of the test period.

The collector subsystem outlet temperature was maintained at about 284°C (543°F) during the test period. Inlet oil temperature was 184° to 200°C (363° to 392°F). Collector subsystem Caloria flow rate was 3 to 4 ℓ/s (47 to 63 gal/min) during most of the test but varied considerably, becoming about 4.5 ℓ/s (71 gal/min) late in the test period.

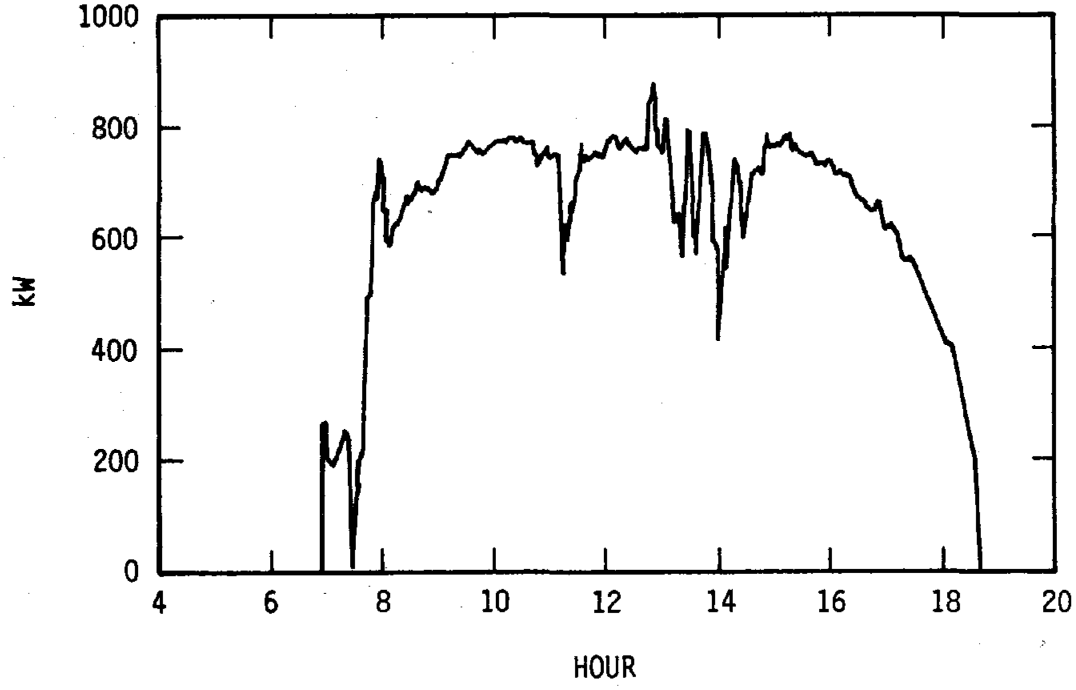


Figure 1. Collected Power, 177-1980

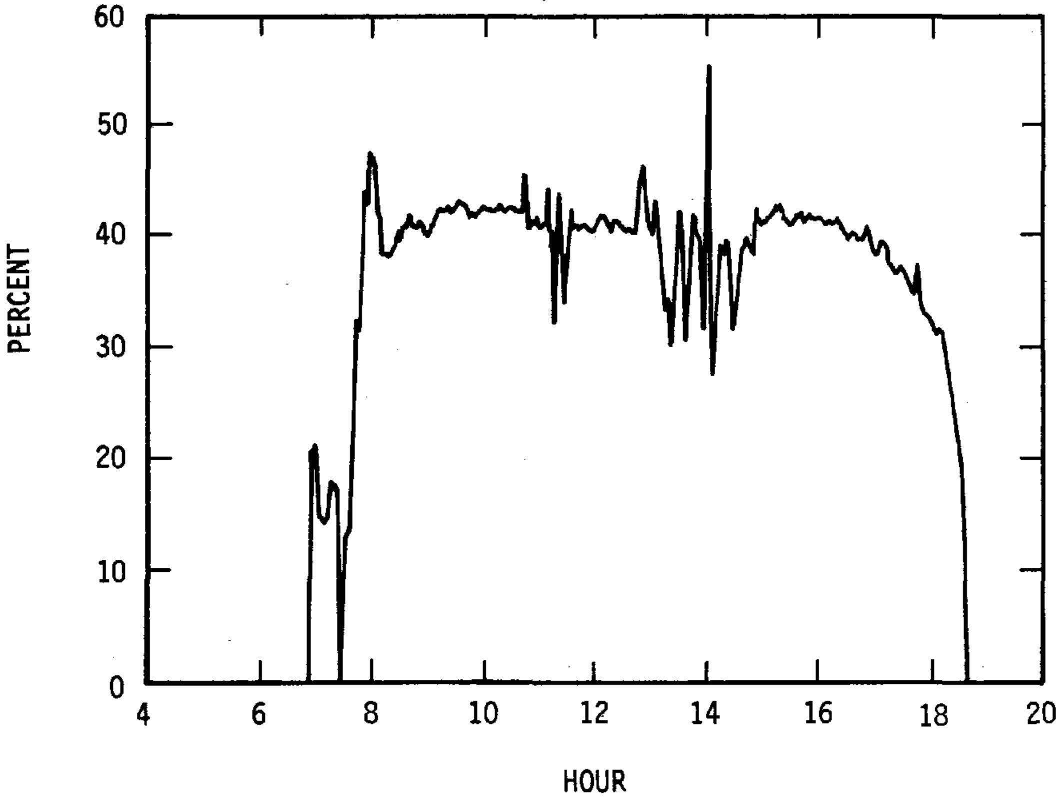


Figure 2. Efficiency, 177-1980

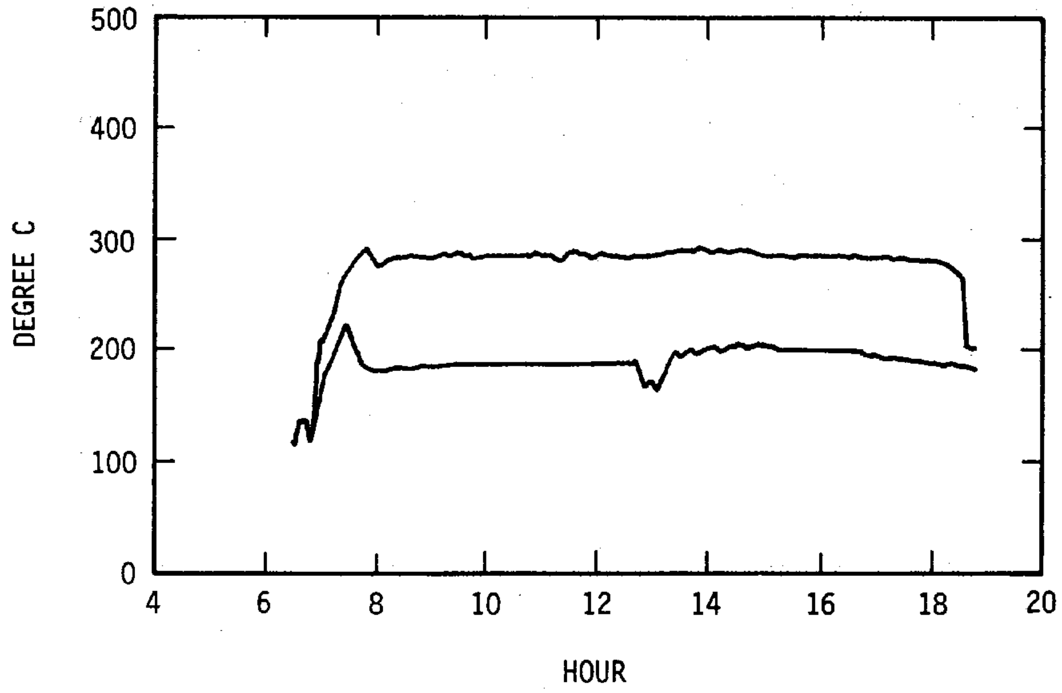


Figure 3. Inlet and Outlet Temperatures, 177-1980

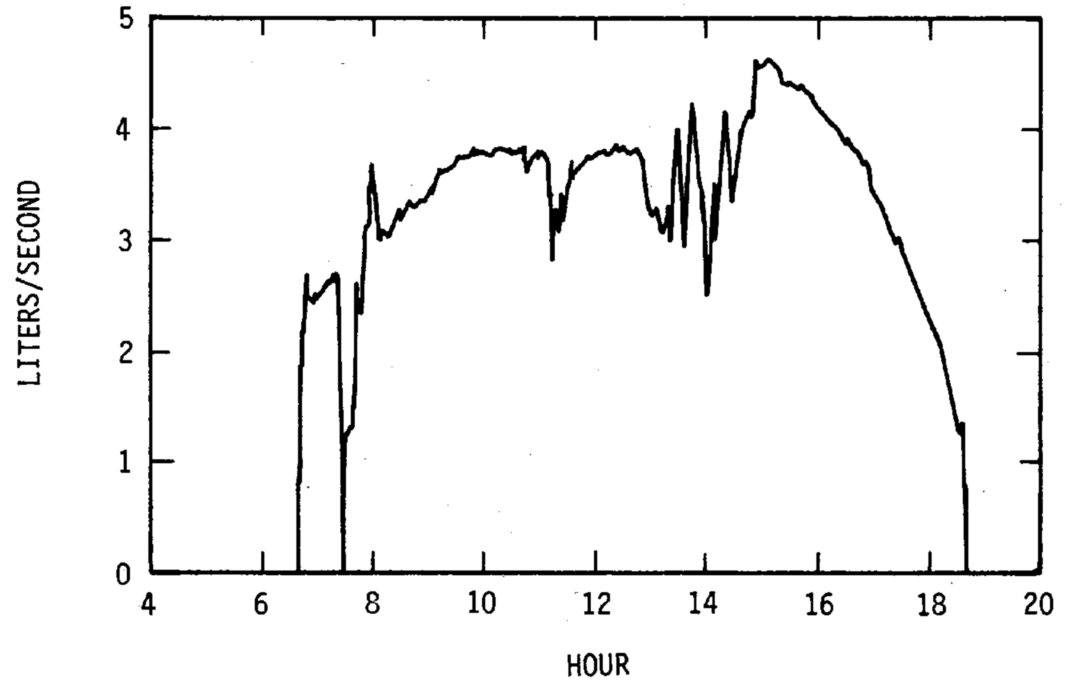


Figure 4. Flow Rate, 177-1980

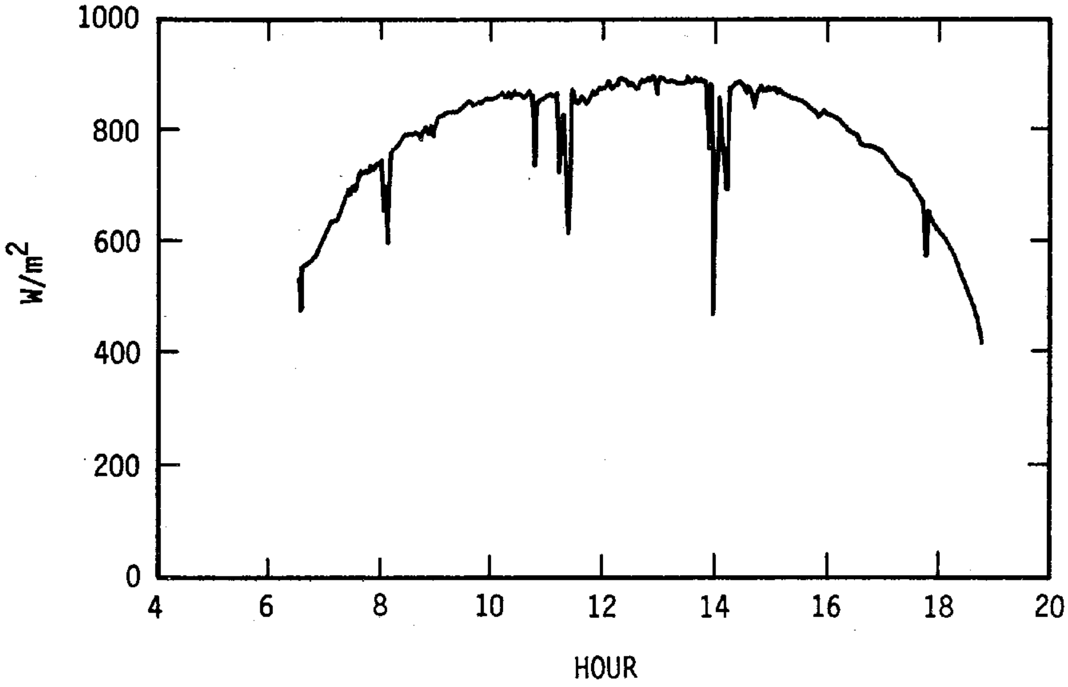


Figure 5. Insolation, 177-1980

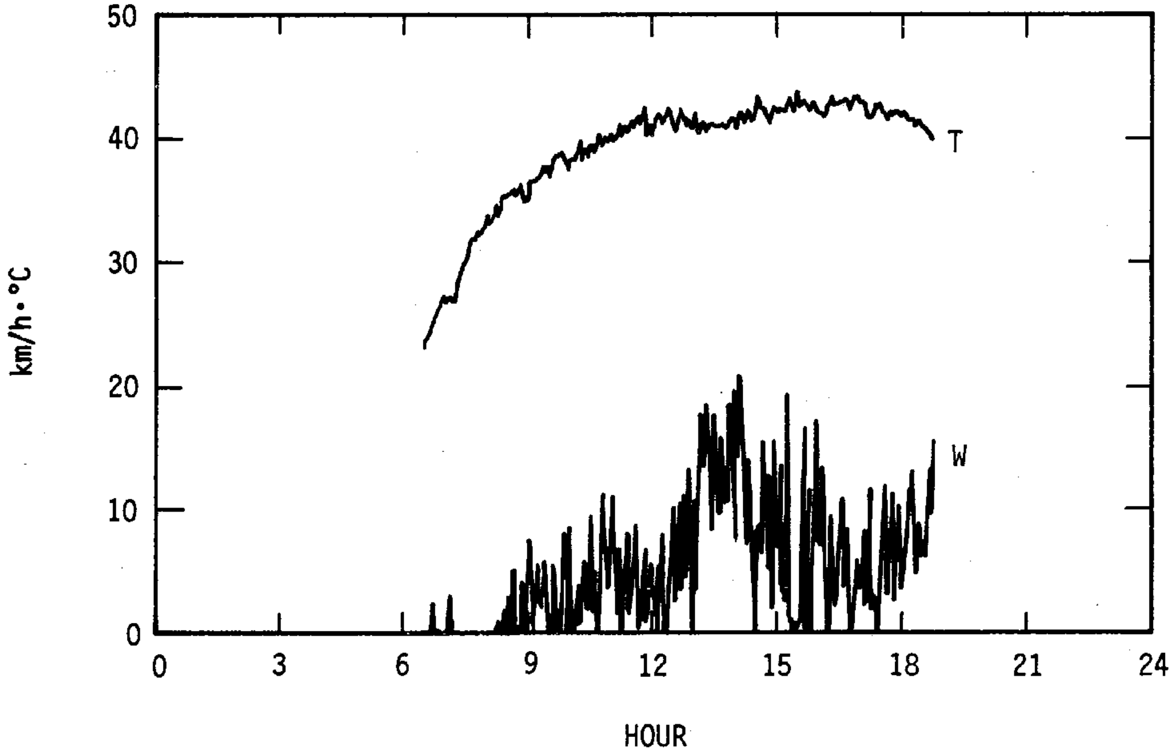


Figure 6. Wind Speed and Ambient Temperature, 177-1980

Day 186 Results

Stormy weather, including high winds and blowing dust, occurred on the intervening days between 25 June and 4 July collector subsystem performance evaluation tests. Collectors were stowed when blowing dust was most pronounced, but reflector surfaces were dirtied somewhat. The receiver cover tubes were wiped prior to day 186 tests.

Thermal energy was collected at a rate of about 800 kW (1,000 hp). The collector subsystem efficiency varied from about 38% to over 42% during the test period with brief periods of higher efficiency. The average solar collector subsystem efficiency throughout the day was 36.7%.

Day 186, 5 July, was clear with good insolation, about 960 W/m^2 ($304\ Btu/ft^2 \cdot h$) at noon. The ambient temperature was about 35°C (95°F) at 9 a.m.; the high temperature was about 44°C (111°F). Wind speeds varied around 10 km/h (6 mi/h) in the morning, becoming somewhat higher in the afternoon.

Collector subsystem outlet oil temperature was maintained at about 264°C (507°F) early in the morning but dropped gradually to about 253°C (487°F) by 3 p.m. The inlet temperature varied from about 283° to 289°C (541° to 552°F) during the test. The collector subsystem Caloria flow rate varied greatly during the day as the control system attempted to maintain system outlet temperature at the desired, constant level. The flow rate climbed from about 3.5 ℓ/s (46 gal/min) at 8 a.m. to 5.5 ℓ/s (73 gal/min) at 10 a.m. and then varied from about 5.3 ℓ/s (70 gal/min) to 6.3 ℓ/s (83 gal/min) during the rest of the test period.

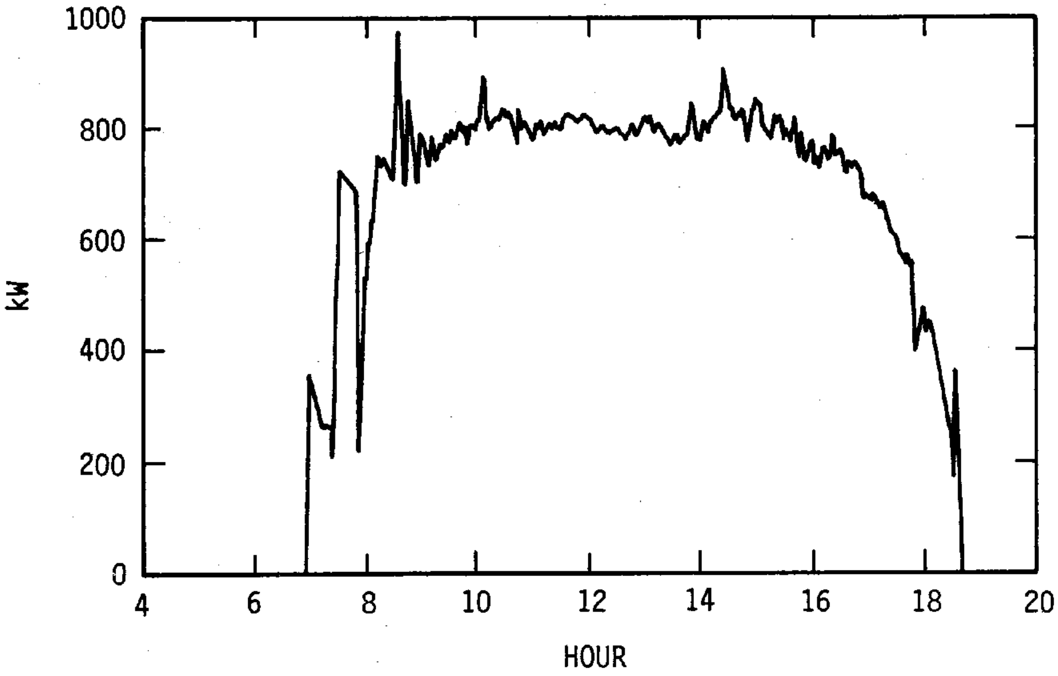


Figure 7. Collected Power, 186-1980

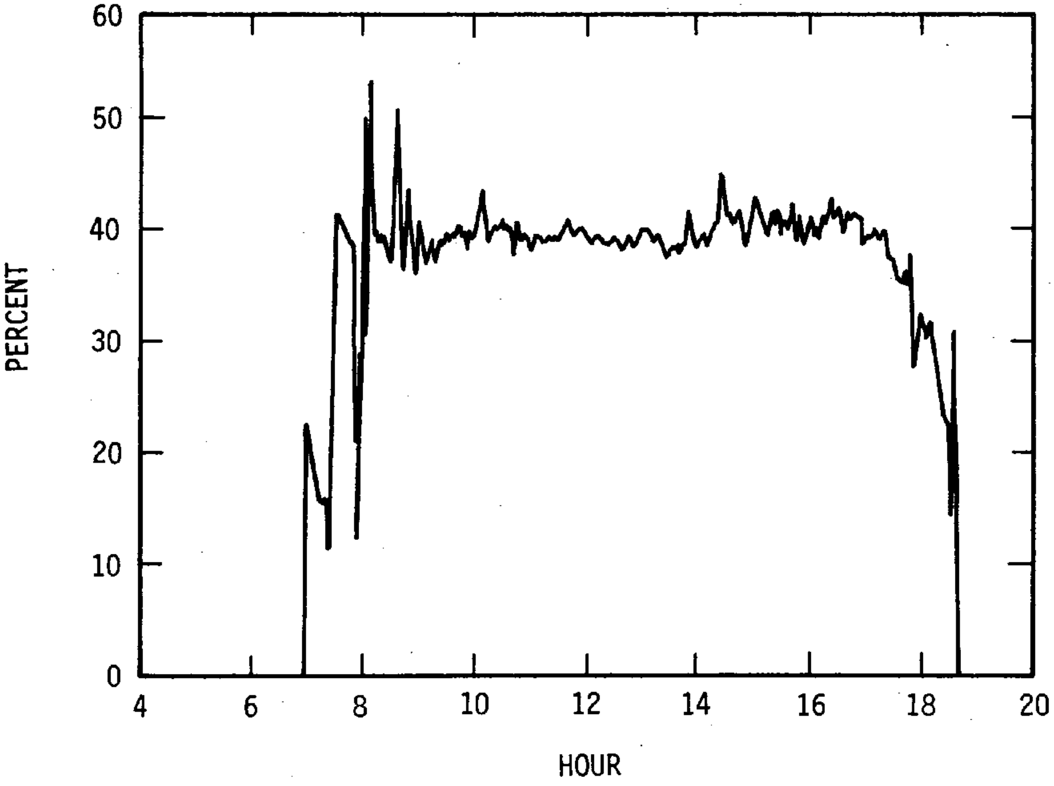


Figure 8. Efficiency, 186-1980

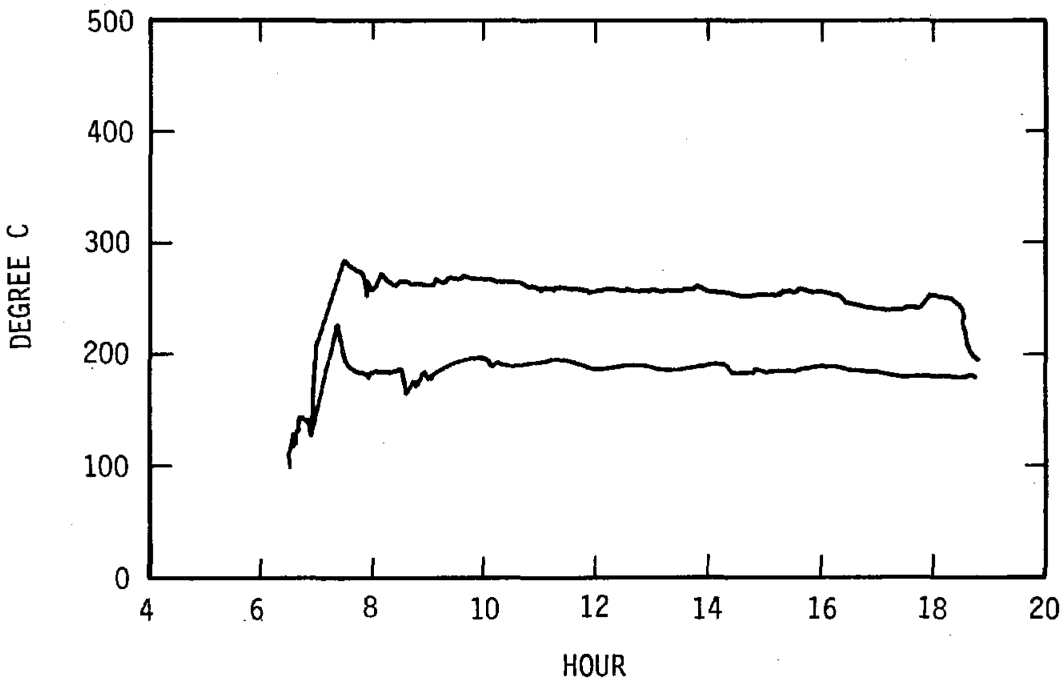


Figure 9. Inlet and Outlet Temperatures, 186-1980

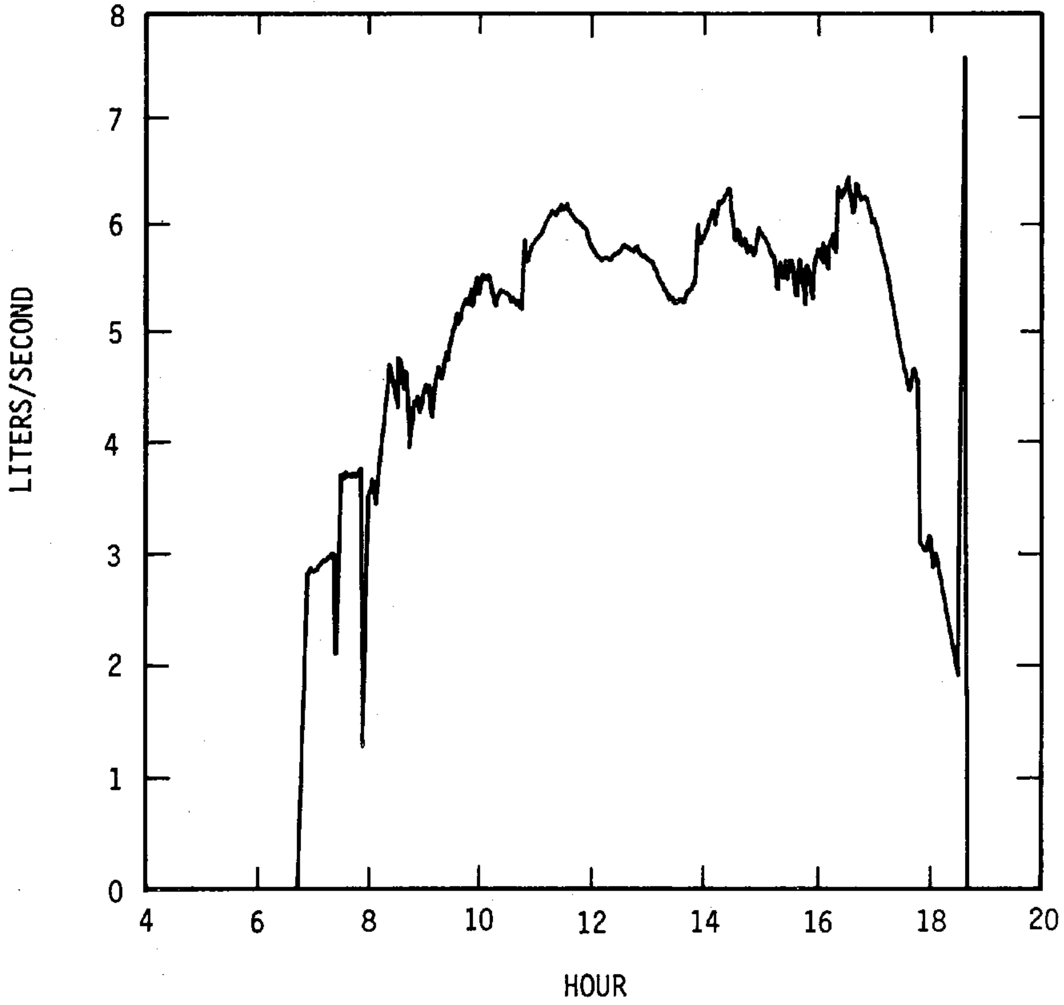


Figure 10. Flow Rate, 186-1980

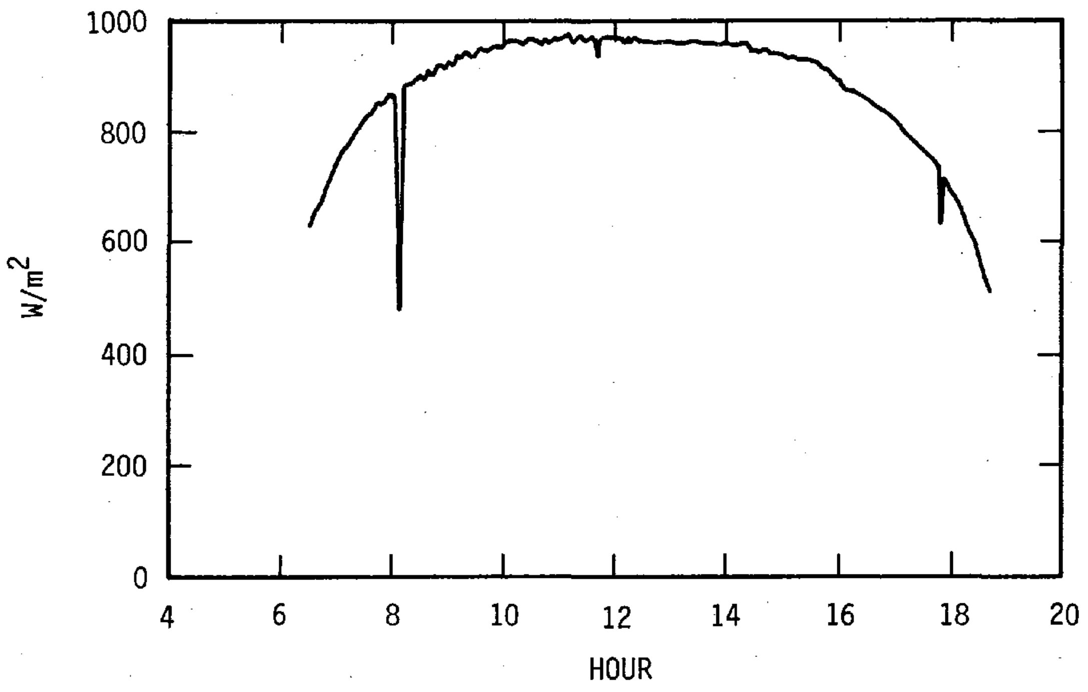


Figure 11. Insolation, 186-1980

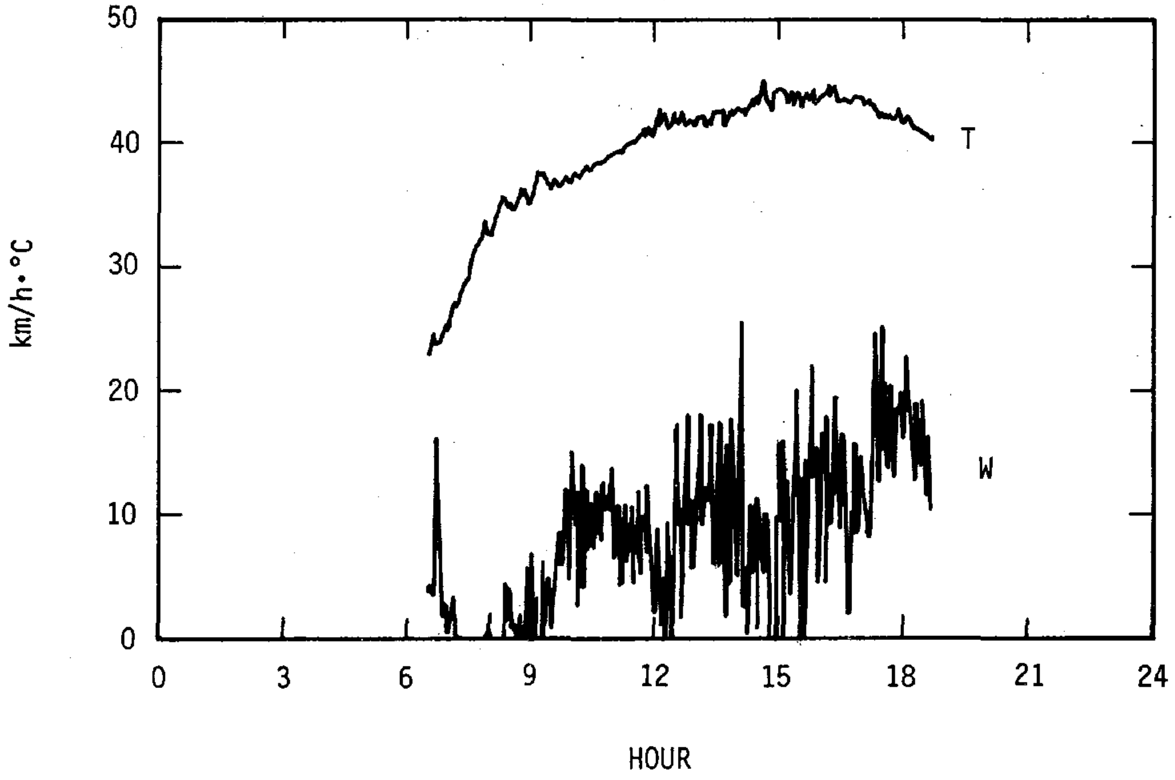


Figure 12. Wind Speed and Ambient Temperature, 186-1980

Day 187 Results

Thermal energy was collected at a rate of about 650 to 700 kW (872 to 939 hp) on day 187 (5 July). Collector subsystem efficiency was computed to be from about 36% to 38% during the 8 a.m. to 5 p.m. period. The average collector subsystem efficiency for the entire day was 34.4%.

Day 187 was mostly clear. However, morning insolation was somewhat reduced, and a brief cloudy period occurred at about 12:30 p.m. Ambient daytime temperatures were about 34°C (93°F) at 9 a.m. and near 40°C (104°F) in the afternoon. Wind speeds were highly variable with a representative measurement of 10 km/h (6 mi/h).

Collector subsystem outlet temperature was maintained at about 276°C (529°F) during the performance test. Inlet Caloria temperature was 185° to 200°C (365° to 392°F). Collector subsystem flow rate ranged from about 3.4 ℓ/s (45 gal/min) early in the test day to nearly 5 ℓ/s (66 gal/min) in the afternoon in order to control system fluid outlet temperature.

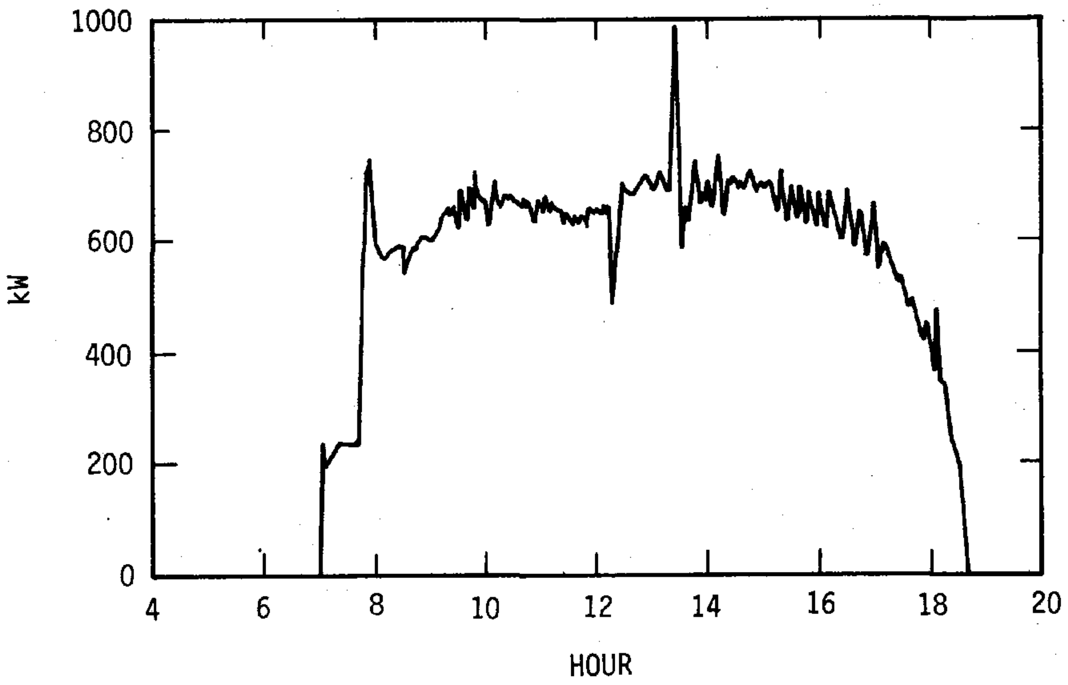


Figure 13. Collected Power, 187-1980

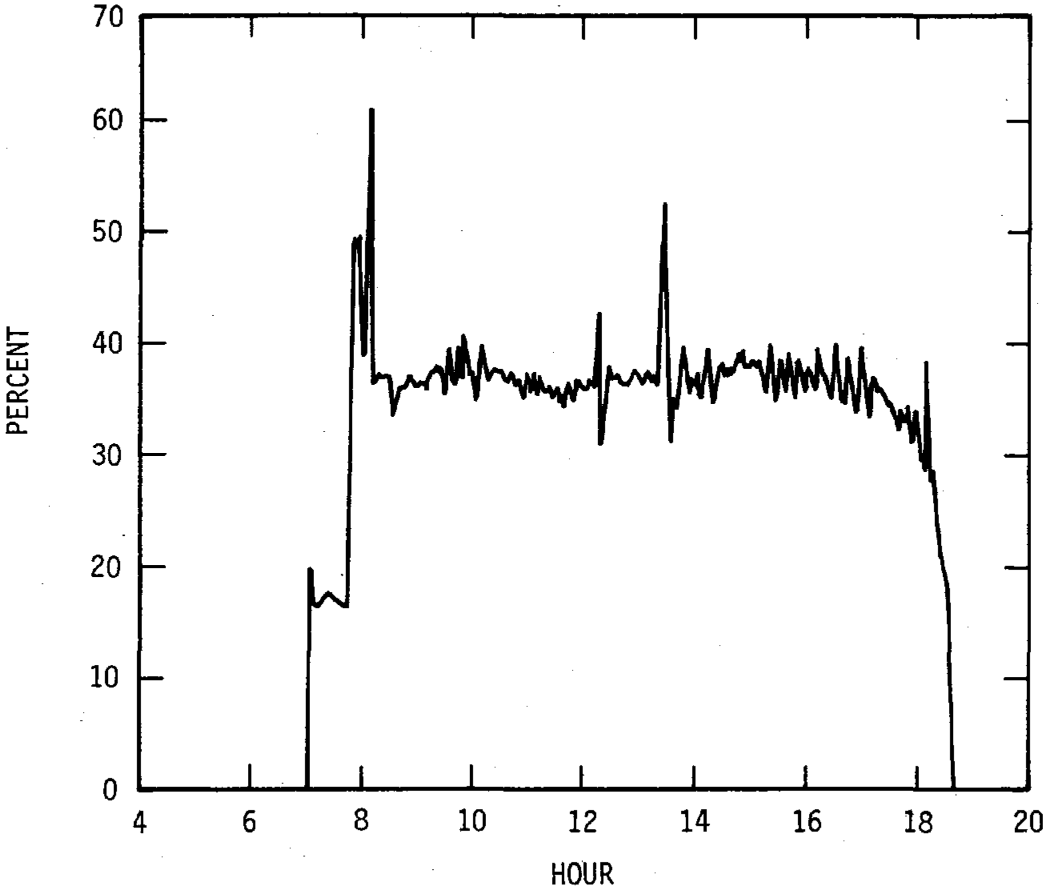


Figure 14. Efficiency, 187-1980

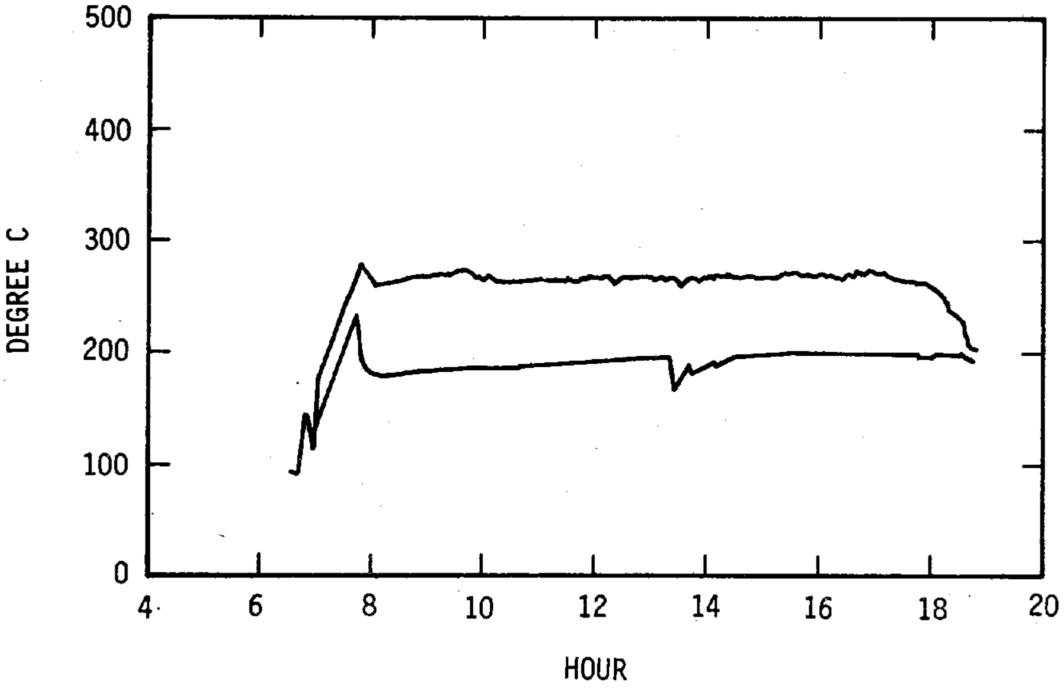


Figure 15. Inlet and Outlet Temperatures, 187-1980

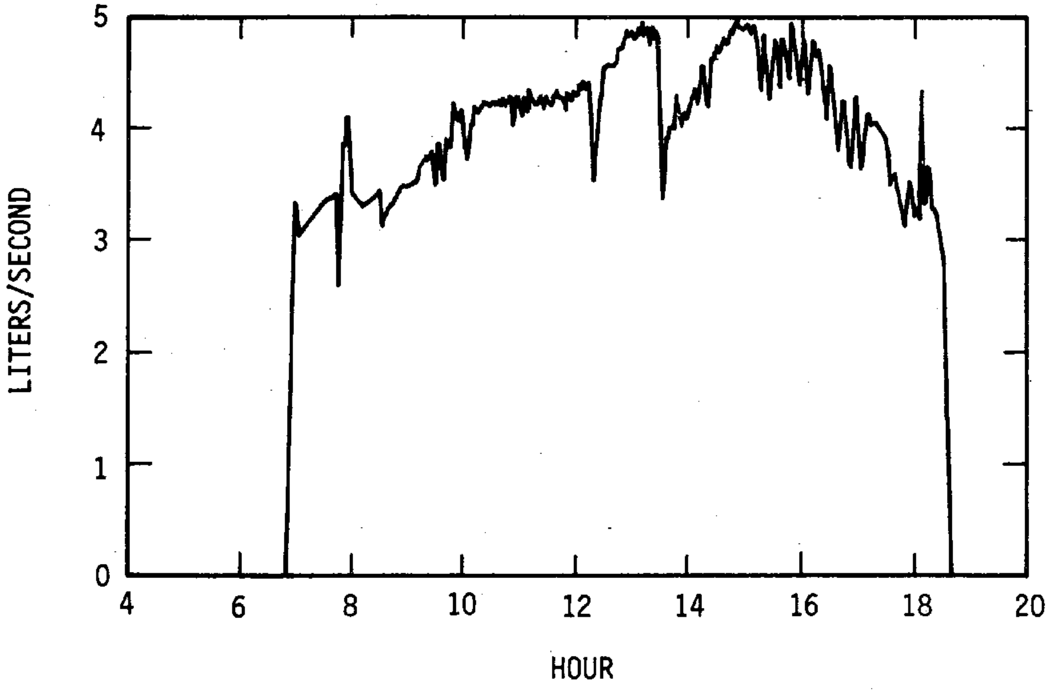


Figure 16. Flow Rate, 187-1980

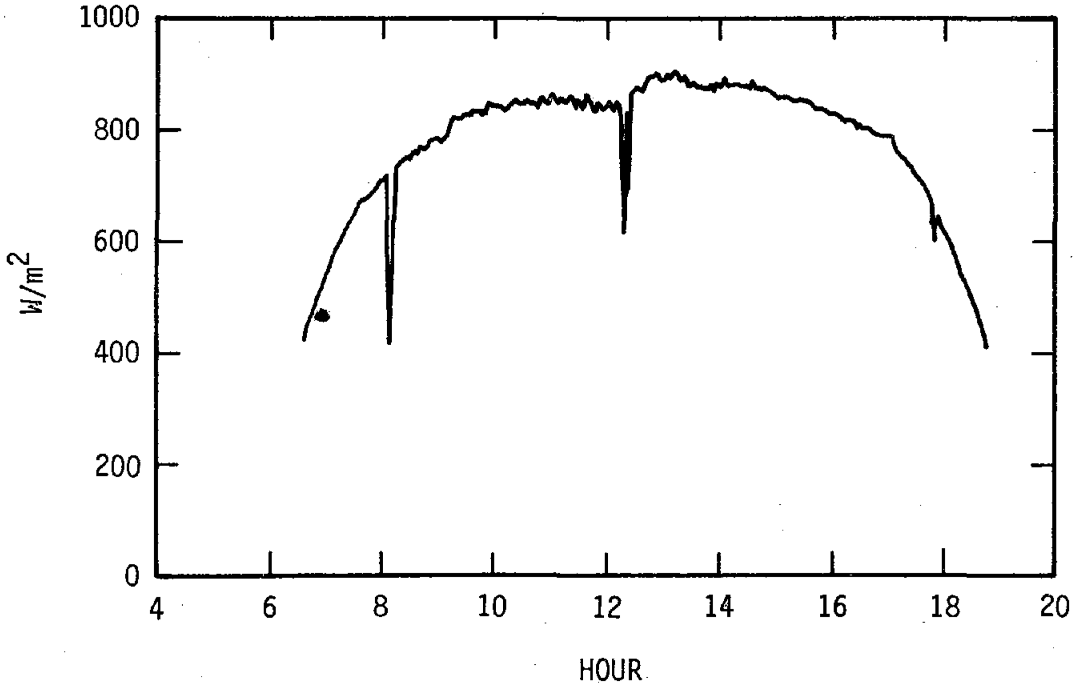


Figure 17. Insolation, 187-1980

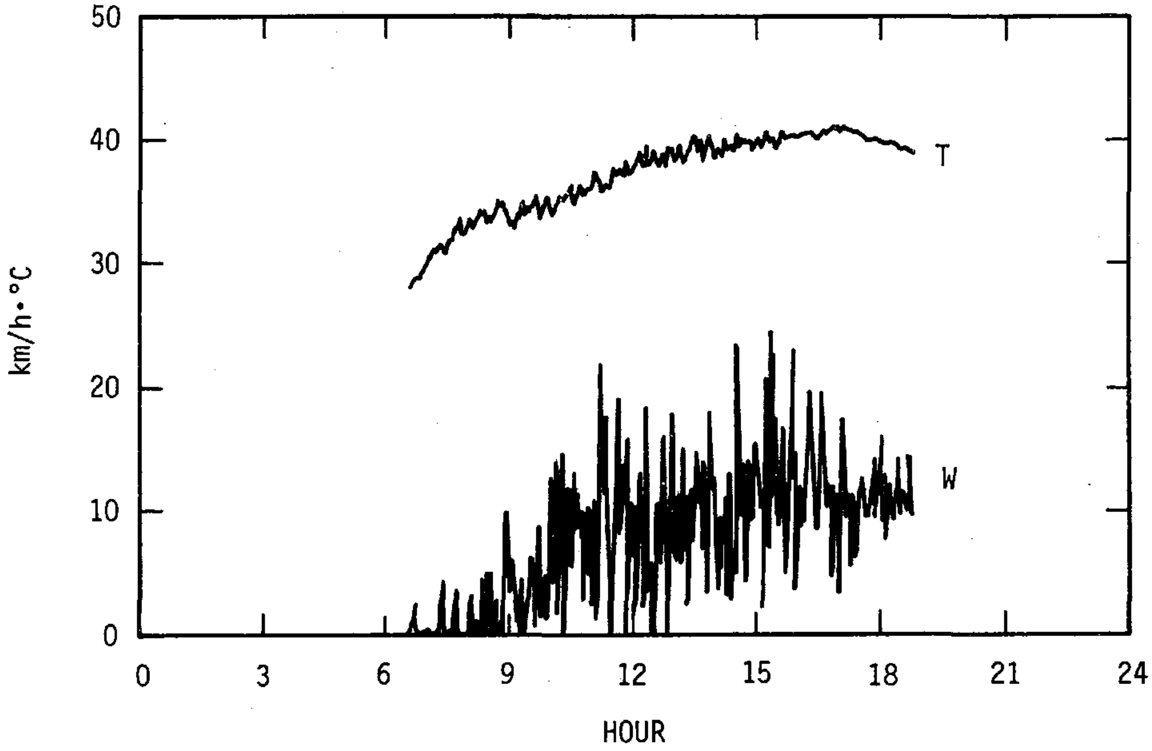


Figure 18. Wind Speed and Ambient Temperature, 187-1980

SOLAR COLLECTOR SUBSYSTEM PERFORMANCE PREDICTIONS

A comparison was made between the collector field subsystem performance at the Coolidge Solar Irrigation Facility and the predicted collector field performance, using a systems analysis model and Phoenix, Arizona, typical meteorological year (TMY) weather data. The systems analysis model calculates field performance on an hourly basis for an entire year and takes into account such effects as field thermal losses, end losses, shadowing, incidence angle effects, and reduced reflectance of dirty collectors. The equations for collector performance (normal incidence) and incidence angle modifier were derived from data taken at the Collector Module Test Facility in Albuquerque, New Mexico. The equation for field thermal losses was derived from tests performed at the Coolidge facility. The results from the model indicate an annual average collector field efficiency of about 20% at design temperature with daily average efficiencies reaching 30% to 32% around the summer solstice. If the collectors could be continuously cleaned, the model indicates an annual average efficiency of about 24% with daily average efficiencies of 35% to 37% around the summer solstice. Actual collector field efficiencies measured at the Coolidge facility with recently cleaned collectors on 25 June and 4 and 5 July 1980 were 36.9%, 36.7%, and 34.4%, respectively. These daily average efficiencies agree very closely with the 35% to 37% predicted for a clean field near the summer solstice.

Figures 1 and 2 are plots of calculated collector field subsystem thermal output and efficiency, respectively, for dirty collectors. Figures 3 and 4 are plots of calculated collector field subsystem thermal output and efficiency, respectively, for continuously cleaned collectors.

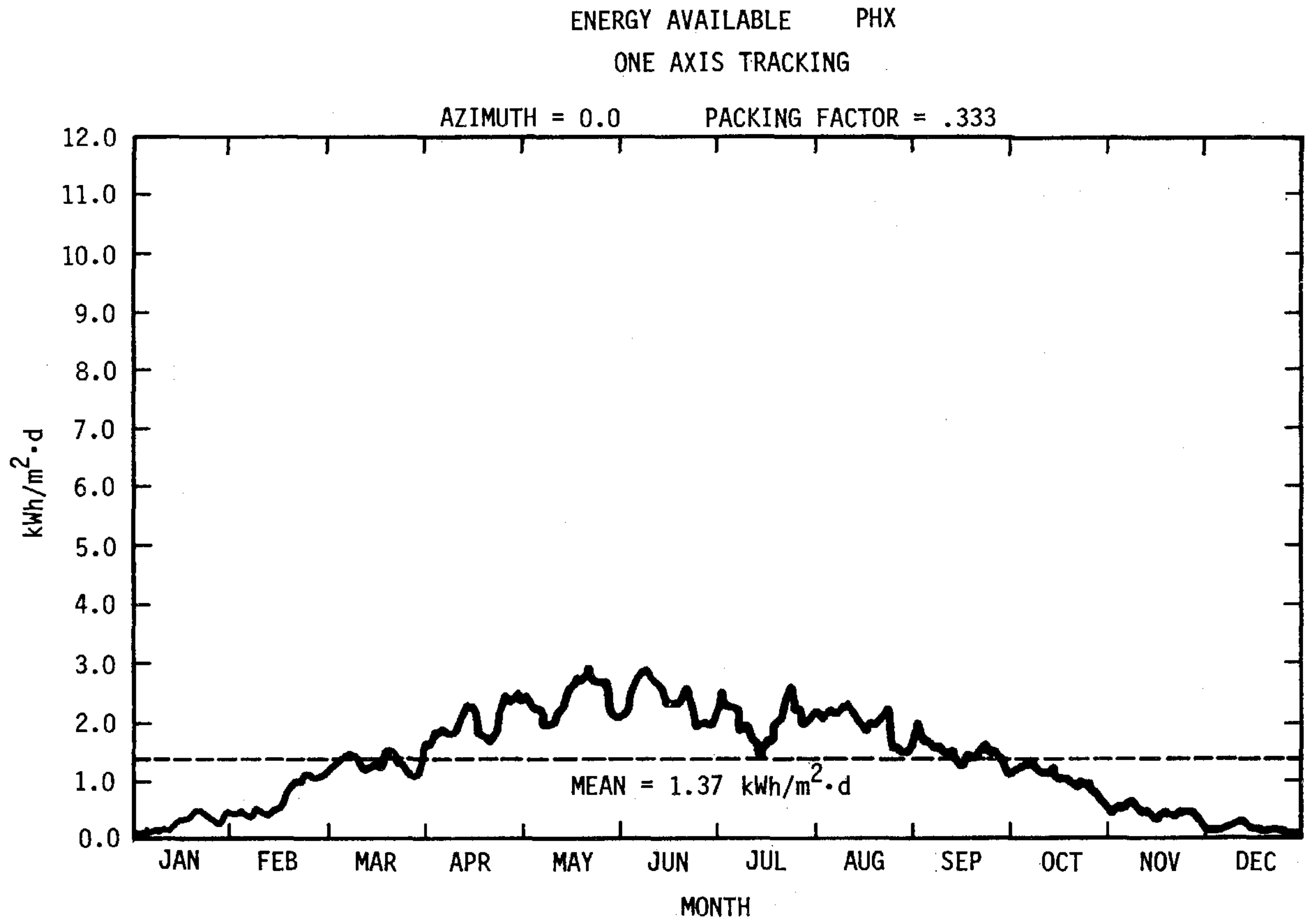


Figure 1. Calculated Collector Field Subsystem Thermal Output: Dirty Collectors

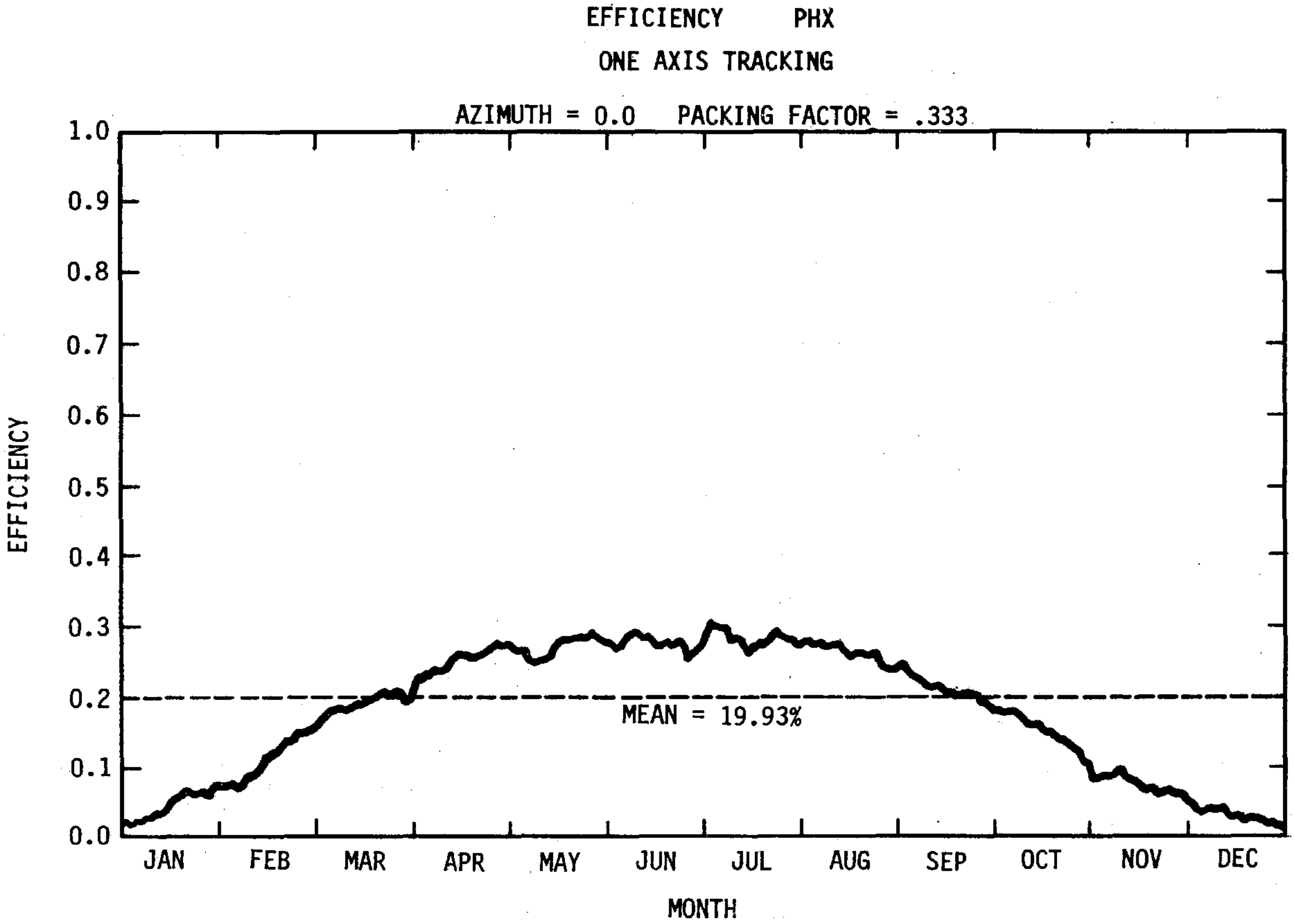


Figure 2. Calculated Collector Field Subsystem Efficiency: Dirty Collectors

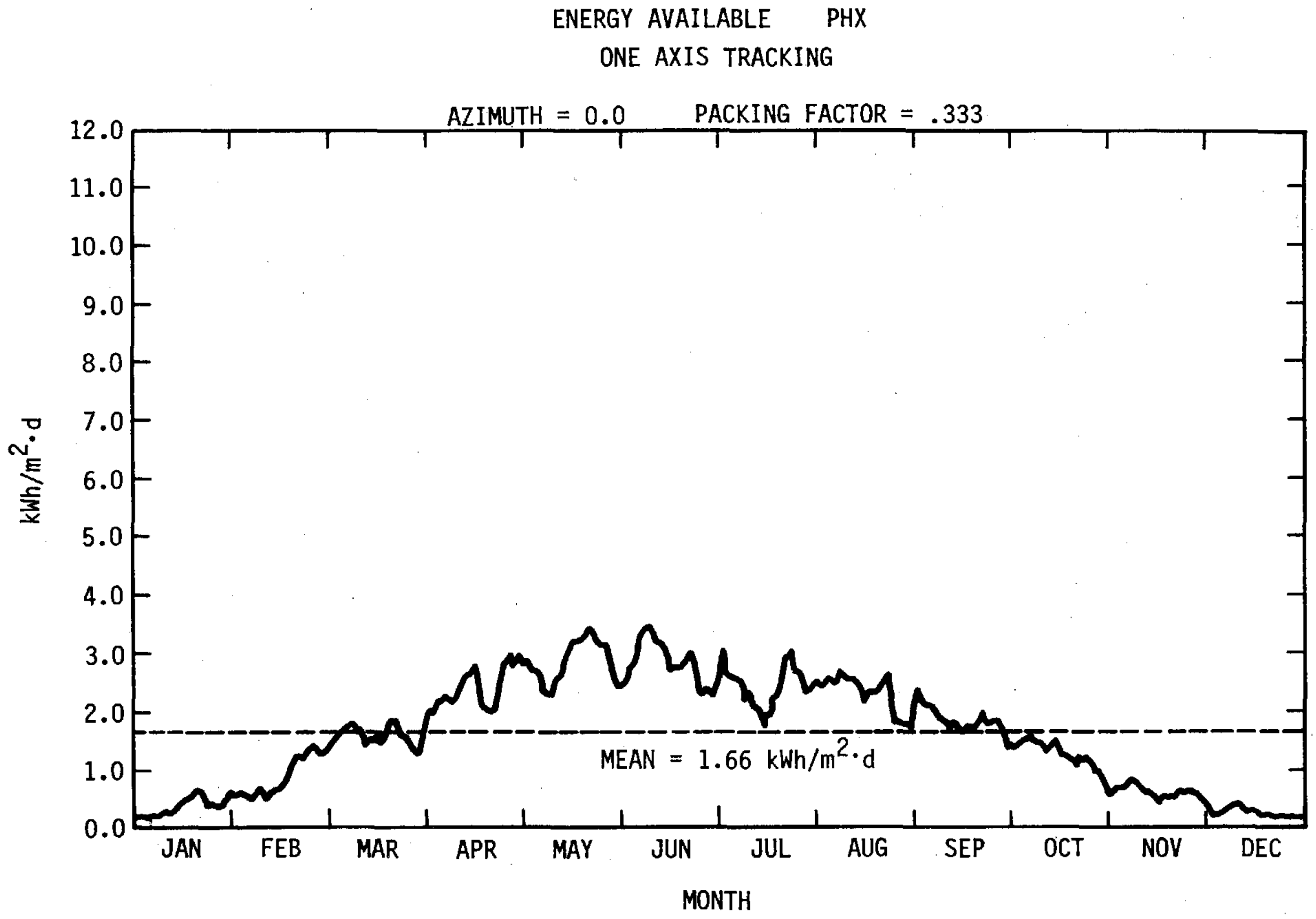


Figure 3. Calculated Collector Field Subsystem Thermal Output: Continuously Cleaned Collectors

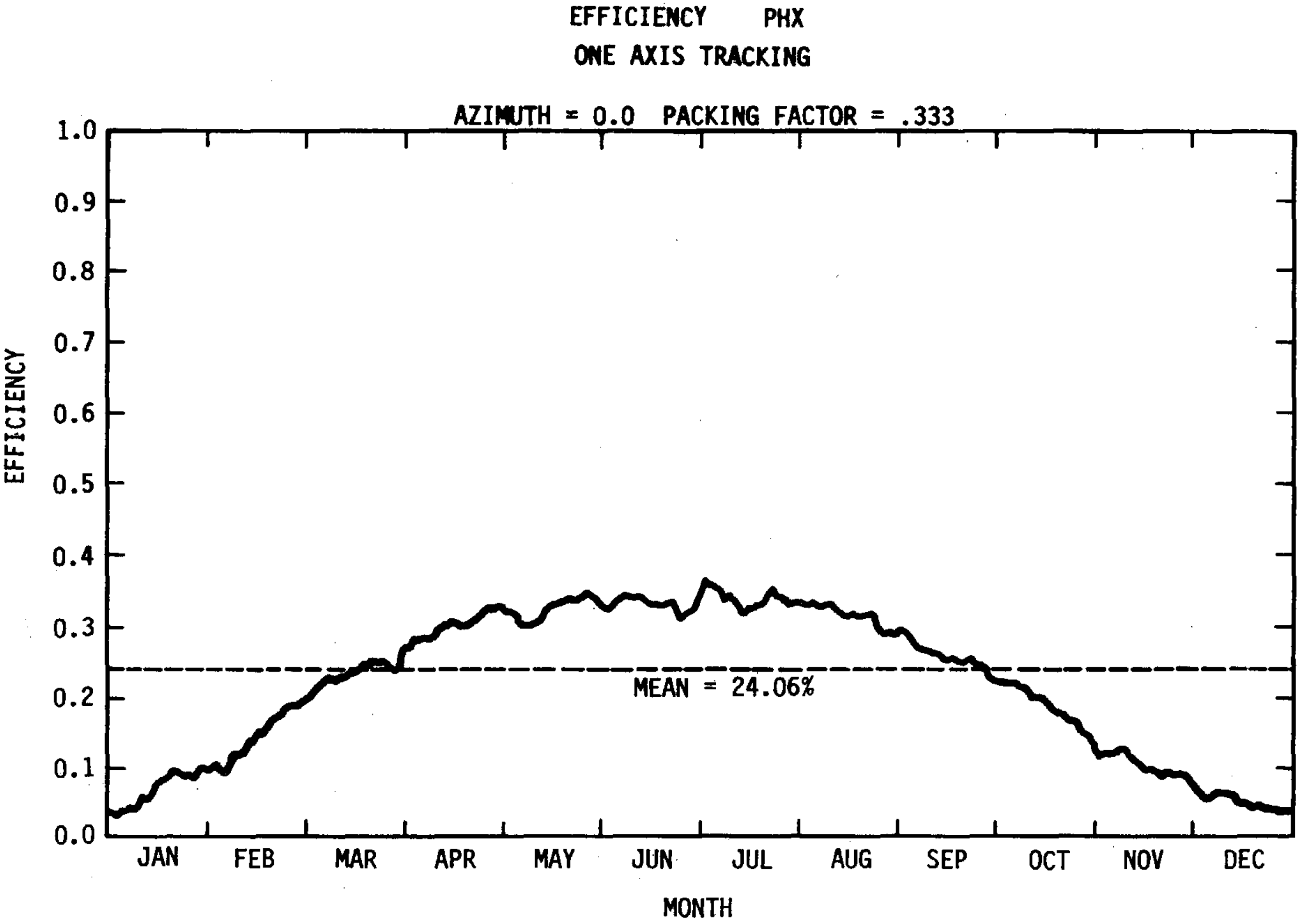


Figure 4. Calculated Collector Field Subsystem Efficiency: Continuously Cleaned Collectors

STEADY-STATE THERMAL LOSS TEST OF THE COLLECTOR SUBSYSTEM AT THE COOLIDGE, ARIZONA, SOLAR IRRIGATION FACILITY,

15 APRIL 1980

Purpose

The purpose of this test was to study the steady-state thermal losses in the collector subsystem fluid loop at Coolidge, Arizona.

Test Procedure

On 15 April 1980, the collector subsystem was prepared by pointing the collectors toward the west in the morning and toward the east in the afternoon. The directions were chosen in order to allow the receiver to radiate to the sky while being shaded from the sun by the edge of its trough. The fluid loop was then put into operation by circulating the Caloria through the loop and the gas-fired heater. The heater was used to supply the heat required to bring the fluid loop up to temperature.

Thermal loss data were collected for six different combinations of flow rates and inlet Caloria temperatures. For each data point, the flow rate was fixed by fixing the speed of the collector subsystem pump. The inlet Caloria temperature was held at the desired level by the gas-fired heater. These conditions were maintained for approximately 2 hours to achieve temperature stability throughout the subsystem prior to gathering the data at each test point.

The fluid loop schematic is shown in Figure 1. As shown, the collector subsystem consists of eight individual collector loops.

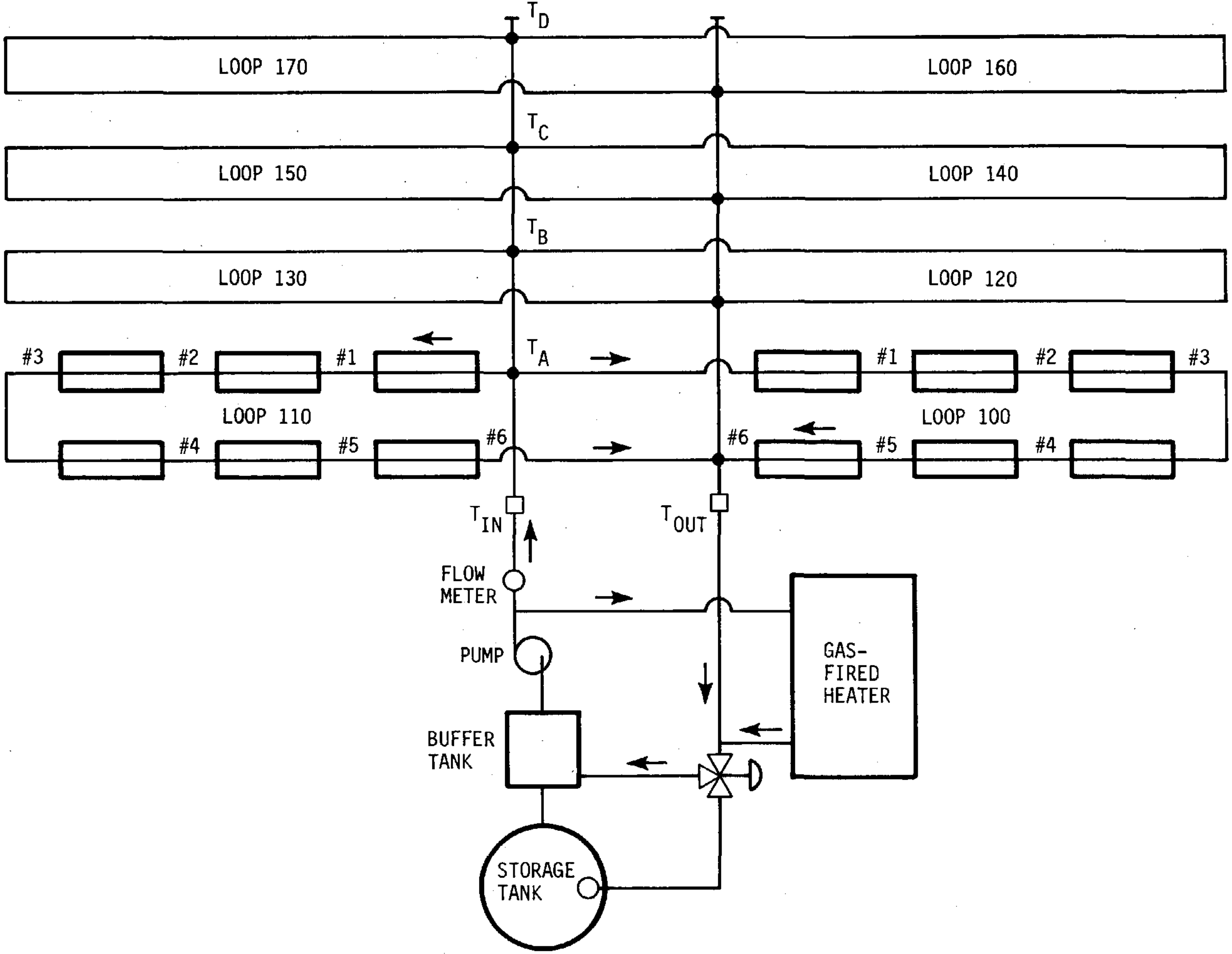


Figure 1. Fluid Loop Schematic

Each loop consists of 48 collector modules plumbed in series. At the outlet of each string of eight collectors in each loop is a resistance temperature detector (RTD). They are numbered 1 through 6 in each loop as shown. At each test point, temperature readings were taken at each of these RTDs. In addition, the temperatures at the inlet to each loop, the inlet to the collector subsystem, and the outlet from the collector subsystem were determined by thermocouples, as shown.

Test Results

The test results are presented in Table 1 and Figure 2. Table 1 lists the data as collected at each test point. Figure 2 is a plot of the total thermal losses from the collector subsystem versus the midpoint receiver temperature above ambient. Midpoint receiver temperature is defined as the fluid temperature at the midpoint of the individual collector loops averaged over the field. In addition, included is a plot of the receiver losses alone as determined at the Collector Module Test Facility in Albuquerque, New Mexico, for the same collector modules. The thermal losses from the pipelines alone were then calculated by subtracting the receiver losses from the total losses. The results were plotted as the calculated pipe loss on Figure 2.

Discussion

The calculated pipeline steady-state thermal losses in the collector subsystem will represent 8% of the energy collected on a good summer day. This rather high loss substantiates an increasingly strong feeling at Sandia National Laboratories that "standard practice" in fluid transport system design needs to be reevaluated for solar applications.

The major known contributors to these heat losses are the numerous pipe anchors and valves in the collector subsystem pipelines. In addition, the insulation at the top of the flexhoses has slipped downward, exposing the top few inches to the atmosphere.

Table 1

Collected Temperature Data, °F

Loop No.	100						120						140						160					
RTD No.	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Test Point No.																								
1	522	505	488	464	443	426	512	494	471	456	440	418	506	488	472	452	433	416	499	486	464	448	426	409
2	538	527	512	501	487	488	529	517	500	492	481	468	523	511	501	488	476	465	514	508	494	486	469	459
3	489	482	470	462	451	443	481	472	458	452	444	434	476	465	459	449	439	430	469	466	454	447	434	427
4	471	458	438	425	408	395	463	447	425	416	402	382	458	442	429	412	397	381	453	443	424	409	388	373
5	432	421	398	385	369	358	424	409	387	377	364	348	418	403	389	373	359	347	409	401	385	374	357	345
6	442	439	424	417	408	401	434	427	415	411	403	393	430	423	416	407	399	392	425	422	413	407	397	389

Loop No.	110						130						150						170					
RTD No.	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Test Point No.																								
1	502	481	466	453	435	421	500	488	452	451	427	420	508	486	466	452	427	416	506	484	464	438	430	410
2	524	513	507	499	488	479	524	520	493	496	476	478	531	518	504	494	475	470	526	511	499	480	477	469
3	482	470	462	454	444	438	477	473	449	453	435	436	481	470	459	451	437	433	479	467	457	442	440	430
4	465	441	425	410	394	383	458	446	411	409	386	382	463	442	425	412	389	381	462	443	425	398	392	375
5	421	400	388	376	362	345	416	406	376	374	351	347	422	403	388	374	352	345	419	400	385	362	358	345
6	432	422	417	409	401	394	430	426	405	409	394	385	435	425	416	410	397	393	433	423	415	401	400	391

Table 1 (Continued)

Collected Temperature Data, °F

Test Point No.	Flow Rate gpm	T_{In} (^oF)	T_{Out} (^oF)	T_{AMB} (^oF)	Wind mph
1	30.0	540.0	416.0	85.4	0.0
2	60.5	545.4	472.0	88.4	1.3
3	60.9	495.0	434.0	90.1	3.0
4	29.0	488.4	380.0	87.4	3.6
5	28.8	445.5	348.5	83.2	4.7
6	60.3	448.0	393.0	72.4	0.0

TEST POINT No.	T_A (^oF)	T_B (^oF)	T_C (^oF)	T_D (^oF)
1	538	537	535	533
2	547	547	547	541
3	494	494	494	491
4	488	488	488	487
5	445	443	443	440
6	446	446	446	444

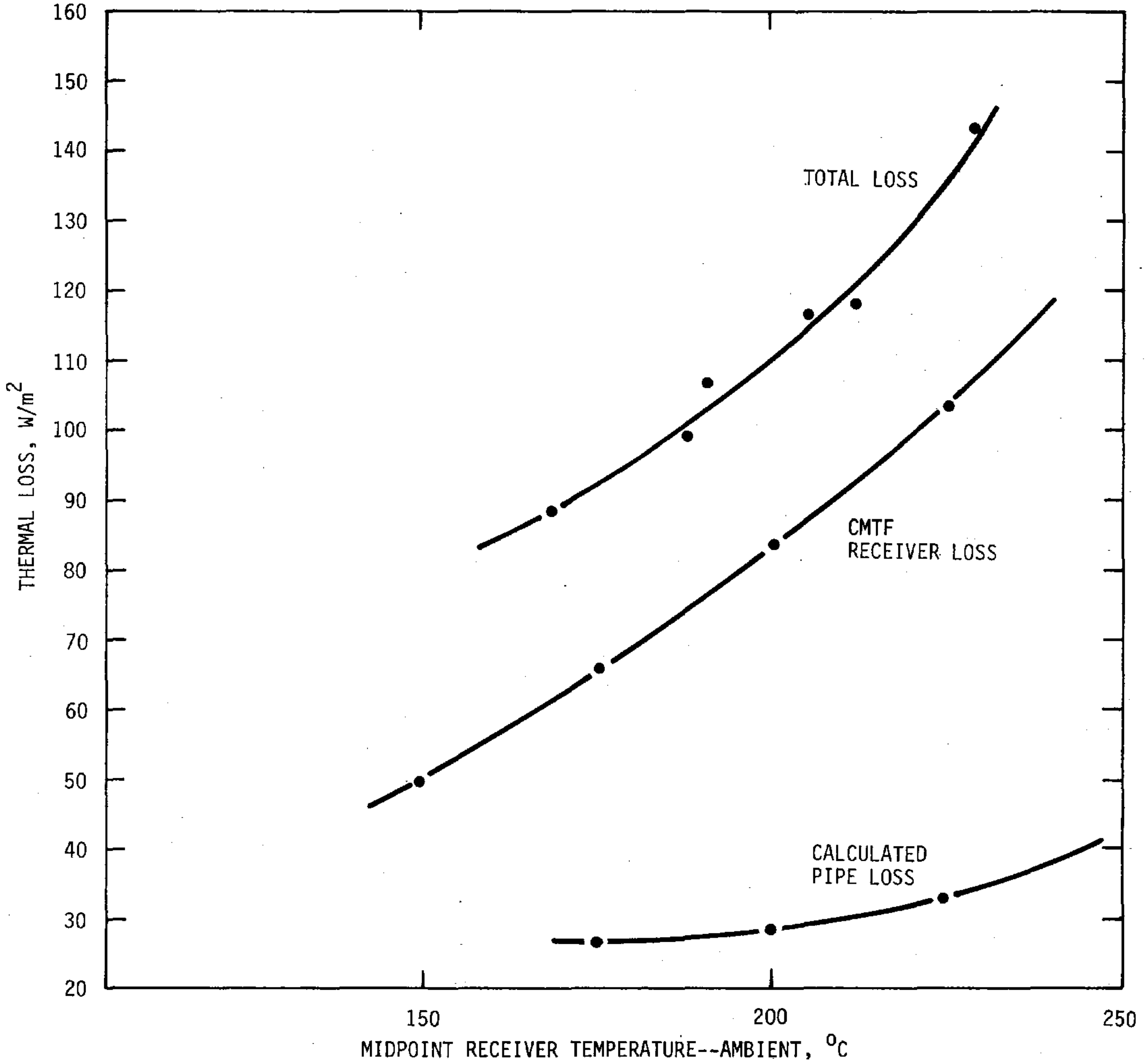


Figure 2. Total Thermal Losses vs. Midpoint Receiver Temperature above Ambient

SUNDSTRAND ORGANIC RANKINE CYCLE SUBSYSTEM PERFORMANCE TESTS AT THE COOLIDGE, ARIZONA, SOLAR IRRIGATION FACILITY, 29, 30, AND 31 JANUARY 1980

Subsystem Description

The principal components of the Sundstrand Organic Rankine Cycle (ORC) Subsystem are the vaporizer assembly, power conversion module, and generator. The solar-generated thermal energy of the Caloria HT-43 from the storage tank is transferred to toluene in the vaporizer. The toluene is expanded through the turbine to drive the generator, producing electrical power. Figure 1 is a schematic of the entire 150-kW_e Solar Irrigation Facility illustrating the subsystem components as they were installed.

The vaporizer assembly consists of three sections: the preheater, vaporizer, and superheater. The assembly is a fluid-to-fluid heat exchanger. A sketch of the equipment (Figure 2) identifies major items in the assembly.

Caloria that has been heated by the solar collectors is pumped through the superheater section, the vaporizer section, and the preheater sections and then pumped back through the solar collectors. At the same time, toluene is pumped into the preheater through the vaporizer and superheater sections, transferring the heat from the Caloria to the toluene. This heat transfer vaporizes the toluene, which is then piped to the turbine on the power conversion module (PCM). A level sensor in the vaporizer section is provided to signal the level control valve on the PCM to open or close as needed to regulate the amount of toluene entering the vaporizer assembly. This mechanism ensures that the amount of toluene needed to meet the vapor requirements of the system is present in the vaporizer assembly.

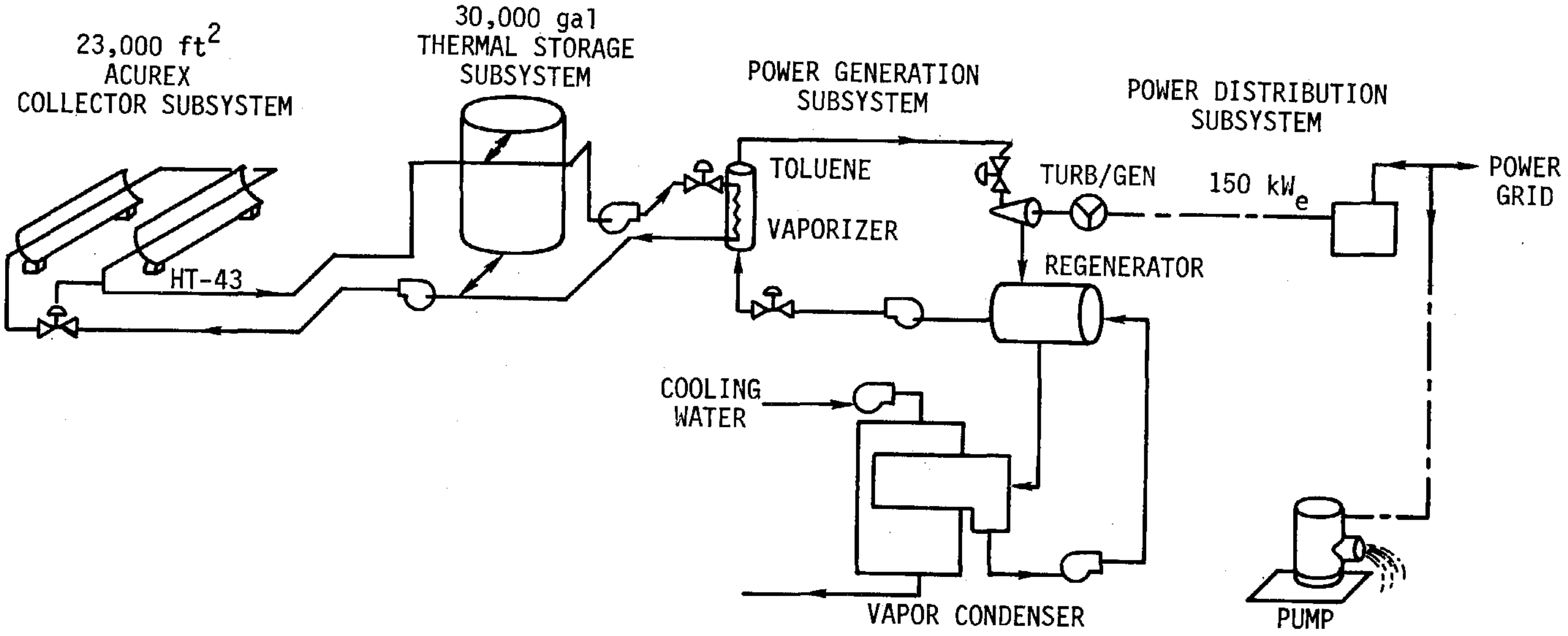
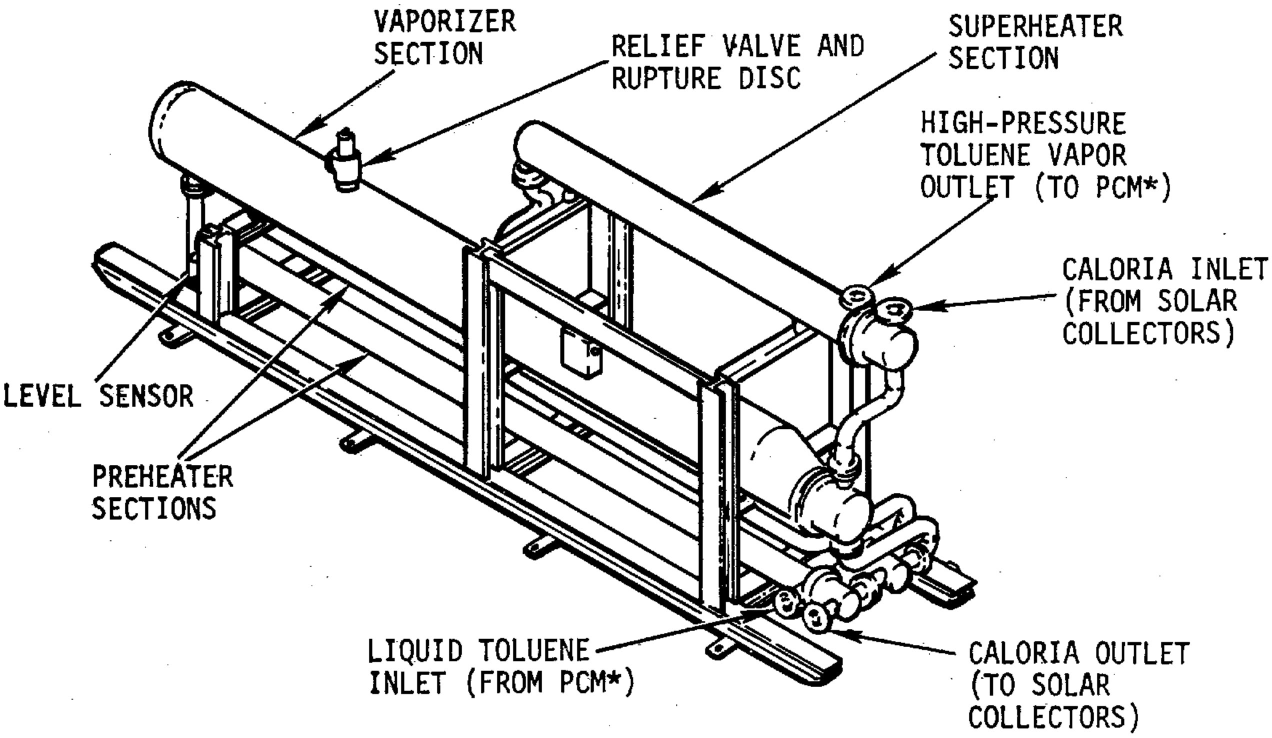


Figure 1. Schematic Diagram of the 150-kW$_e$ Solar Irrigation Facility



*POWER CONVERSION MODULE

Figure 2. Vaporizer Assembly

The PCM components include the turbine/feed pump assembly, gearbox, regenerator assembly, noncondensable removal system, and liquid/vapor toluene plumbing with related filters and pumps. These components are identified in Figure 3. A description of the components follows.

1. Turbine/Feed Pump Assembly: The turbine/feed pump assembly is mounted on a welded framework at one end of the PCM frame. The turbine exhaust outlet is connected to the regenerator by a bellows. The output shaft is connected to the gearbox by a flexible steel coupling. The two-stage main feed pump is mounted on the other end of the turbine shaft. The turbine bearings are lubricated with the working fluid, toluene. The normal operating speed of the turbine is 9,300 rpm.

2. Gearbox: The gearbox and turbine are mounted on opposite ends of a common support framework. This arrangement eases the shaft alignment and eliminates the relative motion of the shafts due to thermal expansion of the framework. The gearbox has an oil pump, sight glass, drain and fill plugs, and an oil filter. The oil is maintained at 93°C (199°F) by an external finned-tube oil cooler. The gearbox output speed is maintained at 1,800 rpm.

3. Regenerator Assembly: The regenerator assembly houses the regenerator core. As high-temperature toluene vapor enters the housing from the turbine, some of the vapor's heat is absorbed by the liquid toluene flowing through the regenerator core toward the vaporizer assembly (this preheats the liquid). As a result, less heat is needed at the vaporizer assembly to vaporize the toluene. The cooled vapor in the regenerator housing is then piped to the vapor condenser assembly, where it is liquified, and the condensate is returned to the hotwell. The system toluene level can be checked at three sight glasses on the side of the hotwell.

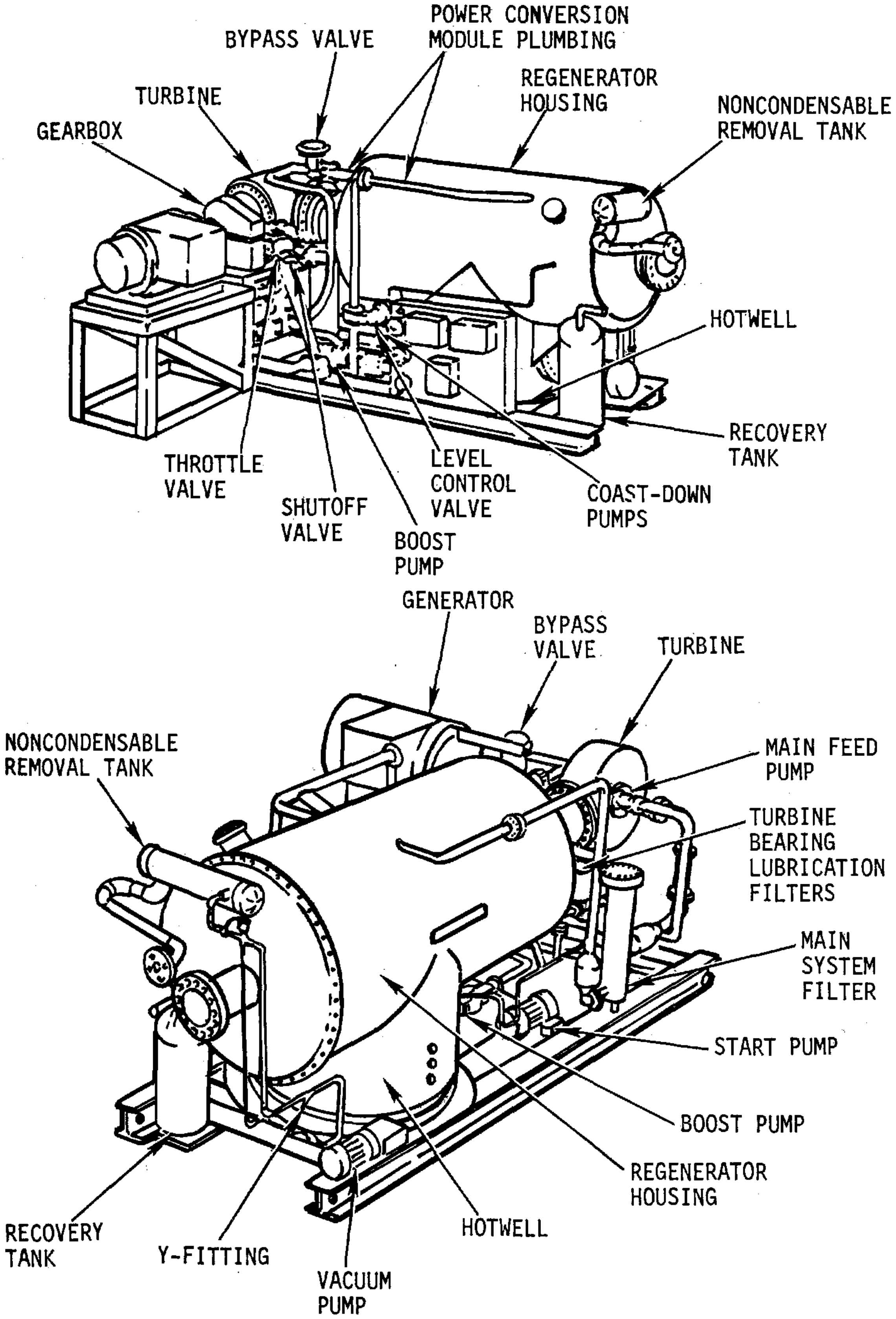


Figure 3. Power Conversion Module

4. Noncondensable Removal System: The noncondensable removal system draws noncondensable gases (mostly nitrogen) from the vapor condenser core. Before system startup, a vacuum pump in the system lowers the pressure in the regenerator assembly to 20.7 MPa (3.0 psia). (During steady-state operation, the pressure is maintained at 8.136 MPa [1.18 psia].) As the system is running, the noncondensables are drawn from the core through a heat exchanger to condense the remaining toluene vapor. The condensed toluene flows from the heat exchanger to the vapor condenser before flowing to the hotwell. The remaining gases are drawn through a strainer before being pumped to the atmosphere by the vacuum pump. The system is activated as needed when a temperature differential between toluene vapor in the condenser and gas in the removal system indicates a buildup of nitrogen in the vapor condenser.

The primary piece of equipment in the heat rejection subsystem is the vapor condenser. It uses outside air and cascading waterflow to cool and condense toluene vapor passing through tube bundles.

After leaving the regenerator housing, the toluene vapor enters the vapor condenser tubes. Two fans force air over the tubes while a spray of water keeps the tubes wet. The resulting evaporation process cools and condenses the toluene vapor. The condensed liquid flows back to the hotwell on the PCM. The cooling water is recirculated, and additional water is automatically added to replace water lost in the evaporation process. The vapor condenser was manufactured by Niagara Blower Company.

The main piece of equipment in the power distribution subsystem is the electrical generator. It is rated at 250 kVA and 60 hertz and is a three-phase, synchronous, ac unit that operates at 1,800 rpm with an output of 480 volts. The efficiency of the generator is 95.6% at 0.8 power factor. The generator was especially designed and manufactured for this solar system by Kato.

Purpose

The purpose of this test series was to determine the performance characteristics of the Sundstrand ORC Subsystem under design conditions and under a variety of off-design conditions.

Test Procedure

On 29, 30, and 31 January 1980, the Sundstrand ORC Subsystem was operated utilizing heated Caloria HT-43 supplied from the thermal storage subsystem at a variety of flow rates and temperatures. Prior to each day's testing, the thermal storage tank was conditioned by the gas-fired heater.

Test Results

A listing of the data collected from the series of 16 tests is presented in Table 1. Figure 4 is a plot of gross cycle efficiency versus generator output. Gross cycle efficiency is defined as the generator electrical power output divided by the thermal power input to the vaporizer by the Caloria.

The design point parameters as provided by Sundstrand Corporation are presented in Table 2 so they may be compared to the test data.

Table 3 is a listing of all the parasitic electrical power consumed by the ORC subsystem over a range of generator output power. The parasitic power includes the power consumed by the Caloria pump at the vaporizer. These data are from an independent test series conducted by J. P. Abbin, Sandia Laboratories, Albuquerque, New Mexico, on 3, 4, and 5 December 1979.

The test results indicate that the actual design point gross cycle efficiency is 19.7%, which is very close to the manufacturer's projected value of 20.2%. Subtracting the subsystem parasitic power, which averaged about 24 kW_e (22.7 Btu/s), from the 200-kW_e (189.6-Btu/s) design point yields a design point net cycle efficiency of 17.3%.

Table 1

Test Data

Run Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Date	1-29-80	1-29-80	1-29-80	1-30-80	1-30-80	1-30-80	1-30-80	1-30-80	1-30-80	1-31-80	1-31-80	1-31-80	1-31-80	1-31-80	1-31-80	1-31-80
Generator Output, kW_e	192.9	229.9	75.3	201.6	218.2	215.8	196.9	165.6	143.6	115.6	76.0	22.5	168.0	206.3	189.4	106.3
Ambient Temperature, °F	61.1	60.3	60.2	65.5	65.3	65.3	65.3	65	64.7	64.4	64.7	64.5	64.1	72.9	72.3	72.9
Toluene																
Hotwell, °F	107.2	107.8	96.7	96.6	100.0	100.9	99.2	105.1	106.1	101.9	101.9	100.1	97.7	113.2	110.8	104.1
psia	0.634	0.786	0.295	0.53	0.53	0.53	0.53	0.77	0.53	0.53	0.28	0.28	0.77	0.33	0.72	0.38
Regenerator Liquid in, °F	110.3	110.9	99.3	99.1	102.2	103.7	102.0	106.2	105.7	100.4	97.9	96.6	99.1	114.8	113.3	105.3
Preheater in, °F	229.1	230.1	237.2	239.5	242.4	242.3	244.5	253.4	251.3	245.3	242.1	243.1	242.0	245.7	261.1	262.1
Boiler, °F	430	448	364	436	444	443	436	427	414	399	374	332	421	--	424	382
psia	160	189	80	168	180.2	179	166	151	134	116.2	89	55	151	184.7	151.7	99.7
Superheater out, °F	491.0	480.1	472.2	499.0	493.0	490.8	492.7	495.8	488.5	477.2	462.8	434.3	485.5	507.9	523.6	511.3
Turbine in, °F	481.7	472.2	461.8	492.9	487.5	485.2	486.9	489.7	482.2	470.7	455.4	425.6	478.9	501.9	516.7	503.0
psia	139	165	67	147	158	157	146	132.5	116.7	99.7	77.0	47.1	132.7	160.0	131.2	84.7
Turbine out, °F	313.6	307.7	311.4	334.9	332.6	330.9	334.9	347.2	341.6	337.3	331.8	324.9	334.6	340.3	360.0	354.9
Condenser Liquid out, °F	110	113	83	96	99	99	96	109	96	91	85	77	98	--	109	92
Flow Rate, lbm/hr	14,282	17,315	6,682	14,668	16,070	15,979	15,356	13,385	11,588	9,748	8,016	4,675	13,445	15,730	12,674	8049
Thermal Power Input, kW	1067	1255	492.1	1089	1169	1158	1116	966	831.7	695.8	565.0	313.7	972.2	1169.1	950.0	595.6
Efficiency, %	18.07	18.32	15.30	18.51	18.67	18.63	17.64	17.15	17.26	16.61	13.45	7.17	17.28	17.65	19.93	17.85
Caloria HT-43																
Superheater in, °F	526.1	529.9	500.4	526.7	524.9	523.8	519.8	514.4	508.0	497.6	585.2	460.7	498.8	551.6	557.3	553.2
Preheater out, °F	372.3	388.5	319.8	383.3	392.5	392.8	386.7	383.1	370.3	355.7	334.7	307.3	389.2	381.3	366.6	333.8
Flow Rate, lbm/hr	33,510	42,001	13,524	36,611	42,053	42,139	38,540	34,519	29,974	25,127	18,631	11,036	42,720	33,105	24,964	14,195
Thermal Power Output, kW	999	1159	460	1022	1086	1077	997	878	794	679.6	527.9	312.5	903.8	1106.2	931.2	601.0
Efficiency, %	19.31	19.84	16.37	19.73	20.08	20.04	19.75	18.86	18.09	17.01	14.40	7.20	18.59	18.65	20.34	17.69

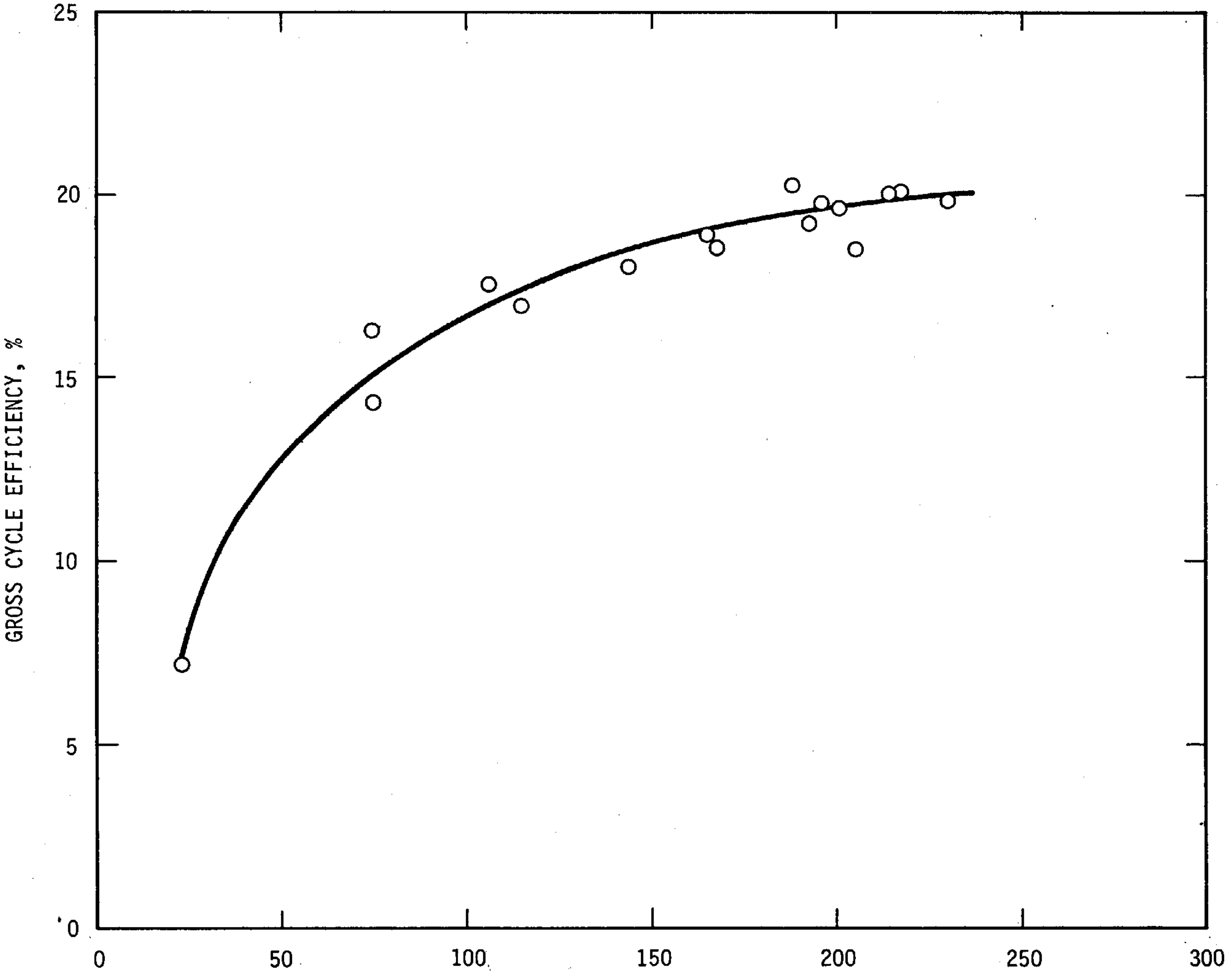


Figure 4. Generator Output, kW_e

Table 2

Design Point Parameters

	200-kW ORC Design Conditions	
Parameter Location	Pressure psia	Temperature °F
Hotwell	1.4	105
Feed pump out	260.0	110
Regenerator cut liquid	255.0	285
Vaporizer out	153.0	515
Turbine in	152.0	513
Turbine out	1.5	360
Regenerator out vapor	1.4	134
Condenser out	1.2	105

Operating Parameters	
System flow rate	14,031 lbm/h (approx. 33 gpm)
Electrical output power	200 kW_e Power factor = 1
Overall system efficiency	0.202

Table 3

Parasitic Power Consumption

Data Point	Generator Output kW_e	Parasitic Power kVA
1	231	24.5
2	235	27.8*
3	235	22.6
4	213	24.2
5	200	24.3
6	200	24.0
7	156	22.7
8	154	24.0
9	118	23.6

*Condenser vacuum pump running

A breakdown of the parasitic power consumed, as determined by University of Arizona personnel, is as follows:

Component	Min. Power kW_e	Min. Power (Btu/s)	Max. Power kW_e	Max. Power (Btu/s)
Vaporizer Caloria pump	4.0	(3.79)	5.4	(5.12)
Vapor condenser	8.9	(8.436)	8.9	(8.44)
Power conversion module	12.7*	(12.04)	15.1*	(14.31)
Total	25.6	(24.26)	29.4	(27.87)

*These measurements were made with the condenser vacuum pump running.

The condenser vacuum pump consumes about 3.5 kW_e (3.32 Btu/s) and runs infrequently. Subtracting 3.5 kW_e (3.32 Btu/s) from the average total parasitic power listed above also results in 24 kW_e (22.8 Btu/s).

Discussion

A key finding illustrated in Figure 4 is that the gross cycle efficiency was nearly constant over a wide power range. The high efficiency over a wide power range is a valuable attribute in any power system, and these test results may indicate the most energy-efficient control strategy for systems with a variable load. The subsystem power output for the tests was varied by manually regulating the hot Caloria flow from storage. Varying the Caloria flow had the effect of moving the vaporizer boiler section boiling point in the same direction, i.e., decreasing the hot Caloria flow decreased the boiling point while maintaining an essentially constant superheater outlet temperature and efficiency. This effect suggests a simple control scheme in which the turbine runs "wide open" at all times and only the heat input to the engine system is varied. As a consequence of this scheme, the turbine would not require expensive and complex variable admission or throttle devices; also, the turbine would see a minimum of thermal cycling due to variable inlet temperatures or variable mechanical loading on the turbine wheel blading, which occur when a variable admission system is used.

Another item of interest from the tests was the difference between the engine efficiency calculated from thermal input based on the hot Caloria HT-43 measurements versus the toluene measurements. This difference could be explained by uncertainty about the properties of the Caloria or the toluene. Past experience at the Midtemperature Solar Systems Test Facility (MSSTF) and Willard seems to indicate that the toluene properties may be the culprit. This conclusion is based on the fact that at the MSSTF the engine efficiencies based on the T66 oil measurements have been consistently 5% to 10% higher than those based on the toluene measurements, which are similar to the current test results at Coolidge. At Willard, however, the engine efficiencies based on the HT-43 measurements consistently agree with the R113 measurements within 5%. Toluene has been used as a Rankine cycle working fluid for a relatively short time, and, thus, there has not been any particular emphasis on getting good thermodynamic properties. In light of toluene's new role, research should be sponsored to accurately generate and verify its thermodynamic and heat transfer properties.

AN ESTIMATE OF THE PARASITIC ENERGY REQUIREMENT OF THE COOLIDGE SOLAR IRRIGATION FACILITY

The total energy requirement to operate the collector subsystem, power conversion subsystem, and control building is monitored on a daily basis. During May, June, and July, daily parasitic energy consumption ranged from less than 200 kWh_e (6.82×10^8 Btu) up to 380 kWh_e (13.0×10^8 Btu), with the average use being 230 kWh_e (7.85×10^8 Btu). On a representative, fully operational day, about 270 kWh_e (9.21×10^8 Btu) was used by the plant. Of this total, about half of the energy was used by the power conversion system. The collection system used an estimated 60 kWh_e (2.05×10^8 Btu), with the remainder required for the control building lights, air conditioner, and miscellaneous equipment.

The peak parasitic power requirement has been 41.3 kW_e (39.2 Btu/s). This demand is the sum of building, collector subsystem, and power conversion subsystem demands. Some of these demands have been quantified in short-term tests. The results of these tests follow.

Collector Tracking Subsystem

Power was measured as all tracking units were raised and lowered in unison at the control console in the control building. About 10.7 kW_e (10.14 Btu/s) was used, of which about 0.05 kW_e (0.47 Btu/s) was used by the console itself with tracking units inoperative. Thus, all tracker drive motors together required about 10.2 kW_e (9.67 Btu/s).

Average tracking system power requirements during normal tracking operation were computed by estimating the duty cycle for each motor run time was 2.6% of the operating time. The computed average power demand is 2.6% of 10.2 kW_e (9.67 Btu/s) or 0.3 kW_e (0.28 Btu/s) for the tracking system.

Collector Field Pump

The power required by the solar collector subsystem Caloria pump varied from 1.3 kW_e (1.23 Btu/s) at a flow rate of 1.9 ℓ/s (30 gal/min) to 5.2 kW_e (4.9 Btu/s) at 5.2 ℓ/s (82 gal/min) for Caloria at about 205°C (400°F).

Vaporizer Caloria Pump

Vaporizer Caloria pump power demand was measured with different Caloria temperatures and generator outputs. The power requirement ranged from about 4.0 kW_e (3.79 Btu/s) to 5.4 kW_e (5.12 Btu/s).

Condenser Cooling Tower

The two-wattmeter method was used to measure power used by the cooling tower water pump and two fans. Each fan requires about 3.8 kW_e (3.60 Btu/s); the water pump uses about 1.3 kW_e (1.23 Btu/s). Together, these three units use about 9 kW_e (8.5 Btu/s) during operation.

Power Conversion Module

Power was measured at the load side of the 125-ampere PCM console circuit breaker in panel HA. Measurements ranging from 12.7 kW_e (12.04 Btu/s) to 15.1 kW_e (14.31 Btu/s) were obtained with the turbine operating and the generator supplying power to the utility electrical grid system.

Summary

Daily parasitic electrical energy usage by the solar power plant averaged about 230 kWh_e (7.85×10^8 Btu) during May, June, and July. A more representative value for a fully operational day is estimated to be 270 kWh_e (9.21×10^8 Btu). Approximately half the energy is used by the power conversion module, 20% by the collector subsystem, and 30% by the control building including air conditioner.

STATIC TEST OF THERMOCLINE STORAGE TANK AT COOLIDGE, ARIZONA,
14 THROUGH 16 NOVEMBER 1979

Purpose

The purpose of this test was to study the rate of growth of the thermocline in the thermal storage tank at Coolidge under static conditions.

Test Procedure

The tank was prepared by first heating it uniformly to 287°C (550°F) from the top down to the lower diffuser, using the gas-fired heater. To establish a thermocline, the Organic Rankine Cycle (ORC) subsystem was operated with a 200-kW_e (189.6-Btu/s) output. The temperature of the Caloria returned to the bottom of the storage tank by the ORC subsystem was 160°C (320°F). At the end of this process, the temperature profile in the tank was as shown by the solid line in Figure 1.

The initial thickness of the thermocline was probably caused by turbulence at the lower diffuser both during the heating process and during the initial injection of colder Caloria from the ORC subsystem. The upper diffuser was closed off, and the lower diffuser pipeline was left open to allow the tank to act as an expansion tank for the remainder of the system. The tank was held in this condition for the duration of the test.

The test began at 8:15 p.m., Wednesday, 14 November, and ended 1:43 p.m., Friday, 16 November. The temperature profile of the Caloria in the tank was determined by monitoring type K thermocouples on the outside of the skin of the tank. These had been welded to the tank prior to the installation of the insulation.

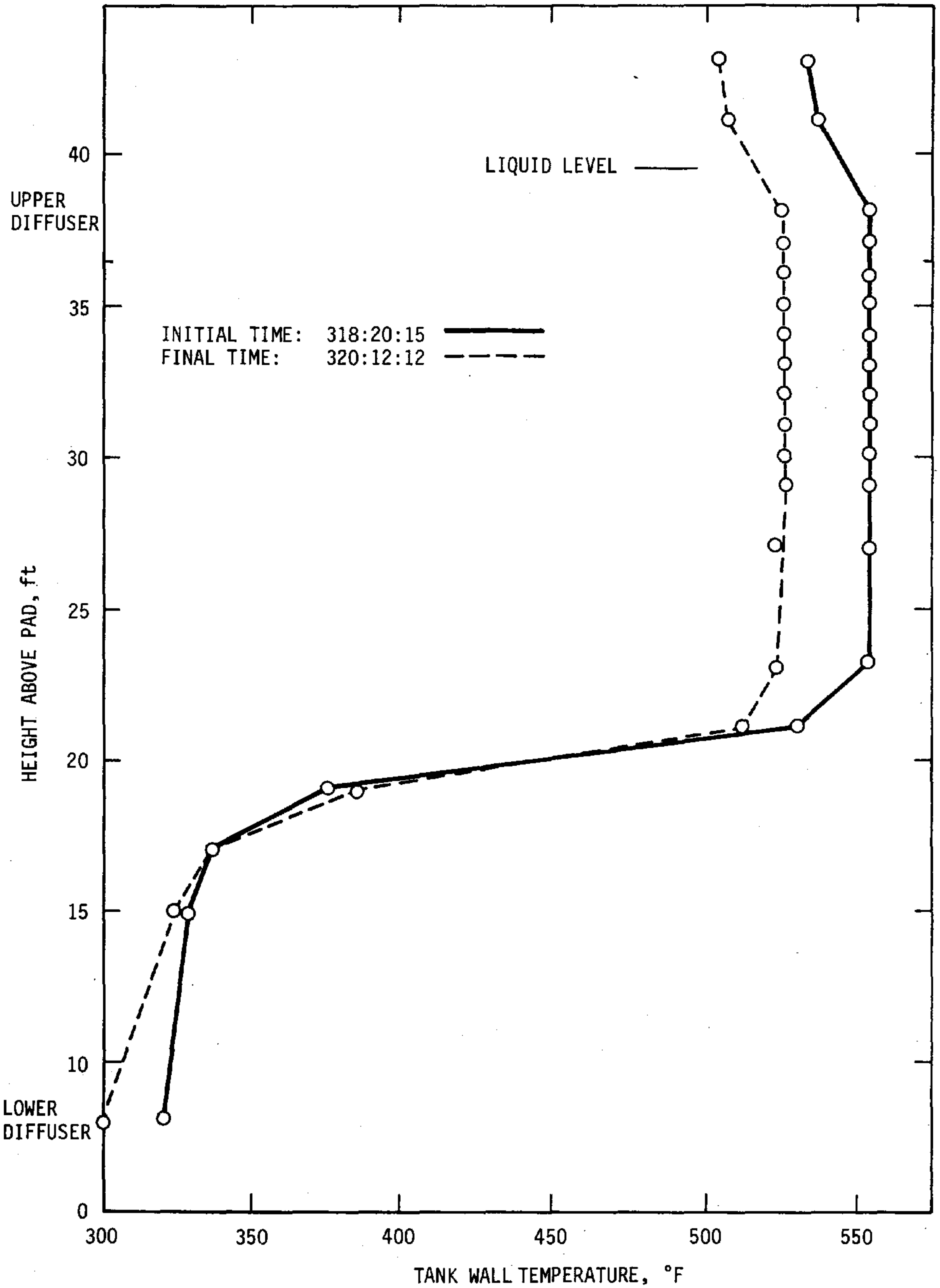


Figure 1. Thermal Storage Tank Temperature Profile

Test Results

The test results are presented in Figures 1 through 4. Figure 1 presents the temperature profile of the skin of the tank at the beginning and end of the test. Figure 2 is a plot of the upper bulk oil temperature versus time during the test. Figure 3 shows the temperature at several points on the dome of the tank and on the manhole cover on the side of the tank. Figure 4 is a plot of the ambient air temperature and wind speed during the test.

Discussion

The vertical resistance temperature detector (RTD) probe in the center of the tank was used only to verify that no horizontal temperature gradient existed in the upper portion of the tank. The other RTDs were not yet properly set up. It was then assumed that the skin temperature of the tank would be equal to the Caloria temperature all the way down the tank.

The thermocline proved to be stable and did not grow in size throughout the test. However, the upper bulk Caloria temperature decreased at the rate of 0.381°C (0.686°F) per hour. The purpose of presenting the extra thermocouple readings on the thermal storage tank, the wind velocity, and the ambient air temperature in the test results is to permit a study of the thermal loss mechanisms that are present.

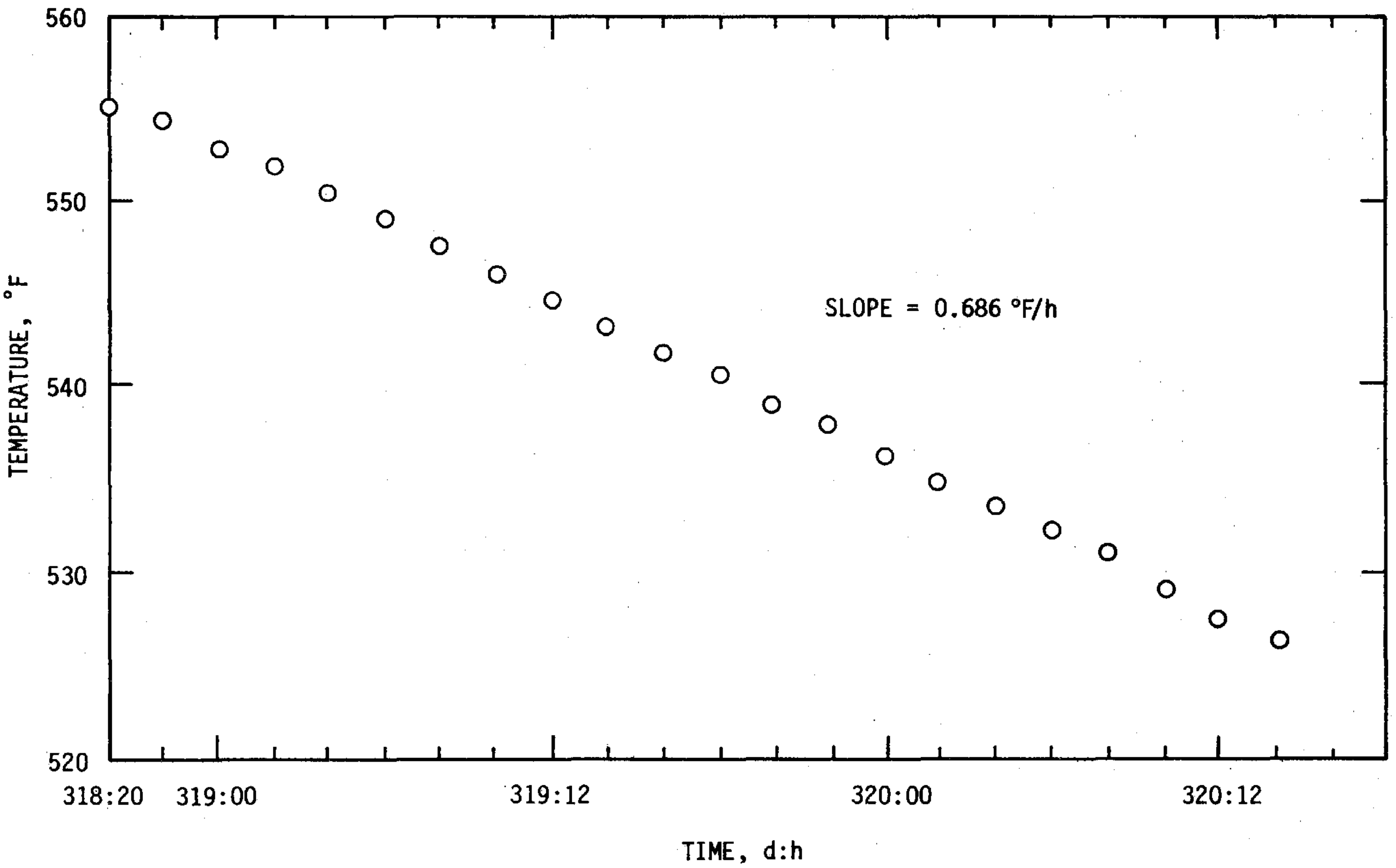
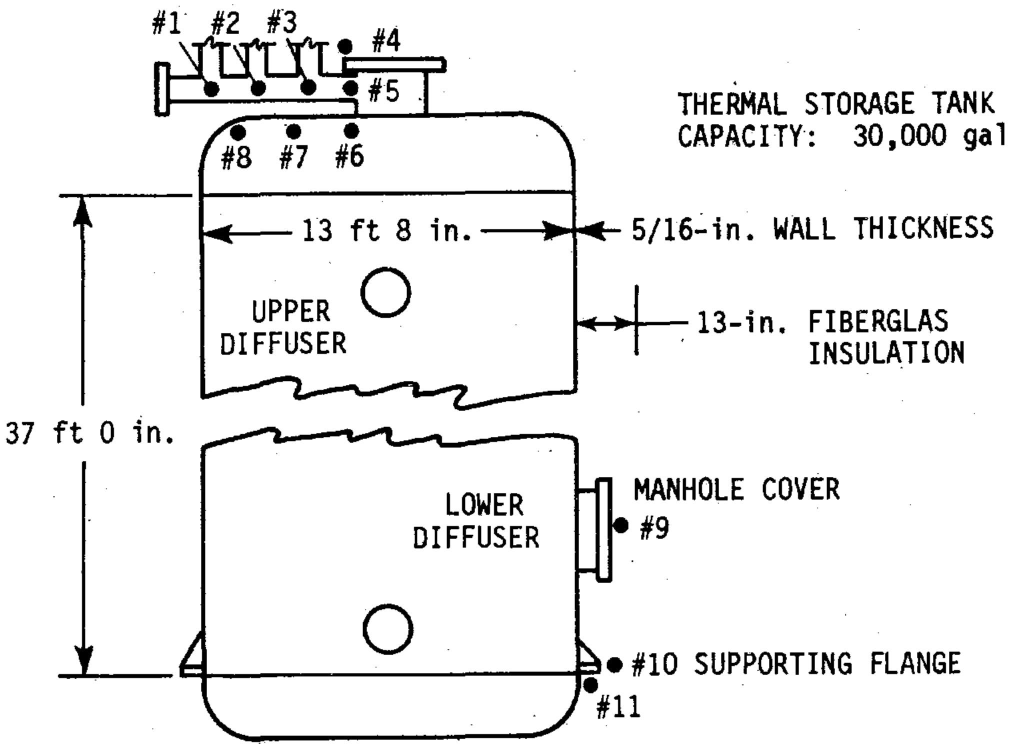


Figure 2. Upper Bulk Caloria Temperature vs. Time



TIME	THERMOCOUPLE TEMPERATURE, °F										
DAY:HR:MIN	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11
318:20:15	74.7	85.3	111.5	174.7	307.2	465.6	528.1	536.5	---	174.7	144.3
319:00:00	73.8	85.6	112.8	175.3	309.6	464.5	524.8	534.0	---	171.8	140.0
319:04:00	64.9	77.0	104.5	176.9	307.8	465.3	522.0	531.3	---	169.9	134.9
319:08:00	74.5	74.3	99.1	172.9	308.5	466.7	519.6	528.6	---	166.3	130.8
319:12:00	114.3	108.1	129.0	183.7	311.3	463.3	517.6	525.9	---	171.1	143.2
319:16:00	101.7	108.7	130.6	184.8	315.9	460.0	514.4	521.8	---	177.6	152.9
319:20:00	81.3	94.6	122.9	177.1	311.4	458.6	511.7	519.1	---	175.5	146.5
320:00:00	76.8	90.5	119.8	176.5	314.6	458.1	509.0	516.5	---	171.1	140.4
320:04:00	72.3	86.2	116.2	177.1	317.5	456.1	506.3	513.5	---	168.6	136.9
320.08.00	72.9	73.6	98.8	174.7	321.4	455.5	503.6	510.8	203.2	163.8	129.2
320:12:12	119.5	115.2	138.2	198.1	320.9	453.9	500.9	508.6	---	167.5	140.9

Figure 3. Extra Thermocouple Readings on Thermal Storage Tank

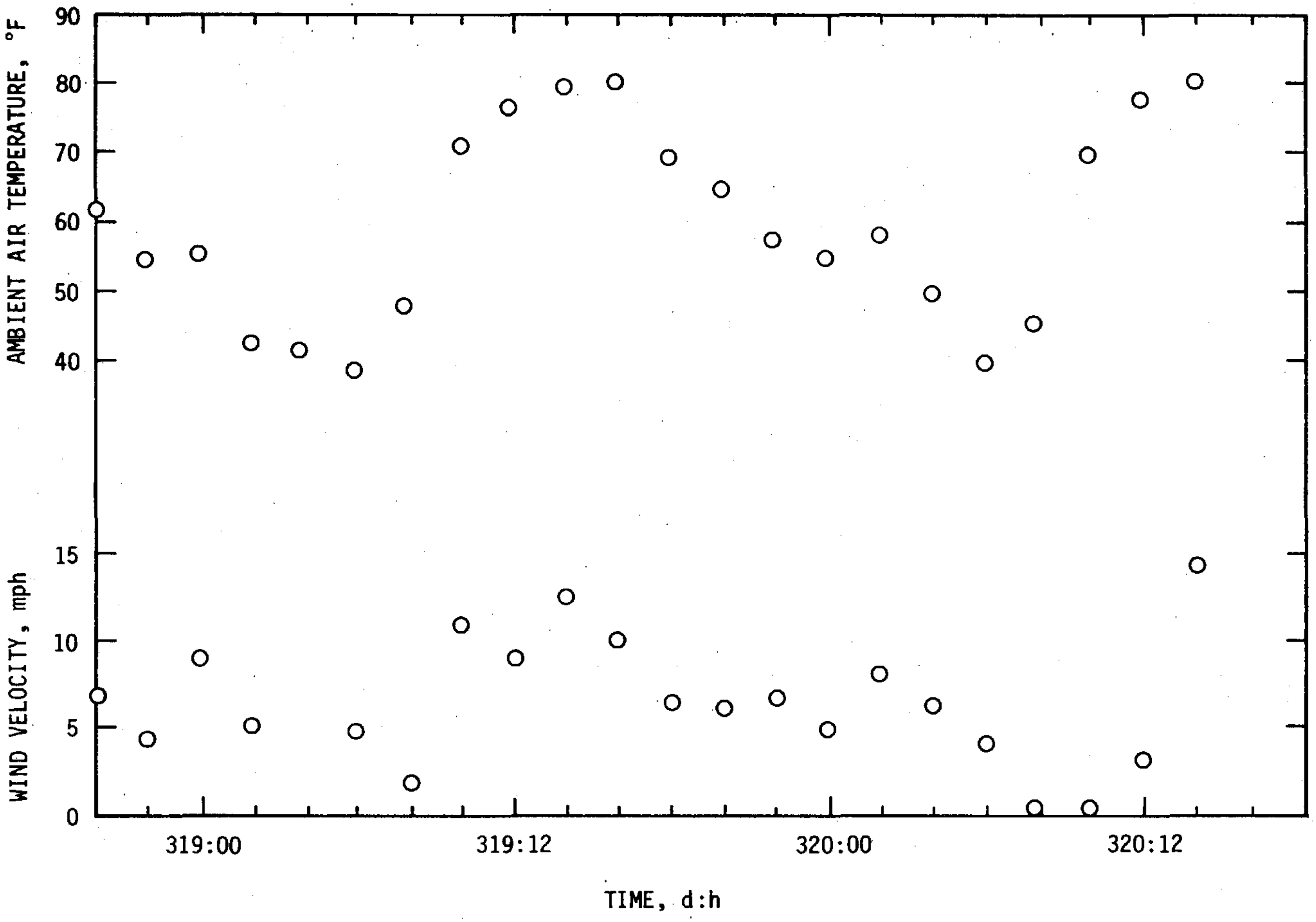


Figure 4. Ambient Air Temperature and Wind Velocity vs. Time

COOLIDGE, ARIZONA, THERMAL STORAGE SUBSYSTEM
THERMOCLINE GROWTH TEST,
17 THROUGH 21 APRIL 1980

Purpose

The purpose of this test was to illustrate the growth characteristics of a thermocline established and maintained in the storage tank at Coolidge, Arizona, over a 5-day period with the system in daily operation.

Significant leakage through the three-way bypass valve obscured the test results. This test will be repeated after a new three-way valve is installed. The test report is presented here for general information.

Test Procedure

For the purpose of this test, the thermocline is defined as that layer of fluid in the storage tank that has a temperature of 260°C (500°F) on top and 232°C (450°F) on the bottom. The thickness of the thermocline is the distance separating the 260°C (500°F) and 232°C (450°F) Caloria.

In the course of normal operation at Coolidge, any thermocline that may have formed in the storage tank during the day is purged from the top of the tank at the end of the day and utilized by the Organic Rankine Cycle (ORC) subsystem. This procedure is made possible by the flexibility of the ORC subsystem, i.e., the ORC will operate when the temperature of the Caloria supplied to it ranges between 287°C (550°F) and 215°C (420°F).

In order to allow a thermocline to form and grow for the 5-day test period, the following restraints were imposed on the system.

1. The ORC subsystem was stopped when the storage tank could no longer supply it with Caloria at 260°C (500°F) or above and
2. Flow from the bottom of the storage tank to the collector subsystem was allowed only when the temperature of the Caloria being supplied was at 232°C (450°F) or less.

In addition, the tank was initially conditioned for the investigation by cooling its storage volume below 221°C (430°F).

On 17 April 1980 at 10:20 a.m., the system was put into operation. The above initial condition and operating restraints had been imposed on the system. This insured that once the system was put into operation a thermocline would exist and be maintained in the storage tank.

During the course of this test, the thermocline was first moved down and then up daily. This was accomplished by operating the collectors alone until midafternoon. Then the ORC subsystem was started and operated simultaneously with the collectors until the thermocline reached the top of the storage tank. The system was then stopped for the night. The procedure was followed during the first three days of the test. The last two days were mostly cloudy, and insufficient energy was collected for turbine operation.

The temperature profile of the Caloria in the storage tank was monitored daily at collector subsystem startup, at ORC startup, and at system shutdown. The thermocouples welded to the outside of the storage tank were used to obtain the temperature readings.

Two diffusers exist in the top of the storage tank, as shown in Figure 1. The lower of the two was valved off during this entire test series.

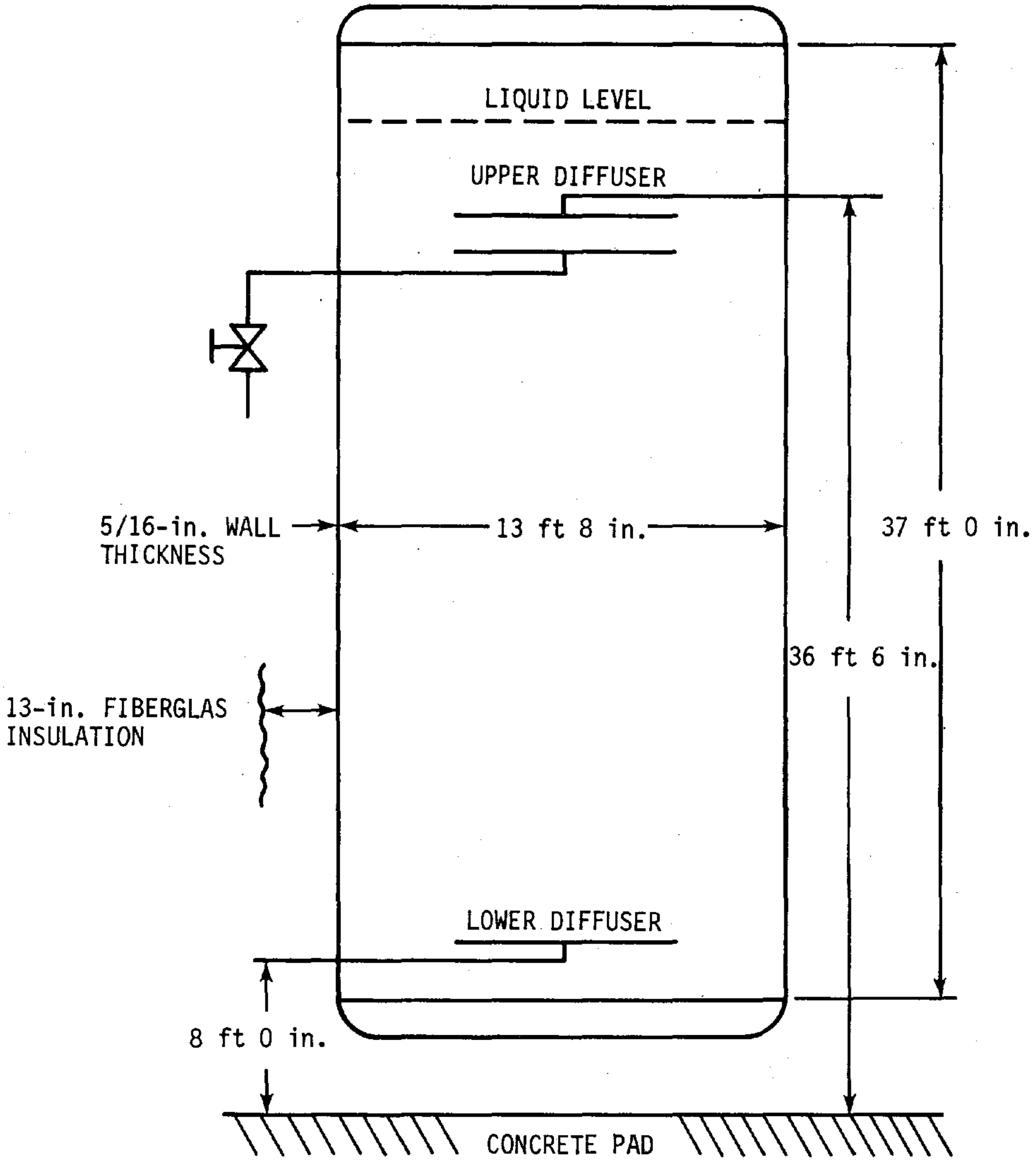


Figure 1. Tank Configuration

Test Results

The test results are presented graphically in Figures 2 through 7. Figure 2 shows how the thickness of the thermocline changed with time. Figures 3 through 7 show the temperature profiles of the storage tank as they were measured each day.

Figure 2 shows the thermocline thickness changing in discrete steps in a regular pattern during the first two days, followed by only minor changes on the third day. These steps are identified as "a," "b," and "c." Step "a" occurred during the first portion of the day, when the collectors alone were in operation. Step "b" occurred during the time when the collectors and ORC subsystem were in simultaneous operation. At the end of step "b," the thermocline was at the top of the storage tank. During step "c," the thermocline remained static at the top of the storage volume overnight.

Little change was observed in the thermocline thickness while it remained static. This result agrees with a test reported earlier on the growth rate of the thermocline under static conditions.

The extreme growth of the thermocline on the fourth day occurred during midday, when the sky was "mostly cloudy." During this time, the flow through the collector field was held in a circulating mode by the bypass valve for 5 hours. The purpose of the bypass valve is to allow the Caloria to circulate through the collector field during its warmup period at the beginning of the day or during a period of insufficient insolation. Whenever the Caloria temperature at the collector field outlet exceeds 279.4°C (535°F), the bypass valve is actuated, sending the Caloria to the top of the storage tank. Figure 6 indicates that a large quantity of cool Caloria was pumped into the top of the storage tank during the day. The only possible explanation is that the bypass valve was allowing a portion of the 204°C (400°F) Caloria that was circulating through the collector field to leak past it into the top of the storage tank. Prior to running this test, it was known that some leakage was present, but the leakage was believed to be small. Now it is estimated to be 0.6 ℓ/s (10 gal/min), which

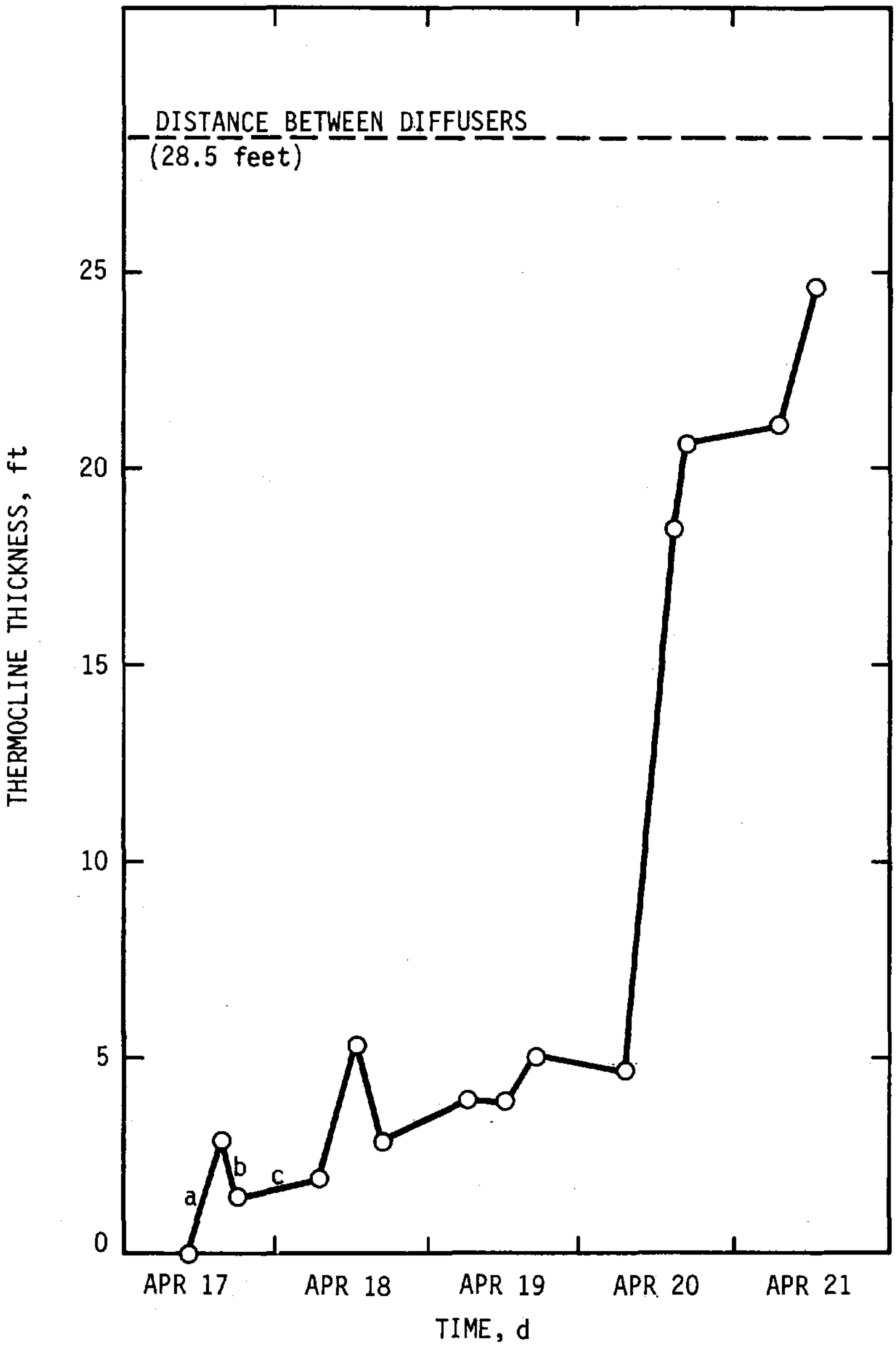


Figure 2. Thermocline Thickness vs. Time

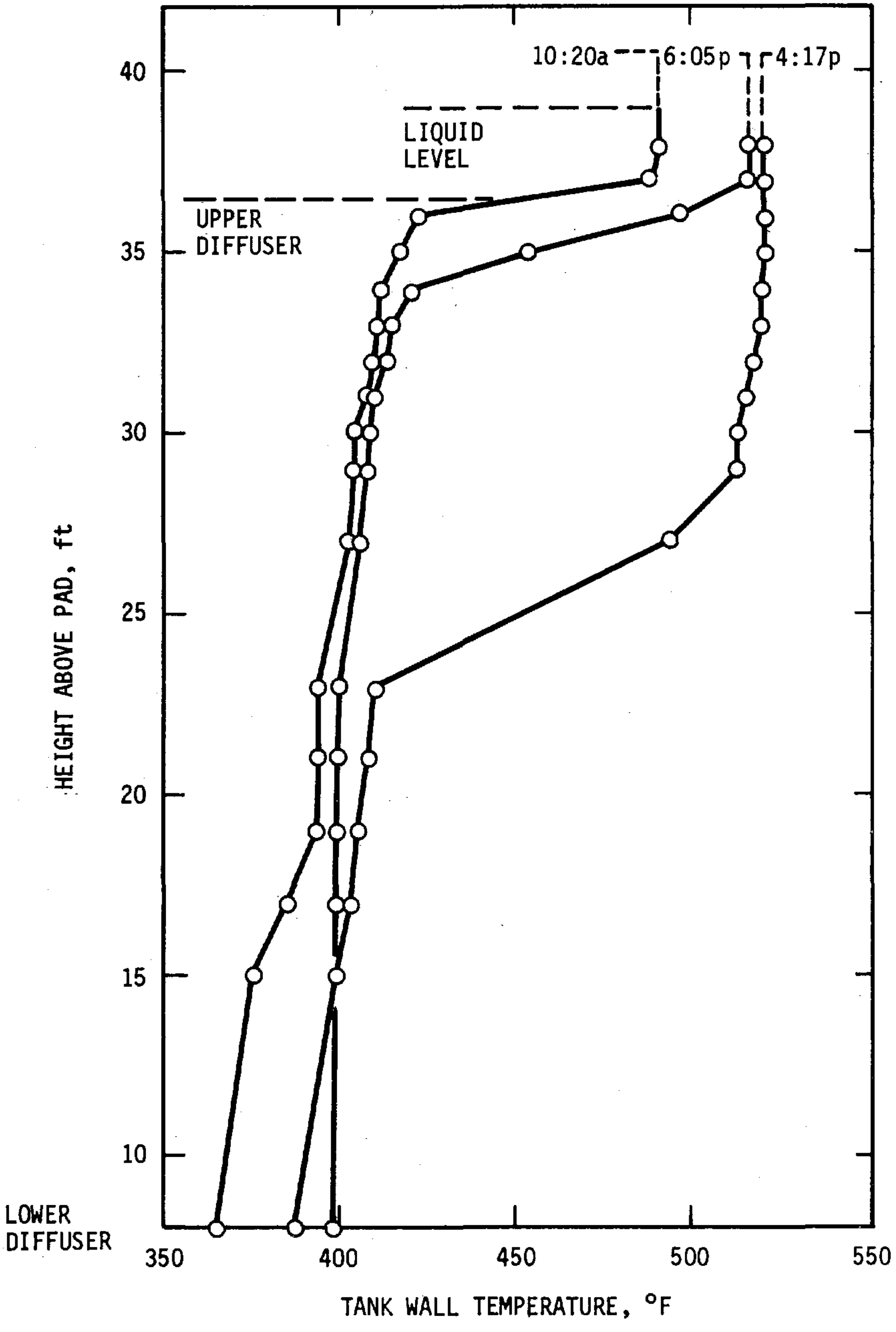


Figure 3. Thermal Storage Tank Temperature Profile, 17 April 1980

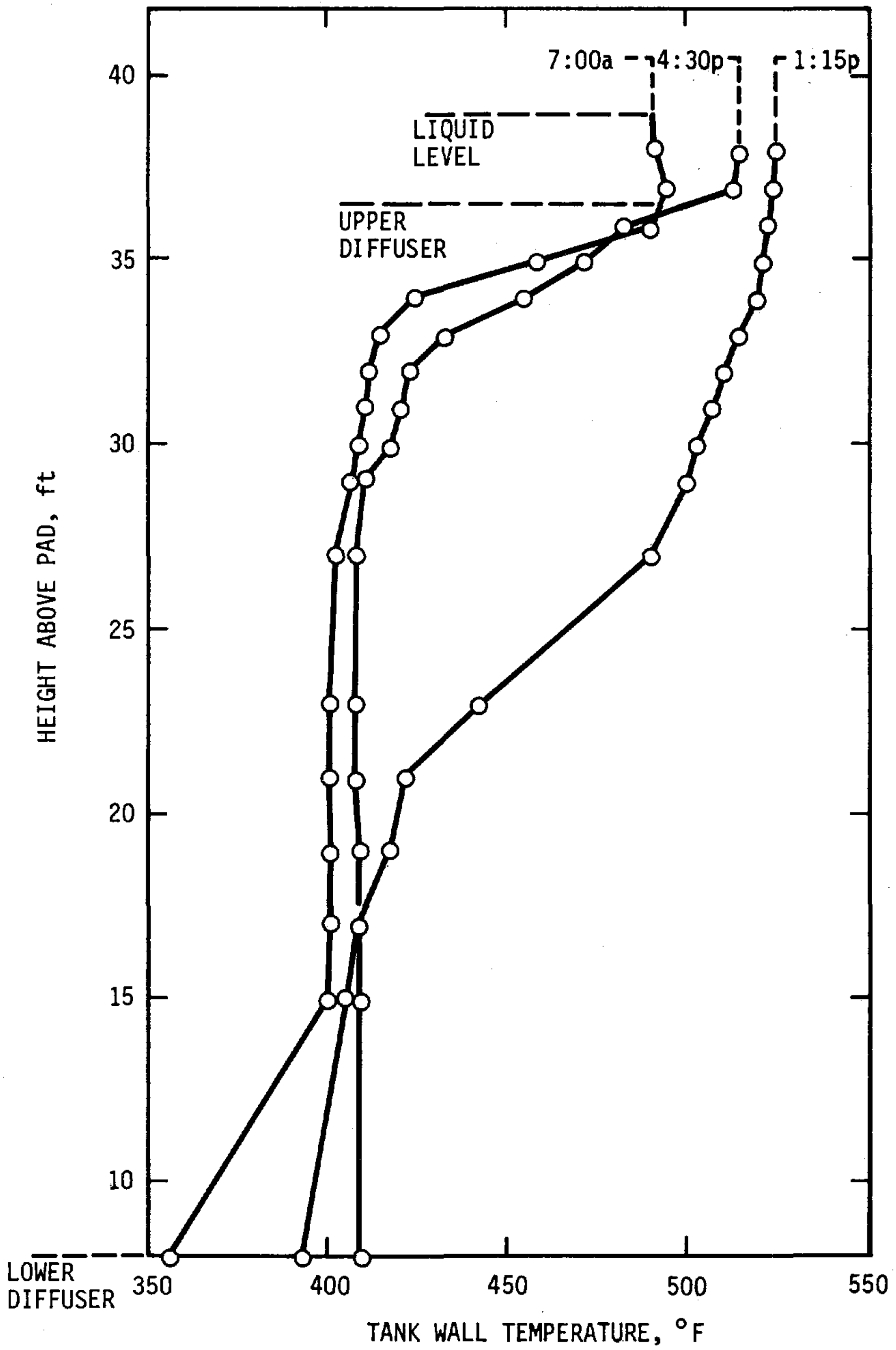


Figure 4. Thermal Storage Tank Temperature Profile, 18 April 1980

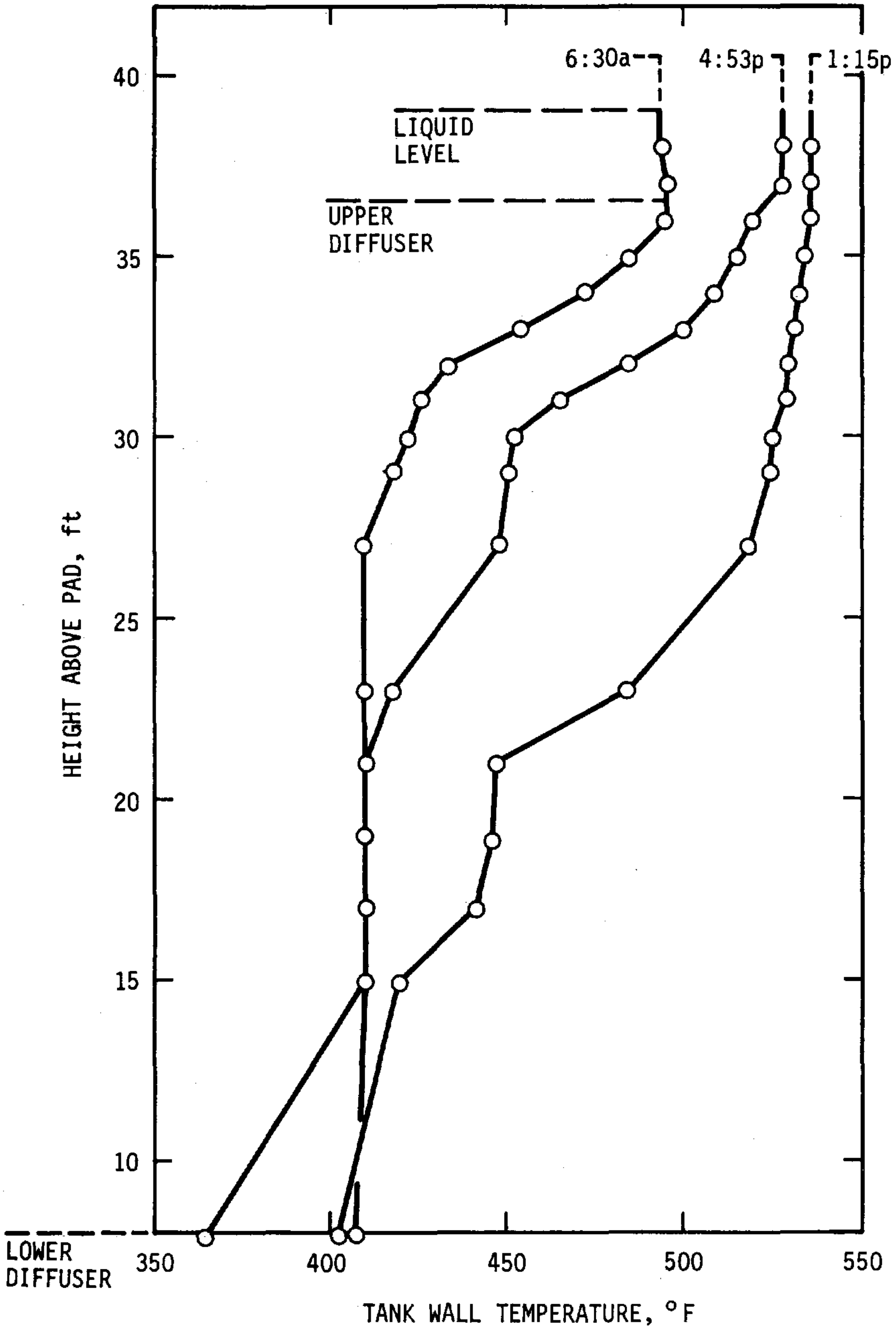


Figure 5. Thermal Storage Tank Temperature Profile, 19 April 1980

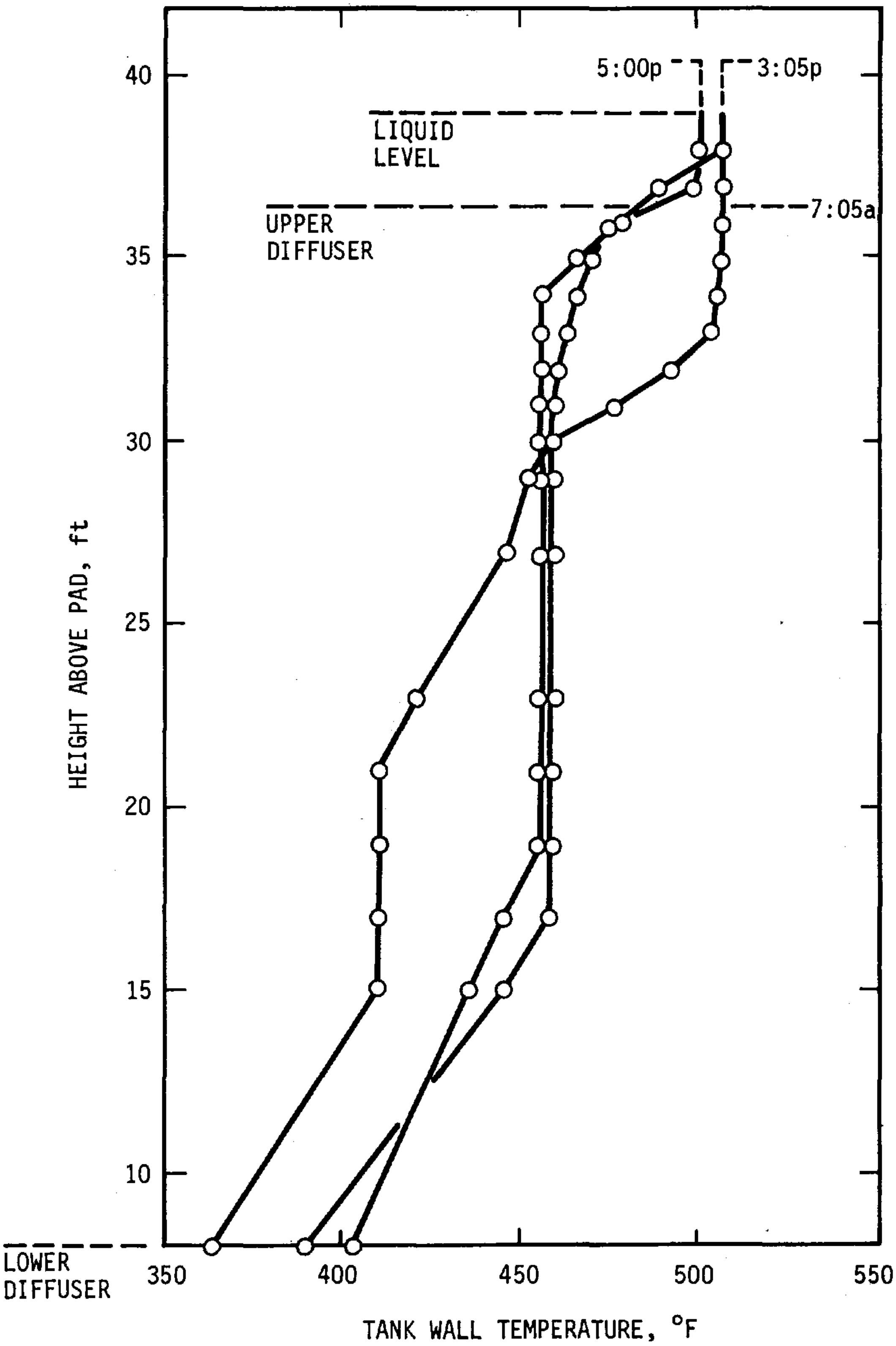


Figure 6. Thermal Storage Tank Temperature Profile, 20 April 1980

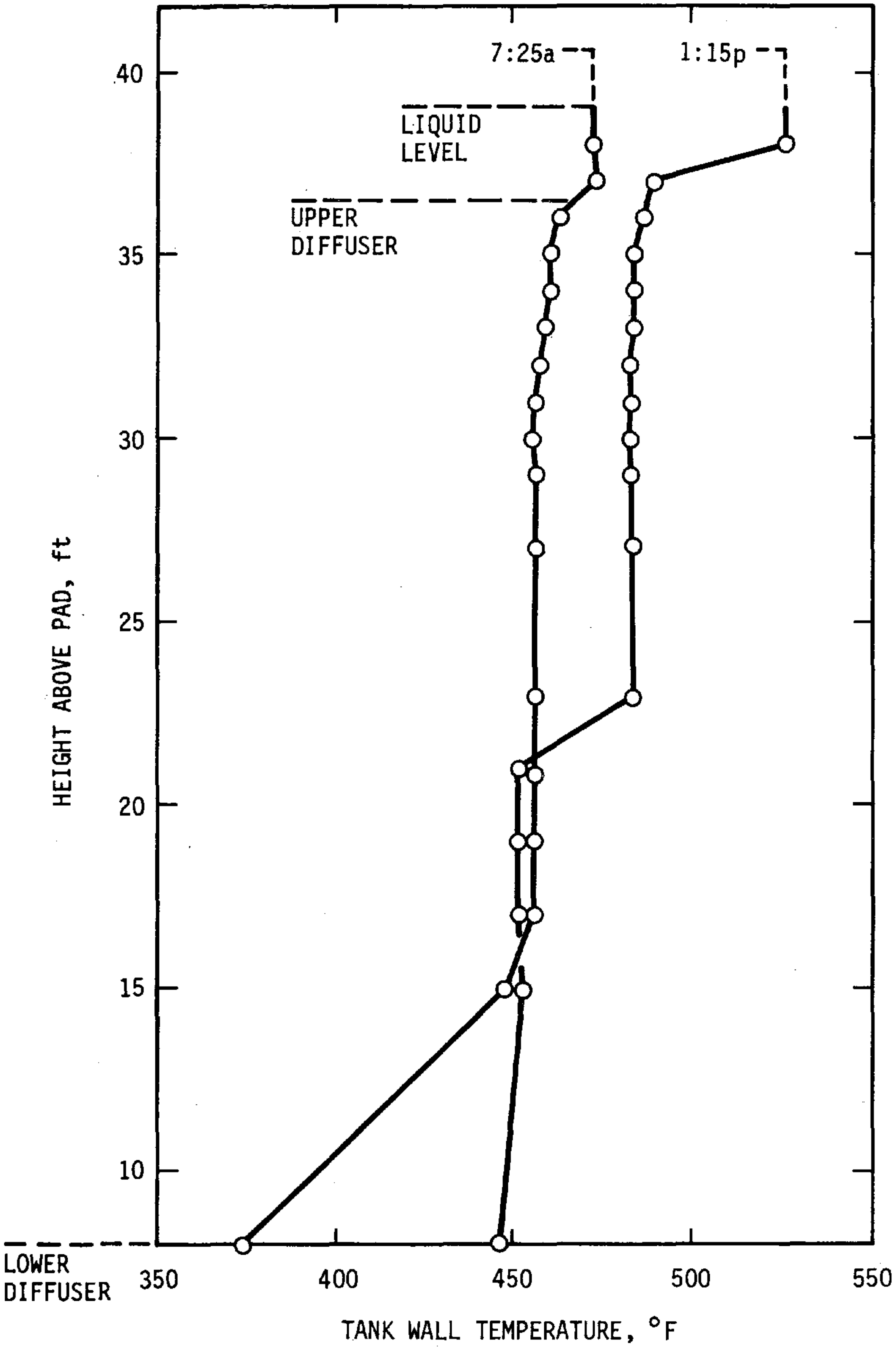


Figure 7. Thermal Storage Tank Temperature Profile, 21 April 1980

is large compared to the 1.9-ℓ/s (30-gal/min) flow rate during circulation.

The significant leakage through the bypass valve also occurs during collector field warmup each morning. This not only introduces cool Caloria to the top of the storage tank but also extends the warmup time of the collector field.

The fifth day of the test was also cloudy; however, some heat was added to storage.

Discussion

The thickness of the thermocline would probably have remained relatively small throughout the course of the test had it not been for the leaking bypass valve. It is the author's opinion that a three-way diverting valve with a conventional spool would be a better choice than the three-way ganged butterfly diverting valve used at Coolidge.

The lower of the two diffusers in the top of the storage tank was not utilized during this test series, which demonstrates that the system will function this way. It is the author's opinion that the test results would look less favorable if the lower diffuser had been used for adding Caloria to the top of storage in keeping with the system's original design. The conclusion is that future designs need not include a second diffuser at the top of a thermocline storage tank.

EXAMPLES OF THERMOSIPHONING AT COOLIDGE, ARIZONA

by

R. W. Harrigan

During a recent trip to the Coolidge Deep Well Irrigation Project, several clear examples of thermosiphoning were noted. While no quantitative measurements were made (temperatures were usually recorded as cold, warm, hot, and very hot to the touch), the qualitative results are worth discussing.

The piping around the mixing and thermocline tanks is shown in Figure 1. During the observations of thermosiphoning, there was no flow in the collector field since the day was overcast and rainy. The three-way valve, V_1, in the collector return line was open to the mixing tank, and there was hot fluid in the mixing tank from the previous day. A thermometer, T, in the collector return line near V_1 indicated the fluid at that point was about 193°C (380°F).

The first indication of thermosiphoning was in the fossil-fuel heater line. Valve V_3 was open, and, even though there was no pumped flow in this line, the uninsulated pipe at point P_1 (where the insulation stopped) was quite hot. In addition, only the top part of the uninsulated pipe was hot (too hot to keep your hand on it); the bottom was cold to the touch. The top of the uninsulated pipe cooled gradually with distance from P_1, with both the top and bottom of the uninsulated pipe reaching ambient temperature in about 3.048 to 4.57 metres (10 to 15 feet). The large temperature difference between the top and bottom of the pipe at point P_1 is even more remarkable since a light misty rain was falling on the pipe to cool it.

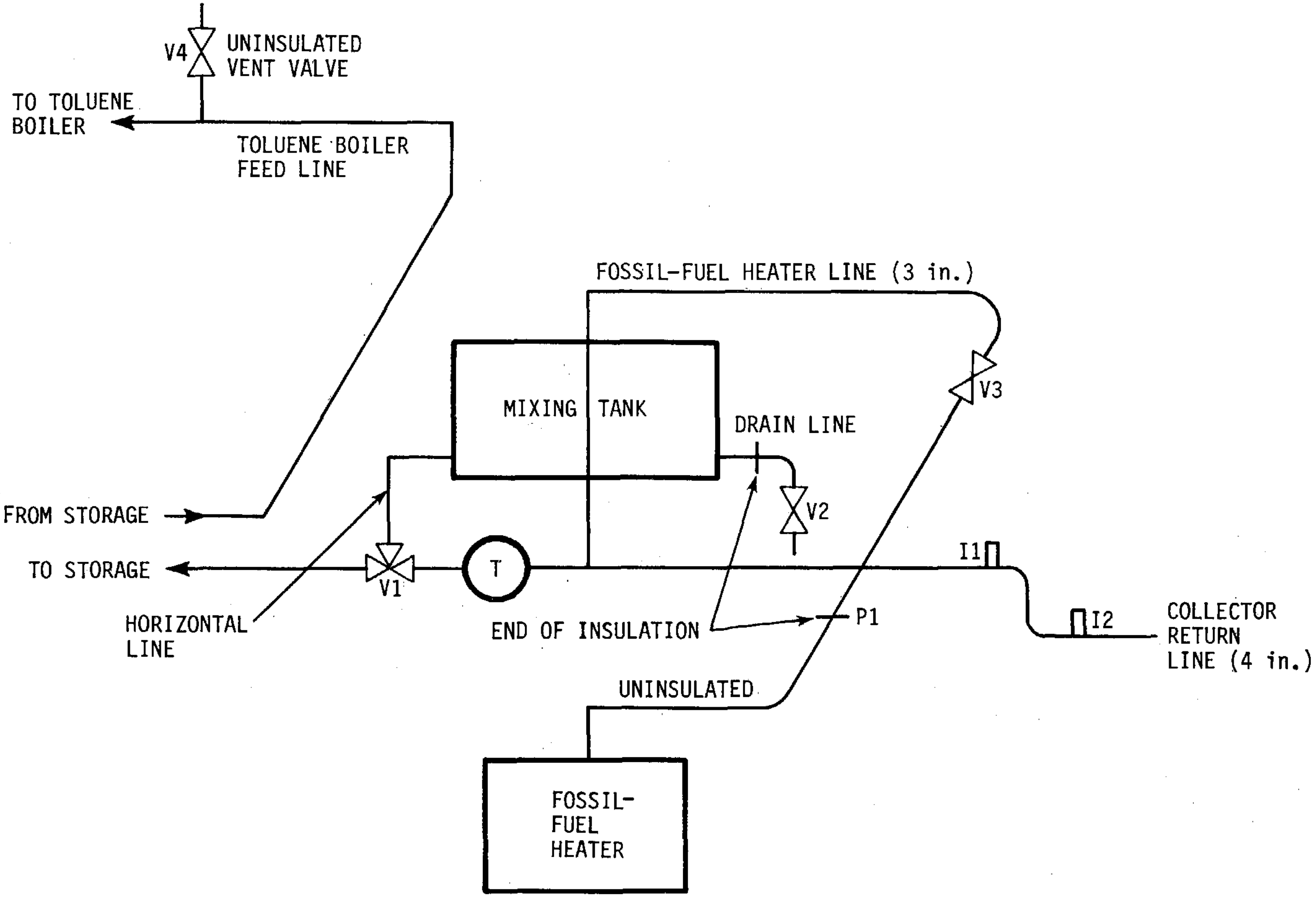


Figure 1. Mixing Tank and Thermocline Tank Piping

To further check on thermosiphoning, valve V_3 was then closed. The uninsulated pipe at P_1 cooled to ambient over several hours. When V_3 was subsequently opened, P_1 again heated up as above, indicating the presence of thermosiphoning.

In order to see the effect of a drop in elevation of a hot line on thermosiphoning, points I_1 and I_2 were examined. I_1 and I_2 are instrumentation posts welded directly to the collector return line. Since there was no flow through the collector field, it might be expected that I_1 and I_2 would be cool. However, it was found that I_1 was quite warm to the touch, while I_2 was cold. This indicates the possibility of thermosiphoning from the mixing tank to I_1. In addition, I_2 being cold indicates that the drop in elevation between I_1 and I_2 (about 0.3048 metre [12 inches]) is enough to stop thermosiphoning.

Another interesting observation was made at the mixing tank drain line. This line comes from the bottom of the mixing tank and is insulated only part way along its length, so that the elbow in the line is exposed. The distance from the elbow to valve V_2 is about 76.2 to 101.6 mm (3 to 4 inches). The elbow in the drain line was very hot, too hot to touch, while valve V_2 was cold. This indicated good thermal communication between the mixing tank and the elbow in the drain line but poor thermal communication between the elbow and valve. This would be expected if thermosiphoning were the major thermal transport mechanism. As a verification of the phenomenon observed, valve V_2 was opened to drain hot fluid through the line to heat up the entire line. After cooling for about an hour, the valve was again cold and the elbow was very hot.

An analogous situation, but with the valve inverted from V_2, was found in the line supplying hot oil from storage to the toluene boiler. Valve V_4, which extended about 101.6 to 152.4 mm (4 to 6 inches) above the insulated toluene boiler feed line, was found to be very hot to the touch. The fluid in the toluene boiler feed line was hot because the turbine was in operation, demanding hot fluid from storage.

While no quantitative conclusions are possible at this stage, it seems obvious that very significant amounts of thermosiphoning are occurring and that relatively small dips in line elevation may be sufficient to stop at least some thermosiphoning.

EQUIPMENT PROBLEMS AND SOLUTIONS FOR THE COOLIDGE, ARIZONA, SOLAR IRRIGATION FACILITY

Introduction

The Coolidge Solar Irrigation Facility began operation in October 1979. Since 1 January 1980, the plant has operated daily except for a period from mid-February to early March. On 12 February, a fire in the collector system pump shroud area necessitated pump removal and repair, and inclement weather delayed repair efforts. Other problems have affected plant operation for a short period, caused one system to be inoperative, or resulted in reduced performance. This report describes the primary problems encountered during the year and lists solutions and potential solutions to the problems.

Collector Tracking Units

Collector tracking systems have required considerable attention to assure proper operation. On a typical operating day, from 1 to 3 of the 48 tracking units needed maintenance attention or repair. Malfunctions can be categorized as moisture-related, sensor photodiode, and control circuitry problems.

Moisture in sensor windows and sensor cable connectors has caused incorrect focusing and searching. Moisture collected through condensation or entered during rainfall. Disassembly and wiping or air drying corrected the tracking problem. Sealing the connectors appears to have remedied the connector moisture problem at Coolidge. Sensor case design has been modified to minimize moisture entrance.

Photodiode arrays in many sensors have cracked, resulting in inaccurate tracking. Photodiodes now are being encased in a different material, and replacement of sensor assemblies is being proposed by the manufacturer.

Sensor control circuitry failures also have caused some tracking problems. Some failed relays and resistors have been replaced in the field. Other control boards were returned to the manufacturer for repair.

Collector Drive Motors

Five drive motors failed in February and March and two others failed later because rear shaft bearings had broken loose from the cases. The motors were repaired by a Tucson shop and by Superior Electric, the manufacturer. The failures were attributed to manufacturing problems; required corrections will be made by the manufacturer. A contributing circumstance was an apparent lack of testing with motors mounted in the collector system application orientation.

Flexible Hoses

The bending motion required of flexible hoses is variable. Some hoses are bent into an "S" shape, and, in many groups, nonplanar bending is necessary. Because compound bending hastens the failure of the hoses, improved means for interconnecting collector groups are being sought.

Thirty-six of 96 flexhose covers have failed to date, and several flexible hose insulation covers have become detached from collector attachment points. To limit the incidence of failure, wider attachment rings and different clamps are being evaluated.

Nearly all flexible hose covers located at the north end of collector groups have deteriorated due to sunlight reflection and have subsequently torn in flexure. A sun shield, which prevents reflection of concentrated sunlight onto the flexhose cover, is being tested at Coolidge. Installation of shields throughout the collector field is being proposed by the manufacturer.

Receivers

Collector receiver tube black chrome coatings have deteriorated visibly. In most collector loops, deterioration is substantial in the two highest temperature groups, moderate in the two medium-temperature groups, and slight in the two groups experiencing the lowest temperatures. An evaluation of the effect of receiver surface changes on performance is contemplated.

Receiver Covers

Inadequate end sealing of collector receiver glass covers has permitted dust intrusion, which is most apparent with tubes at the ends of collector groups. There, sunlight reflection is apparent. One collector group at Coolidge has been retrofitted with a modified insulation cover that abuts the glass receiver cover and reduces dust intrusion. The insulation appears to have minimized dust intrusion since installation. Further evaluation will precede a possible complete retrofit.

Receiver Insulation

Receiver tubes at collector group ends rotate within stationary foam glass insulation covers. The relative motion has increased the foam glass insulation interior diameters, causing the covers to sag. Another insulation material is recommended where relative motion is substantial.

Pump Leakage and Fire

Both pumps moving Caloria through the collector system and to the vaporizer have experienced excessive leakage from shaft seal areas. Vaporizer pump leakage began during the initial operation and continues despite seal replacement and other repair efforts performed in late February. The initial leakage apparently was caused by metal filings or slag from construction.

Collector system pump leakage developed over a period of operation, becoming substantial by February. Late on 12 February, a fire occurred in the pump shroud area, causing system shutdown. Hot Caloria apparently autoignited near the leakage location. New pump bearing and seal and motor electrical cable were required. Inclement weather, replacement part procurement, and repair efforts halted plant operation for 23 days.

It was determined that the pump seal area should be purged by inert gas flow or cooled during operation. A carbon dioxide purging system, using refillable cylinders and a flow control valve, was connected to each pump. Seal replacement and carbon dioxide usage have reduced, but not eliminated, collector system pump leakage. Another seal, of a different material, is being acquired for evaluation.

The fire caused a reevaluation of plant operation. Leak stoppage has become a high-priority task. Emergency procedures have been developed to respond to fire, leakage, and personnel injury incidents. Additional fire extinguishing and first aid equipment was procured and strategically located.

Pneumatic System Leakage

On many occasions, excessive air usage by pneumatic valve actuators resulted in system shutdown after extended operation. Additional air compressor capacity was obtained, one actuator was replaced, connections were tightened, and other actuators were serviced. Air leakage has decreased but is still a problem. However, the additional compressor capability has made air loss a problem which does not threaten operation.

Storage Tank Leakage

Caloria continues to leak from flanged manhole covers on the side of the main storage tank. Securing bolts have been retightened periodically, but leakage soon begins again. The primary effects are insulation contamination and dirty appearance.

Flow Control Valves

Valves installed to control the flow of Caloria to the various collector loops soon became clogged with pipe contaminants. The valve interiors were removed for repair and never reinstalled. The oil flow rate to each of the eight collector loops is apparently nearly equal as judged by outlet temperature measurements. Thus, the valves are not deemed necessary.

Three-way, butterfly-type valves, used to direct Caloria to alternative locations, have experienced leakage into the closed path. Actuator replacement has decreased leakage.

External leakage has occurred from valve stems and flanged connections of many remotely, and manually, actuated valves. The result is unattractive and, with insulation contamination, potentially a fire danger. Flange bolts have been retightened; repacking of some valve stems is planned.

Toluene Leakage

Some toluene replenishment has been required due to losses from connections and from the separator tank. Valve packing has been tightened at two locations, eliminating leakage. Separator tank loss is believed to be normal.

Organic Rankine Cycle (ORC) Vacuum Leakage

The vacuum in the power conversion system decreases from the 0.71-metre (28-inch) working level to perhaps 0.38 metre (15 inches) overnight. In 48 hours, the vacuum drops to nearly zero. Leakage tests for pressurized inert gas and retightening of connections reduce the vacuum loss for a short time. The effect of vacuum loss is to increase vacuum pump usage.

Vaporizer Level Sensor

The sensor which measures toluene level (or quantity) in the vaporizer gives erroneous values. Because these values are used to control the flow of toluene, visual observation of the sight glass level and operator control of the level are required. Replacement with a different type of level sensor is scheduled for September 1980.

Turbine Gearbox Lubrication System

Gearbox lubrication pressure became too small during extended operation on a hot day, resulting in turbine shutdown. The input pressure can be adjusted; upward adjustment of the lubrication system pressure has eliminated the problem.

Generator Synchronization

The control system causing the generator to produce electricity compatible with the utility grid system malfunctioned in late spring. Operator control of synchronization during startup thus was required for about 2 months. A malfunctioning control system component was identified and replaced and the system readjusted by onsite technicians with telephone direction from the manufacturer.

Cooling Tower Pump

Cooling tower pump outage occurred on several occasions, resulting in turbine shutdown. The pump overload sensor was replaced; outage has not recurred.

Toluene Contamination

Caloria was inadvertently added to the toluene supply during routine replenishment, making the supply about 10% oil. Reduced power system performance, particularly vaporizer performance, and discoloration of toluene were the problem symptoms. Contamination by Caloria then was suspected and later was confirmed by laboratory tests.

The Caloria gradually was removed from the vaporizer, which acted as a distillation unit. The process involved ORC operation--during which time separation occurred, Caloria removal from the vaporizer, and toluene replenishment.

Measurement Devices

A relay in the direct insolation monitor (DIM) failed in June, causing failure of additional relays. While awaiting repair, operator actuation of the DIM control was required. The faulty relay was identified and repaired onsite.

Flow meter measurements were doubted, so meters were recalibrated. Periodic recalibration may be required.

High-gain transmitters of insolation, temperature, and flow measurements have failed on three occasions. Repair required shipment to the manufacturer.

Resistance temperature detectors (RTDs) used for temperature measurement at many plant locations have failed or exhibit signs of impending problems. Two indications of potential failure are cracked terminal strips and corroded wire sensors.

Summary

A number of maintenance problems occurred during the year. Two problems, collector system pump failure and pneumatic control system air pressure losses, resulted in system shutdown. However, only pump repair caused extended shutdown. Other problems, such as vaporizer level sensor and collector tracker system malfunctions, increased operational requirements and may have reduced plant performance. These and other problems have led to improvements which have increased plant reliability and performance and decreased operational requirements. Second-year operation will evaluate improvements and provide further testing of original equipment.

OPERATING COSTS FOR THE COOLIDGE, ARIZONA, SOLAR IRRIGATION FACILITY

The Coolidge Solar Irrigation Facility has been operated on a daily basis during the hours of solar energy availability. One or more persons have been in attendance during all plant operations. Plant personnel have attended to operational tasks, repair and maintenance jobs, data gathering activities, visitor information responsibilities, and plan improvement efforts. The operational requirements, quantified operator time, and operational supply costs are difficult to separate from other requirements. However, an estimate is presented below.

Operators initiate plant operation by opening a safety valve, preventing oil loss from the storage tank. Then they turn on the collector system. Daily efforts include monitoring the operation and assuring that operation is normal. Power conversion system operation has required continued observation and some manual control. Manual control of the separator coolant flow valve is required during startup preparations. Inspection of the storage tank nitrogen supply, pump CO_2 supplies, and cooling tower water treatment chemical supply is required daily; replenishment is accomplished as needed. Cooling water quality must be analyzed on alternate days. Plant shutdown and site security require additional operating time. Collector washing was categorized, arbitrarily, as recurring maintenance.

It is estimated that these operational activities have required 30 hours of operator effort per week, i.e., 4 to 5 hours per day. Summer requirements have been greater; winter requirements, smaller.

Materials and supplies required for operation include the cooling tower water supply, water treatment chemicals, carbon dioxide to purge pump seal areas, and nitrogen to blanket Caloria in the storage tank. Another operating expense is electrical energy for cooling the building housing electronic control systems. The latter expense depends directly on weather conditions. Many other requirements are related to amount or length of operation, which also varies seasonally.

The list below provides an estimate of operational costs: $78 per week in summer, $26 per week in winter.

Weekly Costs of Plant Operation

	Summer	Winter
Water (municipal)	$20	$ 5
Water treatment	35	10
Nitrogen	5	5
CO_2	8	6
Electricity (cooling est.)	10	--
Total cost per week	$78	$26

Power conversion system operation will be nearly automatic after installation of a replacement vaporizer level sensor in September 1980. Planned installation of a remotely actuated safety valve will further automate operation. The labor reduction will be evaluated during the upcoming year.

Material costs also might be reduced somewhat. For example, less CO_2 would be used with nighttime shutdown, but manual valve operation probably would be required. Materials usage will be monitored carefully and reduced where possible during the 1980-81 operating period.

RECURRING MAINTENANCE REQUIREMENTS FOR THE COOLIDGE, ARIZONA, SOLAR IRRIGATION FACILITY

Introduction

The amount of time devoted to recurring maintenance tasks and the cost of supplies and replacement materials for those efforts have been recorded since late January 1980. The attempt to quantify recurring maintenance needs required identification of those activities. Maintenance tasks, as distinguished from repair efforts, are defined to be recurring, expected efforts. Repair activities are those required due to equipment failures or accidents and usually occur unexpectedly. Daily operating requirements also were distinguished from maintenance requirements. Operational activities include inspection and replenishment of condenser cooling tower water treatment chemicals, Caloria storage tank nitrogen supply, and Caloria pump CO_2 supplies.

Tasks

Recurring maintenance requirements of the collector subsystem include cleaning the reflector surfaces, the receiver glass cover tubes, and the tracker sensor windows as required, greasing bearings and checking drive unit gearbox oil levels (replenishing if required) on a bimonthly basis, testing electric drive motors, also bimonthly, and inspecting and adjusting collector module receiver tube and sensor alignment quarterly. Periodic, perhaps monthly, inspection of the fluid transfer system for leakage or other changes is recommended. Valve stems should be lubricated on a periodic basis. Caloria transfer system condensate must be drained weekly.

In the power conversion subsystem, monthly requirements include greasing bearings and inspecting start pump and turbine gearbox oil levels (adding as needed), checking toluene level, and inspecting bolts and fittings (tightening, if required). Toluene and gearbox oil filters, as well as gearbox oil, must be changed annually. The cooling tower requires periodic cleaning, perhaps monthly. A vacuum leakage inspection also should be conducted periodically.

Air compressors require monthly inspection and periodic change of lubricant and periodic cleaning of air filters. Pneumatic system leakage should be tested monthly and fittings tightened as required. Electrical relays should be dusted, perhaps by blown air, on a periodic basis. Other recurring tasks include pyranometer adjustment and equipment calibration. Site activities include cleanup and pest (insect, animal, and weed) control efforts. Safety shutdown devices require monthly testing; fire extinguishers require semiannual testing.

Time

Recurring maintenance tasks have required a recorded effort averaging 17.6 hours per week. The collector system required about 8.0 hours, the fluid transfer system 4.8 hours, and the power conversion system 4.8 hours. The effort varied substantially from week to week, as shown in Table 1. The differences can be attributed to labor availability as well as task requirements.

Materials

Collector system maintenance supplies include lubricants for bearings and gearboxes, materials for cleaning collector surfaces, fuses, and relay cleanser. The fluid transfer system requires degreaser for cleaning operations and some lubricant for the valves. Power conversion system requirements include pump lubricant, toluene filter, and gearbox lubricant and filter. Some replacement toluene and Caloria may be required, primarily depending on leakage. Other items needing periodic replacement include power supply filter and test panel light bulbs. Air compressor filter and oil must be changed periodically. Herbicide is required for adequate grounds maintenance; some pesticide is required for control building use.

Table 1

An Estimate of Recurring Maintenance Requirements for Collector, Fluid Transfer and Storage, and Power Conversion Systems

Week Ending On	Collector System		Fluid System		Power System		Total	
	Manpower Hours	Materials $	Manpower Hours	Materials $	Manpower Hours	Materials $	Manpower Hours	Materials $
Jan 22	12.8		---		2.3		15.1	
29	3.7	30	2.0	2	5.1	3	10.8	35
Feb 5	7.7		.8		1.2		9.7	
12	11.8		2.3		3.6		17.7	
19	8.7		---		3.0		11.7	
26	14.2	80	.8	4	1.5	5	16.5	89
Mar 4	5.2		---		1.5		6.7	
11	1.2		1.6		2.0		4.8	
18	9.1		3.7		3.5		16.3	
25	3.9	35	.4	4	3.6	5	7.9	44
Apr 1	17.0		20.6		7.3		44.9	
8	6.3		17.0		16.1		39.4	
15	3.5		1.0		5.1		9.6	
22	6.2		5.4		6.5		18.1	
29	6.7	80	5.0	5	2.0	10	13.7	95
May 6	14.8		29.3		5.8		49.9	
13	3.0		18.2		3.0		24.2	
20	3.8		2.2		2.8		8.8	
27	22.7	35	1.9	5	6.0	80	30.6	120
June 3	2.2		1.5		2.5		6.2	
10	4.2		3.2		3.2		10.6	
17	9.9		1.5		8.5		19.9	
24	25.9	80	2.2	5	10.5	50	38.6	135
July 1	11.0		.8		3.5		15.3	
8	4.5		3.0		7.9		15.4	
15	6.2		1.7		8.4		18.3	
22	2.3		7.0		8.0		17.3	
29	4.7	35	5.1	20	4.0	320	13.8	375
Aug 5	1.2		.5		1.1		2.8	
12	4.6	80	5.3	2	3.6	5	13.5	87
Average Weekly Requirements	8.0 hrs	$15.20	4.8 hrs	$1.60	4.8 hrs	$15.90	17.6hrs	$32.70

Some maintenance items are used for periodic servicing and replacement, while others are used as required. Service intervals vary from daily to annually. Table 1 contains an estimate of the cost of maintenance materials during the 8-month period mid-January to mid-August 1980. Since an inexact usage schedule exists, costs arbitrarily were apportioned to the last week of each month. Lubricant was the largest collector system expense; a 0.21-m^3 (55-gallon) drum of toluene and gearbox lubricant and filter were the major power conversion system costs. The average weekly expenditure for recurring maintenance materials was $32.70. At this rate, the annual cost would be about $1700.

Data Improvement

Classification of certain tasks or costs by operation, maintenance, repair, or other category was difficult. In some cases, categorization may have been arbitrary. Maintenance tasks were being identified throughout the year, methods for performing some duties had to be learned on-the-job, and regular task schedules are still being developed. Thus, the information presented in Table 1 is only a first estimate of recurring maintenance requirements. Additional maintenance effort data will be recorded during the upcoming year.

Summary

Recurring maintenance requirements of the Coolidge Solar Irrigation Facility were estimated to be 17.6 man-hours per week and $1700 materials cost per year. Continued data gathering efforts will attempt to improve this estimate.

CONSTRUCTION COSTS FOR THE COOLIDGE, ARIZONA, SOLAR IRRIGATION FACILITY

The original system design for the Coolidge, Arizona, Solar Irrigation Facility specified 4548.5 m^2 (48,960 ft^2) of collector aperture area. The installed collector field consists of 2140.49 m^2 (23,040 ft^2). The field reduction was necessitated by rising contract costs. Before the field reduction decision was made, the site had been prepared for the full-size field. The preparation included foundations for collectors and pipe supports. The costs presented here have been adjusted to exclude the expenses associated with site preparation and foundation installation for the second half of the collector field.

The total cost incurred for the design, procurement, construction, and startup of the facility over the 2-year period ending 30 September 1979 was $5,512,000. Of this amount, approximately $2,023,000 was used on labor costs incurred by Acurex Corporation and $3,489,000 went to subcontracts, equipment purchases, etc.

The same system if built today would cost significantly less--only $2,551,000, owing to nonrecurring costs of labor, engineering, management, data acquisition equipment, and experience with similar systems.

Table 1 presents a cost breakdown and compares the actual system cost with the recurring costs of the same system. In Table 1, the item called "Installed Collectors" consists of collector hardware, installing the collectors on the foundations, and plumbing the collector field. The item entitled "General Construction" consists of site preparation, collector foundations, mechanical contract work on the site, electrical contract work on the site, and the total costs of the insulation for the pipelines and tanks on the site.

Table 1

Breakdown of Construction Costs

	Actual Cost of Current System		Recurring Costs of Same System	
Item	$ 000	$\$/\text{ft}^2$	$ 000	$\$/\text{ft}^2$
Installed Collectors	810	35	530	23
General Construction	833	36	645	28
Site Preparation and Foundations	(184)	(8)		
Mechanical Contract	(346)	(15)		
Electrical Contract	(230)	(10)		
Insulation Contract	(69)	(3)		
Building	50	2	50	2
ORC	1068	46	650	27
Storage Subsystem	209	9	150	7
Controls and Data Acquisition Equipment	358	16	150	7
Design and Field Support	1493	65	150	7
Management	530	23	200	9
Initial Operational Expenses				
System Completion	65	3	10	0.5
Water Supply, ORC Shelter, Emergency Generator, ORC Lube System				
System Startup and Dedication	90	4	10	0.5
Safety Improvements	6	-	6	-
Fire Hydrant, etc.				
Total	$5512	$239	$2551	$111

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