SANDIA REPORT

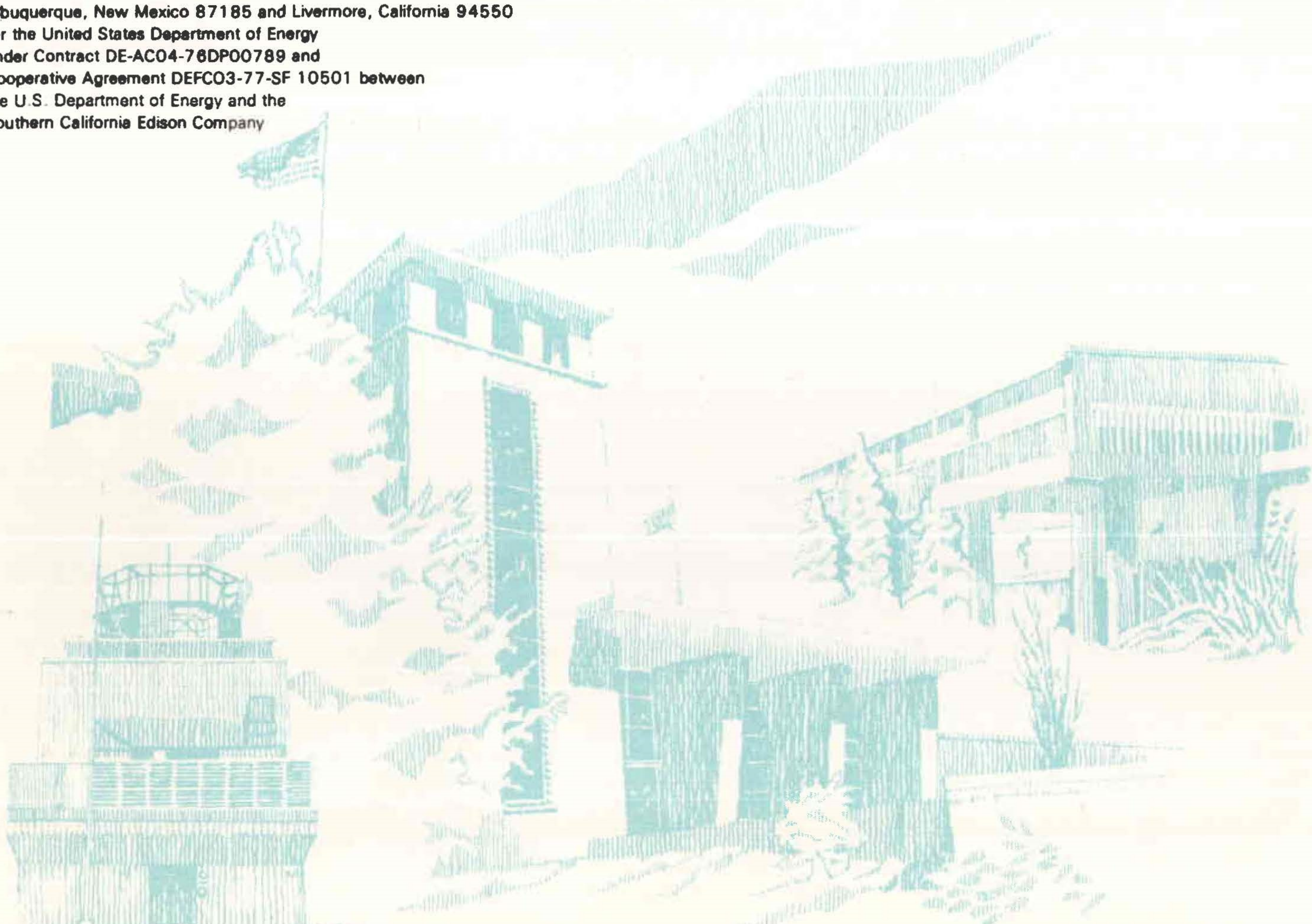
SAND83-8015 • Unlimited Release • UC-62c

Printed July 1983

10 MWe Solar Thermal Central Receiver Pilot Plant: Thermal Storage Subsystem Evaluation—Subsystem Activation and Controls Testing Phase

S. E. Faas

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 and
Cooperative Agreement DEFC03-77-SF 10501 between
the U.S. Department of Energy and the
Southern California Edison Company



Printed in the United States of America
Available from
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A04
Microfiche copy: A01

SAND83-8015
Unlimited Release
Printed July 1983

UC62c

10 MWe SOLAR THERMAL CENTRAL RECEIVER PILOT PLANT:

THERMAL STORAGE SUBSYSTEM EVALUATION -- SUBSYSTEM ACTIVATION AND CONTROLS TESTING PHASE

Scott E. Faas
Systems Evaluation Division
Sandia National Laboratories, Livermore

ABSTRACT

This report evaluates data taken on the Thermal Storage Subsystem at Solar One, the 10 MWe Solar Central Receiver Pilot Plant near Daggett, California. The period covered is the activation and initial controls testing phases from May 5, 1982, through September 30, 1982. The data show the system has been operated frequently, accepting and returning thermal energy as designed. The thermal storage tank wall stresses are low, thermal degradation and losses of heat transfer oil are minimal, and solar-related hardware problems that occurred were resolved.

CONTENTS

	Page
Summary	11
Introduction	13
The 1040 Tests	13
1040A Tests	13
1040B Tests	13
Data Evaluation During the 1040 Tests	14
Thermal Storage Subsystem Description	14
Thermal Performance	20
Historical Overview of Thermal Storage Subsystem Operation	20
Thermal Energy Requirements for the 1040 Tests	22
Thermocline Sharpness	25
Electrical Energy Production	27
Thermal Storage Unit Tank Wall Stress	27
Heat Transfer Fluid Losses and Degradation	31
Initial Mass Loss of Caloria HT-43	31
Thermal Degradation of Caloria HT-43	32
Composition of Fresh Caloria	32
Composition of Aged Caloria	35
Hardware Problems	37
Thermal Storage Unit Tank Leak	38
Oil Pump Vapor Lock	39
Flange Leaks	39
Conclusions	40
APPENDIX A--REDUCTION OF HISTORICAL TSU DATA	42
APPENDIX B--SUPPORTING DOCUMENTATION	44
REFERENCES	56

ILLUSTRATIONS

No.		Page
1	Thermal Storage Subsystem Schematic	16
2	Construction of the Thermal Storage Unit	17
3	Ullage Maintenance Unit	18
4	Thermal Storage Unit Power History	21
5	Thermal Storage Unit Useful Energy History	23
6	Comparison of Predicted and Actual TSU Axial Temperature Profiles	26
7	Thermal Storage Unit Tank Cross-section	28
8	Thermal Storage Unit Horizontal Wall Stress	29
9	Thermal Storage Unit Vertical Wall Stress	30
10	Total Ion Chromatogram for Fresh Caloria	34
11	Total Ion Chromatogram for Fresh Caloria--Expanded Plot of Low Molecular Weights	34
12	Total Ion Chromatogram for Aged Caloria	35
13	Total Ion Chromatogram for Aged Caloria--Expanded Plot of Low Molecular Weights	36
14	Thermal Storage Unit Temperature History	37

TABLES

		Page
I	General Thermal Storage Subsystem Design Parameters	19
II	Thermal Storage Subsystem Design Maximum Operating Conditions	19
III	Brief Thermal Storage Subsystem Operating History	22
IV	Thermal Storage Subsystem Thermal Energy Consumption During the 1040 Tests	24
V	Thermal Storage Subsystem Electrical Production	27
VI	Typical Physical Data and Information Available on Caloria HT-43	33

Summary

The U.S. Department of Energy (DOE) in cooperation with Southern California Edison and the Los Angeles Department of Water and Power constructed Solar One, a 10 MWe solar central receiver pilot plant, near Daggett, California. This report was prepared by Sandia National Laboratories, Livermore, on behalf of the DOE in accordance with the 10 MWe Central Receiver Solar Thermal Pilot Plant Data Evaluation Plan (Ref. 1).

In this report, the evaluation of the Thermal Storage System (TSS) of Solar One is covered over the subsystem activation and control testing phase from May 1, 1982, through September 30, 1982; events earlier than May 1982 or later than September 1982 are included as required to complete the discussion.

The Thermal Storage Subsystem (TSS) at Solar One consists of a Thermal Storage Unit (TSU) composed of an insulated cylindrical steel tank filled with a compacted bed of rock and sand impregnated with heat transfer oil, a bank of heat exchangers to heat the oil, and a bank of heat exchangers to generate steam using the hot oil. Steam from the receiver is used to heat the heat transfer oil in the charging heat exchangers to 304°C. The oil is circulated through the rock and sand bed transferring heat into the bed. Steam is generated in the extraction heat exchangers using hot oil obtained by reversing the flow through the rock and sand bed.

Instrumentation is installed throughout the TSS for process control and subsystem evaluation. The information from this instrumentation obtained during the subsystem activation and controls testing phase is useful for a general review of subsystem performance. Specific performance testing is still to be done, and particular subsystem capabilities, such as operation at rated power and thermal capacity, are yet to be determined. Therefore, this report contains a preliminary evaluation of the TSS at Solar One with the expectation that more complete evaluations will follow in the future.

Thermal storage activation and controls testing consumed 2254 MWhr of thermal energy through September 30, 1982. The majority of this energy, some 72 percent, was used for testing, auxiliary steam generation, and heating the Thermal Storage Unit. The remaining 20 percent was consumed by various loss mechanisms which are all within design limits. The electrical energy produced while connected to the grid, a byproduct of testing, was 29.05 MWhr-net. An axial temperature gradient or a thermocline can be produced in the Thermal Storage Unit in excess of design temperature gradients, but is highly dependent on the operation of the Thermal Storage System.

Thermal Storage Unit tank wall stresses over the period from May through December 1, 1983, have all been within allowable stress limits. Plugging of the heat transfer fluid distribution manifolds embedded in the oil, rock and sand bed has not been observed.

It is estimated that between 2.8 and 5.6 percent of the initial heat transfer oil inventory was boiled away when initially heated compared to the 2 to 3 percent predicted. Heat transfer fluid losses due to thermal degradation have been low, 1 percent or less, since temperatures in the Thermal Storage Unit have been below the decomposition threshold temperature for most of the time.

Hardware problems related to the solar function of the plant have occurred and were resolved. The most significant problem was heat exchanger flange leaks. Flange leaks in the heat exchangers may continue to be a maintenance problem in the future since the repair methods utilized have not been proven and the cause of the leaks is not completely understood.

The Thermal Storage Subsystem is fundamentally operational at this time and serves to reliably provide auxiliary steam to maintain feedwater quality and steam blanketing while reducing plant parasitic electrical requirements. The appraisal of the Thermal Storage Subsystem as an alternate steam source for electrical production will be completed when the extraction heat exchangers are released for performance testing.

THERMAL STORAGE SUBSYSTEM EVALUATION: SUBSYSTEM ACTIVATION AND CONTROLS TESTING PHASE

Introduction

The U.S. Department of Energy (DOE) in cooperation with Southern California Edison and the Los Angeles Department of Water and Power constructed Solar One, a 10 MWe solar central receiver pilot plant, near Daggett, California. This report was prepared by Sandia National Laboratories, Livermore, on behalf of the DOE in accordance with the 10 MWe Central Receiver Solar Thermal Pilot Plant Data Evaluation Plan (Ref. 1).

In this report, the evaluation of the Thermal Storage Subsystem (TSS) of Solar One is covered over the subsystem activation and control testing phase from May 1, 1982, through September 30, 1982; events earlier than May 1982 or later than September 1982 are included as required to complete the discussion. The subsystem activation and control test sequence, known as test 1040, consisted of two phases: test 1040A and test 1040B. The following section briefly describes these tests.

The 1040 Tests

1040A Tests--Test series 1040A was the initial warming of the Thermal Storage Unit (TSU), a tank filled with rock, sand, and a heat transfer oil. The intent of heating the TSU was to drive off the water entrained in the rock, sand, and oil. The required temperatures depended on the local boiling temperature of water in the tank, which was a function of the local hydrostatic head of oil. For test convenience, the boiling temperature of water at the bottom of the TSU--121°C (250°F)--was used as the minimum temperature to be acheived throughout the tank.

Since the receiver was involved in priority testing, the heat source used for heating the TSU was an oil-fired boiler capable of providing 1.48 MPa, 198°C (215 psi, 388°F) saturated steam at flow rates up to 9072 kg/hr (20,000 lbm/hr). The oil-fired boiler provided a much easier control of temperature and heat rate than would have been permitted by the receiver. A flange connection in the steam piping located downstream of desuperheater DS-301 had been installed during TSU construction, thus allowing attachment of temporary piping from the oil-fired boiler. Steam entering this connection was blocked from passing into the main steam line by hand valves, thereby forcing the steam through the charging heat exchangers where it was condensed and cooled to heat the oil. The condensate produced was contaminated with solids from its passage through the heat exchangers and had to be dumped into the plant waste water drains. This steam cleaning of the heat exchangers and of related piping was another objective of test 1040A.

1040B Tests--Test 1040B consisted of the thermal storage controls checkout and tuning tests. These tests activated all the control loops in the TSS and refined their intrinsic control parameters to acheive stable control. Receiver steam was used to test the charging heat exchangers, and heat transfer oil discharged from the TSU at rated conditions was used to test the extraction heat exchangers.

Data Evaluation During the 1040 Tests

Data were acquired throughout the 1040 tests for evaluation. However, these tests did not allow carefully controlled performance tests to be conducted, since their emphasis was on making the TSS controllable, according to design, for subsequent performance testing (i.e., for the 1100 test sequence described in Ref. 2). Therefore, the data from the 1040 tests are useful for general review but not for detailed evaluation. Testing specifically targeted to assess performance must be conducted before data can be obtained for detailed evaluation.

The limitations imposed by the nature of the 1040 tests do not exclude several concerns from being addressed. A candidate list of questions is presented below:

1. How much energy must be invested to make the TSS operational?

2. How much water was driven off from the oil, rock, and sand and how did this affect activation of the subsystem?

3. What was the effect of heating on the heat transfer oil during the 1040 tests?

4. Can a thermocline be created and maintained?

5. Was any significant maintenance required?

6. What were the thermal storage tank wall stresses? Is there any sign of high stresses due to differential thermal expansion between the tank wall and oil, rock, and sand bed?

These questions will be addressed in some manner in this report. The thrust of the report is the assessment of the TSS thermal performance; items pertaining to the operation of the TSS will be left to others for detailed discussion. Information on system operation and controls testing can be found in Ref. 3.

Thermal Storage Subsystem Description

At Solar One, there are four major subsystems: the Collector Subsystem, Receiver Subsystem, Electrical Power Generation Subsystem, and Thermal Storage Subsystem. The Collector Subsystem is a field of heliostats that reflect and concentrate incident solar radiation on the receiver. The Receiver Subsystem uses the concentrated solar radiation to boil high pressure water and to superheat the resulting steam. The superheated steam is then directed to the Electrical Power Generation Subsystem for producing electricity or to the Thermal Storage Subsystem (Figure 1) for energy storage. Steam can be delivered to both the Thermal Storage Subsystem and the Electrical Power Generation Subsystem at the same time. An overall plant description is available in Ref. 4.

Superheated steam sent to the TSS is first conditioned with a desuperheater to a temperature of 343°C (650°F). This procedure protects the heat transfer oil from excessive thermal degradation as the oil is heated in the charging heat exchangers, since it reduces the film temperature. The desuperheated steam is then sent to one or both series or trains of the charging heat exchangers shown in the lower portion of Figure 1. A single series or train of charging heat exchangers consists of a condenser, subcooler, surge tank, steam trap, and the associated piping and valves. In the charging heat exchangers, the steam is condensed and subcooled, heating the heat transfer oil.

The condensate is piped to the flash tank, shown in the lower left corner of Figure 1, after passing through a valve which regulates the condenser pressure. The flash tank serves as a steam separator and allows the feedwater system in the Electrical Power Generation Subsystem to recover the heat in the thermal storage condensate. Hot heat transfer oil is piped from the charging heat exchangers to the Thermal Storage Unit, which consists of an insulated carbon steel tank filled with oil, rock, and sand.

The construction of the Thermal Storage Unit (TSU) is shown in Figure 2. The tank, which is filled with rock and sand, has regions of sand and rock only, and regions of sand mixed with rock. Embedded in the rock and sand are three pipe manifolds which evenly distribute heat transfer oil through the bed. The top and bottom manifolds are designed to handle full flow, while the intermediate or auxiliary manifold is designed for low flow. Oxygen cannot be tolerated in the region above the oil, rock, and sand called the ullage space. The heat transfer oil reacts quickly with oxygen at operating temperatures to form a viscous black residue. Hydrocarbon vapors that are also present in the ullage space may form an explosive mixture with oxygen. Therefore, the ullage space is maintained at a slight positive pressure to prevent oxygen from infiltrating. The control of the ullage pressure is the responsibility of the Ullage Maintenance Unit or UMU.

The Ullage Maintainence Unit, shown in Figure 3 along with the TSU, consists of valving, a gas blower, and a burn stack for removal of gases from the ullage space when the pressure is too high; it also has a storage tank, a pump, and valving to send low weight hydrocarbon fluids to the ullage space to vaporize and increase the ullage pressure when it is too low. The UMU contains the regulators and piping for backup pressure control with nitrogen gas.

The remaining components in the TSS are the extraction heat exchangers. A series or train of extraction heat exchangers, shown in the upper portion of Figure 1, consists of a preheater, a boiler, and a superheater. The flow of hot heat transfer oil from the TSU to the extraction heat exchangers can be directed to either or both the boiler and the superheater to allow separate control of extraction steam pressure and temperature.

Tables I and II contain a summary of TSS specifications.

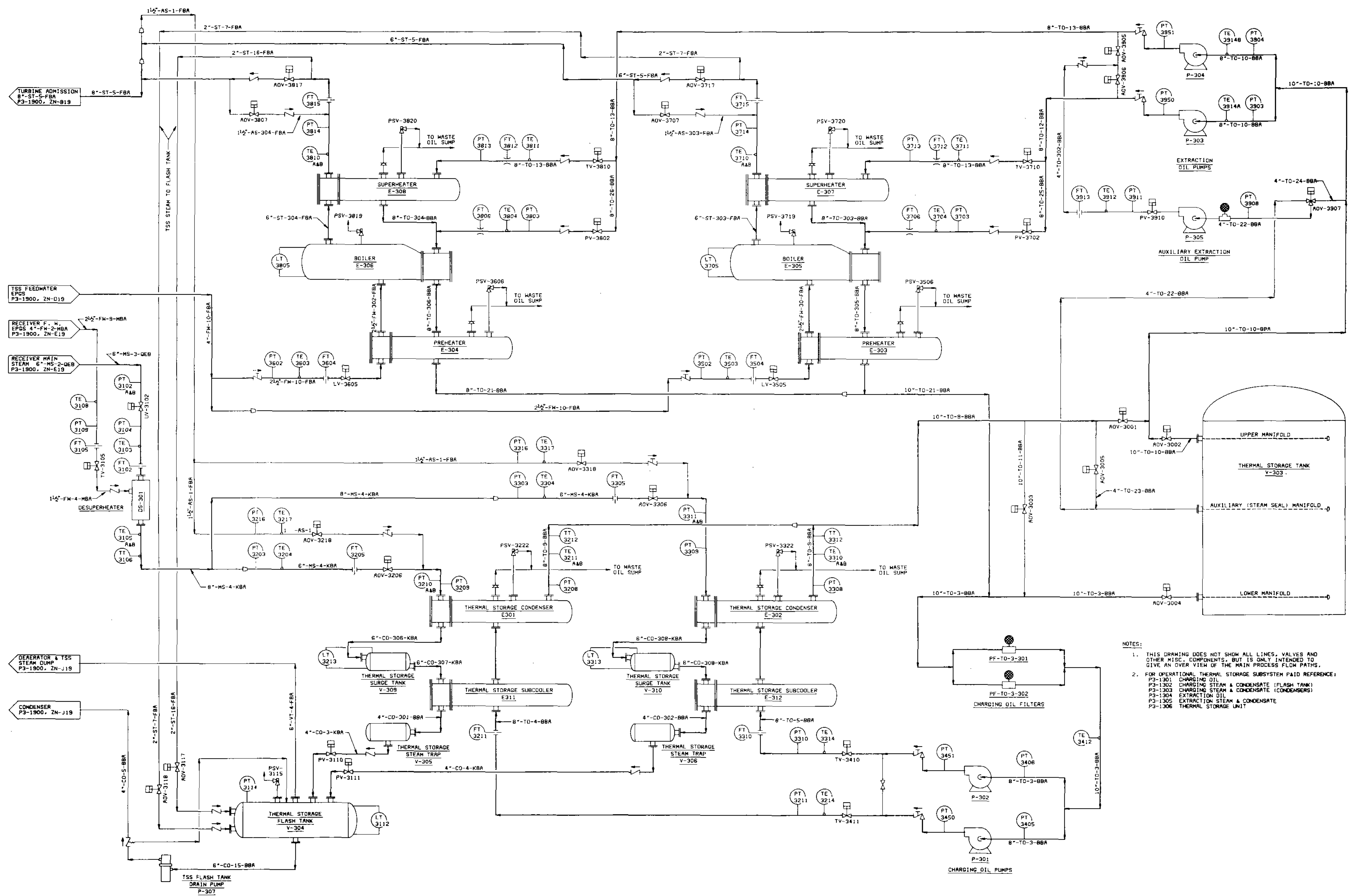


Figure 1. Thermal Storage Subsystem Schematic

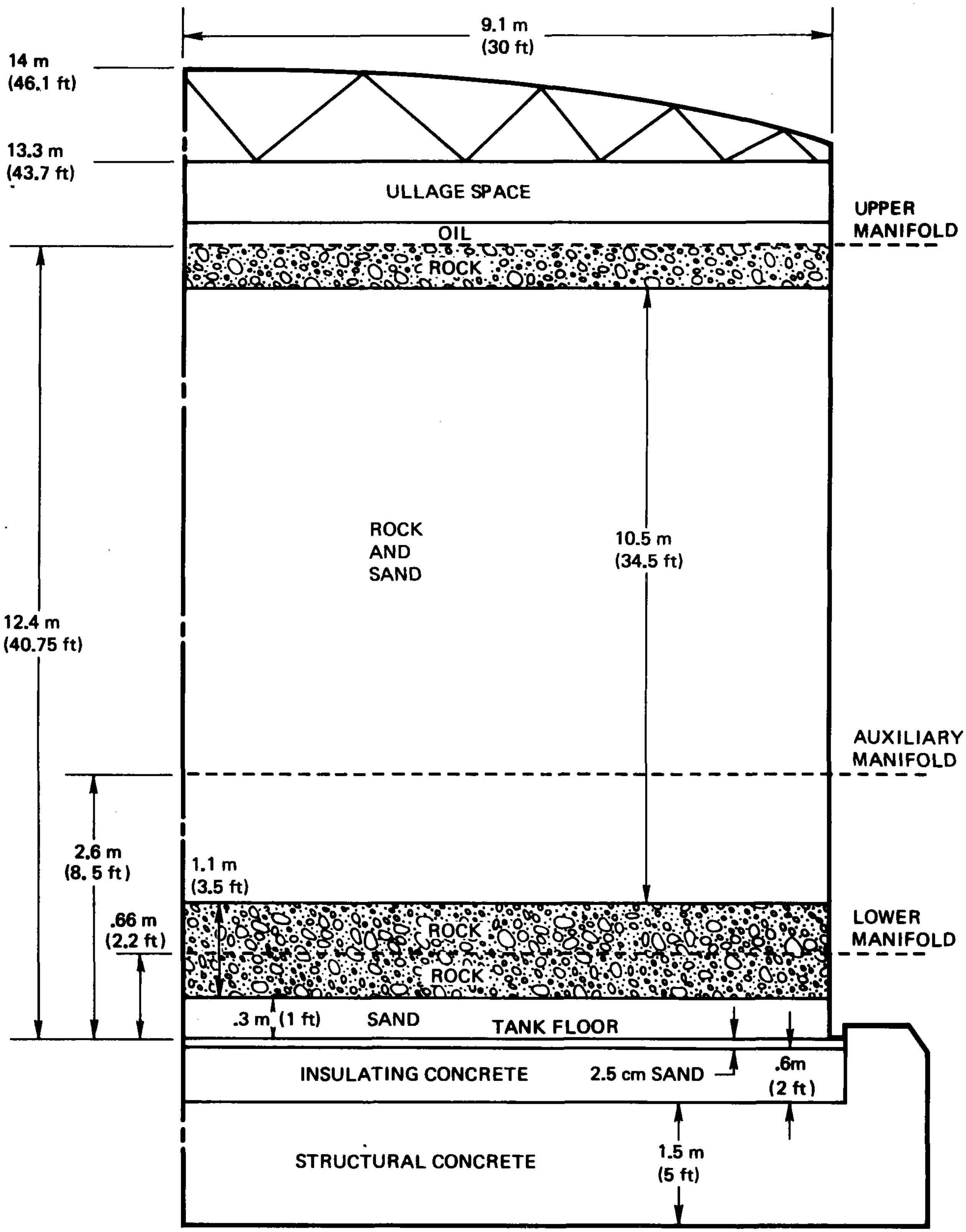


Figure 2. Construction of the Thermal Storage Unit

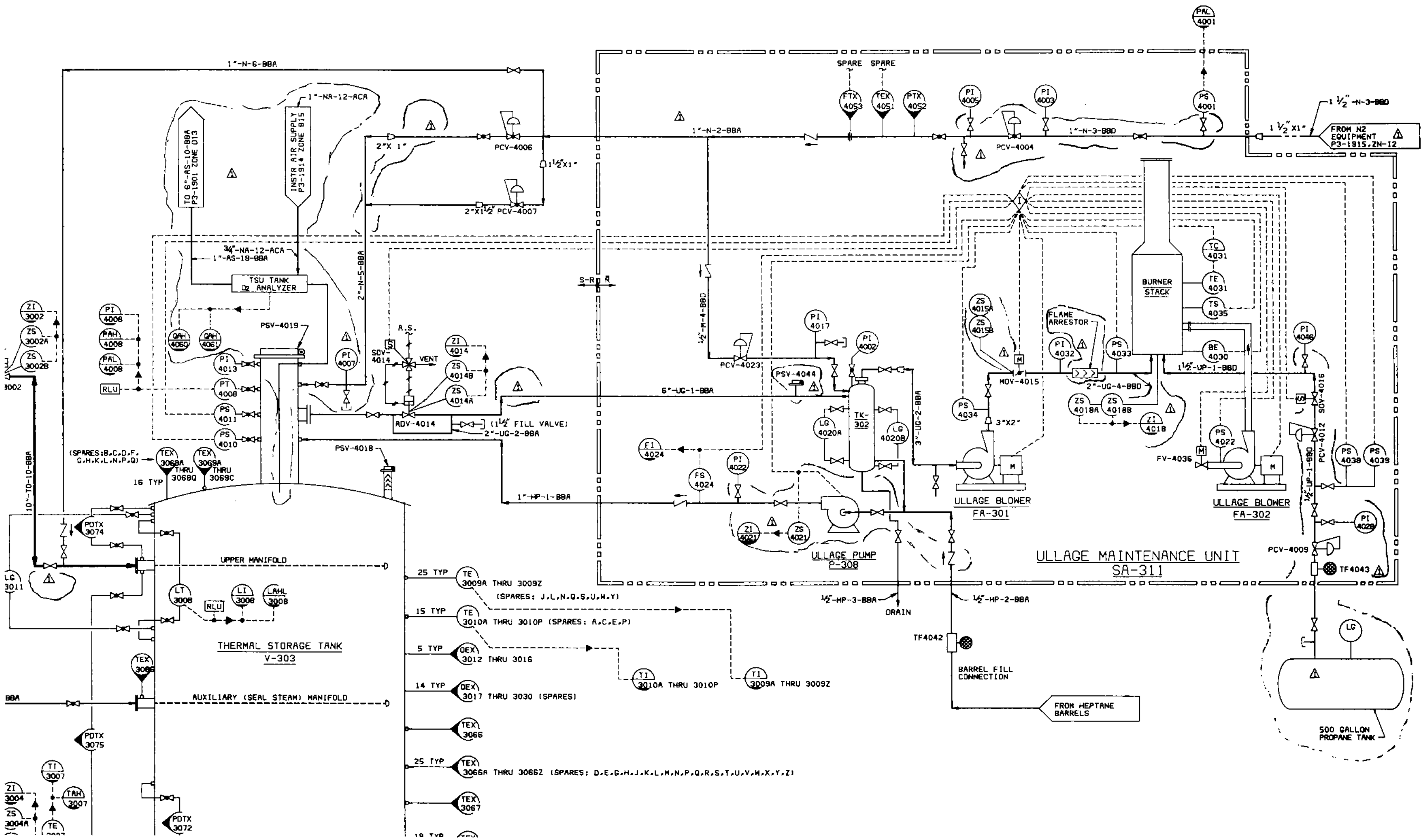


Figure 3. Ullage Maintenance Unit

TABLE I

GENERAL THERMAL STORAGE SUBSYSTEM DESIGN PARAMETERS

Energy to produce 7 MWe (net) for 4 hours	135 MWhr(t)
Energy for turbine roll	8 MWhr(t)
Heat exchanger hot standby steam	1 MWhr(t)
Heat loss during 20-hour hold	4 MWhr(t)
Sealing and blanketing steam	10 MWhr(t)
15% contingency	24 MWhr(t)
Total TSU thermal capacity	182 MWhr(t)

TABLE II

THERMAL STORAGE SUBSYSTEM DESIGN MAXIMUM OPERATING CONDITIONS*

	Maximum Operating Conditions
Charging Heat Exchangers	
Inlet steam to condenser	343°C (650°F) 9.6 MPa (1400 psia) 29,500 kg/hr (65,000 lbm/hr)
Condensate from subcooler	224°C (435°F) 9.3 MPa (1350 psia) 29,500 kg/hr (65,000 lbm/hr)
Inlet oil to subcooler	218°C (425°F) 0.46 MPa (67 psia) 242,000 kg/hr (533,500 lbm/hr)
Exit oil from condenser	304°C (580°F) 0.22 MPa (32 psia) 242,000 kg/hr (533,500 lbm/hr)
Extraction Heat Exchangers	
Inlet oil to superheater	302°C (575°F) 0.46 MPa (67 psia) 67,000 kg/hr (147,000 lbm/hr)
Inlet oil to boiler	302°C (575°F) 0.37 MPa (53 psia) 200,000 kg/hr (441,000 lbm/hr)
Exit oil from preheater	218°C (425°F) 0.21 MPa (31 psia) 267,000 kg/hr (588,000 lbm/hr)
Inlet feedwater to preheater	121°C (250°F) 3.37 MPa (490 psia) 24,900 kg/hr (55,000 lbm/hr)
Outlet steam from superheater	277°C (530°F) 2.76 MPa (400 psia) 24,900 kg/hr (55,000 lbm/hr)
Thermal Storage Unit	
Upper manifold	304°C (580°F) 533,000 kg/hr (1.176×10^6 lbm/hr)
Lower manifold	218°C (425°F) 533,000 kg/hr (1.176×10^6 lbm/hr)
Auxiliary manifold	218°C (425°F) 44,000 kg/hr (97,000 lbm/hr)

*Derived from Ref. 5

Thermal Performance

The thermal performance discussed in this chapter uses data taken from May through September 1982.

Historical Overview of Thermal Storage Subsystem Operation

Plots of the thermal power delivered or removed from the Thermal Storage Unit (TSU) as a function of time are shown in Figure 4. The bar height shows the average thermal power over the time period (width) indicated. Bars extending above the dashed horizontal line indicate when the Thermal Storage Subsystem (TSS) received steam to heat the TSU. Bars below the horizontal dashed lines indicate when energy in the TSU was lost to the environment or when steam was generated in the extraction heat exchangers. These data were taken not at regular intervals but according to TSS testing activity. It should also be noted that the data were not always taken just before or just after any activity in the TSS, and therefore some change in energy, though small, was not and cannot be accounted for. This omission results in some error in the average power calculation.

The plots in Figure 4 provide an overview of the type and magnitude of the TSU activity. The activity of the TSU is fairly low through May into late August. The trend of the cumulative energy is generally upward, with most of the energy loss from the TSU going to the environment. From late August through the end of September, the TSU activity is greater, showing larger thermal energy flows into and out of the TSU. A brief summary of the TSS operation is presented in Table III.

During the months of May, June, July, and early August, the emphasis of 1040 testing was on heating the TSU to its operating temperature. This temperature was first accomplished with an oil-fired rental boiler and was continued with receiver steam. The rental boiler was capable of only about 5 MW maximum thermal output. No energy was extracted from the TSU except by natural loss mechanisms and escaping steam as water boiled out of the TSU bed. When receiver steam was available, the maximum thermal energy capable of being delivered to thermal storage was increased to the receiver output. However, during this period, a great deal of light hydrocarbons and residual water began to be boiled off at a rate proportional to that of the thermal energy being delivered to the TSU. The UMU, which was designed for the much smaller light hydrocarbon generation rate of conditioned or aged oil, was overwhelmed at thermal power levels approaching 10 MW(t). The UMU problem, weather, and minor equipment failures combined to keep the level of activity low.

The heat transfer oil had been fairly well "dried" of light hydrocarbons and water by late August, and the top half of the TSU had been heated to a temperature of about 282°C (540°F). A train of extraction heat exchangers had been operated intermittantly for several weeks, and the steam had been exhausted to the atmosphere, thereby cleaning up the interior surfaces of the heat exchangers and piping. From this point on, the TSS was operated as often and at as high a power level as weather and equipment allowed.

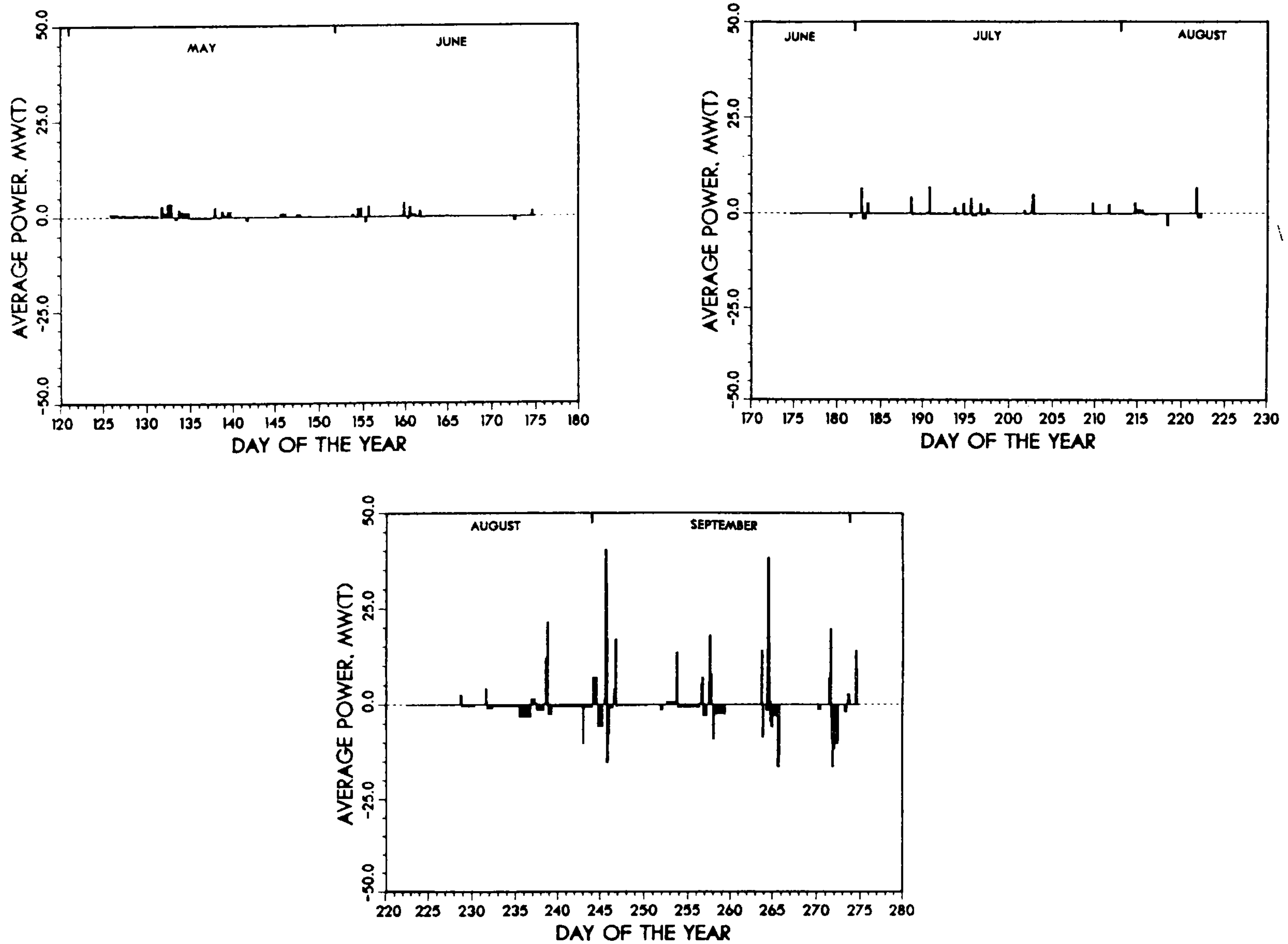


Figure 4. Thermal Storage Unit Power History

TABLE III

BRIEF THERMAL STORAGE SUBSYSTEM OPERATING HISTORY

Activity	Date
1. Test 1040A begins using rental boiler.	5/5/82
2. Test 1040A ends.	6/11/82
3. Test 1040B charging controls testing begins.	6/21/82
4. Test 1040B extraction controls testing begins.	7/22/82
5. First generation of electricity from thermal storage. Power generated at 5.0 MW(e) gross peak. One train of heat exchangers in operation.	8/24/82
6. First simultaneous operation of both trains of charging heat exchangers.	8/26/82
7. Auxiliary steam begins to be generated by TSS routinely.	8/30/82
8. Generator on-line using steam generated by thermal storage for 16 hours at an average power of 1.2 MW(e) gross.	9/28-29/82

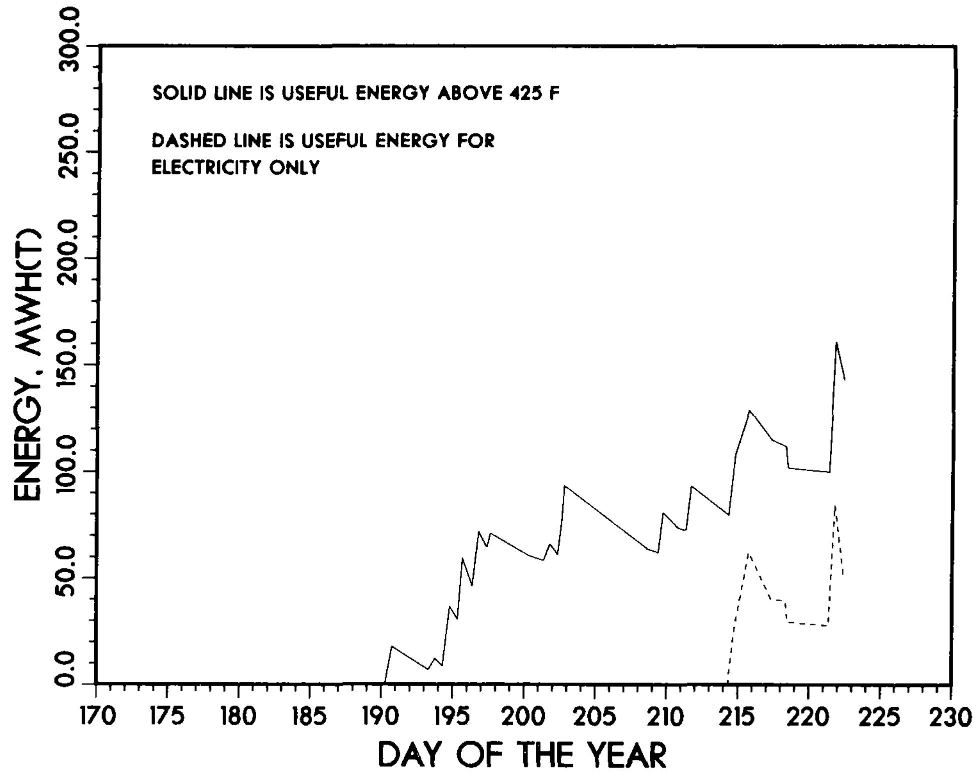
The useful energy history of the TSU is shown in Figure 5. The solid line represents the energy in regions above 218°C (425°F) and the dashed line shows the energy in regions above 287°C (550°F). Energy at temperatures above 218°C is considered good for seal and standby steam generation; energy at temperatures above 287°C is considered acceptable for electricity production. However, the first time electricity was generated with storage-generated steam on day 236 (August 24), the TSU temperatures were all below 287°C. Electricity was generated on this occasion by running the extraction boilers at a lower pressure, thus increasing the amount of steam superheating in order to meet turbine requirements. Achieving turbine operation at rated extraction pressure requires heat transfer oil at 287°C or greater.

Tabulations of the calculated energies and average powers used to create Figures 4 and 5 can be found in Appendix B.

Thermal Energy Requirements for the 1040 Tests

Bringing the TSS to an operational state requires an investment of thermal energy. Understanding where and why this energy was consumed will help designers reduce, or at least plan for, the thermal energy consumption required to bring future plants on-line.

Table IV presents an energy breakdown for the 1040 tests. The energies quoted are estimates derived from integrating the TSU energy (see Appendix A), energy loss tests (Ref. 8), and approximate calculations. Definitions of the various energies identified in Table IV are as follows:



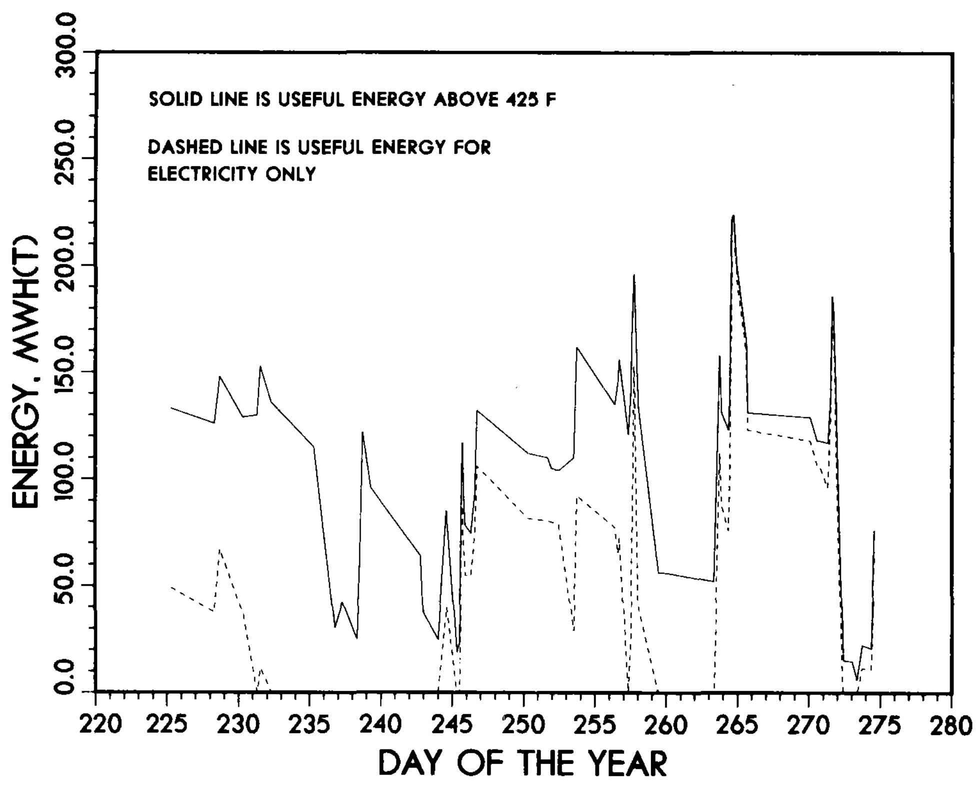


Figure 5. Thermal Storage Unit Useful Energy History

Energy Lost to Environment from TSU - Energy lost by the TSU, based on the heat loss rate after the foundation heat loss rate reached a constant value.

Energy Used to Heat the Foundation - Energy lost by the TSU, heating the foundation and the inactive regions of the TSU until the heat loss rate reached a constant value.

Energy Used to Dry TSU Bed - Energy consumed to boil off water and light molecular weight hydrocarbons from the TSU bed.

Energy Used for Extraction Testing - Energy consumed for heating the extraction heat exchanger(s) to operating temperature and then generating steam for testing extraction controls.

Energy Used to Generate Auxiliary Steam - Energy consumed for heating the extraction heat exchanger(s) to operating temperature and then generating steam for the deaerator and turbine seals.

Energy in TSU on 9/30 - Amount of energy relative to ambient contained within the TSU bed on September 30 at 1744 hours.

Total Energy Delivered to TSU - Sum of all the above energies including the energy for charging controls testing.

Energy Used to Warm Charging Heat Exchangers - Energy consumed for heating the charging heat exchangers to operating temperature.

TABLE IV

THERMAL STORAGE SUBSYSTEM THERMAL ENERGY CONSUMPTION DURING THE 1040 TESTS

Energy Consumption	Energy, $MWhr_t$	%
Energy Lost to Environment From TSU	271	12
Energy Used to Heat the Foundation	51	2
Energy Used to Dry TSU Bed	142	6
Energy Used for Extraction Testing	921	41
Energy Used to Generate Auxiliary Steam	274	12
Energy in TSU on 9/30	423	19
Total Energy Delivered to TSU	2082	92
Energy to Warm Charging Heat Exchangers	172	8
Total Estimated TSS Energy Consumption During the 1040 Tests	2254	100

The important feature of the energies quoted in Table IV is their relative magnitude. The majority of the thermal energy consumption was for heating the bed to operating temperature, generating steam supporting plant operations, and generating steam for controls testing. Energy losses to the environment and foundation, energy for drying the TSU, and energy for warming the charging heat exchangers were relatively small. Therefore, a designer should first be concerned with how the subsystem controls will be tested and the subsystem operated during TSS activation to realize the greatest effect on thermal energy consumption. Second, the designer should be concerned with reducing heat losses.

Since no data on other solar central receiver power plants are available at this time, it cannot be determined whether the thermal energy consumption to activate and test the TSS at Solar One is relatively excessive or insignificant. In terms of an average day's receiver output, the total estimated TSS consumption is equivalent to about fourteen days of receiver operation.

Several comments on the information in Table IV are appropriate. The energy loss to the environment, listed as 12 percent of the energy directed to the TSS, does not mean that the system loses 12 percent of its energy per day. This figure is the energy lost over five months, during which the TSU was inactive for periods of time because of weather and equipment problems. When the TSS is operated routinely according to design, undergoing a charge and extraction cycle every day or several times a week, the average daily energy delivered to the TSU will be larger and the fraction of energy lost to the environment should drop to less than 3 percent. Further testing will ascertain the correct value.

Knowing the amount of energy used to dry the TSU bed allows the amount of water originally in the bed to be calculated. Roughly 2 MWhr of energy were used to boil out the light hydrocarbons, leaving 140 MWhrs for boiling water. This amount corresponds to 2.0×10^5 kg (215 tons) of water or 3.2 percent of the mass of rock and sand. This is an impressive and somewhat surprising figure. Since the energy to dry the TSU bed is derived by subtracting all other energies from the total energy delivered, the error in this figure could be large. Visual observation of the rate of steam release and measured ullage pressures during bed drying indicated the water fraction to be closer to 1 percent. However, whether 1 percent or 3.2 percent, the amount of water to be boiled out of the TSU is worth considering when preparing system design and start-up plans for similar thermal storage subsystems. In the case of Solar One, an 8-inch safety vent was disassembled, providing a constant vent on the TSU during the bed drying. This vent was adequate to vent any steam generated.

Thermocline Sharpness

The TSU of Solar One stores high and low temperature energy in the same packed bed using the principle of density stratification to effect thermal stratification. The result is a more compact and economical storage device. However, the storage capacity of such a device is affected by the sharpness of the division between the hot and cold regions of the packed bed. The transition region between hot and cold, commonly called the thermocline, must be minimized to maximize the storage capacity of the TSU. This section briefly discusses how large a temperature gradient can be produced.

Thermocline sharpness or a large temperature gradient between the hot and cold regions is affected by the thermo-physical properties of the sand, rock, and heat transfer oil and the operation of the TSU. Two axial temperature profiles of the TSU bed are shown in Figure 6 along with a predicted axial temperature profile. The predicted axial temperature profile was reproduced from a computer simulation plot contained in Ref. 5 and is the "steady-state" temperature profile after five full charge-discharge cycles.

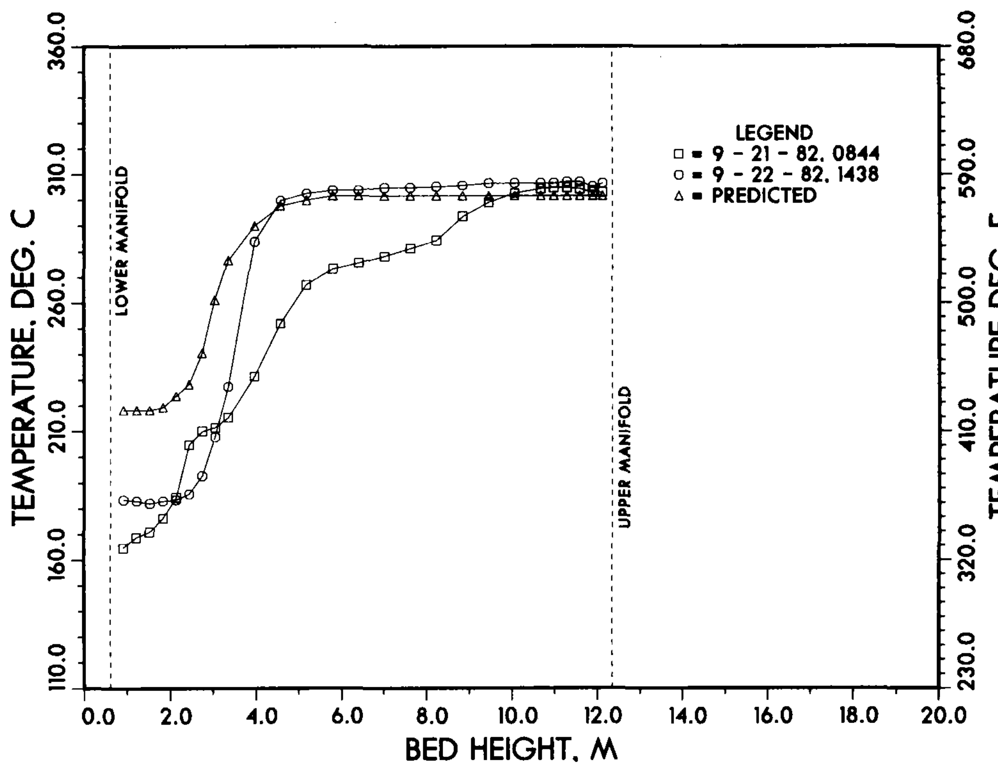


Figure 6. Comparison of Predicted and Actual TSU Axial Temperature Profiles

During the 1040 tests there was not one full charge-discharge cycle, much less five. The controls testing prioritized operating the TSU as an arbitrary source and sink of thermal energy over minimizing the thermocline thickness. Therefore, it is not surprising to see the variability depicted in Figure 6. The temperature gradient for 9/21/82, 0844, is 15°C/m (8°F/ft); for 9/22/82, 1438, the gradient is 50°C/m (27°F/ft); and for the predicted temperature profile, the gradient is 20°C/m (11°F/ft). It is interesting to note the marked difference between the 9/21/82, 0844 temperature profile and the 9/22/82, 1438 temperature profile. In the intervening 30 hours, 97 percent of the active region of the TSU was heated to a temperature of 307°C (585°F) effectively eliminating the thermocline region. The TSU was then discharged for extraction controls testing on the following day. This created the large temperature gradient on 9/22/82.

In summary, a large temperature gradient can be produced in the TSU bed, but the gradient can vary from day to day, depending on TSU operation. However, no average thermal gradient or thermocline thickness can be determined at this time.

Electrical Energy Production During Activation and Initial Testing

The major use of the TSS is as an alternate source of steam for operating the turbine-generator to produce electricity. The net electrical energy production of the TSS during the 1040 tests is shown in Table V. It is important to realize the production of electricity was the occasional by-product of the 1040 tests and not their goal. Therefore, the relatively small amount of electricity produced is not surprising. What is relevant is that the TSS and turbine can operate together as a system on a regular basis.

TABLE V

THERMAL STORAGE SUBSYSTEM ELECTRICAL PRODUCTION DURING ACTIVATION

Date		Electrical Energy MWhr Net
8/24		1.4
8/30		3.03
9/13		2.7
9/14		1.1
9/15		6.27
9/16		3.6
9/21		2.0
9/22		2.0
9/28		6.6
9/29		0.35
	Total	29.05

Thermal Storage Unit Tank Wall Stress

A major concern in the design of the TSU was the tank design. The final tank design is a standard circular cylinder with a truss-supported roof. The tank is bedded on a layer of sand over insulating concrete. The walls are of varying thicknesses as shown in Figure 7. The wall-to-floor joint is a 90-gusset reinforced butt joint. The tank is constructed of ASTM 1537 class 2 carbon steel and has an allowable stress at 600°F of 204 MPa (29,660 psi), a yield stress of 414 MPa (60,000 psi), and an ultimate stress of 552 MPa (80,000 psi) (Ref. 5).

The tank design covered seismic stresses, tank wall stresses due to hydrostatic head of the contents, differential thermal stresses between the rock and sand bed and wall, and the differential thermal stresses at the wall-to-floor and wall-to-roof junction. These analyses are covered in Ref. 5. The phenomena of "thermal ratcheting," in which the heated tank expands more than the rock and sand bed, allowing the bed to settle, and which is followed by a cooldown of the tank, causing high tensile hoop stresses as the bed prevents contraction of the tank wall, was considered and found to be a remote possibility. Thermal ratcheting is unlikely because during normal operation, the tank wall and bed were predicted to be in full contact and stressed below their elastic limit. Stresses in excess of the yield stress are required to promote thermal racheting. However, a tank design of this nature is a new engineering effort, and strain gages were mounted on the tank so actual tank wall stresses could be compared to predictions. Strain gage rosettes were placed on the exterior of the TSU tank at the 0.3, 0.6, 0.9, 1.2, 1.5, 5.5, 12.5, and 13.1 m (1, 2, 3, 4, 5, 18, 41, and 43 ft) levels at azimuths of 45, 193, and 347 degrees.

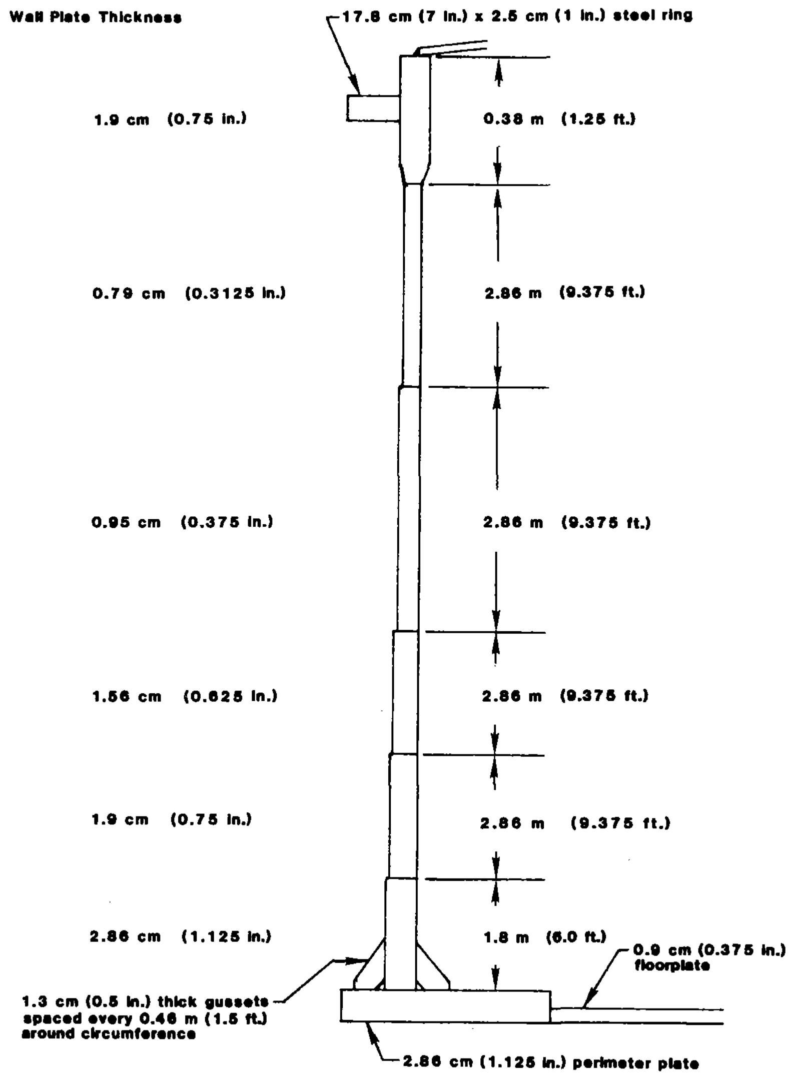


Figure 7. Thermal Storage Unit Tank Cross-section

Strain gage readings were taken during the construction and operation of the tank through December 1, 1982. These figures were reduced to vertical and horizontal stress values and reported in Ref. 9. The estimated accuracy of these average stress values is ± 50%. The average stresses at each elevation in both the horizontal and vertical direction are shown in Figures 8 and 9 from the completion of tank construction in June 1981 until December 1982. The tank was filled with oil in July 1981. The TSU began to be heated in May 1982 and underwent a steady increase in average temperature until late July 1982, when heat extraction began to take place for generation of steam. After this date, the TSU experienced frequent thermal cycling.

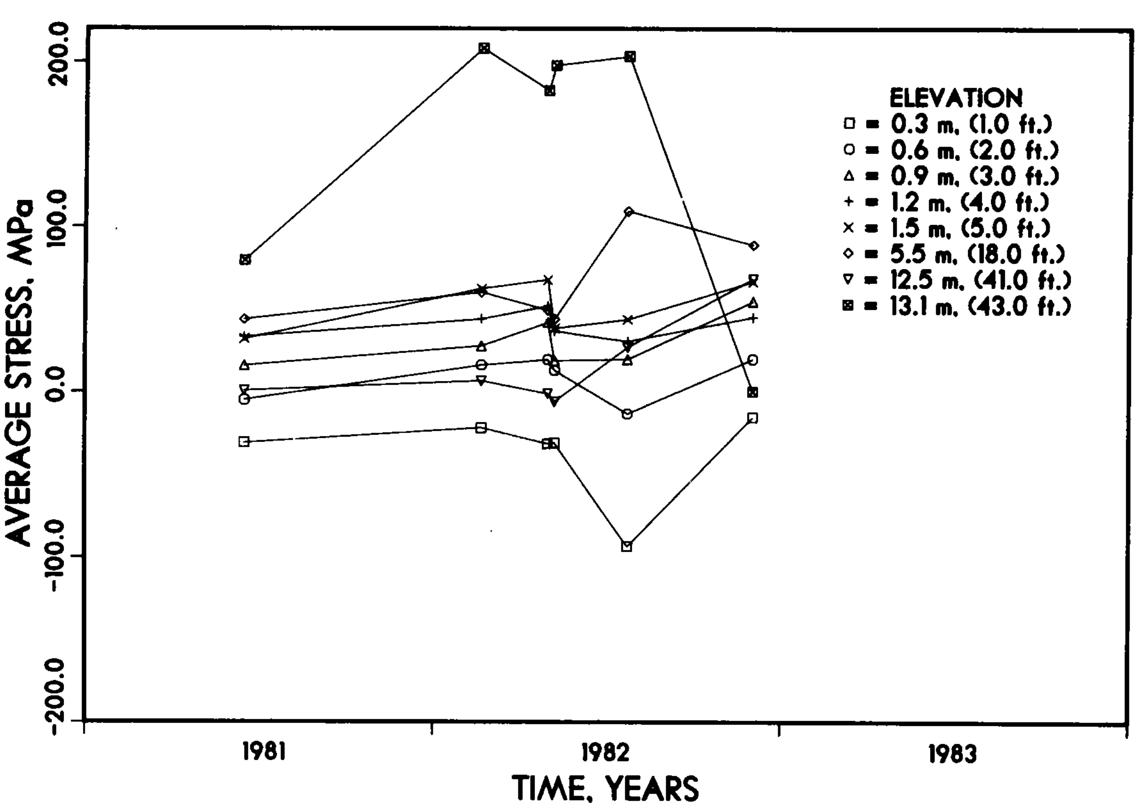


Figure 8. Thermal Storage Unit Horizontal Wall Stress

The horizontal stresses indicate a general trend toward a more compressive (negative) stress, followed by a trend toward a more tensile (positive) stress after May 1982. The general increase in horizontal wall stress is believed due to the heating of the TSU. The 13.1 m (43 ft) level stress is at or just above the allowable stress for much of the period shown and then plummets to essentially no stress. This peculiar behavior can be explained by faulty instrumentation or by local stress effects. The strain gage at this level, which contributes a high stress figure to the average, is near

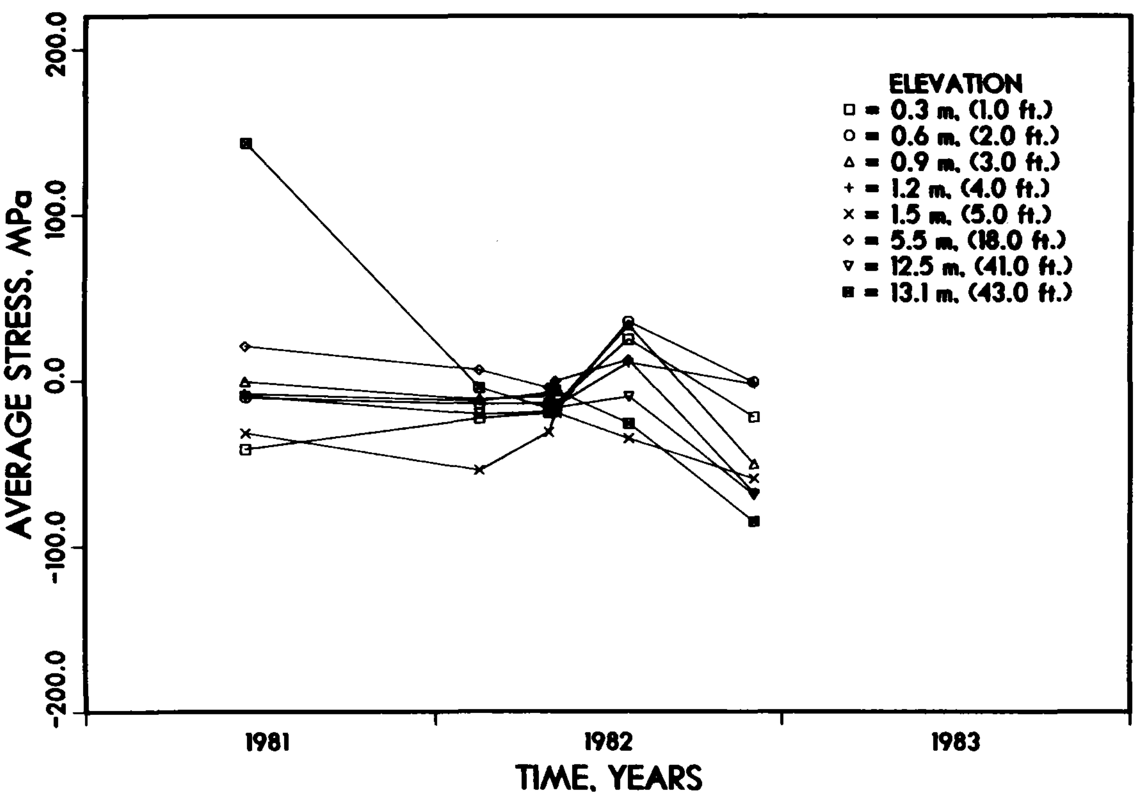


Figure 9. Thermal Storage Unit Vertical Wall Stress

an attachment for a roof truss. This proximity may have created the local high stresses recorded by this strain gage rosette. On December 1, the rosette was found to have failed, which may mean some gages had given previous defective readings. In either event, the stress occurs in a noncritical area above the oil level, never exceeds the yield stress, and is not a great concern at this time. In general, the horizontal stresses are all within the allowable stress. No trends indicate that thermal ratcheting is present.

The vertical stresses are the reverse of the horizontal stresses. There is a trend to a more tensile stress initially, followed by a trend toward a more compressive stress during the time the TSU was heated. The initial trend toward a more tensile stress in the lower 0.9 m (3 ft) of the tank is curious, since it had been predicted that the stress in this region would become compressive during initial heating. This region could only be heated by thermal conduction and would have a thermal gradient, causing the base of the tank to be of smaller diameter than the area at the 0.9 m level. Unfortunately, no good explanation is presently available. In general, the vertical stresses are also below the allowable stress and indicate no meaningful trends.

Heat Transfer Fluid Losses and Degradation

The heat transfer fluid used in the TSS is a hydrocarbon oil known as Caloria HT-43 and is produced by Exxon Corporation. Laboratory testing revealed Caloria HT-43 suffers a rapid loss of mass upon initial heating since heating drives out low molecular weight compounds. After this initial loss, the mass loss rate settles down to a lower rate dominated by thermal decomposition processes. This section discusses the experience gained operating an actual dual-media storage unit with Caloria HT-43 as the heat transfer oil.

Initial Mass Loss of Caloria HT-43

According to Refs. 6 and 7, when Caloria is initially heated, approximately 2 to 3 percent of the mass is typically boiled away. The actual amount varies from lot to lot of Caloria. When the TSU safety vent (which had been opened for steam release during heating with the rental boiler) was closed, light hydrocarbon fluid and water began to collect in the heptane storage tank of the UMU. This fluid was condensed in the cooler interconnecting piping when gases were withdrawn by the UMU from the TSU in order to lower the pressure in the ullage space.

After a week or two, it became apparent that a large quantity of hydrocarbon fluid was going to be condensed rather than routed to the UMU burn stack for disposal in the gaseous phase as had been originally expected. From June 30, 1982, to August 25, 1982, some 15,000 liters (4000 gallons) of hydrocarbon fluid had been removed. After August 25, an accurate record of fluid removal is not available, since a certain amount of the hydrocarbon fluid was returned to the TSU to maintain ullage pressure during extraction, and then it was removed again during charging. However, discussions with the test staff and plant operations crew place the amount of hydrocarbon condensate removed from August 25 through September 30 at a maximum of 5700 liters (1500 gallons). So approximately 20,700 liters (5500 gallons) of hydrocarbon condensate, or about 2.8 percent of the initial fluid inventory, had been removed during the 1040 tests.

This amount appears to be close to predictions based on laboratory tests. However, an unknown mass of ullage gas was not condensed and therefore burned by the UMU, which increases the total mass loss. A sample of ullage gas taken August 10 indicates that all but 15 percent of the gas was condensable at that time, but it is questionable that this sample represents the average ullage gas composition over a three-month period. Attempts to calculate the mass loss by using the amounts of Caloria that were added to maintain tank level are confounded because a net removal of Caloria was required by the thermal expansion of the oil.

The initial mass loss is therefore less than the thermal expansion of the oil from ambient to operating temperature (28 percent) and more than the amount of hydrocarbon fluid condensation (2.8 percent). A more probable range is 2.8 percent to 5.6 percent, since it is unlikely that the mass burned was greater than the mass condensed. Most of this initial lost mass was of existing low molecular weight hydrocarbons in the oil, but some comes from thermal decomposition.

The unexpectedly large amount of hydrocarbon condensate caused a disposal problem. Condensate was first placed in spare drums and, finally, into a small oil tank trailer for eventual disposal. Operators of future similar thermal storage systems should be prepared to handle truckloads of flammable hydrocarbon fluids during start-up.

Thermal Degradation of Caloria HT-43

One of the major concerns during the design of the TSS was selecting a heat transfer oil with acceptable thermal degradation. Caloria HT-43 was selected on the basis of its relatively economical fluid replenishment cost performance. Other fluids, costing more than Caloria, had lower fluid loss rates but had higher replacement costs. Testing was performed and the results used to select a candidate fluid. These tests, no matter how elaborate, could not simulate the actual conditions that the heat transfer fluid would operate under in a real system. Therefore, during the 1040 tests, samples of heat transfer oil were removed from the subsystem piping at regular intervals for subsequent analysis of thermal degradation. The results of these analyses are presented below.

Composition of Fresh Caloria--Fresh or unaged Caloria HT-43 is described as an aliphatic hydrocarbon fluid with a considerable amount of branched structure. A small amount of oxidation inhibitor is added to improve the oil's high temperature performance. Table VI lists the properties of Caloria HT-43 as published by the manufacturer (Ref. 6). Since it was desired to note changes in the composition of Caloria HT-43, a gas chromatograph-mass spectrograph unit available at Sandia National Laboratories Livermore was selected as the analytical tool for this work.

A total ion chromatogram for fresh Caloria HT-43 is shown in Figure 10. The gas chromatograph mass spectrometer was able to clearly resolve the presence of completely saturated molecules having 15 to 20 carbon atoms. Above and below this number of carbon atoms, no dominant isomer exists and no peaks are found, except for the small unidentifiable peak near the origin. This peak is identified simply as light fractions.

An expanded plot of the region out to 20 carbons is shown in Figure 11. Very little structure can be noticed between the peaks, indicating the predominance of straight chain hydrocarbons in this mass range.

These two plots indicate that Caloria HT-43 is a mixture of many isomer molecular forms with completely saturated molecules prevalent between 15 and 20 carbons. Unfortunately, not much more can be said using this analytical technique or, probably, using any other, since there are so many isomers, each in low concentration. For example, there are 366,319 isomers of $C_{20}H_{42}$ alone.

TABLE VI

TYPICAL PHYSICAL DATA AND INFORMATION AVAILABLE ON CALORIA HT-43

Caloria HT43		
Manufacturer:	Exxon Corporation	
Description:	Paraffinic base stock with a high temperature oxidation inhibitor	
Properties:	Density at 15°C, gms/cc	0.8587
	Color, ASTM	L1.0
	Viscosity, cSt at 40°C	29.6
	cSt at 100°C	5.4
	SSU at 100°F	153
Viscosity index		115
Flash point, COC, °C		204
Pour point, °C		-9
Phenol, mass %		0.002
Saturates, mass % (ASTM D 2007)		91.0
Specific Heat @ 55°F, Btu/lb-°F		0.65
Thermal Conductivity @ 550°F, Btu-lb-ft °F		0.0492

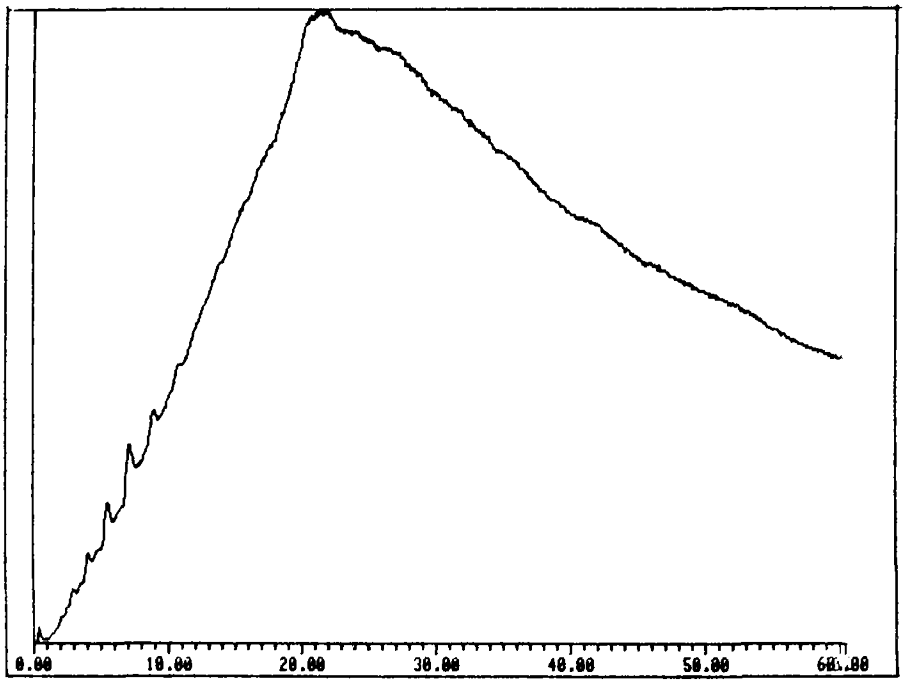


Figure 10. Total Ion Chromatogram for Fresh Caloria

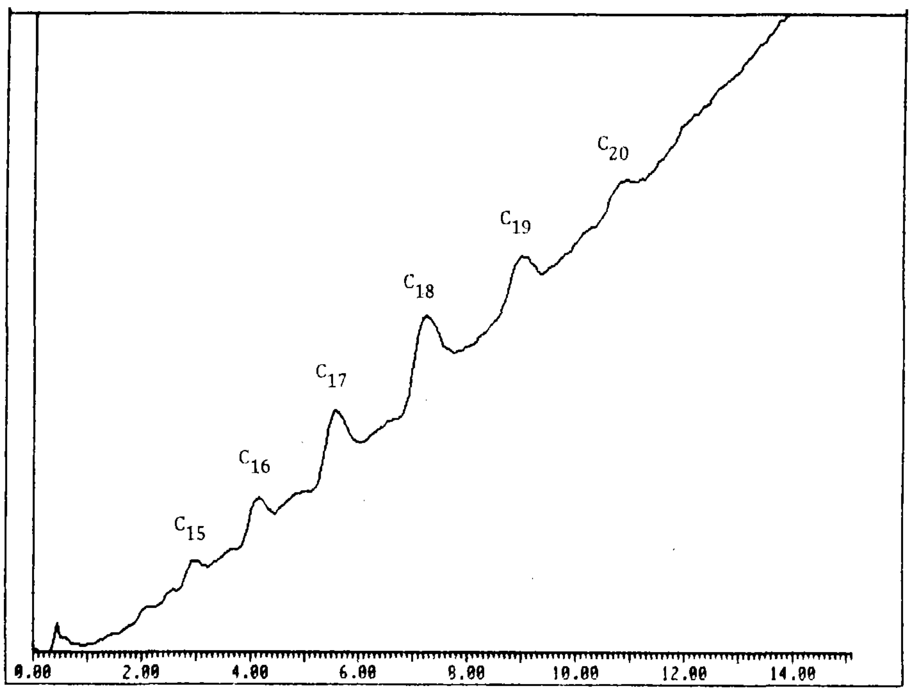


Figure 11. Total Ion Chromatogram for Fresh Caloria--
Expanded Plot of Low Molecular Weights

Composition of Aged Caloria--A sample of Caloria HT-43 that was withdrawn from the TSS on October 7, 1982, was analyzed in the same manner as the fresh Caloria HT-43 sample. The sample had been aged for five months at temperatures varying from ambient to operating temperatures. The total ion chromatogram of this sample is shown in Figure 12; an enlargement of the portion that includes molecules of up to 20 carbon atoms is shown in Figure 13. Comparing these two plots to those of fresh Caloria HT-43 reveals some added structure between the peaks that were previously identified as completely saturated molecules. This added structure may be due to an increase in the amount of unsaturated molecules. There is also an increase in the amount of light fractions relative to the bulk. Both these increases indicate a small degree of chain breaking. The low peaks near the top of the plot in Figure 12 have not been identified.

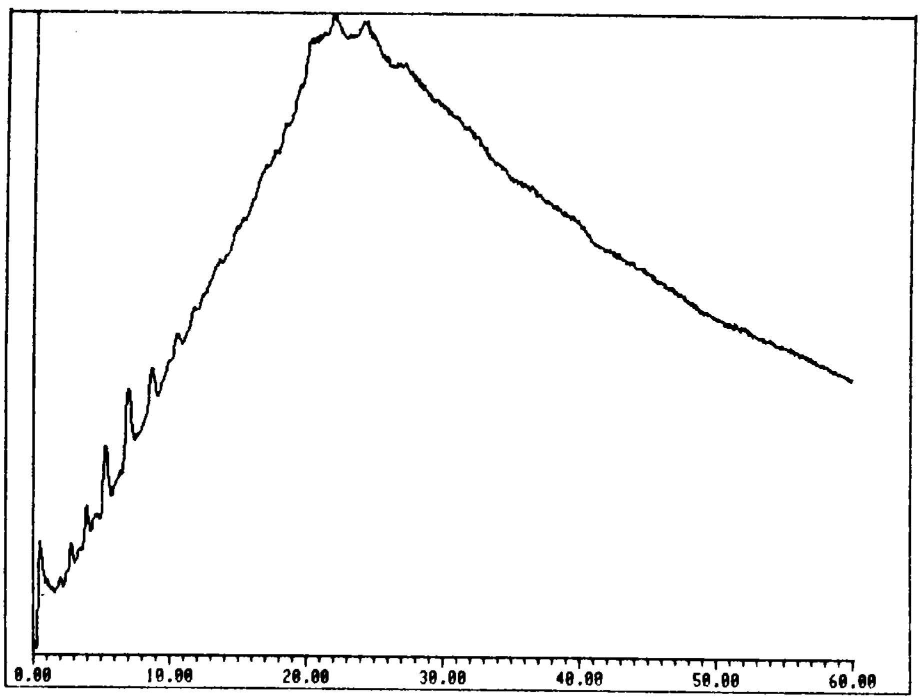


Figure 12. Total Ion Chromatogram for Aged Caloria

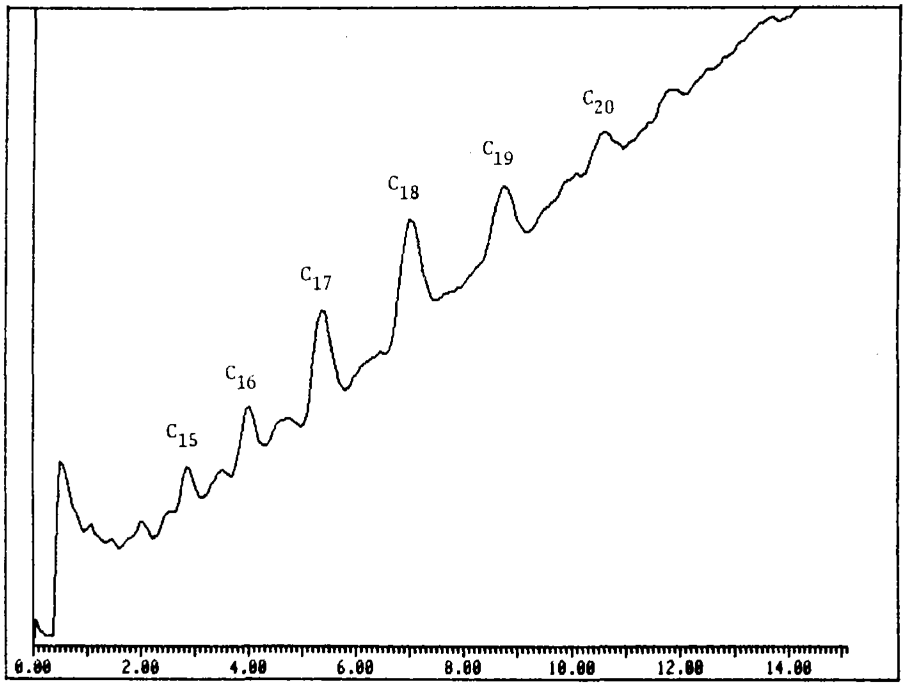


Figure 13. Total Ion Chromatogram for Aged Caloria--Expanded Plot of Low Molecular Weights

Two samples of the ullage gas were taken and analyzed at an outside laboratory. Both samples had high levels of hydrogen gas, indicating hydrogen atoms were being stripped from the molecules. This phenomenon can be caused by breaking up a molecule or by increasing the double bonding between carbon atoms. It had been noticed that the oil had darkened from a yellow color to a tan color during its initial heating. This change in color could be the result of oxidation of the oil or increased double bonding which changes the spectral qualities of the oil, or both. However, ultraviolet testing revealed very small increases of double bonding and oxidation.

The aged Caloria HT-43 therefore is showing barely noticeable and very limited thermal degradation over the five-month period from May to October. No mechanism for degradation is seen to be favored at this time; in fact, the evidence shows many modes of degradation are probably active. The very small degree of degradation is not surprising when a statistical summary of the TSU, and thus of the heat transfer oil, temperature history is made.

Figure 14 is a plot of a TSU temperature history in which the y-axis is fractional mass-weighted time and the x-axis is temperature. The bars are the fractional mass-time product for 10°C (18°F) intervals and indicate the relative time the oil existed in each temperature interval. The statistical survey was performed from May 5, 1982, through October 7, 1982.

References 6 and 7 both provide an Arrhenius-type equation for Caloria HT-43 weight loss rate from thermal degradation as a function of temperature. Integrating these equations with the temperature history available for the TSU produces a high estimate of weight loss at 1.32 percent of the fluid inventory (using the equation from Ref. 6) and a low estimate of 0.47 percent (using the equation from Ref. 7). Since the Caloria HT-43 spent relatively little time over 270°C where the loss rate is equal to about 1 percent per year, it is not surprising that the degree of thermal degradation is minor.

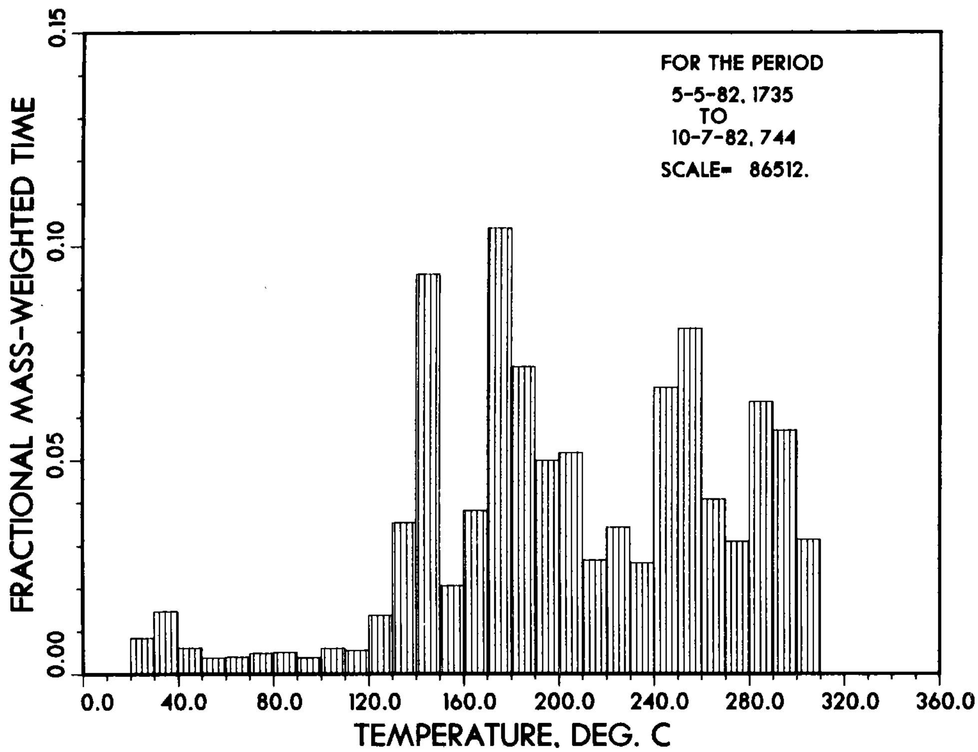


Figure 14. Thermal Storage Unit Temperature History

Hardware Problems

The TSS storage subsystem has its share of hardware problems. The majority are common maintenance items, such as weeping valve stem packings. However, some problems are completely unique to the thermal storage subsystem and warrant review.

Thermal Storage Unit Tank Leak

The TSU containing the dry crushed gravel and sand mixture was filled with Caloria HT-43 from July 7 through July 11, 1981. On August 7, 1981, oil was discovered leaving the north foundation drain pipe. Subsequent investigation revealed that the oil was originating from the TSU tank bottom and not from the tank sides. The flow rate of the leaking oil was estimated at 3.8 liters (one gallon) per day and did not increase. A number of cores were drilled horizontally into the tank foundation on the north side to locate the leak. The core drills revealed a pool of oil beneath the tank which was soaking into the low density insulating concrete. This pool was located within 1.52 to 2.13 m (5 to 7 ft) of the tank's north perimeter, beginning at the north-south axis and proceeding west circumferentially for about 3.66 m (12 ft).

The TSU tank is constructed with a butt-welded, gusset-reinforced wall-to-floor junction. The perimeter plates are much thicker (2.86 cm or 1-1/8 in.) than the interior floor plates (0.95 cm or 3/8 in.), adding stiffness to this junction. The weld at the thick-plate and thin-plate junction was a more difficult weld to produce, causing numerous starts and stops. Since the chance of a weld flaw is much greater where a weld is begun or ended, this weld became suspect as the leak source. A welded overlap joint which occurs along the north-south centerline in the thin plate and which terminates at the thick plate also increases the probability of a weld flaw at the thick-plate to thin-plate junction. This weld was another suspected leak source.

Evidence derived from the core drills and knowledge of tank construction indicated that the leak was most likely located at the thick-plate to thin-plate junction. It was decided to tunnel underneath the tank by jackhammering through the structural concrete curb at the edge of the tank and then into the 0.6 m (2 ft) thick layer of insulating concrete underneath the tank. The alternative was to remove all the rock, sand, and oil in the tank, as well as the manifolds and instrumentation, to repair the leak from the inside.

Plans were made for the tunneling and a contractor was selected to perform the work. Excavation began on November 16, 1981. Tunneling to the junction of the thick and thin plates ended on November 19 with no sign of a leak. It was decided to proceed further inward by 1.2 m (4 ft) toward the center of the tank underneath the thin plate.

The tunnel extension was begun on November 23 and the leak was found that morning. The leak did not originate from a porous weld as suspected but from a flaw in the thin steel plate. The region of the flaw was about 6 mm (0.25 in.) in diameter, and the leak flow rate was estimated at 3.8 liters (1 gallon) per day. Subsequent ultrasonic tests did not reveal an extensive defect in the plate, so it was decided to weld a 15 m (6 in.) diameter patch over the leak. This repair was effected on January 23, 1982.

A leak in the bottom of a tank filled with over 7.26 million kg (8000 tons) of rock, sand, and oil is a serious problem. Some thoughts on reducing the chance of an undetected leak in the bottom of a similar tank are presented below:

1. Consider leak testing the entire tank floor. In the Solar One thermal storage tank, only the welds were inspected with a vacuum box and dye penetrant.

2. Consider filling the tank with 0.3-0.6 m (1-2 ft) of oil only, heating the oil to 93°C (200°F) and allowing it to sit for a week or two. This procedure might locate a leak otherwise undetected, since Caloria may dissolve inclusions in a weld or plate flaw that were previously tested and found satisfactory. Since water will not dissolve foreign materials that Caloria will, water is an unsatisfactory test fluid.

In the final analysis, efforts to reduce the chance of a leak in the bottom of a tank are a function of the money and time available and the risk one is willing to take.

Oil Pump Vapor Lock

Charging oil pump P-301 tripped automatically when its outlet flow fell below 45,000 kg/hr (100 klbh) during thermal storage bed conditioning test 1040A on May 19, 1982. It was found that the flow fell off while the pump was maintaining constant speed. The cause was traced to water in the oil which was flashing to steam in the pump. At first this problem was circumvented by lowering the pump speed, but by May 25 this solution failed to work. The eventual solution was to route oil from the top manifold into an extraction pump, through an extraction train of heat exchangers, and into the inlet of the charging pump. From the charging pump, the oil was circulated through the charging heat exchangers to be heated and returned to the upper manifold. The pump speeds were controlled to maintain a flow of hot oil into the upper manifold and through the TSU. In this fashion, the extraction pump boosted the charging oil pump to maintain oil flow, allowing completion of bed conditioning. Once the oil temperature at the lower manifold rose above the local water saturation temperature, pump vapor lock was eliminated.

The oil pump vapor lock was initially thought to be caused by plugging of the lower manifold with sand that had infiltrated the rock-only zone. The pressure drop across the manifold was monitored and found to be insignificant. Contrary to concerns raised during TSS design, manifold plugging has not shown itself to be a problem.

Flange Leaks

When the TSS had been operated for about six weeks, a number of flange leaks began to occur. Numerous small diameter flanges (8 in. and less) began to seep oil as the temperature of the oil increased and its viscosity decreased. These leaks were repaired by tightening the flange bolts. However, when the water-side heat exchanger flanges began to leak, this solution no longer worked.

From late August to the end of September, leaks on the water-side flanges of the two boilers and subcoolers had developed to the point where action was required. During a plant outage in November, new gaskets were installed on the leaking flanges. One boiler gasket and flange were in good shape. This gasket was wrapped with exfoliated graphite tape, and the flange joint was reassembled. The other boiler required minor repairs to the flange surface and had a new gasket, provided by Sealing Corporation of North Hollywood, California, incorporating exfoliated graphite as the seal.

One subcooler had a new gasket of the original design installed; the other subcooler also had a new gasket of original design but wrapped with exfoliated graphite tape. The subcooler gasket without the exfoliated graphite tape wrap was replaced within 3 weeks with one that was wrapped. As of January 1983, all of the above-mentioned gaskets are sealing properly.

The exact cause of the leaks is not yet known. One cause may be that the bolts were not promptly retorqued after the first few thermal cycles on the equipment. Another cause may be the thermal cycling the piping and heat exchangers endure as a result of the diurnal availability of the sun. A final determination, if at all possible, of the cause of the flange leaks will come only after more subsystem operating time has occurred. Therefore, any resolution of whether a real problem exists and what the solutions are, or may be available, will have to be covered in a later report.

Conclusions

The preceding discussion of the TSS of Solar One can be summarized as follows:

- The TSS has been operated to charge and discharge the TSU successsfully and repeatably.
- Bringing the TSS to an operational state required approximately 2254 MWhr of thermal energy, the majority of which was used to heat the TSU bed and generate steam for extraction testing and auxiliary use.
- A thermocline can be successfully created in the TSU with a temperature gradient exceeding predictions. Operation of the TSU can significantly affect the thermocline region. However, data are not yet available to suggest a particular operating procedure.
- The TSU tank wall stresses are within predicted limits and trends. No thermal ratcheting is indicated.
- Water entrapped in the TSU bed must be considered during initial heating of the TSU. Roughly 3 percent of the rock and sand weight, some 2×10^5 kg (215 tons), was boiled out as water.

- The initial mass loss of heat transfer oil from the boiling off of low molecular weight hydrocarbons was estimated between 2.8 percent and 5.6 percent. Since the heat transfer oil expands with temperature, no additional fresh oil was required. However, disposal of the boiled-off hydrocarbon condensate was bothersome.

- Thermal degradation or decomposition of the heat transfer oil was low, since the oil had spent little time at temperatures high enough to cause significant thermal degradation.

- Hardware problems unique to the TSS have occurred and have been successfully repaired or solved for the present. However, flange leaks may continue to occur in the future until the cause is understood.

APPENDIX A--REDUCTION OF HISTORICAL TSU DATA

This appendix covers the methods used to obtain the integrated TSU energy, the statistical temperature survey of the TSU, and the estimated heat transfer oil mass as a result of thermal decomposition.

Integrated TSU Energy

The data that provide an energy history for the TSS come from 27 thermocouples embedded in the oil, rock, and sand bed of the TSU. Using this temperature data and knowing the distribution of rock, sand, steel, and oil in the TSU, one can integrate the energy contained in the TSU between the 0.6 m (3 ft) and 12.6 m (41.5 ft) level at a particular time. Accounting only the energy contained in sections of the TSU above a certain temperature returns energy available for the two processes the TSS is required to provide: seal steam and steam for electrical production. Dividing the change in energy within the TSU from one time to the next by the change in time gives the average thermal power to or from the TSU over the time period. A computer code performing the integration operation was written because of the large amount of data handling required.

The method of numerical integration used by the computer program is the trapezoidal rule. Variable properties are used for the oil, rock, and sand as listed in Table A-I. Since each section of the TSU bed may have a different distribution of rock, sand, and oil, this feature was incorporated. The energy in the tank was computed by the following calculation:

$$E_{tank} = \sum_{i=1}^{26} [\rho_{oil}(T_m) cp_{oil}(T_m) f_{oil} V_i T_m$$

$$+ \rho_{\substack{rock \\ sand}} cp_{\substack{rock \\ sand}}(T_m) f_{\substack{rock \\ sand}} V_i T_m$$

$$+ \rho_{steel} cp_{steel} V_i T_m] - E_{ref}$$

where,

T_m = $(T_{i-1} + T_i)/2.0$

$Eref_i$ = i^{th} level reference energy at a particular temperature, usually 67°C or 425°F

ρ = density (function of T_m)

cp = specific heat (function of T_m)

f_i = volume fraction at i^{th} level

V_i = volume at i^{th} level

TABLE A-I

TSU BED THERMOPHYSICAL PROPERTIES

Caloria HT-43	
$\rho = 55.0 - 0.0241T$	lb/ft^3
$cp = 0.4 + 5 \times 10^{-4}T$	B/lb-°F
$k = 0.074 - 4.5 \times 10^{-5}T$	B/h-ft-°F
$\mu = 10^{[6.559 - 1.027 \ln T]}$	lbm/h-ft
Gravel and Sand	
$\rho = 165.0$	lb/ft^3
$cp = 0.19 + 0.0001T$	B/lb-°F

Mass of Granite Gravel in TSU = 4532 tons
Mass of Sand in TSU = 2266 tons
Mass of Caloria in TSU @ 425°F = 637 tons
Void fraction of rock alone or sand alone = 0.40
Void fraction of rock and sand mixture = 0.22

TSU Statistical Temperature History and Heat Transfer Oil Mass Loss Calculations

The data used for deriving the TSU statistical temperature history and heat transfer oil mass loss are the historical TSU temperature data mentioned in the previous section. Those data are taken at specific times, so linear interpolation is required to obtain TSU temperatures between data records. In this fashion, a continuous temperature history for the TSU was established. Once a continuous temperature history is available, the various required calculations are straightforward.

For the TSU statistical temperature history, the TSU is divided into 26 disks containing a known volume of oil. The time the oil in each disk spends in each temperature interval of 10°C (18°F) is calculated from the continuous temperature history and multiplied by the mass of the oil in the disk. The oil mass in a disk is calculated at the mean temperature of the 10°C temperature interval. The mass-time products related to a particular 10°C temperature interval for all disks are summed to produce a total mass-time product for that temperature interval. All mass-time products are divided by the sum of the individual products to form values ranging from zero to 1.

The mass loss calculations use the continuous temperature history and the relationships below:

$$w = 7.126 \times 10^{14} \exp(-2.55 \times 10^{4}T) \quad \text{(Ref. 6)}$$

$$w = 1.63 \times 10^{7} \exp(-1.61 \times 14^{4}T) \quad \text{(Ref. 7)}$$

The units of w are grams lost per hour. These equations were numerically integrated, producing the results described in the section on the composition of aged Caloria.

APPENDIX B--SUPPORTING DOCUMENTATION

Thermal Performance History Tabulations

DATE	TIME	DAY	E1	E2	E3	P1
5- 5-82	17:35	125.73	7.26	-411.00	0.00	0.000
5- 6-82	15:28	126.64	23.60	-395.00	16.30	0.747
5-10-82	18:34	130.77	77.30	-341.00	53.70	0.542
5-11-82	7: 7	131.30	82.60	-336.00	5.26	0.419
5-11-82	17:25	131.73	113.00	-306.00	30.10	2.919
5-12-82	8:11	132.34	128.00	-290.00	15.80	1.069
5-12-82	22:26	132.93	176.00	-242.00	47.80	3.356
5-13-82	7:20	133.31	170.00	-249.00	-6.24	-0.701
5-13-82	16:14	133.68	186.00	-233.00	16.20	1.819
5-14-82	22:18	134.93	221.00	-197.00	35.10	1.167
5-17-82	9: 8	137.38	197.00	-222.00	-24.10	-0.410
5-17-82	21: 2	137.88	226.00	-193.00	28.90	2.432
5-18-82	8: 8	138.34	223.00	-195.00	-2.68	-0.241
5-18-82	17:13	138.72	238.00	-181.00	14.40	1.581
5-19-82	7:39	139.32	242.00	-177.00	3.99	0.277
5-19-82	20:23	139.85	259.00	-160.00	17.00	1.332
5-20-82	7:21	140.31	257.00	-162.00	-2.16	-0.197
5-20-82	16:24	140.68	255.00	-163.00	-1.20	-0.132
5-21-82	7:18	141.30	253.00	-165.00	-2.00	-0.134
5-21-82	15:48	141.66	244.00	-174.00	-9.04	-1.064
5-24-82	9:25	144.39	238.00	-181.00	-6.63	-0.101
5-24-82	16:24	144.68	236.00	-183.00	-1.72	-0.247
5-25-82	8:23	145.35	232.00	-187.00	-4.16	-0.260
5-25-82	16: 2	145.67	238.00	-181.00	6.21	0.812
5-26-82	7:32	146.31	249.00	-169.00	11.40	0.734
5-26-82	22:39	146.94	250.00	-169.00	0.55	0.036
5-27-82	7:40	147.32	250.00	-169.00	0.26	0.029
5-27-82	22:23	147.93	258.00	-161.00	7.94	0.539
5-28-82	10:57	148.46	258.00	-161.00	0.08	0.007
5-28-82	21:59	148.92	259.00	-159.00	1.16	0.105
6- 1-82	8:59	152.37	257.00	-162.00	-2.56	-0.031
6- 1-82	16:18	152.68	257.00	-162.00	0.32	0.044
6- 2-82	7:49	153.33	257.00	-162.00	-0.34	-0.022
6- 2-82	19:30	153.81	263.00	-156.00	6.03	0.516
6- 3-82	7:22	154.31	259.00	-159.00	-3.45	-0.290
6- 3-82	21:53	154.91	288.00	-131.00	28.40	1.954
6- 4-82	7:46	155.32	273.00	-145.00	-14.30	-1.446
6- 4-82	15:38	155.65	294.00	-125.00	20.60	2.614
6- 7-82	9: 0	158.38	281.00	-138.00	-13.30	-0.203
6- 8-82	7:28	159.31	279.00	-140.00	-2.25	-0.100

E1 = ENERGY RELATIVE TO 67 F, MWH(T)
E2 = ENERGY RELATIVE TO 425 F, MWH(T)
E3 = CHANGE IN ENERGY SINCE LAST DATA POINT, MWH(T)
P1 = AVERAGE POWER SINCE LAST DATA POINT, MW(T)

DATE	TIME	DAY	E1	E2	E3	P1
6- 8-82	14: 3	159.59	280.00	-139.00	1.13	0.172
6- 8-82	20:46	159.87	303.00	-116.00	23.30	3.469
6- 9-82	7:34	160.32	295.00	-123.00	-7.60	-0.704
6- 9-82	13:46	160.57	310.00	-108.00	15.00	2.415
6-10-82	9:18	161.39	319.00	-99.70	8.68	0.444
6-10-82	17:37	161.73	331.00	-87.90	11.80	1.420
6-11-82	9: 1	162.38	325.00	-93.60	-5.65	-0.367
6-11-82	11:21	162.47	325.00	-93.60	-0.06	-0.027
6-14-82	13:54	165.58	330.00	-88.80	4.83	0.065
6-15-82	7:39	166.32	329.00	-90.00	-1.18	-0.067
6-16-82	7:23	167.31	327.00	-92.20	-2.19	-0.092
6-18-82	8: 8	169.34	325.00	-93.90	-1.69	-0.035
6-18-82	15:35	169.65	324.00	-94.90	-1.02	-0.137
6-21-82	8:32	172.36	320.00	-98.30	-3.36	-0.052
6-21-82	14:32	172.61	313.00	-106.00	-7.56	-1.261
6-22-82	7:23	173.31	308.00	-111.00	-5.15	-0.306
6-22-82	17:45	173.74	306.00	-112.00	-1.51	-0.145
6-23-82	7:22	174.31	305.00	-113.00	-1.00	-0.073
6-23-82	14:41	174.61	316.00	-103.00	10.90	1.496
6-24-82	7:13	175.30	312.00	-107.00	-4.17	-0.252
6-25-82	7:20	176.31	312.00	-107.00	-0.39	-0.016
6-28-82	7:49	179.33	311.00	-108.00	-0.93	-0.013
6-29-82	7:53	180.33	310.00	-108.00	-0.46	-0.019
6-30-82	7:18	181.30	310.00	-109.00	-0.57	-0.024
6-30-82	12:51	181.54	303.00	-115.00	-6.35	-1.144
7- 1-82	6:54	182.29	301.00	-117.00	-2.10	-0.116
7- 1-82	17:57	182.75	373.00	-45.60	71.90	6.505
7- 2-82	7:16	183.30	351.00	-67.40	-21.80	-1.636
7- 2-82	12:19	183.51	365.00	-54.00	13.40	2.650
7- 6-82	13:34	187.57	346.00	-72.70	-18.60	-0.192
7- 7-82	7: 4	188.29	344.00	-75.10	-2.44	-0.139
7- 7-82	13:56	188.58	372.00	-46.70	28.40	4.135
7- 9-82	6:37	190.28	357.00	-62.10	-15.40	-0.379
7- 9-82	18:23	190.77	436.00	17.00	79.20	6.727
7-12-82	7:17	193.30	415.00	-3.92	-21.00	-0.344
7-12-82	18:38	193.78	430.00	11.60	15.50	1.368
7-13-82	7: 8	194.30	425.00	6.12	-5.49	-0.439
7-13-82	18:59	194.79	455.00	36.60	30.50	2.576
7-14-82	8: 8	195.34	449.00	30.70	-5.93	-0.451
7-14-82	15:38	195.65	478.00	59.30	28.60	3.812

E1 = ENERGY RELATIVE TO 67 F, MWH(T)
E2 = ENERGY RELATIVE TO 425 F, MWH(T)
E3 = CHANGE IN ENERGY SINCE LAST DATA POINT, MWH(T)
P1 = AVERAGE POWER SINCE LAST DATA POINT, MW(T)

DATE	TIME	DAY	E1	E2	E3	P1
7-15-82	8: 32	196. 36	465. 00	46. 30	-13. 00	-0. 767
7-15-82	18: 46	196. 78	491. 00	71. 80	25. 50	2. 493
7-16-82	8: 30	197. 35	483. 00	64. 30	-7. 54	-0. 549
7-16-82	14: 4	197. 59	490. 00	70. 90	6. 58	1. 181
7-19-82	7: 10	200. 30	479. 00	60. 50	-10. 40	-0. 159
7-20-82	7: 59	201. 33	477. 00	58. 30	-2. 22	-0. 090
7-20-82	18: 45	201. 78	485. 00	65. 90	7. 60	0. 706
7-21-82	7: 35	202. 32	480. 00	61. 10	-4. 84	-0. 377
7-21-82	14: 55	202. 62	496. 00	77. 20	16. 10	2. 201
7-21-82	18: 17	202. 76	512. 00	93. 50	16. 30	4. 837
7-27-82	16: 14	208. 68	480. 00	60. 90	-32. 60	-0. 230
7-28-82	9: 36	209. 40	479. 00	60. 40	-0. 51	-0. 030
7-28-82	17: 9	209. 71	499. 00	80. 80	20. 40	2. 699
7-29-82	17: 44	210. 74	492. 00	73. 70	-7. 02	-0. 286
7-30-82	7: 41	211. 32	491. 00	72. 30	-1. 43	-0. 102
7-30-82	16: 38	211. 69	512. 00	93. 30	21. 00	2. 347
8- 2-82	7: 20	214. 31	498. 00	79. 60	-13. 70	-0. 219
8- 2-82	17: 48	214. 74	527. 00	108. 00	28. 40	2. 712
8- 3-82	17: 32	215. 73	548. 00	129. 00	20. 90	0. 881
8- 5-82	7: 33	217. 31	533. 00	115. 00	-14. 30	-0. 377
8- 6-82	7: 46	218. 32	530. 00	112. 00	-2. 92	-0. 121
8- 6-82	11: 19	218. 47	519. 00	100. 00	-11. 50	-3. 236
8- 9-82	8: 22	221. 35	516. 00	97. 10	-2. 98	-0. 043
8- 9-82	17: 59	221. 75	580. 00	161. 00	64. 30	6. 690
8-10-82	9: 17	222. 39	562. 00	143. 00	-18. 50	-1. 206
8-13-82	7: 43	225. 32	552. 00	133. 00	-9. 90	-0. 141
8-16-82	8: 2	228. 33	544. 00	125. 00	-7. 91	-0. 109
8-16-82	16: 58	228. 71	567. 00	148. 00	22. 90	2. 561
8-18-82	7: 26	230. 31	546. 00	128. 00	-20. 40	-0. 529
8-19-82	7: 15	231. 30	547. 00	128. 00	0. 34	0. 014
8-19-82	13: 14	231. 55	571. 00	153. 00	24. 60	4. 112
8-20-82	7: 17	232. 30	553. 00	134. 00	-18. 60	-1. 028
8-23-82	7: 22	235. 31	515. 00	96. 50	-37. 60	-0. 522
8-24-82	18: 37	236. 78	398. 00	-20. 40	-117. 00	-3. 316
8-25-82	7: 45	237. 32	417. 00	-2. 15	18. 30	1. 392
8-26-82	7: 26	238. 31	381. 00	-38. 10	-36. 00	-1. 519
8-26-82	12: 47	238. 53	444. 00	25. 50	63. 60	11. 893
8-26-82	17: 18	238. 72	541. 00	122. 00	96. 60	21. 393
8-27-82	7: 40	239. 32	504. 00	85. 60	-36. 50	-2. 544
8-30-82	18: 51	242. 79	452. 00	33. 30	-52. 30	-0. 629

E1 = ENERGY RELATIVE TO 67 F, MWH(T)
E2 = ENERGY RELATIVE TO 425 F, MWH(T)
E3 = CHANGE IN ENERGY SINCE LAST DATA POINT, MWH(T)
P1 = AVERAGE POWER SINCE LAST DATA POINT, MW(T)

DATE	TIME	DAY	E1	E2	E3	P1
8-30-82	23:22	242.97	406.00	-13.10	-46.40	-10.267
9- 1-82	0:15	244.01	385.00	-33.50	-20.40	-0.819
9- 1-82	14:11	244.59	482.00	63.40	96.80	6.951
9- 2-82	7:51	245.33	380.00	-39.10	-102.00	-5.801
9- 2-82	12:23	245.52	386.00	-32.90	6.17	1.362
9- 2-82	12:59	245.54	407.00	-11.40	21.50	35.871
9- 2-82	13:27	245.56	425.00	6.23	17.70	37.827
9- 2-82	14: 9	245.59	453.00	34.40	28.10	40.208
9- 2-82	15:42	245.65	502.00	82.90	48.60	31.327
9- 2-82	17: 6	245.71	526.00	107.00	23.90	17.077
9- 2-82	19:25	245.81	491.00	71.80	-35.10	-15.137
9- 2-82	20:43	245.86	478.00	58.80	-13.00	-9.998
9- 2-82	22: 1	245.92	467.00	48.70	-10.10	-7.747
9- 3-82	7:35	246.32	459.00	40.00	-8.74	-0.914
9- 3-82	14:14	246.59	485.00	66.20	26.20	3.944
9- 3-82	17:36	246.73	542.00	123.00	56.60	16.822
9- 7-82	7:29	250.31	513.00	94.30	-28.50	-0.332
9- 8-82	16:39	251.69	509.00	90.60	-3.71	-0.112
9- 8-82	22:21	251.93	501.00	82.10	-8.51	-1.493
9- 9-82	10:49	252.45	498.00	78.80	-3.23	-0.259
9-10-82	12:23	253.52	514.00	95.20	16.40	0.641
9-10-82	17:22	253.72	581.00	162.00	67.00	13.450
9-13-82	9:21	256.39	533.00	114.00	-48.00	-0.750
9-13-82	14:49	256.62	562.00	143.00	28.60	5.238
9-13-82	16:42	256.70	575.00	156.00	13.30	7.049
9-14-82	8: 0	257.33	530.00	111.00	-44.90	-2.938
9-14-82	12:12	257.51	555.00	136.00	24.90	5.927
9-14-82	13:41	257.57	581.00	163.00	26.60	17.907
9-14-82	14:35	257.61	592.00	174.00	11.00	12.237
9-14-82	17:21	257.72	614.00	196.00	21.80	7.891
9-15-82	0:33	258.02	549.00	130.00	-65.30	-9.069
9-16-82	11: 7	259.46	462.00	43.00	-87.30	-2.524
9-16-82	15:52	259.66	461.00	42.20	-0.82	-0.173
9-17-82	7:36	260.32	460.00	41.50	-0.67	-0.043
9-20-82	8:59	263.37	454.00	35.70	-5.87	-0.080
9-20-82	17:44	263.74	576.00	158.00	122.00	13.953
9-20-82	21:22	263.89	546.00	127.00	-30.90	-8.493
9-21-82	8:44	264.36	528.00	109.00	-18.10	-1.594
9-21-82	10:51	264.45	558.00	140.00	30.70	14.523
9-21-82	11:48	264.49	594.00	176.00	36.20	38.117

E1 = ENERGY RELATIVE TO 67 F, MWH(T)
E2 = ENERGY RELATIVE TO 425 F, MWH(T)
E3 = CHANGE IN ENERGY SINCE LAST DATA POINT, MWH(T)
P1 = AVERAGE POWER SINCE LAST DATA POINT, MW(T)

DATE	TIME	DAY	E1	E2	E3	P1
9-21-82	13: 8	264.55	623.00	204.00	28.50	21.345
9-21-82	13:57	264.58	635.00	216.00	11.90	14.583
9-21-82	14:57	264.62	641.00	223.00	6.55	6.545
9-21-82	17:34	264.73	643.00	224.00	1.65	0 629
9-21-82	19:28	264.81	634.00	216.00	-8.67	-4.562
9-21-82	22:32	264.94	616.00	198.00	-17.90	-5.838
9-22-82	14:38	265.61	569.00	150.00	-47.80	-2.966
9-22-82	15:42	265.65	551.00	133.00	-17.40	-16.303
9-22-82	17: 1	265.71	532.00	113.00	-19.40	-14.750
9-27-82	1:58	270.08	531.00	112.00	-0.85	-0.008
9-27-82	13:58	270 58	515.00	96.40	-15.90	-1.326
9-27-82	18:21	270.76	515.00	96.00	-0.41	-0.094
9-28-82	7:37	271.32	514.00	95.10	-0.84	-0.063
9-28-82	11:45	271.49	542.00	124.00	28.40	6.878
9-28-82	14:53	271.62	604.00	185.00	61.50	19.613
9-28-82	16:54	271.70	597.00	178.00	-6.63	-3.288
9-28-82	19:19	271.80	575.00	157.00	-21.90	-9.043
9-28-82	20:19	271.85	559.00	140.00	-16.30	-16.337
9-28-82	23: 9	271.96	526.00	107.00	-33.20	-11.700
9-29-82	7: 1	272.29	446.00	27.30	-79.80	-10.141
9-29-82	7:54	272.33	437.00	18.20	-9.10	-10.306
9-29-82	10: 2	272.42	417.00	-2.04	-20.20	-9.471
9-30-82	0:56	273.04	415.00	-3.23	-1.20	-0.080
9-30-82	7: 0	273.29	404.00	-14.50	-11.30	-1.861
9-30-82	9:13	273.38	400.00	-18.80	-4.25	-1.918
9-30-82	15: 0	273.63	416.00	-2.37	16.40	2.836
9-30-82	17:44	273.74	423.00	4.13	6.50	2.379

E1 = ENERGY RELATIVE TO 67 F, MWH(T)
E2 = ENERGY RELATIVE TO 425 F, MWH(T)
E3 = CHANGE IN ENERGY SINCE LAST DATA POINT, MWH(T)
P1 = AVERAGE POWER SINCE LAST DATA POINT, MW(T)

Available Energy History Tabulations

DATE	TIME	DAY	E1	E2
5- 6-82	15:28	126.64	0.00	0.00
5-10-82	18:34	130.77	0.00	0.00
5-11-82	7: 7	131.30	0.00	0.00
5-11-82	17:25	131.73	0.00	0.00
5-12-82	8:11	132.34	0.00	0.00
5-12-82	22:26	132.93	0.00	0.00
5-13-82	7:20	133.31	0.00	0.00
5-13-82	16:14	133.68	0.00	0.00
5-14-82	22:18	134.93	0.00	0.00
5-17-82	9: 8	137.38	0.00	0.00
5-17-82	21: 2	137.88	0.00	0.00
5-18-82	8: 8	138.34	0.00	0.00
5-18-82	17:13	138.72	0.00	0.00
5-19-82	7:39	139.32	0.00	0.00
5-19-82	20:23	139.85	0.00	0.00
5-20-82	7:21	140.31	0.00	0.00
5-20-82	16:24	140.68	0.00	0.00
5-21-82	7:18	141.30	0.00	0.00
5-21-82	15:48	141.66	0.00	0.00
5-24-82	9:25	144.39	0.00	0.00
5-24-82	16:24	144.68	0.00	0.00
5-25-82	8:23	145.35	0.00	0.00
5-25-82	16: 2	145.67	0.00	0.00
5-26-82	7:32	146.31	0.00	0.00
5-26-82	22:39	146.94	0.00	0.00
5-27-82	7:40	147.32	0.00	0.00
5-27-82	22:23	147.93	0.00	0.00
5-28-82	10:57	148.46	0.00	0.00
5-28-82	21:59	148.92	0.00	0.00
6- 1-82	8:59	152.37	0.00	0.00
6- 1-82	16:18	152.68	0.00	0.00
6- 2-82	7:49	153.33	0.00	0.00
6- 2-82	19:30	153.81	0.00	0.00
6- 3-82	7:22	154.31	0.00	0.00
6- 3-82	21:53	154.91	0.00	0.00
6- 4-82	7:46	155.32	0.00	0.00
6- 4-82	15:38	155.65	0.00	0.00
6- 7-82	9: 0	158.38	0.00	0.00
6- 8-82	7:28	159.31	0.00	0.00
6- 8-82	14: 3	159.59	0.00	0.00

E1 = USEFUL ENERGY ABOVE 425 F, MWH(T)
E2 = USEFUL ENERGY FOR ELECTRICITY PRODUCTION, MWH(T)

DATE	TIME	DAY	E1	E2
6- 8-82	20:46	159.87	0.00	0.00
6- 9-82	7:34	160.32	0.00	0.00
6- 9-82	13:46	160.57	0.00	0.00
6-10-82	9:18	161.39	0.00	0.00
6-10-82	17:37	161.73	0.00	0.00
6-11-82	9: 1	162.38	0.00	0.00
6-11-82	11:21	162.47	0.00	0.00
6-14-82	13:54	165.58	0.00	0.00
6-15-82	7:39	166.32	0.00	0.00
6-16-82	7:23	167.31	0.00	0.00
6-18-82	8: 8	169.34	0.00	0.00
6-18-82	15:35	169.65	0.00	0.00
6-21-82	8:32	172.36	0.00	0.00
6-21-82	14:32	172.61	0.00	0.00
6-22-82	7:23	173.31	0.00	0.00
6-22-82	17:45	173.74	0.00	0.00
6-23-82	7:22	174.31	0.00	0.00
6-23-82	14:41	174.61	0.00	0.00
6-24-82	7:13	175.30	0.00	0.00
6-25-82	7:20	176.31	0.00	0.00
6-28-82	7:49	179.33	0.00	0.00
6-29-82	7:53	180.33	0.00	0.00
6-30-82	7:18	181.30	0.00	0.00
6-30-82	12:51	181.54	0.00	0.00
7- 1-82	6:54	182.29	0.00	0.00
7- 1-82	17:57	182.75	0.00	0.00
7- 2-82	7:16	183.30	0.00	0.00
7- 2-82	12:19	183.51	0.00	0.00
7- 6-82	13:34	187.57	0.00	0.00
7- 7-82	7: 4	188.29	0.00	0.00
7- 7-82	13:56	188.58	0.00	0.00
7- 9-82	6:37	190.28	0.00	0.00
7- 9-82	18:23	190.77	17.60	0.00
7-12-82	7:17	193.30	6.81	0.00
7-12-82	18:38	193.78	12.00	0.00
7-13-82	7: 8	194.30	8.68	0.00
7-13-82	18:59	194.79	36.60	0.00
7-14-82	8: 8	195.34	30.70	0.00
7-14-82	15:38	195.65	59.30	0.00
7-15-82	8:32	196.36	46.30	0.00

E1 = USEFUL ENERGY ABOVE 425 F, MWH(T)
E2 = USEFUL ENERGY FOR ELECTRICITY PRODUCTION, MWH(T)

DATE	TIME	DAY	E1	E2
7-15-82	18:46	196.78	71.80	0.00
7-16-82	8:30	197.35	64.30	0.00
7-16-82	14: 4	197.59	70.90	0.00
7-19-82	7:10	200.30	60.50	0.00
7-20-82	7:59	201.33	58.30	0.00
7-20-82	18:45	201.78	65.90	0.00
7-21-82	7:35	202.32	61.10	0.00
7-21-82	14:55	202.62	77.20	0.00
7-21-82	18:17	202.76	93.50	0.00
7-27-82	16:14	208.68	63.60	0.00
7-28-82	9:36	209.40	62.20	0.00
7-28-82	17: 9	209.71	80.80	0.00
7-29-82	17:44	210.74	73.70	0.00
7-30-82	7:41	211.32	72.30	0.00
7-30-82	16:38	211.69	93.30	0.00
8- 2-82	7:20	214.31	79.60	0.00
8- 2-82	17:48	214.74	108.00	26.20
8- 3-82	17:32	215.73	129.00	62.20
8- 5-82	7:33	217.31	115.00	40.30
8- 6-82	7:46	218.32	112.00	39.40
8- 6-82	11:19	218.47	102.00	29.50
8- 9-82	8:22	221.35	99.90	27.80
8- 9-82	17:59	221.75	161.00	84.40
8-10-82	9:17	222.39	143.00	52.10
8-13-82	7:43	225.32	133.00	49.10
8-16-82	8: 2	228.33	126.00	37.60
8-16-82	16:58	228.71	148.00	67.10
8-18-82	7:26	230.31	129.00	37.30
8-19-82	7:15	231.30	130.00	0.00
8-19-82	13:14	231.55	153.00	11.60
8-20-82	7:17	232.30	136.00	0.00
8-23-82	7:22	235.31	115.00	0.00
8-24-82	18:37	236.78	30.40	0.00
8-25-82	7:45	237.32	42.50	0.00
8-26-82	7:26	238.31	25.00	0.00
8-26-82	12:47	238.53	60.70	0.00
8-26-82	17:18	238.72	122.00	0.00
8-27-82	7:40	239.32	95.90	0.00
8-30-82	18:51	242.79	64.00	0.00
8-30-82	23:22	242.97	37.40	0.00

E1 = USEFUL ENERGY ABOVE 425 F, MWH(T)
E2 = USEFUL ENERGY FOR ELECTRICITY PRODUCTION, MWH(T)

DATE	TIME	DAY	E1	E2
9- 1-82	0:15	244.01	24.80	0.00
9- 1-82	14:11	244.59	85.10	40.00
9- 2-82	7:51	245.33	19.10	0.00
9- 2-82	12:23	245.52	23.20	0.00
9- 2-82	12:59	245.54	38.50	16.20
9- 2-82	13:27	245.56	50.70	28.00
9- 2-82	14: 9	245.59	69.60	45.20
9- 2-82	15:42	245.65	102.00	77.30
9- 2-82	17: 6	245.71	117.00	87.40
9- 2-82	19:25	245.81	92.80	66.20
9- 2-82	20:43	245.86	84.60	65.10
9- 2-82	22: 1	245.92	78.30	54.90
9- 3-82	7:35	246.32	74.70	54.10
9- 3-82	14:14	246.59	93.40	75.20
9- 3-82	17:36	246.73	132.00	106.00
9- 7-82	7:29	250.31	112.00	81.60
9- 8-82	16:39	251.69	110.00	80.30
9- 8-82	22:21	251.93	105.00	79.80
9- 9-82	10:49	252.45	104.00	78.90
9-10-82	12:23	253.52	110.00	28.90
9-10-82	17:22	253.72	162.00	92.30
9-13-82	9:21	256.39	135.00	77.50
9-13-82	14:49	256.62	146.00	64.90
9-13-82	16:42	256.70	156.00	72.40
9-14-82	8: 0	257.33	121.00	0.00
9-14-82	12:12	257.51	141.00	25.70
9-14-82	13:41	257.57	164.00	72.90
9-14-82	14:35	257.61	174.00	75.80
9-14-82	17:21	257.72	196.00	153.00
9-15-82	0:33	258.02	134.00	40.10
9-16-82	11: 7	259.46	55.90	0.00
9-16-82	15:52	259.66	56.40	0.00
9-17-82	7:36	260.32	55.70	0.00
9-20-82	8:59	263.37	52.00	0.00
9-20-82	17:44	263.74	158.00	112.00
9-20-82	21:22	263.89	131.00	87.70
9-21-82	8:44	264.36	123.00	76.00
9-21-82	10:51	264.45	144.00	99.50
9-21-82	11:48	264.49	176.00	135.00
9-21-82	13: 8	264.55	204.00	177.00

E1 = USEFUL ENERGY ABOVE 425 F, MWH(T)
E2 = USEFUL ENERGY FOR ELECTRICITY PRODUCTION, MWH(T)

DATE	TIME	DAY	E1	E2
9-21-82	13:57	264.58	216.00	208.00
9-21-82	14:57	264.62	223.00	223.00
9-21-82	17:34	264.73	224.00	224.00
9-21-82	19:28	264.81	216.00	211.00
9-21-82	22:32	264.94	200.00	193.00
9-22-82	14:38	265.61	164.00	159.00
9-22-82	15:42	265.65	150.00	137.00
9-22-82	17: 1	265.71	131.00	123.00
9-27-82	1:58	270.08	129.00	118.00
9-27-82	13:58	270.58	118.00	106.00
9-27-82	18:21	270.76	118.00	106.00
9-28-82	7:37	271.32	117.00	96.10
9-28-82	11:45	271.49	137.00	127.00
9-28-82	14:53	271.62	186.00	172.00
9-28-82	16:54	271.70	180.00	170.00
9-28-82	19:19	271.80	162.00	152.00
9-28-82	20:19	271.85	149.00	130.00
9-28-82	23: 9	271.96	117.00	95.00
9-29-82	7: 1	272.29	42.50	20.00
9-29-82	7:54	272.33	34.20	10.50
9-29-82	10: 2	272.42	15.10	0.00
9-30-82	0:56	273.04	14.70	0.00
9-30-82	7: 0	273.29	8.41	0.00
9-30-82	9:13	273.38	6.18	0.00
9-30-82	15: 0	273.63	16.90	6.98
9-30-82	17:44	273.74	22.30	11.40
10- 1-82	8:55	274.37	20.70	10.90
10- 1-82	12:49	274.53	69.10	56.60
10- 1-82	13:50	274.58	76.20	66.40
10- 5-82	10:16	278.43	0.10	0.00
10- 6-82	6:36	279.27	0.00	0.00
10- 6-82	9:17	279.39	0.00	0.00
10- 6-82	13:20	279.56	22.50	15.90
10- 6-82	16:14	279.68	87.10	78.80
10- 6-82	17:11	279.72	94.70	79.80
10- 7-82	7:44	280.32	80.40	67.10
10- 7-82	10:13	280.43	75.60	66.10
10- 7-82	13: 6	280.55	87.30	60.40
10- 7-82	14: 7	280.59	88.80	27.90
10- 7-82	17:16	280.72	102.00	11.20

E1 = USEFUL ENERGY ABOVE 425 F, MWH(T)
E2 = USEFUL ENERGY FOR ELECTRICITY PRODUCTION, MWH(T)

FRACTIONAL MASS WEIGHTED TIME FOR THE PERIOD
5- 5-82, 17:35 TO 10- 7-82, 7:44

	FRACTION	TEMPERATURE RANGE C		TEMPERATURE RANGE F	
1	0.0085	20.0 -	30.0	68.0 -	86.0
2	0.0147	30.0 -	40.0	86.0 -	104.0
3	0.0062	40.0 -	50.0	104.0 -	122.0
4	0.0038	50.0 -	60.0	122.0 -	140.0
5	0.0040	60.0 -	70.0	140.0 -	158.0
6	0.0049	70.0 -	80.0	158.0 -	176.0
7	0.0051	80.0 -	90.0	176.0 -	194.0
8	0.0038	90.0 -	100.0	194.0 -	212.0
9	0.0061	100.0 -	110.0	212.0 -	230.0
10	0.0056	110.0 -	120.0	230.0 -	248.0
11	0.0137	120.0 -	130.0	248.0 -	266.0
12	0.0354	130.0 -	140.0	266.0 -	284.0
13	0.0935	140.0 -	150.0	284.0 -	302.0
14	0.0207	150.0 -	160.0	302.0 -	320.0
15	0.0382	160.0 -	170.0	320.0 -	338.0
16	0.1042	170.0 -	180.0	338.0 -	356.0
17	0.0718	180.0 -	190.0	356.0 -	374.0
18	0.0499	190.0 -	200.0	374.0 -	392.0
19	0.0517	200.0 -	210.0	392.0 -	410.0
20	0.0266	210.0 -	220.0	410.0 -	428.0
21	0.0343	220.0 -	230.0	428.0 -	446.0
22	0.0259	230.0 -	240.0	446.0 -	464.0
23	0.0669	240.0 -	250.0	464.0 -	482.0
24	0.0807	250.0 -	260.0	482.0 -	500.0
25	0.0408	260.0 -	270.0	500.0 -	518.0
26	0.0309	270.0 -	280.0	518.0 -	536.0
27	0.0636	280.0 -	290.0	536.0 -	554.0
28	0.0570	290.0 -	300.0	554.0 -	572.0
29	0.0315	300.0 -	310.0	572.0 -	590.0
30	0.0000	310.0 -	320.0	590.0 -	608.0

BMAX= 9.01297E+03 XMASS= 2.14978E+05 BTOT= 8.65122E+04

TOTAL TIME INTERVAL= 154.59 DAYS = 3710.2 HRS.

AVERAGE TIME IN EACH TEMPERATURE RANGE= 9.66 HRS.

AVERAGE MASS OF OIL IN THE TSU= 559625. KG.

----- PREDICTIONS BASED ON SNLL STUDIES -------

LOST MASS OF CALORIA OVER PERIOD IS 7731.17 KG.

PERCENT MASS LOST= 1.38 PERCENT

PROJECTED YEARLY MASS LOSS= 18254. KG.

PROJECTED YEARLY MASS LOSS RATE= 3.26 PERCENT/YEAR

----- PREDICTIONS BASED ON MDAC/ROCKETDYNE STUDIES -------

LOST MASS OF CALORIA OVER PERIOD IS 2740.37 KG.

PERCENT MASS LOST= 0.49 PERCENT

PROJECTED YEARLY MASS LOSS= 6470. KG.

PROJECTED YEARLY MASS LOSS RATE= 1.16 PERCENT/YEAR

REFERENCES

1. L. G. Radosevich, "10 MWe Central Receiver Solar Thermal Pilot Plant Data Evaluation Plan," Sandia National Laboratories, Livermore, SAND82-8027, December 1982.

2. J. S. Anderson and J. W. Smith, "10 MWe Central Receiver Solar Thermal Pilot Plant Test Operations Plan," Sandia National Laboratories, Livermore, to be published (March 1983).

3. MDAC 1040 Test Report

4. "Pilot Plant Station Manual (RADL Item 2-1), Volume I, System Description," SAN/0499-57, MDCG8544, December 1980.

5. G. R. Morgan, "Thermal Storage Subsystem Analysis Report (RADL Item 5-1)," Dept. of Energy Report SAN/0499-28, February 1980.

6. V. P. Burolla, "Prediction of Yearly Fluid Replenishment Rates for Hydrocarbon Fluids in Thermal Energy Storage Systems," Sandia National Laboratories, Livermore, SAND79-8209, April 1979.

7. G. R. Schneider and G. R. Morgan, "Thermal Stability Tests of Heat Transfer Fluids for Transfer and Storage of Thermal Energy," McDonnell Douglas Corporation Report MDC 69331, December 1980.

8. S. E. Faas, "Thermal Storage Unit Transient Cooldown Test Results," inhouse memo, Sandia National Laboratories.

9. Private Communication to S. E. Faas from G. R. Morgan, January 1983.

UNLIMITED RELEASE

INITIAL DISTRIBUTION

U. S. Department of Energy
Forrestal Building
1000 Independence Avenue, S.W.
Washington, D.C. 20585
Attn: F. Morse
K. T. Cherian
C. B. McFarland
M. Scheve

U.S. Department of Energy
P.O. Box 5400
Albuquerque, NM 87115
Attn: J. E. Weisiger
G. Pappas

U.S. Department of Energy
Solar One Field Office
P.O. Box 366
Daggett, CA 92327
Attn: S. D. Elliott

U. S. Department of Energy
1333 Broadway
Oakland, CA 94612
Attn: R. W. Hughey

University of Houston
Solar Energy Laboratory
4800 Calhoun
Houston, TX 77704
Attn: A. F. Hildebrandt

AMFAC
P.O. Box 3230
Honolulu, HI 96801
Attn: G. E. St. John

ARCO Power Systems
7061 S. University, Suite 300
Littleton, CO 80122
Attn: F. A. Blake

ARCO Power Systems
302 Nichols Drive
Hutchins, TX 75141
Attn: R. L. Henry

Arizona Public Service Company
P.O. Box 21666
Phoenix, AZ 85036
Attn: M. Brown
E. Weber

Babcock and Wilcox
91 Stirling Avenue
Barberton, OH 44203
Attn: G. Grant
I. Hicks

Bechtel Group, Inc.
P.O. Box 3965
San Francisco, CA 94119
Attn: E. Y. Lam

Black and Veatch Consulting Engineers
P.O. Box 8405
Kansas City, MO 64114
Attn: J. C. Grosskreutz
S. L. Levy

Boeing Engineering and Construction Company
P.O. Box 3707
Seattle, WA 98124
Attn: J. R. Gintz
R. B. Gillette

Combustion Engineering, Inc.
1000 Prospect Hill Road
Winsor, CT 06095
Attn: C. R. Buzzuto

El Paso Electric Company
P.O. Box 982
El Paso, TX 79946
Attn: J. E. Brown

Electric Power Research Institute
P.O. Box 10412
Palo Alto, CA 94303
Attn: J. Bigger
E. DeMeo

Exxon Enterprises, Inc.
P.O. Box 592
Florham Park, NJ 07932
Attn: T. L. Guckes

Foster Wheeler Development Co.
12 Peach Tree Hill Road
Livingston, N.J. 07039
Attn: R. J. Zoschak

Georgia Institute of Technology
Atlanta, GA 30332
Attn: C. T. Brown

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91103
Attn: V. T. Truscello

Los Angeles Department of Water and Power
P.O. Box 111
Los Angeles, CA 90051
Attn: J. A. Klueger

Martin Marietta Aerospace
P.O. Box 179, MS L0450
Denver, CO 80201
Attn: L. Oldham
H. C. Wroton

McDonnell Douglas Astronautics Company
5301 Bolsa Avenue
Huntington Beach, CA 92647
Attn: R. L. Gervais
H. H. Dixon

Olin Chemical Company
Metals Research Laboratory
91 Shelton Avenue
New Haven, CT 06511
Attn: E. F. Smith
N. Christopher

Pacific Gas and Electric Company
77 Beale Street
San Francisco, CA 94105
Attn: R. E. Price

Pacific Gas and Electric Company
3400 Crow Canyon Road
San Ramon, CA 94526
Attn: H. E. Seielstad

Pioneer Mill Company (AMFAC)
P.O. Box 727
Lahaina, HI 96761
Attn: R. K. MacMillan

Rockwell International
Energy Systems Group
8900 De Soto Avenue
Canoga Park, CA 91304
Attn: T. Springer

Rockwell International
Rocketdyne Division
6633 Canoga Park, CA 91304
Attn: R. G. Surette

Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401
Attn: B. Gupta
R. Hulstram

Southern California Edison
P.O. Box 325
Daggett, CA 92327
Attn: P. Skvarna

Southern California Edison
P.O. Box 800
Rosemead, CA 92807
Attn: J. N. Reeves (25)

Stearns-Roger
P.O. Box 5888
Denver, CO 80217
Attn: W. R. Lang

Stone and Webster Engineering Corporation
P.O. Box 1214
Boston, MA 02107
Attn: R. W. Kuhr

Westinghouse Electric Corporation
Advanced Energy Systems Division
P.O. Box 10864
Pittsburgh, PA 15236
Attn: J. R. Maxwell

R. S. Claassen, 8000; Attn: D. M. Olson, 8100
A. N. Blackwell, 8200
B. F. Murphey, 8300
C. S. Selvage, 8000A
R. J. Gallagher, 8124
M. J. Fish, 8125
L. Gutierrez, 8400; Attn: R. A. Baroody, 8410
H. Hanser, 8440
J. F. Barham, 8460
J. B. Wright, 8450
J. J. Bartel, 8452 (2)
S. E. Faas, 8452 (9)
A. C. Skinrood, 8452 (10)
W. G. Wilson, 8453
J. B. Woodard, 8454
D. G. Schueler, 9720
J. V. Otts, 9722
Publications Division 8265, for TIC (27)
Publications Division 8265/Technical Library Processes Division, 3141
Technical Library Processes Division, 3141 (3)
M. A. Pound, 8214, for Central Technical Files (3)

Org.	Bldg.	Name	Rec'd by	Org.	Bldg.	Name	Rec'd by

Sandia National Laboratories