

# CONTRACTOR REPORT

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## **10 MWe Solar Thermal Central Receiver Pilot Plant Mode 5 (Test 1150) and Mode 6 (Test 1160) Test Report**

**McDonnell Douglas Astronautics Company**

Prepared by Sandia National Laboratories, Albuquerque, New Mexico 87185  
and Livermore, California 94550 for the United States Department of Energy  
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10 MWe SOLAR THERMAL  
CENTRAL RECEIVER PILOT PLANT  
MODE 5 (TEST 1150) AND MODE 6 (TEST 1160)  
TEST REPORT

Contract Report Prepared  
Under SNLL Contract 84-8173

McDonnell Douglas Astronautics Company

ABSTRACT

The purpose of this report is to document the test results and conclusions pertinent to operating Mode 5 (charging only) and Mode 6 (extraction) of the Thermal Storage Subsystem of Solar One. Mode 5 was demonstrated successfully, particularly during periods of cloud passages over the sun. Dual charging train testing, while successful, revealed that dual train operation was not often necessary or desirable. Mode 6 testing was demonstrated for both single and dual train operation; stable single train operation was demonstrated at 0.7 MWe (gross). The extractable energy capacity of the Thermal Storage Unit was demonstrated to exceed the design requirements during Mode 6 testing.





## SOLAR THERMAL TECHNOLOGY FOREWORD

The research and development described in this document was conducted within the U.S. Department of Energy's (DOE) Solar Thermal Technology Program. The goal of the Solar Thermal Technology Program is to advance the engineering and scientific understanding of solar thermal technology, and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates solar radiation by means of tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver. Parabolic dishes up to 17 meters in diameter track the sun in two axes and use mirrors or Fresnel lenses to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multi-module system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100°C in low-temperature troughs to over 1500°C in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve promising system concepts through the research and development of solar thermal materials, components, and subsystems, and the testing and performance evaluation of subsystems and systems. These efforts are carried out through the technical direction of DOE and its network of national laboratories who work with private industry. Together they have established a comprehensive, goal directed program to improve performance and provide technically proven options for eventual incorporation into the Nation's energy supply.

To be successful in contributing to an adequate national energy supply at reasonable cost, solar thermal energy must eventually be economically competitive with a variety of other energy sources. Components and system-level performance targets have been developed as quantitative program goals. The performance targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and making optimal component developments. These targets will be pursued vigorously to insure a successful program.

The work presented in this report was performed as part of the Solar One subelement of the Systems Experiments task. The test report for the Thermal Storage Subsystem of Solar One presented herein will serve as an aide in the future designs of thermal storage subsystems.



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## Section 1

### INTRODUCTION

Solar One is the world's largest solar-thermal central receiver power plant. It is designed to produce 10 MWe net power for 4 hours on the design winter day and for 7.8 hours on the design summer day. The plant is also designed to generate 7 MWe net power for up to 4 hours from stored energy. The principal elements of the plant, shown schematically in Figure 1.1, include: (a) the Collector System, which consists of 1818 heliostats surrounding the central tower, (b) a water-steam single-pass external receiver, (c) a Thermal Storage System, which stores heat in a single tank filled with oil and rock (with a thermocline temperature boundary separating the hot and cold regions) (d) a standard steam-Rankine Electrical Power Generation System, and (e) the Plant Support and Control Systems. Detailed information regarding the design and operation of each of these plant systems is included in Reference 1.

Solar One uses water/steam as both the receiver fluid and the turbine working fluid (Figure 1.1). Steam is generated by 1818 individually controlled heliostats reflecting the sun's image on the boiler mounted on top of a 220-foot tower. The superheated steam is piped to the bottom of the tower where the flow path splits to the thermal storage and/or the steam turbine system. Steam flow is controlled so that any portion from 0 to 100 percent can be diverted into either or both systems. The Thermal Storage System (TSS) acts as a buffer to the turbine during periods of rapid changes in insolation and produces steam when required to provide up to 4 hours of electrical power generated at 7 MWe net output or to provide seal steam. With these systems, it is possible to operate the plant in any of eight (8) basic operating modes. The energy flow paths for each of the operating modes are shown in Figure 1.2.

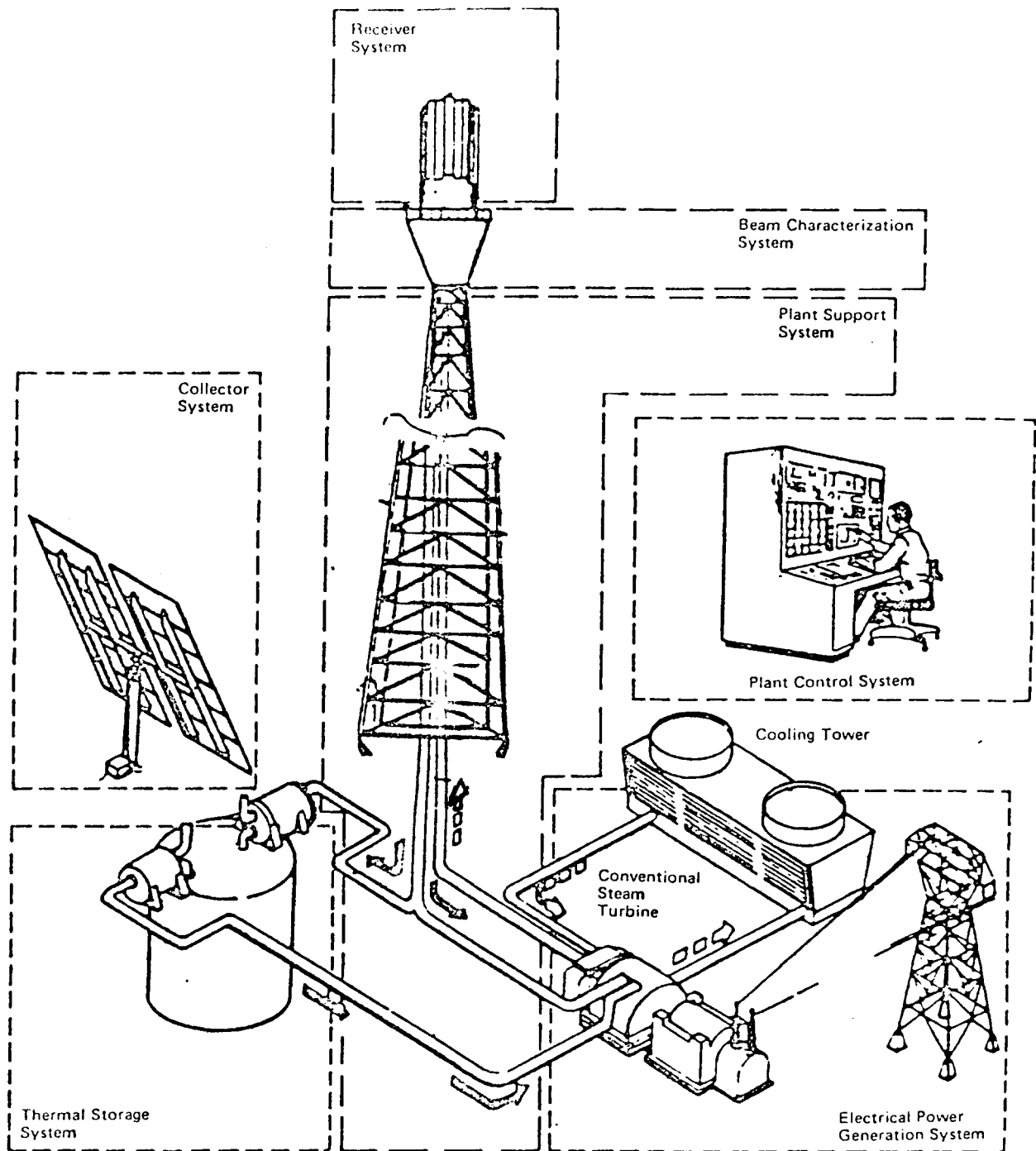


Figure 1.1. Solar One System Schematic

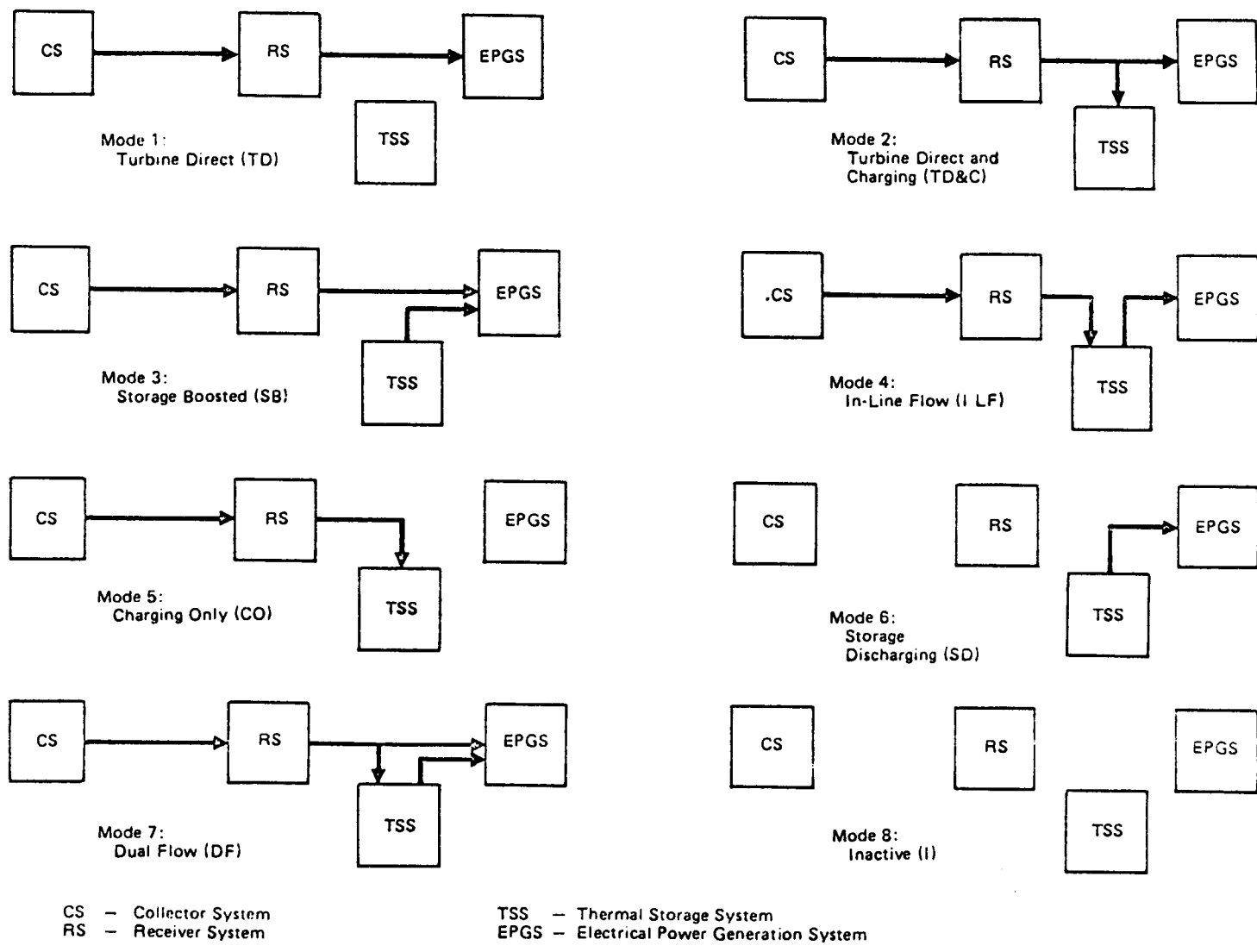


Figure 1.2. Solar One Plant Operating Modes

The principal flow paths, including major components and related process instrumentation, are shown in Figures 1.3 and 1.4. Figure 1.3 shows the feedwater, receiver, steam systems, and the turbine generator equipment. It also shows abbreviated schematics for thermal storage. Figure 1.4 shows the detailed characteristics of the thermal storage system. It includes the charging and extraction equipment as well as the thermal storage unit (tank).

## 1.1 Purpose

Documentation of plant operations and testing in Mode 1 (turbine direct) is included in Reference 2. Documentation of plant operations and testing in Modes 2 (turbine direct and charging), 3 (storage boosted), 4 (in-line flow), and 7 (dual flow), all involving the combined operation of thermal storage and the electrical power generation system, is included in Reference 3. The purpose of this report is to document the test results and conclusions pertinent to Modes 5 (charging only) and 6 (storage discharging). These modes represent single-flow-path modes involving thermal storage alone.

This report is organized to discuss the operating modes on an individual basis. The dedicated mode sections contain the following six subsections.

- o Summary of Mode Operation
- o Test Goals and Objectives
- o Design Summary
- o Test Approach and Critical Instrumentation
- o Test Results
- o Conclusions

Throughout the report are a number of "Solar Data Plots." These figures were computer generated using a standard format. In certain instances data called out in the legend is either not applicable or was not available and is noted with an "N/A" in the legend.



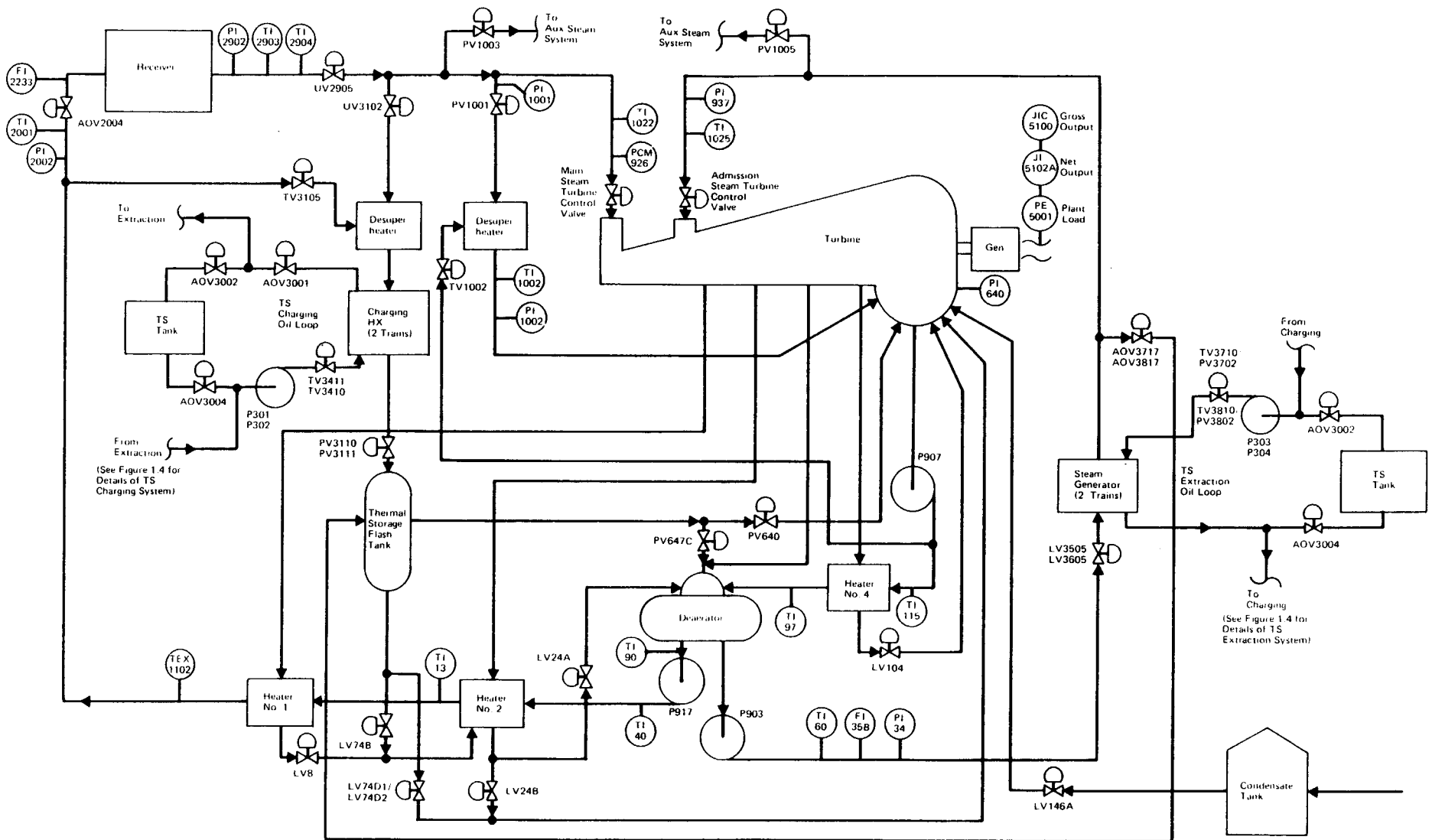


Figure 1.3. Major Flow Paths Active During Modes 5 and 6



## 1.2 System Description and Operation

The Thermal Storage System consists of 4 elements or subsystems. These are shown schematically in Figure 1.5 and consist of: (1) charging circuit, (2) steam generation or energy extraction circuit, (3) thermal storage unit (TSU), and (4) ullage maintenance unit (UMU). Figure 1.6 is a photo of the principal equipment. The charging and extraction process trains consist of twin units in parallel, each capable of processing up to 50 percent of the heat and fluid flow. This facilitates the required wide throttling range (20:1), improves reliability, and facilitates maintenance (1 train can be on-line while the other is being serviced). All heat exchanger units except the kettle boilers are shell and tube heat exchangers with the low pressure oil in the shell and the high pressure steam and water in the tubes. All heat exchangers are U-tube construction to minimize thermal stresses from the daily startup.

Superheated steam from the receiver (solar boiler) enters the desuperheater at 1465 psia and 950°F where it is mixed with a controlled amount of feedwater to limit the steam inlet temperature to the condensing heat exchanger to 650°F. This is the maximum safe temperature for limited exposure to avoid excessive degradation of the oil. The steam and water pressure in the charging heat exchangers is retained close to the high inlet steam pressure, 1365 psia, by a control valve at the flash tank which controls the rate at which water leaves the subcooler.

During charging, oil is removed from the lower manifold at 425°F, circulated through the filter and charging pump, heated through the subcooler and condenser, and re-enters the TSU through the upper manifold. Flowrate is adjusted by a throttling valve and variable speed pump so that oil leaving the condenser is at the design value of 580°F.

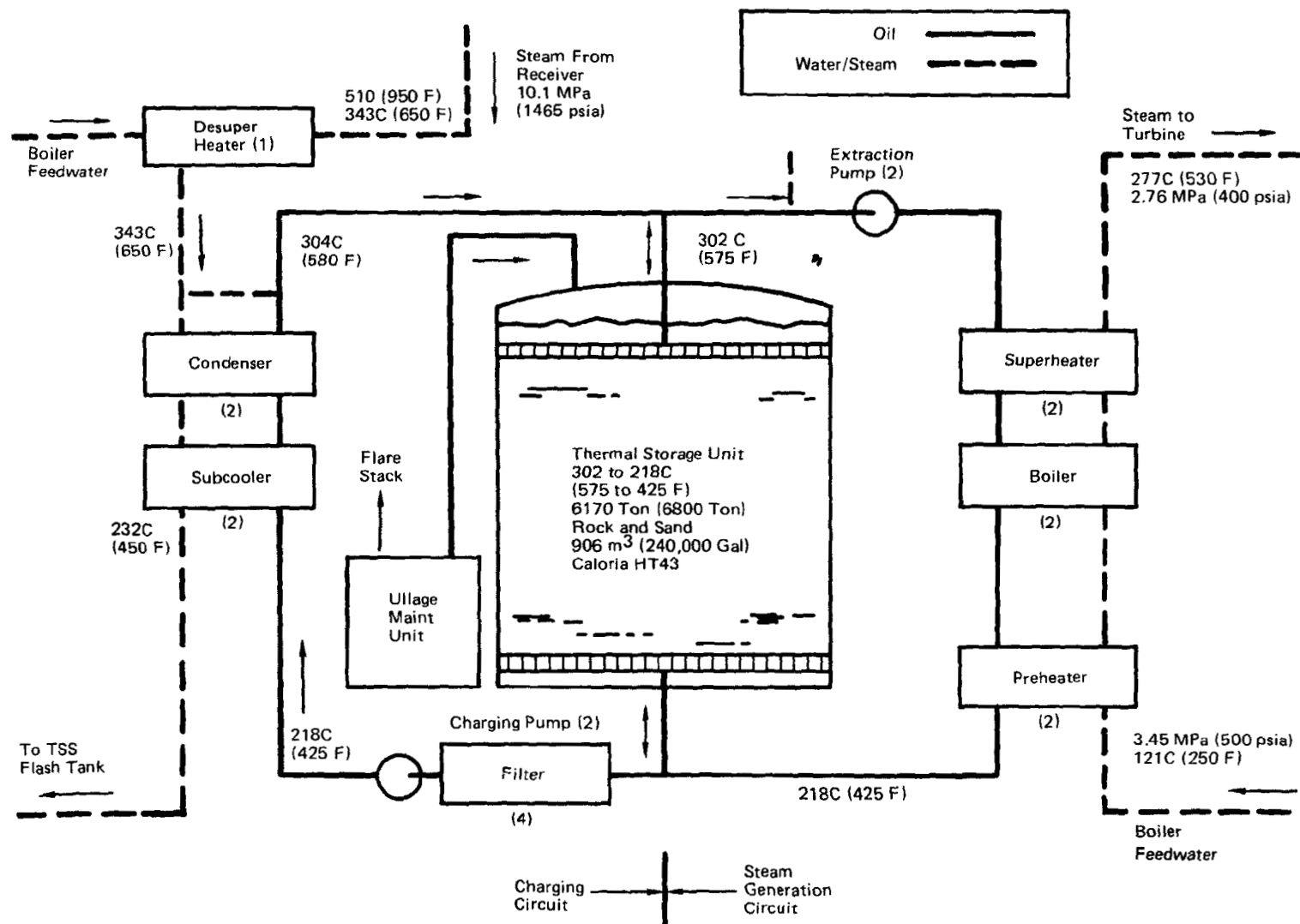


Figure 1.5. Thermal Storage System Schematic

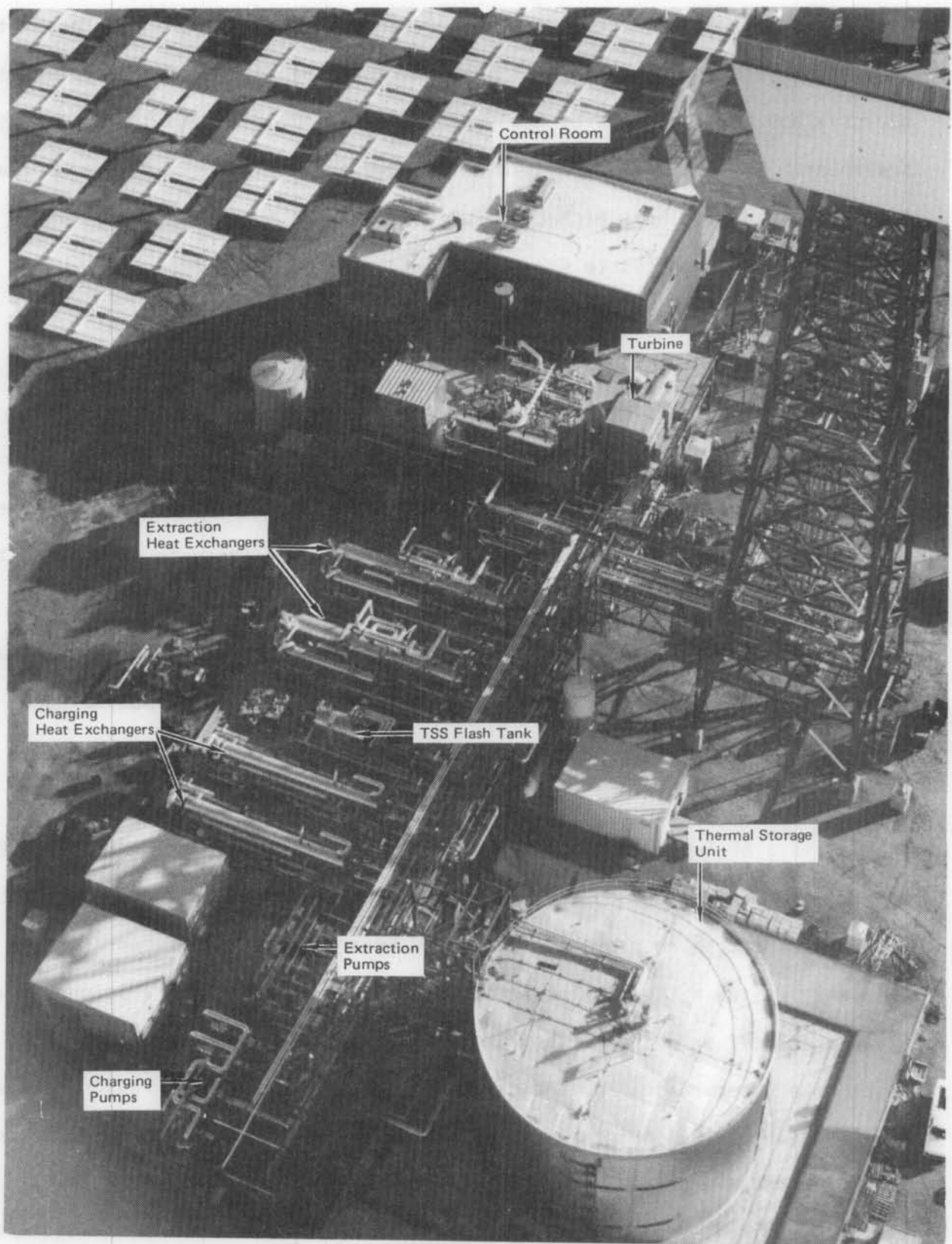


Figure 1-6. Principal Thermal Storage System Equipment

The steam generation circuit, using two parallel trains, is designed in a similar manner to the charging circuit. Oil leaves the TSU at 575°F, circulates through the preheater, boiler, and superheater, and returns to the TSU through the lower manifold at 425°F. Feedwater enters the subcooler at 500 psia and 250°F and leaves the superheater at 400 psia and 530°F with 85°F superheat. The kettle boiler is a U-tube design and is the only one of the five shell and tube heat exchangers with oil on the tube side. The kettle type boiler was selected to simplify control of the extraction network.

The charging and steam generation circuits are interconnected with the TSU in a manner that allows simultaneous charging and extraction or individual operation at independently varying flowrates. Fluid temperatures are held constant during operation so that varying heat input and output is satisfied by varying flowrate. Because fluid flowrates were designed to vary by 20 to 1, variable speed motors are used to drive the oil circulation pumps (thus conserving energy and easing the valve throttling requirements). The variable speed pumps, along with the dual train system, reduce the maximum turndown ratio required in a single train to a more manageable 10 to 1 operation.

The TSU is a 60-foot diameter, 45-foot high welded steel tank containing 6800 US tons of rock and 240,000 gal of Caloria HT43 (Figure 1.7). The cold and hot regions of the rock bed are separated by a fairly sharp temperature gradient, called a thermocline, that moves up and down the tank as energy is being extracted or added to the TSU. The hot side of the thermocline is toward the upper region and the cold side is toward the lower region of the tank. Oil enters either the top or the bottom of the rock bed, depending on the operational mode, and is distributed evenly across the bed by the two internal manifolds. The position of the thermocline determines the state of

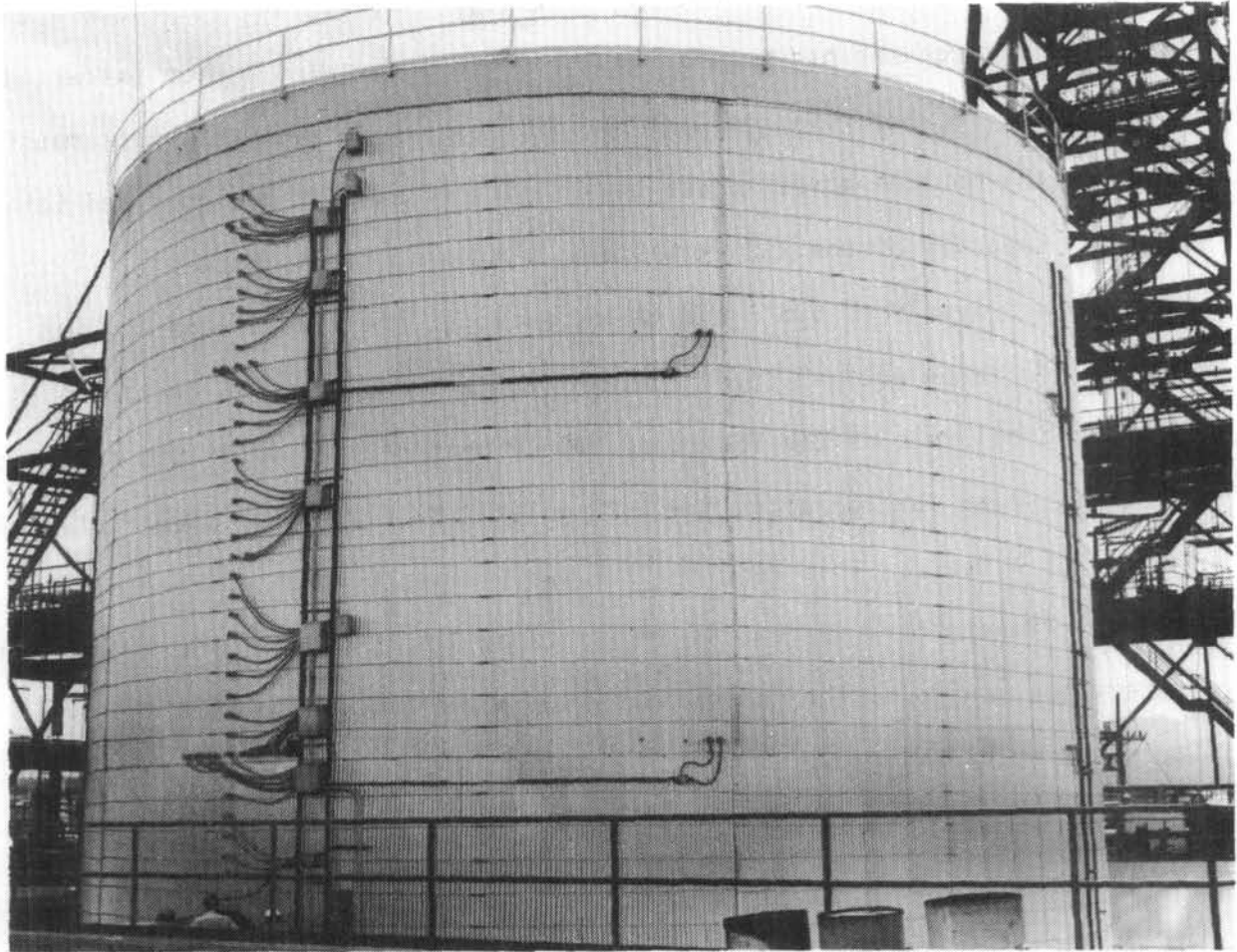


Figure 1-7. Thermal Storage Unit (TSU)

charge of the TSU. When it is at the upper manifold, the TSU is "empty" of energy. When the thermocline is at the bottom manifold, the TSU is "full" of energy.

When charging, cold oil is removed from the bottom manifold, heated, and returned through the upper manifold. During charging, the oil circulates downward through the bed moving the thermocline downward. When extracting energy, the flow is reversed with hot oil leaving through the upper manifold and the thermocline moves in the upward direction. The design rated total thermal capacity of the TSU is  $170 \text{ MWh}_t$  ( $580 \times 10^6 \text{ Btu}$ ), between temperature levels of  $575^\circ\text{F}$  and  $425^\circ\text{F}$ , although the actual capacity was determined to be greater (over  $200 \text{ MWh}$  [ $683 \times 10^6 \text{ Btu}$ ]. See section 3.5). The principal role of the TSU is to supply heat between  $575^\circ\text{F}$  and  $425^\circ\text{F}$  to generate steam for operating the turbine at 7 MW electrical power output for a period of 4 hours. This requires  $135 \text{ MWh}$  ( $461 \times 10^6 \text{ Btu}$ ) of thermal energy. Ninety-five percent is delivered at  $575^\circ\text{F}$ , but, as the thermocline enters the manifold, the temperature is allowed to drop to  $560^\circ\text{F}$  before termination of oil flow.

After discharging energy in the  $425^\circ\text{F}$  to  $575^\circ\text{F}$  range, the TSU still retains a large amount of thermal energy below  $425^\circ\text{F}$ . This energy is available to generate seal steam at approximately 200 psia and  $340^\circ\text{F}$ . Seal steam can be generated by circulating hot oil from the upper manifold or from an intermediate manifold 8 feet above the floor of the tank. The intermediate manifold allows the low energy oil in the bottom to be utilized for seal steam and warmup without degrading the high-temperature oil in the upper portion of the tank.



The TSU is insulated with 12 inches of fiberglass on the sides, 24 inches of calcium silicate board on the top, and is supported by 24 inches of low density insulating concrete (no steel reinforcing) between the tank bottom and structural foundation. This insulating system permits the TSU to hold heat for up to 2 days with only a relatively small loss. The design heat loss is 4 MWh ( $13.6 \times 10^6$  Btu) for a 20 hour period when fully charged or approximately 2-1/2 percent of the design rated available energy, 170 MWh ( $580 \times 10^6$  Btu).

Caloria has about a 9 percent change in density from 425°F to 575°F, requiring the TSU to act as an oil expansion chamber as well as the energy repository. The system must be completely closed and sealed to avoid damaging the Caloria from contact with air. A small positive pressure in the ullage space keeps air out. The value of the pressure is limited by the vent valve to a maximum of 18 inch water column since the tank is not a pressure vessel. The operating pressure variation is controlled by the ullage maintenance unit, which vents and pressurizes the TSU ullage space to retain a small positive pressure of gases during charging and extraction. The nominal maximum is 11 inches of water, thus providing a margin below the safety vent valve setting.

The ullage maintenance unit (UMU) consists of a storage tank to collect condensables discharged from the TSU, a flare stack to burn noncondensables, a pump to pressurize the TSU using liquid from the storage tank which evaporates in the TSU, and suitable controls. A backup gaseous nitrogen system is also provided for safety.

### 1.3 Flow Measurement

By design, Solar One does not have explicit flow measurements for all significant flow paths. As a result, the values of water and steam flows

through many paths which influence plant performance are unknown or at best can only be inferred from other flow measurements. During the design phase of the project, this approach was approved based on cost considerations and the fact that some flows could be reasonably deduced based on measured parameters. Implicit in this approach are the assumptions that existing flow measurements are accurate and that flow paths not intended for operation are tightly shut off and leak free. In fact neither of these two assumptions proved to be valid. This produced substantial uncertainty regarding both measured and derived flow information and resulting in substantial data scatter.

Also, in order to measure flow over a wide range, target and turbine type flowmeters were used extensively in the Solar One design. The target meter employs a strain gage mounted to the target shaft which measures target deflection. These meters were employed for both feedwater and steam measurements.

The target meters repeatedly experienced two types of failures which occurred with greater frequency in steam applications (high temperature) than in water. The first type of failure involved the debonding of the strain gage from the target shaft (which normally resulted in a zero flow reading). The second type of failure involved failure of the shaft pressure seal which separates the process fluid from the electronic package (strain gage assembly). When the seal failed, water and/or steam would migrate into the electronic portion of the meter resulting in its malfunction.

Other problems which were also experienced by the target type flowmeters included strain gage output signal drift with meter temperature, bent target

shafts due to flow surges and failed check valves, and target misalignment which resulted in interference between the target and wall. This latter problem caused the flow signal to appear to "stick" in place. In general, target type meters yielded marginal results as far as providing data for control systems and engineering evaluations. They proved to be high maintenance items with limited lifetimes, especially when used to measure steam flows.

Turbine type flowmeters were used with good success in the thermal storage charging and extraction oil systems. In this service, they were exposed to hot Caloria at charging and extraction oil temperatures of 425°F and 575°F, respectively. Based on their successful use in the thermal storage oil systems, and on advertised capability for measuring steam flow, turbine type flowmeters were installed in the thermal storage charging steam system. Experience showed that the turbine wheels and supporting structure were far too delicate to survive in the highly turbulent steam flow condition or to withstand high velocity water droplets which pass through the lines during the initial heat up period. During warmup, care was exercised to open all available charging steam line drains. However, remaining moisture droplets still seemed to cause impact damage to the turbine wheels and support structure. The net result was that the charging steam turbine flowmeters would only typically survive in a functional state for anywhere from hours to days.

## Section 2

### MODE 5 (CHARGING ONLY)

During Mode 5 (Charging Only) operation, the plant is operated in a "sun following" control strategy under manual control. All of the receiver steam flows to the thermal storage charging heat exchangers to heat the Thermal Storage Unit oil. The total steam flow and resulting charge rate may fluctuate significantly depending on the amount of thermal (solar) power supplied to the plant. Operator control over input power is limited to commanding selected heliostats to "Track" or "Standby".

#### 2.1 Summary of Mode 5 Operation

Mode 5 is used whenever it is desired to charge thermal storage while a plant electrical power output is not required (or when partly cloudy conditions would result in severe receiver transients, thus precluding Mode 2 operation). Since it is not necessary to provide high temperature steam for the charging process, the receiver steam temperature can be controlled to a 660°F outlet condition or higher (as required) to provide additional control margin or steam superheat. As in the case of Mode 4, the energy collection process is limited by the capability of the charging heat exchangers to absorb energy. Also, as the thermal storage system becomes fully charged, the capability of the equipment to absorb energy goes to zero. An operator action is required to reduce the level of energy input or initiate operation in another operating mode to prevent a plant trip from occurring. The principal components, flowpaths, and process sensors associated with this operating mode are highlighted in Figures 2.1 and 2.2.

By design, Mode 5 operation can utilize one or both thermal storage charging trains simultaneously. The number of charging trains selected depends on the

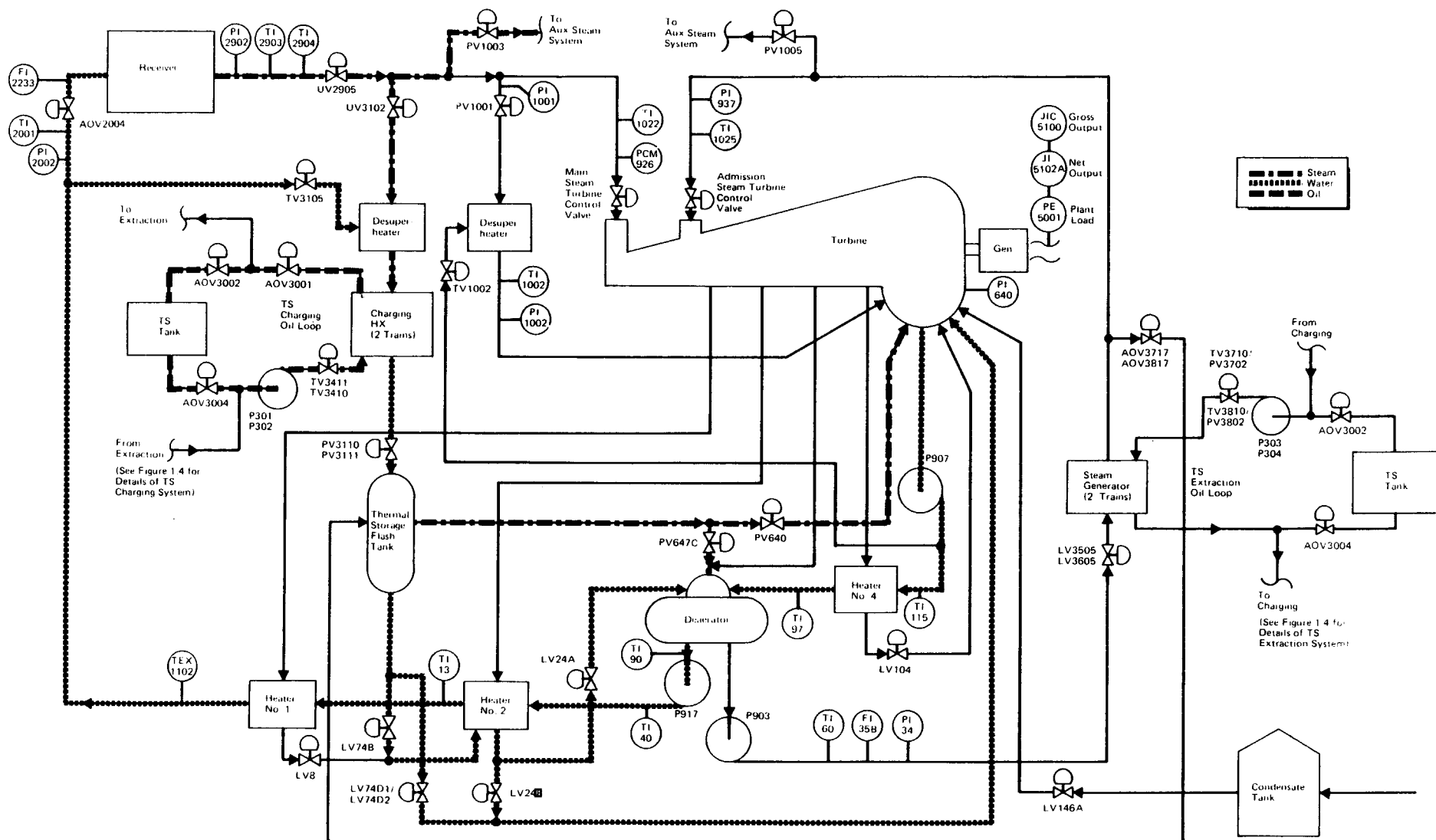


Figure 2.1. Major Flow Paths Active During Mode 5 Operation

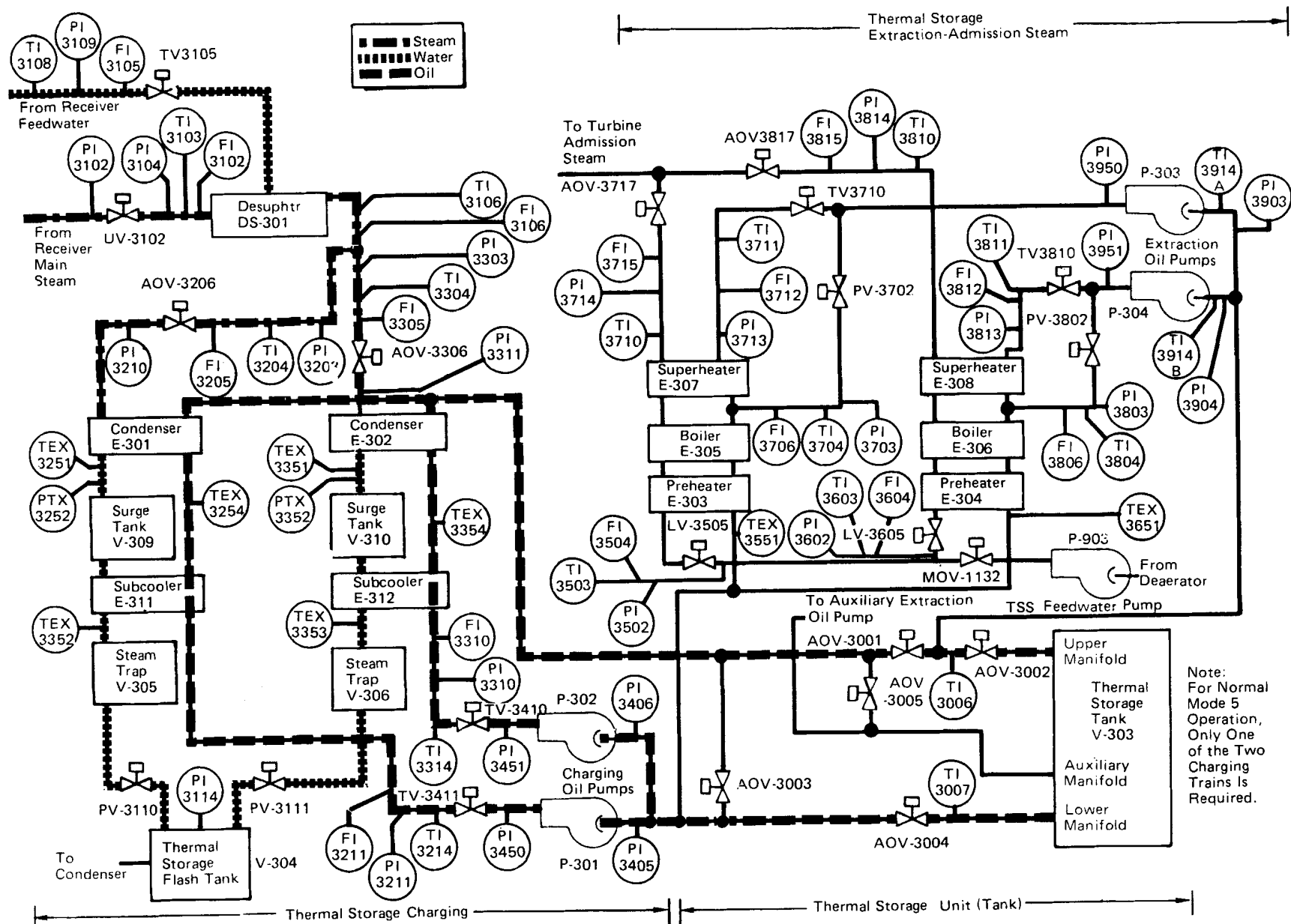


Figure 2.2. Major Thermal Storage Flow Paths Active During Mode 5 Operation

ability of the charging system to accept 100 percent of the current receiver steam output while providing for the desired turndown in response to receiver transients. Initially, each charging train was sized to accommodate 50 percent of the design point receiver flow. During the course of the test program, the flow capacity of the critical thermal storage condensate drain valves (PV 3110 and PV 3111) was increased to provide a higher train steam side flow capability. Combining this hardware modification with the fact that no oil-side heat exchanger tube fouling was evident and that the Caloria was routinely exercised through a larger temperature differential than the original design value of 150°F, it was found that in most cases each charging train could accommodate 100 percent of the available receiver flow. As a result, single train charging operation during Mode 5 operation (also during Mode 4 operation) became the preferred operating approach.

Several other factors further enhanced this approach of using a single charging train during any type of charging operation. First, the desire to minimize plant parasitic power demands favored the use of a single train. Second, equipment operating problems associated with the variable speed charging oil pump power inverters, oil side heat exchanger flange leaks, and tubesheet leaks sometimes resulted in one of the two charging trains being out of service. Third, the added complexity of operating both charging trains simultaneously increased the burdens of the Plant Equipment Operator with "outdoor" equipment startup and maintenance responsibilities and the Control Operator responsible for operation from the control room. The control room issues involved insufficient visibility of the additional charging train due to the limited number of control room display terminals (four Subsystem Distributed Process Controller CRT operator stations).

Turndown of the charging system was also an issue during Mode 5 test operation, particularly during partly cloudy periods. The use, whenever possible, of a single charging train resulted in the greatest turndown flexibility in the event of cloud passage. By contrast, turndown during two train operation required that at some point one of the two trains be shutdown due to low flows. As charging steam flow recovered, the second charging train would have to be restarted to accept its assigned portion of the flow. Experience showed that this restart required tens of minutes, clearly incompatible with the receiver operation which could cycle between low and high flows in a matter of seconds during cloud passage.

#### 2.1.1 Mode 5 Control

Control of steam flow into the thermal storage system is provided by the main steam inlet control valve (UV 3102). The main steam inlet control valve can be operating in any of four control modes depending on the desired plant operating mode. The four control modes are flow control, pressure control (receiver outlet), turbine electrical load control or TSS charging system inlet pressure control.

In the flow control mode, the main inlet valve is used to control a desired flowrate into the charging system and is used during TSS startup and during mode transitions such as from Mode 1 to Mode 2 or Mode 5 to Mode 2. The flow loop feedback measurement can be selected from one of 3 possible flowmeter arrangements; FI 3102 - main steam inlet flow, FI 3106 - main steam plus desuperheater spray water flow, or FI 3102A - charging train steam flow for one or both trains (FI 3205, FI 3305) as backup for failure of FI 3102 or FI 3106. In the pressure control mode the receiver outlet pressure is controlled by sensing the pressure (PI 1001) at the bottom of the downcomer line near the



steam dump valve. This control mode is used when the steam dump system is out of service (i.e., in override mode) for control in Mode 5 or during transitions to or from Mode 5.

Control of the temperature of the steam into the two TSS charging trains is provided by spraying condensate from the RS feedwater pump into the TSS main steam inlet line desuperheater. The water flow necessary to maintain a steady state desuperheater outlet temperature is calculated from the enthalpy relationships for the main inlet steam flow and desuperheater inlet pressure (PI 3104) so that the setpoint is always approximately 60°F above the steam saturation temperature (650°F maximum).

The TSS inlet pressure to each of the two charging train condensers is controlled by modulating the condensate drain valves (PV 3110 and PV 3111) located between the TSS subcoolers and the TSS flash tank. Redundant pressure measurements in each train are high-selected (for reliability) and compared to the pressure setpoint. The condenser pressure setpoint is maintained 100 psi below the commanded steam dump system pressure. As the receiver outlet pressure varies, the condenser pressure setpoint will automatically track it to maintain a differential pressure across the main steam inlet valve, UV 3102, of 100 psi. For dual train operation, a single pressure controller is used to control both drain valves to prevent coupling between the two valves. (This configuration was established during the Mode 5 test program.)

The oil temperature at the outlet of each of the 2 charging trains is controlled by varying the oil flowrate through each charging condenser by modulation of the temperature control valves TV 3411 (Train 1) and TV 3410

(Train 2). The outlet oil temperature is fixed at a value equal to the oil temperature setpoint of 570°F over the range of inlet oil temperatures from 260°F to 425°F.

The TSS charging oil pump for each train is slaved to the commanded oil temperature control valve position. The speed of the pump is varied to maintain a differential pressure across the valve such that the commanded valve position is maintained at 70 percent open (the setpoint equals 30 percent since the oil temperature valve is a fail-open valve). To provide the required turndown in oil flowrate the oil pump speed will decrease until the minimum pump speed is reached. At this time the oil temperature control valve will begin closing down from the 70 percent open command position to provide the remaining turndown in oil flowrate.

#### 2.1.2 Mode 5 Initiation

Mode 5 operation is typically initiated by a transition from steam dump operation, although transitions from Mode 2 or Mode 4 are also possible. The sequence of events and equipment operation were developed during the Mode 5 test program. Thermal storage charging system startup and Mode 5 operation may be initiated by Subsystem Distributed Process Control (SDPC) automation sequences and the transition from steam dump operation to Mode 5 may also be accomplished under Operational Control System (OCS) supervisory control. The automation sequences for starting and stopping the TSS charging trains are both mechanized. The train start sequence is used to align the oil temperature controllers, the oil pump speed controllers, the TSS condenser pressure controllers, and provide commands to the Interlock Logic System (ILS) to align the TSU manifold valving and steam block valves. The oil temperature controller is set to manual and the temperature control valve is

open 70 percent. The charging oil pump is set to run at minimum speed, the condenser pressure controller is set to auto, and the ILS is commanded to open the middle manifold of the TSU tank. The middle manifold of the tank is open to permit circulation of "cold" oil through the charging heat exchangers during the startup period without adding "cold" oil to the top of the TSU. The charging oil pumps are started a minimum of 20 minutes prior to initiation of steam flow to the charging trains to allow warmup of the condensers such that the temperature differential between inlet steam and outlet oil is minimized to reduce heat exchanger thermal "shock."

Two minutes after initiating the start sequence, the oil pump speed is increased and when oil flow exceeds 130KLBH, the oil flow loop is put into auto with a setpoint of 200KLBH and the oil pump controller is put into auto. Twenty minutes after initiating the start sequence, the "Enable" switch is set and a signal is sent to ILS to open the steam block valve (3206/3306). At this time, if steam conditions are correct, auto pressurization of the charging train(s) may be initiated. Although receiver steam temperature setpoints of 660°F and 960°F were the bounds of the Mode 5 design range, typical Mode 5 operating conditions were within a range of 775°F to 850°F. The lower temperatures helped to minimize receiver energy losses while still maintaining adequate superheat margin for cloud transient operation.

For Mode 5 operation at total receiver flows exceeding 90 KLBH, two charging trains are required. Therefore, if flow conditions are expected to exceed this value following startup, two trains must be started and simultaneously pressurized. The charging train inlet steam valves (3206/3306) are not modulating valves, therefore, to prevent severe pressure transients when the valves are opened, a differential pressure limit (across the valves) of 100

psi prior to valve opening was established. This precludes starting a second charging train after the first one has been pressurized. A receiver downcomer pressure range of 750 - 1000 psi was established as the initial condition for charging train pressurization.

Once the auto pressurization sequence has been initiated, digital logic slowly ramps up the TSS inlet pressure by gradually opening UV 3102 at a rate of 30 psig per minute. When the TSS charge inlet pressure is within 200 psi of the receiver outlet pressure the pressurization sequence automatically stops and UV 3102 is switched to flow control. The pressurization sequence can also be stopped at any time by disabling a digital switch. The sequence will also be halted if any of the other UV 3102 control modes, i.e., flow control, pressure control or load control are enabled. The slow rate of pressurization was established to minimize the effects of thermal "shock" on the condensers. Pressurization of the trains will result in an increase in condenser oil outlet temperatures due to the charging steam flow. When the oil temperatures increase to 500°F, a signal is sent to ILS to route oil flow to the TSU top manifold. When the oil temperatures increase to 570°F, the oil temperature controllers switch to auto. If the oil temperatures drop to 540°F or less due to a cloud transient, the oil flows are reduced to a minimum of 100 KLBH until the oil temperatures increase to 570°F.

To establish Mode 5 pressure control, the UV 3102 controller is placed into manual and the steam dump system pressure setpoint is increased to 1400 PSI. UV 3102 is then gradually opened until the steam dump valve (PV 1001) is fully closed and then UV 3102 is placed into the pressure control mode at 1400 PSI. The steam dump pressure setpoint is then increased to 1420 psi to maintain PV 1001 closed.

### 2.1.3 Mode 5 Termination

The charging trains can be stopped (Mode 5 Termination) by enabling the charge train Stop switch to the Stop position. This sends a command to ILS to close the steam block valve (3206/3306). ILS subsequently provides a permissive to allow the charge Shutdown sequence to ramp the TSS main steam inlet valve, UV 3102, closed at a rate providing 1000 psi/min pressure decay. This closes off steam flow to the train(s) reducing the charging oil temperature. When the oil temperature drops below 540°F (Train 1) or 536°F (Train 2) the oil temperature valve is commanded 70 percent open, the oil pump speed controller is put in Manual and a signal is sent to ILS to stop the oil pump (P301/P302) and close the TSU manifold valves (which concludes the Mode 5 shutdown sequence).

A single charge train may be shutdown, while in 2-train operation, by manually closing its steam inlet valve. The oil system for that train will then shutdown as described above. This permits charging turn down as the total receiver flow decreases below the 90 KLBH 1-train steam flow limit.

As the steam flow to the charging system is shutdown, the steam dump valve (PV 1001) will automatically open to accept the receiver flow not routed to the TSS. Once UV 3102 is completely closed, the transition from Mode 5 to steam dump operation is complete.

### 2.2 Mode 5 Test Goals and Objectives

The goals and objectives of the Mode 5 test program were to gather test data in three areas of plant operation for subsequent analysis and comparison to design requirements as well as to provide recommendations for overall plant operation (specific operating conditions within the Mode or Mode-to-Mode performance comparisons). The three areas were steady-state operation, start-up and transitions, and trips.

### 2.2.1 Steady-State Operation

The goal of the steady-state operational testing involved gathering sufficient data in order to make Mode 5 performance estimates. Attempts were made to gather performance-related data over a range of plant operating conditions, subject to reasonable plant operating limits, in order to identify any first-order sensitivities. Measured performance values could then be used to make comparisons between Mode 5 and other operating modes as well as identifying the preferred Mode 5 operating conditions. Both single and dual train tests were conducted, including a determination of the maximum flow conditions (charging rates) for single train operation.

### 2.2.2 Start-Up and Transitions

The goal of Mode 5 start-up tests was to develop an operational timeline, based on equipment operational characteristics and limitations, which would minimize the time required from establishment of steam flow through the steam dump system to steady-state Mode 5 operation. This involved both single and dual charging train operation.

The transition testing involved transitions both to and from Mode 5, from two-train to one-train operation, and steam flow variations resulting from set point changes, collector field modulation, or as a result of naturally occurring (cloud-induced) transients in receiver steam. The mode transitions to Mode 5 involved initial operation in either Mode 4 (in-line flow) or Mode 2 (turbine direct and charging) and shutting down the thermal storage extraction system or turbine operation on main steam, respectively, reach Mode 5. The transitions from Mode 5 involved shutting down the thermal storage charging system to return to steam dump system operation.

Transition testing within Mode 5 involved varying the quantity of receiver steam to the charging system by increasing or reducing the number of heliostats tracking the receiver or by allowing the charging system to absorb all the available receiver steam with its naturally occurring (cloud/insolation) transients. The objectives of these tests were to gain insight into the overall plant response and controllability as well as identifying operational thresholds and limitations of individual components and systems.

The critical mode transition issues involved demonstrating the necessary manual operation sequences (through the Subsystem Distributed Process Control system) and developing timeline data which could be used in the evaluation of Mode 5. It was beyond the scope of the Mode 5 test program to test any automatic control sequences which were initiated and controlled by the Operational Control System (OCS) to accomplish transitions to or from Mode 5.

### 2.2.3 Trips

The goal of the trip evaluation was to verify that the plant would continue to operate in a lower level mode following a trip condition. A trip of a single charging train during dual train operation should result in continued Mode 5 operation whereas a TSS trip should result in a transition to steam dump operation. In the event of a receiver trip during Mode 5 operation, both the charging system and the receiver should shutdown resulting in a non-operating plant.

## 2.3 Mode 5 Design Summary

Before discussing plant test results for Mode 5 operation, a review of the basic operating range and performance predictions (which were developed as

part of the initial plant sizing and overall design activities) will be provided. With this information, it is possible to make direct comparisons to actual operating data and to identify areas of discrepancy or uncertainty. The Mode 5 design summary addresses the water/steam and thermal storage oil portions of the plant. Details involving the individual performance factors associated with the collector field and receiver and discrepancies between actual experience and design values were documented in Reference 2 and will not be repeated here.

The overall design operating envelope for Mode 5 operation is shown in Figure 2.3. The solid lines represent design boundaries for the plant which reflect design operating limits for individual plant systems. The vertical line at the left side of the figure (receiver steam flow of 30,000 lb/hr) represents the lower steady-state limit for receiver operation. The diagonal solid line at the right is the receiver flow corresponding to the maximum design flow of the charging heat exchangers (131,000 LBH). The heat exchanger flow is the receiver flow minus auxiliary steam flow plus the desuperheater spray water flow. The upper and lower horizontal lines correspond to the maximum and minimum (respectively) receiver steam temperature setpoints.

The charging steam operating envelope (downstream of the desuperheater, upstream of the heat exchangers) is shown in Figure 2.4. The operating envelope represents system operating limits for the receiver, the heat exchangers and the desuperheater. The minimum pressure (1335 psia) corresponds to a steam condensing temperature of 580°F (the design charging outlet oil temperature) while the maximum pressure (1500 psia) is related to the maximum receiver operating pressure. The maximum steam temperature (680°F) is based on the maximum (transient) temperature that will not cause



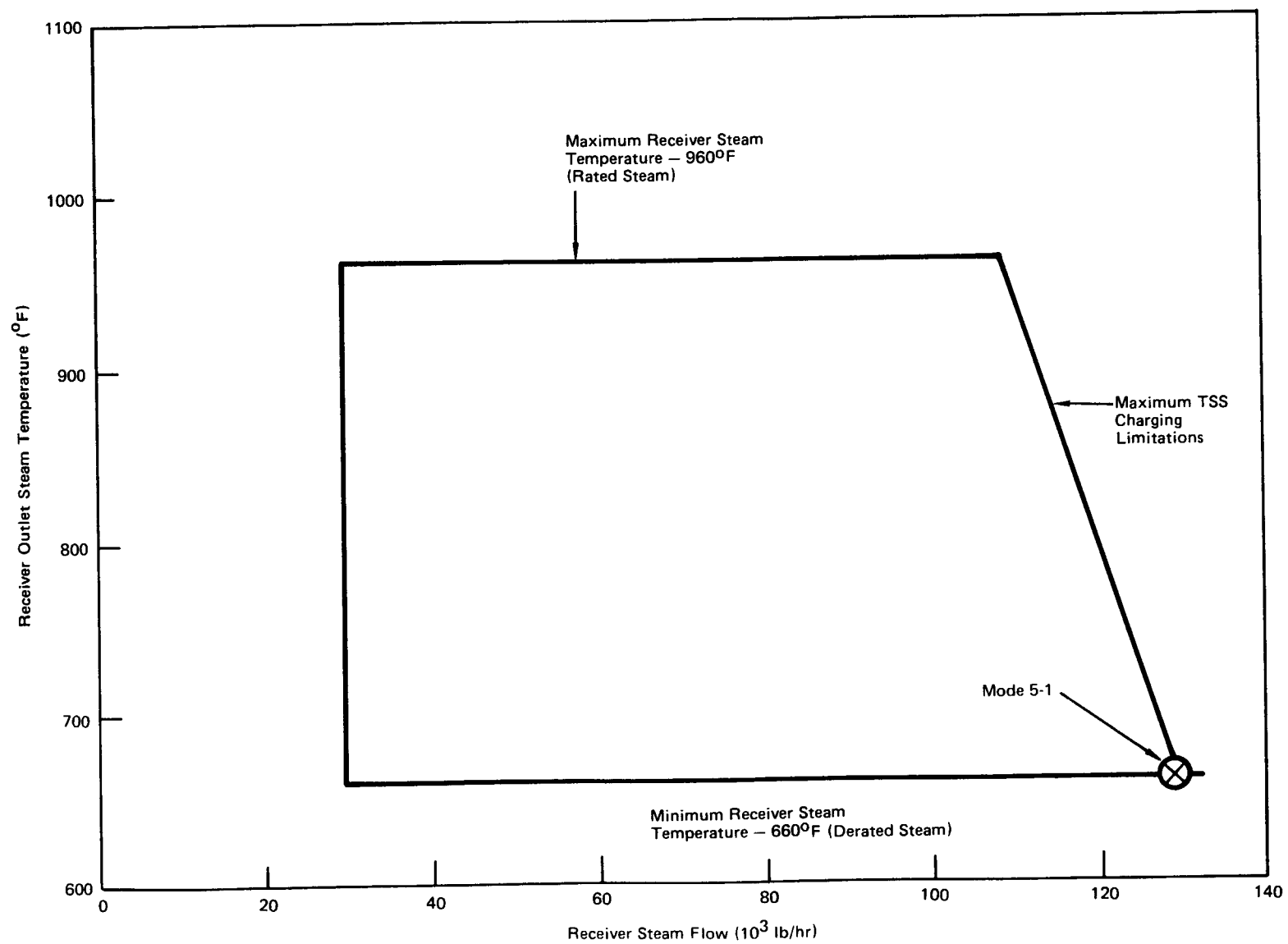


Figure 2.3. TSS Charging Operation Design Envelope

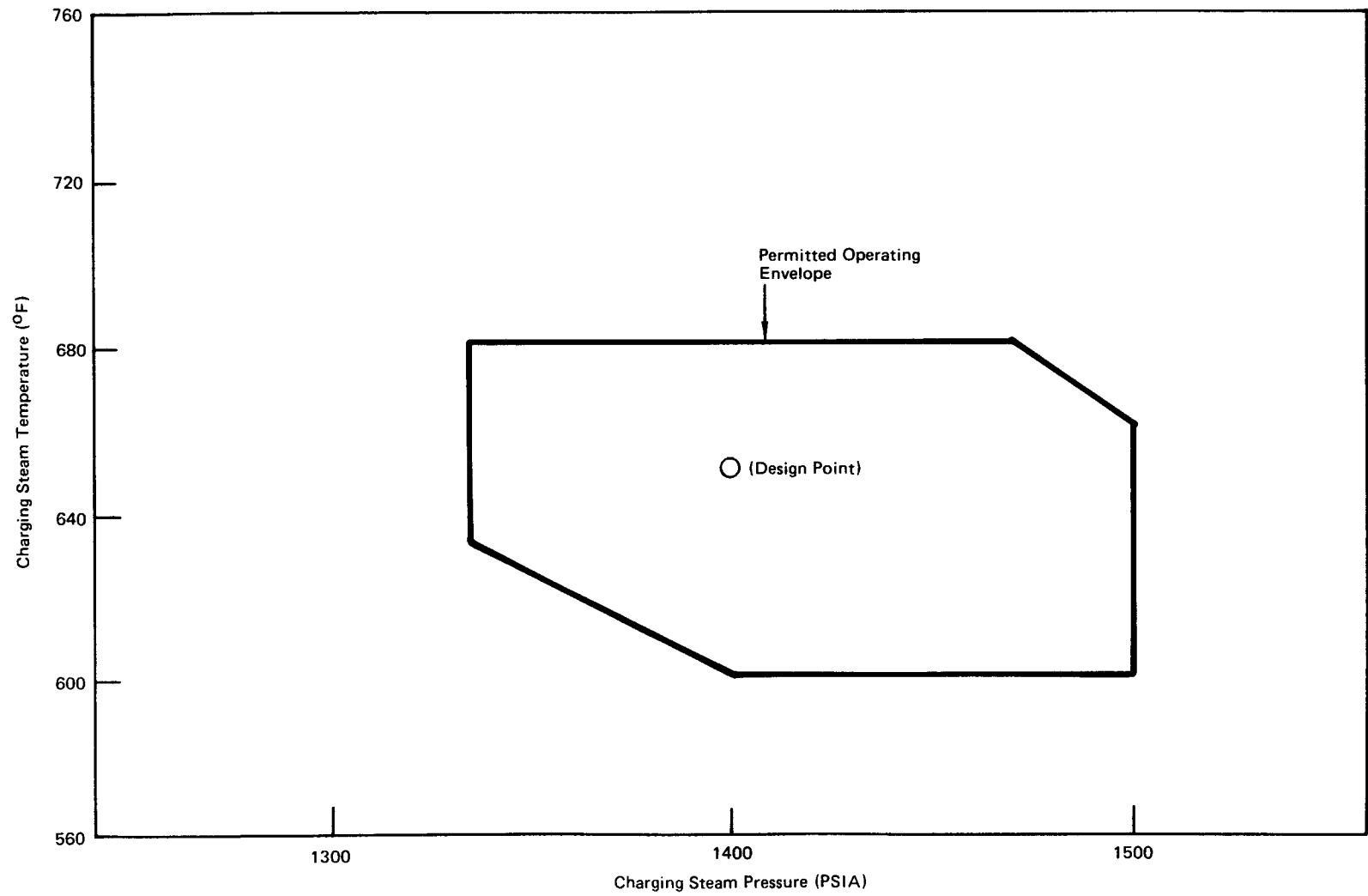


Figure 2.4. Charging Steam Operating Envelope

heat transfer fluid (oil) deterioration, while the minimum steam temperature corresponds to a temperature just above saturation temperature at the operating pressures. The diagonal line at the lower left of the operating envelope corresponds to a minimum pinch point (see Figure 2.5) of approximately 10°F, while the diagonal line at the upper right corresponds to a control margin limit.

Detailed design data involving state point conditions at various locations around the water/steam and charging oil systems are shown in Figure 2.6. The data contained in Figure 2.6 (a and b) represent the predicted plant operating characteristics at maximum charging steam flowrate. The location within the overall Mode 5 operating envelope for this design case is shown in Figure 2.3 (referred to as Mode 5-1). It should be noted that this design data case corresponds to a receiver operating condition (set points) of 660°F and 1450 psi at the control point locations.

An additional aspect of the Solar One plant design involves the thermal storage flash tank heat recovery system. A schematic representation of the major flow paths, system components, and control valves is shown in Figure 2.7. High temperature, high pressure condensate enters the thermal storage flash tank from the charging heat exchangers (top left side of the figure) by flashing into a water/steam mixture across pressure control valve PV 3110 (or PV 3111). The purpose of the heat recovery equipment is to retain the flash tank discharge flows (steam and condensate) in the feedwater system thereby eliminating the heat rejection and corresponding loss of performance if the flows were routed directly to the condenser. The heat recovery is accomplished by routing the flash tank condensate discharge to the shellside of the second point heater through LV 74B. Flash tank steam is directed to the deaerator through PV 647C.

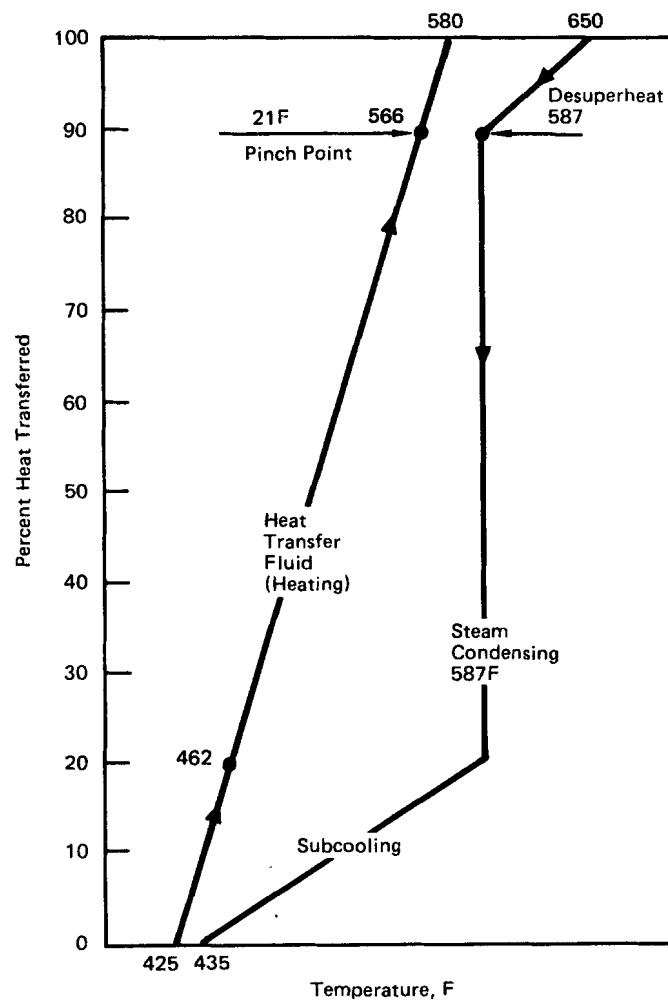
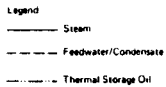


Figure 2.5. Thermal Storage Charging Characteristics



Location Number	Flowrate (kg/hr)	Enthalpy (kJ/kg)	Temperature (°C)	Pressure (psia)
1	80186.7	76.7	108.7	1.228
2	80128.2	77.1	108.8	140.0
2A				
3	80128.2	77.1	108.8	137.8
4	130824.8	260.2	281.0	60.0
5	130824.8	268.8	284.4	2088.0
6	130824.8	283.1	308.4	2082.8
7	130824.8	283.1	308.4	2064.2
7A				
8	130824.8	283.1	308.4	1830.0
9	130824.8	1248.1	689.0	1890.0
10				
11	130000.0	1243.4	685.0	1486.0
12	130000.0	1243.4	685.0	1486.0
13	130000.0	413.8	436.0	1377.0
14	12488.4	1184.8	268.5	180.0
14A	12488.4	1184.8	320.3	50.0
14B				
15A	117613.8	330.8	268.5	188.0
15B				
16				
17				
18				
19	38012.8	304.8	333.8	136.0
20	78900.7	304.8	333.8	136.0
21				
22				
23				
24				
25				
26				
27				
28				
29				
30				
31A				
31B				
32A				
32B				
33				

**SOLAR FACILITIES DESIGN INTEGRATOR**

**STANLEY HARRIS**  
**DAVID COOPER**  
**DAVID**  
**STAN**

**Figure 2.6(a). Mode 5 Operation – High Charge Flow**

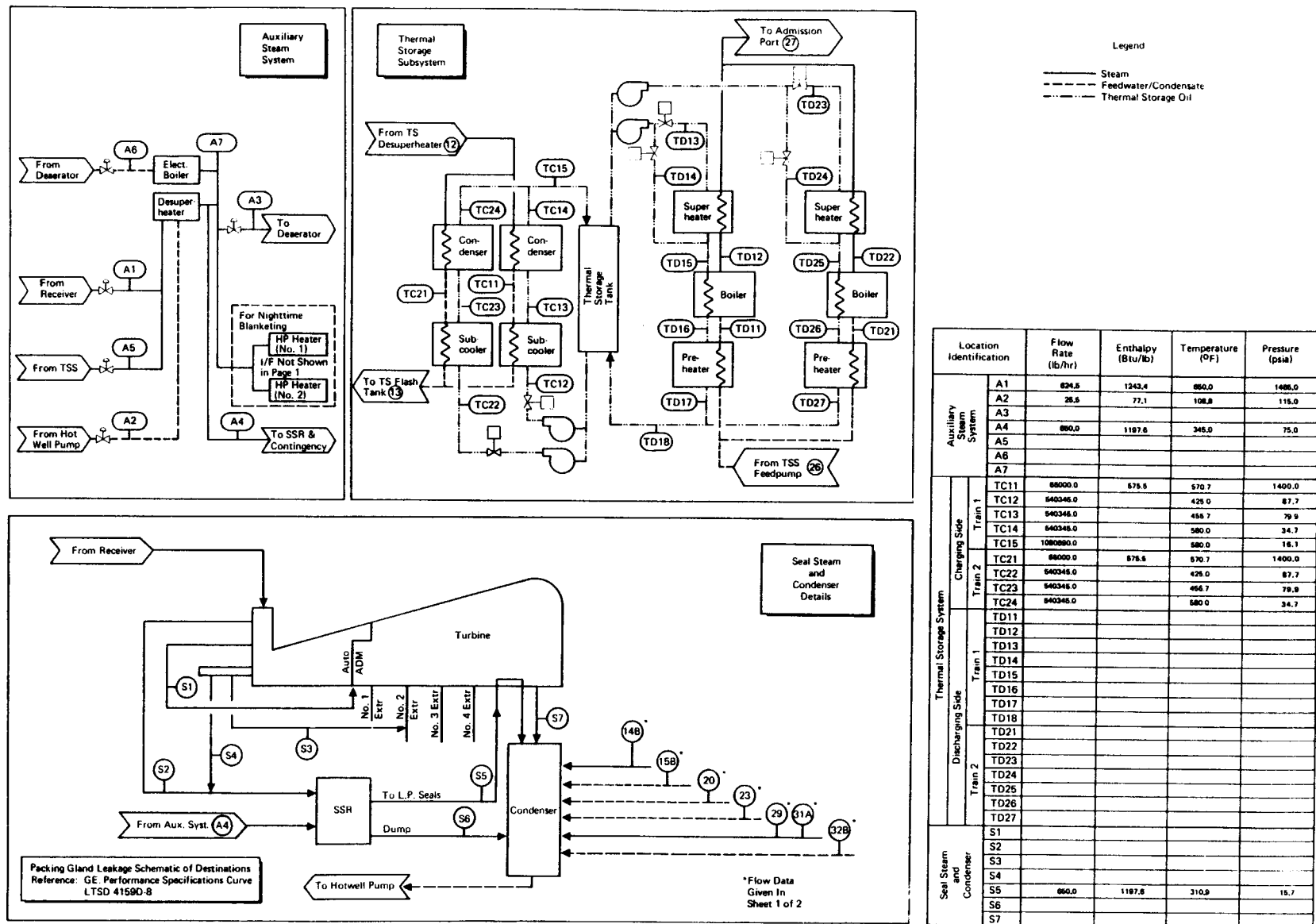


Figure 2.6(b). Mode 5 Operation - High Charge Flow

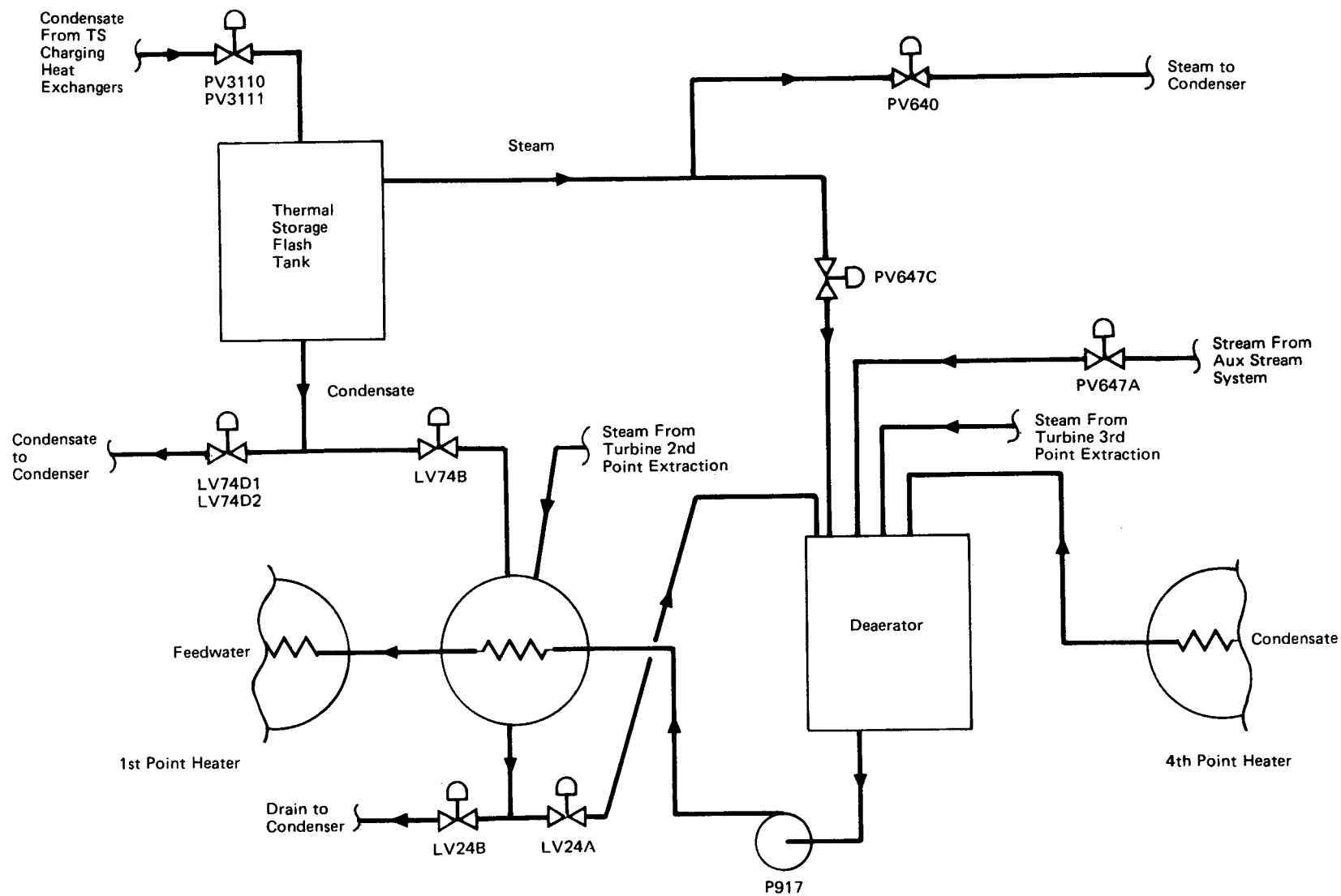


Figure 2.7. Thermal Storage Condensate Heat Recovery Process Schematic

During periods of high charging flows, insufficient steam flow from the flash tank may exist to satisfy the deaerator demand for deaeration. During this period, additional auxiliary steam is provided through PV 647A to satisfy this demand. This auxiliary steam is drawn directly from the main steam downcomer flow (receiver steam) and represents an increment of steam flow lost to the thermal storage charging system. The influence of these heat recovery paths on charging performance is discussed in Section 2.5.

#### 2.4 Test Approach and Critical Instrumentation

The approach to Mode 5 testing involved gathering sufficient operational data such that both the steady state and transition related test objectives described in Section 2.2 could be analyzed. Test time within each of the operating modes was necessarily limited by other plant operating activities such as tuning of control systems, developing operating procedures, gathering test data in other operating modes, developing requirements for automatic software, and testing plant automation functions. Therefore, efforts were made to utilize Mode 5 operating time as efficiently as possible.

As a prerequisite to any Mode 5 testing, it was desirable to have no more than a 50 percent charge in the thermal storage tank. A cold oil temperature at or near the design value of 425°F was also desirable to allow for direct data comparisons to predicted values without data adjustments for off design operating conditions. As a result, prior to any Mode 5 testing, thermal storage discharge operation was established to achieve this desired state of charge.

As a result of the limited time specifically dedicated to Mode 5 testing, the majority of the test time was spent in those areas where the plant could



reasonably be expected to operate. For Mode 5 operation, this primarily meant the use of a single charging train.

Dedicated trip testing was not carried out as part of Mode 5 test program due to other plant operating priorities and the need to gather meaningful Mode 5 test data for reasonable time periods once Mode 5 operations were established. Instead, plant responses were noted during naturally occurring trips involving Mode 5. These separate trip events included trips of the thermal storage system (both single and dual charging trains simultaneously) and the receiver. In this way all possible trip transition logic paths short of complete plant trip were demonstrated by naturally occurring events.

The Mode 5 data base was gathered during 20 days of plant operation extending from January 1983 to November 1983. These were days during which dedicated operation in Mode 5 occurred. This excludes periods when the plant may have been briefly in Mode 5 as part of a transition to other operating modes. Of the 20 operating day data base for Mode 5, the majority of the data used for this report were gathered on 9 test days. The rejection of the remaining operating days is based on too brief an operating period to gather meaningful data, control system troubleshooting and tuning which impacted the meaningfulness of the data, or missing data due to problems with the Data Acquisition System. The 9 test days which serve as the basis of the Mode 5 data base are shown in Table 2.1.

TABLE 2.1    MODE 5 OPERATING DATA BASE

DATE	DAY OF YEAR	MODE 5 DATA PERIOD (DATA POINT)	COMMENT
5/19/83	139	12:00 - 12:05 (1) 14:00 - 14:05 (2) 15:50 - 15:55 (3) 17:00 - 17:05 (4) 17:58 - 18:00 (5)	Max charge rate - single train
6/4/83	155	11:00 - 11:05 (27) 12:30 - 12:35 (28) 13:30 - 13:35 (29) 16:55 - 17:00 (30)	Single train
9/16/83	259	11:00 - 11:05 (17) 12:00 - 12:05 (18) 13:05 - 13:10 (19)	Dual train
9/23/83	266	11:00 - 11:05 (15) 13:00 - 13:05 (16)	Dual train
10/11/83	284	15:00 - 15:05 (20) 15:30 - 15:35 (21)	Dual train
10/12/83	285	12:00 - 12:05 (22) 13:00 - 13:05 (23)	Dual train
10/13/83	286	10:55 - 11:00 (24) 15:40 - 15:45 (25) 17:00 - 17:05 (26)	Dual train
11/2/83	306	12:00 - 12:05 (6) 13:00 - 13:05 (7) 14:00 - 14:05 (8) 15:00 - 15:05 (9) 15:55 - 16:00 (10)	Dual train to single train
11/29/83	333	09:30 - 09:35 (11) 11:00 - 11:05 (12) 13:25 - 13:30 (13) 14:55 - 15:00 (14)	Dual train to single train

The critical instrumentation monitored during Mode 5 tests is shown in Figures 2.1 and 2.2 as appropriate to the indicated "active" flow paths. For reference purposes, the following tag identification prefix conventions are used in these figures:

FI	Flow indication
JI	Electrical power
JIC	Electrical power
PCM	Pressure indication
PE	Plant electrical load (power)
PI	Pressure indication
PTX	Pressure indication
TEX	Temperature indication
TI	Temperature indication

The fact that there are multiple designations for temperature indications, pressure indications, and electrical power is due to the function being served by a particular sensor and the computer system responsible for receiving and processing the data.

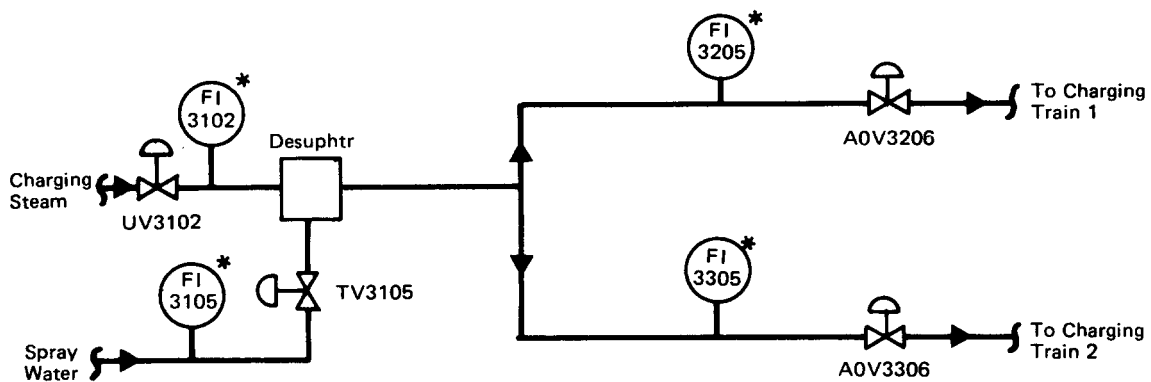
From a data quality and measurement accuracy standpoint , it is important to understand that Solar One is operated as a utility power plant as opposed to a precise laboratory experiment. As a result, the instrumentation used for the most part is of the type normally used in the process and utility industries. In addition, no dedicated pretest and post-test calibration checks were made as would be done in a laboratory experiment to verify the quality of the data being recorded. As a result, uncertainties implicitly exist as to the absolute and relative accuracy of the data recorded.

It should also be understood that the errors in the final data arise not only from the sensors themselves but from the entire data system through which the signals must flow. Most of the sensors used in the plant have accuracies typically on the order of one-half to one percent of full scale value. By the time the data signals are transmitted, digitized, processed, recorded, and converted to engineering units, the accuracy may be more typically in the 2 to 2-1/2 percent range (even for precisely calibrated instrumentation).

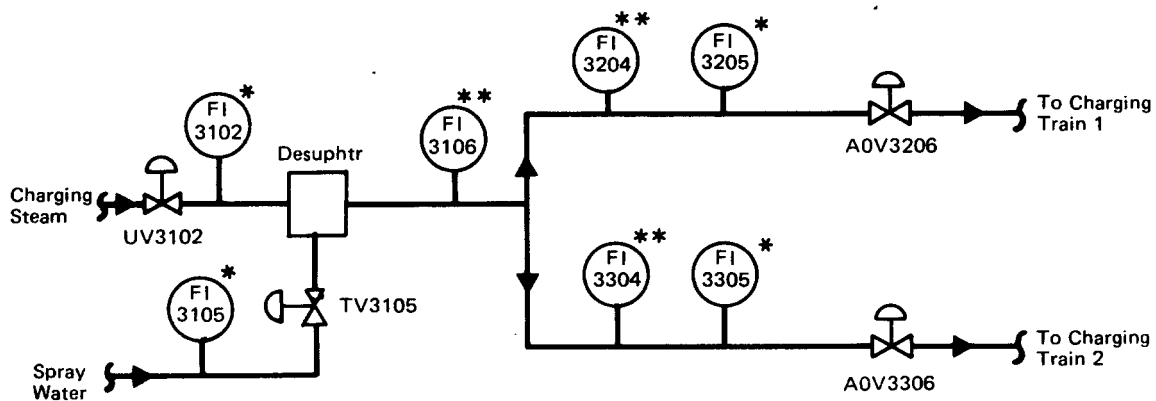
Components in the data system which can contribute to the overall errors are the excitation power supplied, signal conditioning equipment, and the analog-to-digital converters (the precision of the digital system and the calibration curves used to convert the digitized data into engineering parameters are also factors in error contribution).

Implicit in the above discussion regarding data quality and instrumentation accuracy is the assumption that the instruments themselves were able to provide sensed data at their advertised accuracy. In the area of steam flow measurements, where meter survivability became a critical factor, this assumption was not valid. Steam flowmeters, which are contained in both the thermal storage charging and extraction systems, were originally specified to have high turndown measuring capabilities which were compatible with the design requirements of the charging and extraction systems. As a result flowmeters other than standard orifice plates and nozzles were selected.

Figure 2.8 shows the initial and final configurations of the steam flowmeters in the thermal storage charging system. Originally, the charging system utilized three steam flowmeters (FI 3102, FI 3205, and FI3305) and a fourth meter (FI 3105) which monitored desuperheater spray water. All of these meters are of the target type. Flowmeter FI 3102 was intended to provide control signals to main charging inlet control valve (UV 3102) and the spray



Initial Charging Flowmeter Configuration



Final Charging Flowmeter Configuration

\* Target Type Flowmeter  
 \*\* Turbine Type Flowmeter

Figure 2.8. Initial and Final Charging Steam and Spraywater Flowmeter Configurations

water valve (TV 3105) as well as provide a measure of total charging steam flow. The individual charging train flowmeters (FI 3205 and FI 3305) were included initially to provide engineering data for each of the charging trains. They were later used directly in the valve control loops as replacements for FI 3102.

The failure modes of these target meters involved seal problems (where the target shaft penetrated into the steam line) and debonding of the strain gauge that measures target deflection. These problems occurred most frequently with the high temperature service associated with FI 3102 (which is located upstream of the desuperheater). Those meters associated with the individual trains also experienced similar failure mechanisms, but on a less frequent basis.

Due to the success in measuring thermal storage oil flows using turbine type flowmeters, combined with manufacturer's recommendation for use in superheated steam service, the charging system was retrofitted with three turbine flowmeters as shown in Figure 2.8 (final configuration). These meters produced reasonably accurate measurements over the full operating ranges involved. They proved, however, to be very susceptible to damage caused by water droplet carryover experienced during startup as well as due to the highly turbulent environment associated with high velocity steam. Experience showed that the turbine wheel sensing elements survived anywhere from hours to days. As a result, the turbine type flowmeters proved to be unacceptable for this application.

Additional planning and design work was accomplished to install a nozzle flowmeter upstream of UV 3102. Although this proposed meter did not permit the desired flow measurement turndown (based on manufacturer's

specifications), it was intended to gather operational experience with this device and attempt to define its maximum capability. This activity was placed on hold due to schedule and budgetary constraints.

The recurring steam flowmeter problems described above had a detrimental affect on the quality of Mode 5 data gathered during the test program. Since it was the intent of the plant design to infer other steam flows based on these flow measurements, these instrumentation problems cast doubt (from an engineering evaluation standpoint) as to the actual steam flow split between charging trains and the total flow to thermal storage during any one test. This made comparisons between experimental data and predicted performance difficult.

In analyzing the test data for the individual operating modes involving the thermal storage system, the first task involved validation of the charging and/or extraction energy flows based on the alternate flow measurements available. Once proper agreements had been established between the alternate measurements, appropriate plant and system level performance parameters could be calculated for comparison against predicted data.

Once the actual steady state mode test data were gathered, it was possible to begin the process of energy flow correlations described above. Modes 4, 5, and 6 were evaluated and the conclusions drawn regarding the charging and extraction system operations are directly applicable to the other operating modes involving separate or combined charging and extraction operation (Modes 2, 3, and 7). See reference 3.

In an evaluation of the thermal storage charging system, a correlation should exist between the steam side and oil side thermal power based on the respective steam and oil flow measurements (see Figure 2.9) which were "corrected" based on local steam and oil densities. Figure 2.10 (reproduced from Reference 3 with Mode 5 data added) shows the quality of this correlation. Based on this figure, several conclusions can be drawn. First, the degree of data scatter shown indicates that either the steam side measurements or oil side measurements (or both) were highly inaccurate. This data scatter makes any calculated performance parameters meaningless for comparative purposes. The figure also shows that the data points associated with steam flowmeter FI 3102 are unique since they are far removed from the balance of the plotted data. Finally, as a general rule, the data points indicate a charging efficiency of greater than 100 percent (which is physically impossible). This is an indication that either the steam measurements (all three meters) were reading low or the oil flowmeter was reading high.

An alternate correlation plot, also reproduced from Reference 3 with Mode 5 data added, was prepared (Figure 2.11) which is not based on direct measures of charging steam flows. Instead, calculated auxiliary steam flow was subtracted from the measured receiver feedwater flow to estimate the net charging steam flow and resulting steam side power. The auxiliary steam demand was calculated based on the commanded position for the auxiliary steam valve (PV 1003) and its design flow capacity factor (no direct measurement of auxiliary steam flow exists). Implicit in this approach is the assumption that no other main steam flow, path such as the steam dump system or bootleg drains, was active or leaking steam to the condenser.



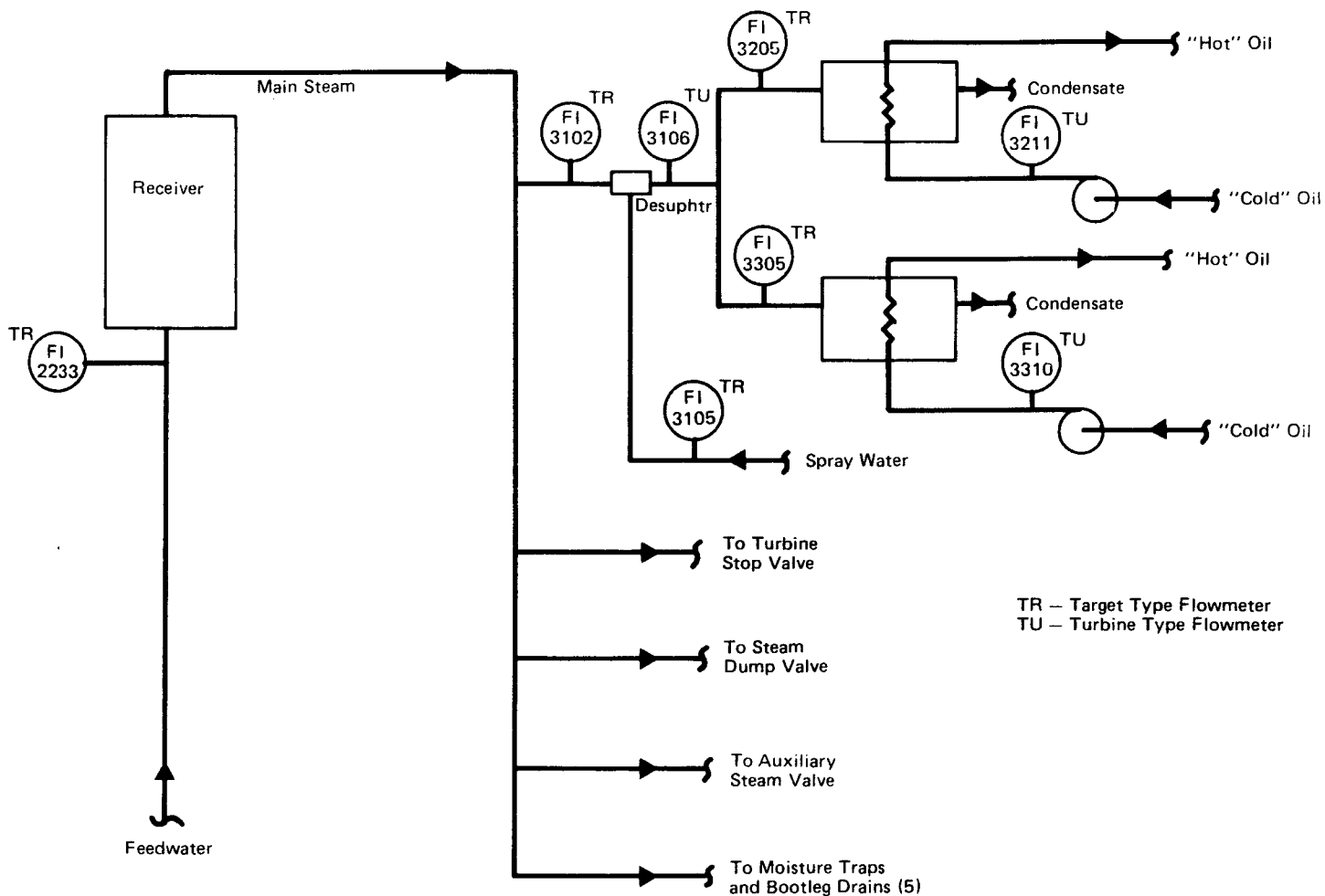


Figure 2.9. Flowmeter Arrangement for Receiver Feedwater, Charging Steam, and Charging Oil Systems

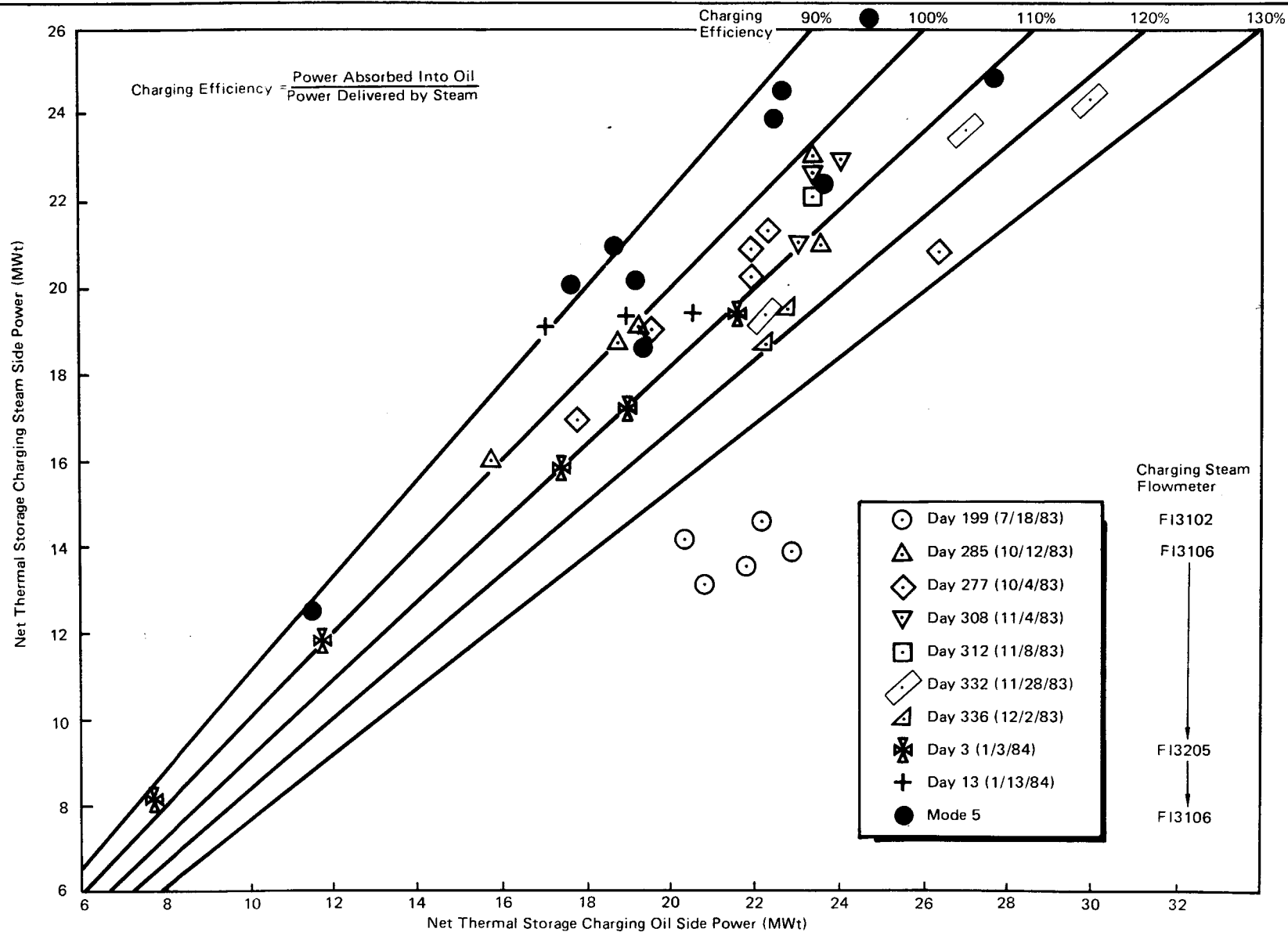


Figure 2.10. Charging System Correlation Between Steam Side and Oil Side Power Flows

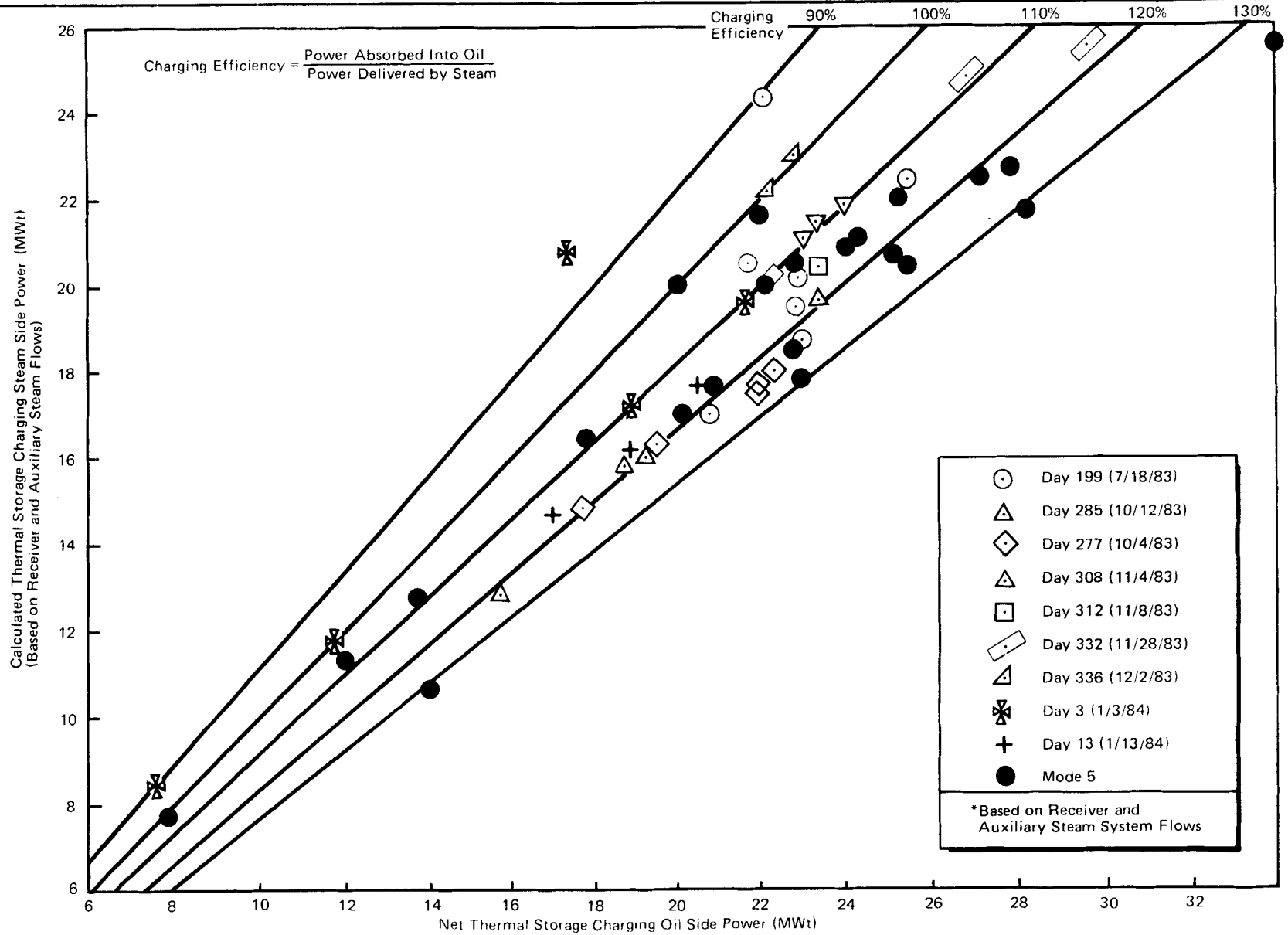


Figure 2.11. Charging System Correlation Between Calculated\* Steam Side Power and Oil Side Power

The results of this correlation, which are shown in Figure 2.11, again exhibit unacceptable data scatter. Also, it was concluded that measured data from steam meter FI 3102 was of questionable value in calculating performance parameters. This conclusion was consistent with the actual operating experience and reliability associated with that meter. During any plant charging operation, it was exposed to the most severe (highest temperature) steam conditions of any steam flowmeter and its lack of reliability reflected this severe operating environment. As in the case of Figure 2.10, data contained in this figure show charging efficiencies greater than 100 percent. Since no steam side flowmeter data were used in this figure, this trend supports the conclusion that the oil flowmeters were biased to read high. Note that if the steam dump system or a bootleg drain were in service or leaking through, this would have biased the data toward a charging efficiency of less than 100 percent.

Several alternate charging power correlations were made, involving additional comparisons between measured and calculated steam flowrates (power) and measured oil flows (power), although none of these correlations yielded acceptable results (good agreement regarding charging power). It was then decided to use data from the charging desuperheater spray water flow measurement to calculate steam flow. By using this water flow measurement, and state point conditions within the charging system, it was possible to calculate the charging steam flowrate and corresponding charging steam side power. Figure 2.12 (also reproduced from Reference 3 with Mode 5 data added) shows the correlation that exists between the calculated steam side power (based on spray water flow) and measured oil side power. It exhibits the best correlation over all others investigated. In general, all of the data points are located along the 120 percent line within a deviation of -10 percent to +5

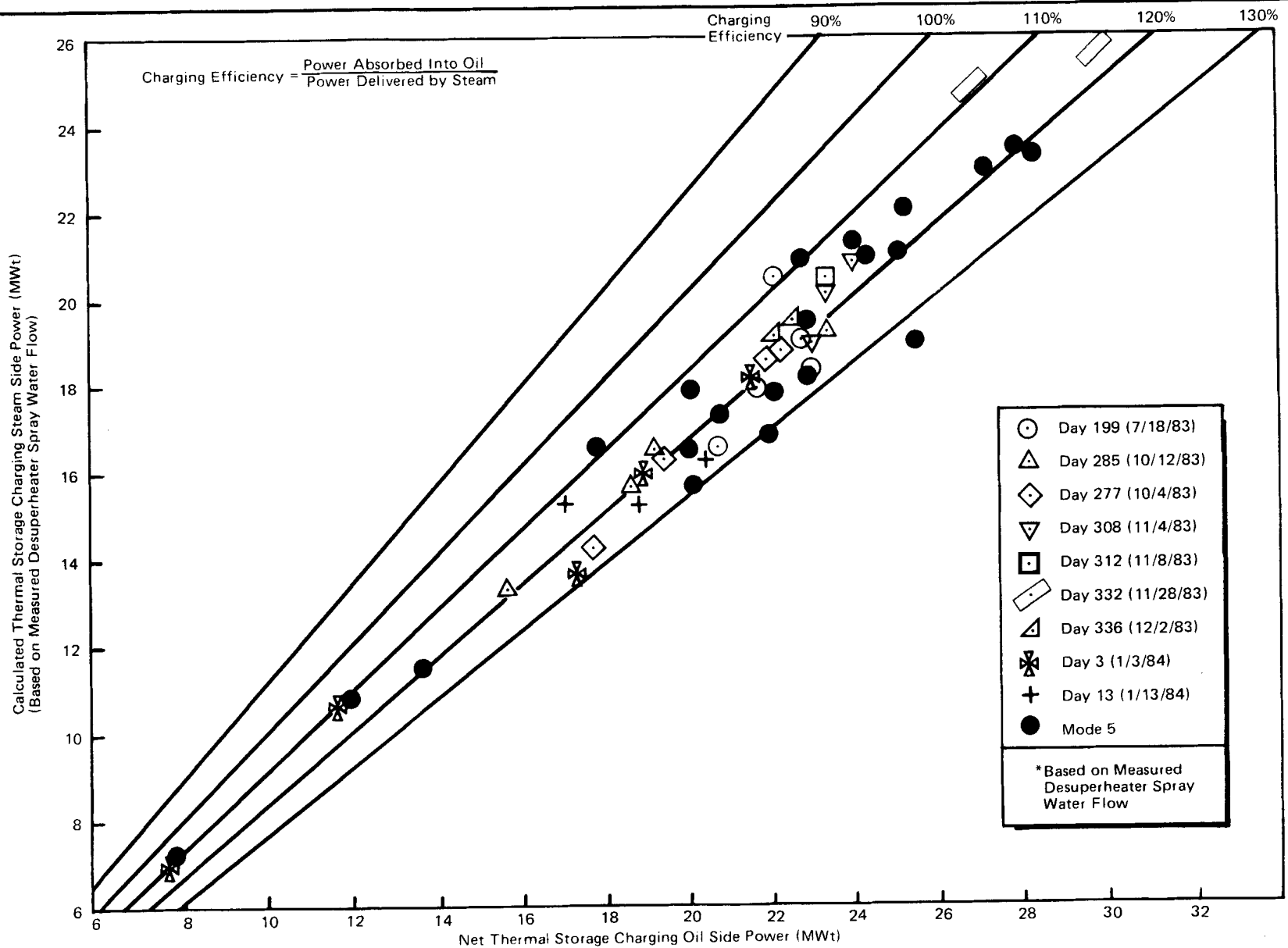


Figure 2.12. Charging System Correlation Between Calculated\* Steam Side and Oil Side Power

percent, with the majority having a deviation of  $\pm 5$  percent about the 120 percent efficiency line. The fact that the correlation is at a charging efficiency greater than 100 percent again argues that the oil flowmeters were indicating artificially high flowrates.

Based on the results of these charging power correlations, the following conclusions were made (for purposes of performance comparison):

- (1) The calculated charging steam flow based on measured spray water flow will become the basis for determining charging steam power, and
- (2) Due to the consistently high values of the calculated oil side power (independent of the correlation attempted), it was concluded that oil side flow data were artificially high by a factor of 15 to 25 percent.

## 2.5 MODE 5 TEST RESULTS

The test results and supporting discussions in this section address the three areas of plant operation discussed in Section 2.2; plant start-up to Mode 5 as well as shutdown from Mode 5 and transitions within Mode 5 (dual to single train, diurnal insolation variation, cloud transients), performance aspects of steady-state plant operation in Mode 5, and the effects of trips which occur while operating in Mode 5.

### 2.5.1 Start-up and Transitions

During the Mode 5 test program, a number of leaks developed in the charging heat exchangers. Leakage occurred in both the steam and oil sides and in the main shell flange joints and at the tube-to-tube-sheet joints. The leaking main flange joint gaskets (3) which were replaced remained leak-free. A review of operating procedures and design limits was conducted to investigate the possibility of leakage resulting from high stresses produced by excessive thermal gradients during steady state operation as well as start-up.

A review of TSS heat exchanger operation experience and start-up temperature data indicated that the charging circuit heat exchangers experienced the largest temperature differences. This resulted from two factors. First, the condenser, which had a relatively small design temperature difference of 63°F, actually operated in a dual mode as a condenser and subcooler with much larger temperature differences. For nine runs investigated, this value was as large as 240°F during steady state operation. Second, the oil coming from the TSU was typically in the 250°F to 300°F range, well below the design temperature of 425°F.

A characteristic of the charging heat exchanger network was that the subcooler water outlet temperature was "anchored" to within 10 to 20°F of the oil inlet temperature. Thus, with the colder oil inlet temperature, the normal channel side temperature drop of 215°F (650° - 435°F) in the condenser/subcooler would increase to 390°F (650° - 260°). If the condenser operated solely in the condensing mode, this would result in a temperature drop of 327°F from the entrance to the exit of the subcooler. If a large amount of subcooling occurred in the condenser, the condenser temperature drop would be higher than the 250°F normal operating limit. The above conditions could occur during steady state operation, or, when superimposed on start-up conditions, could result in even larger temperature differences. A review of charging heat exchanger data from nine operational periods was made to evaluate these temperature differences (see Table 2.2).

During the period of time from day 123 (5/3/83) to day 193 (7/12/83), control tests were being conducted and the thermal storage charging network was started with a variety of steam pressure rise ramps and warm-up modes. During these tests, temperature differences as high as 350°F and 270°F were imposed

TABLE 2.2 CHARGING CIRCUIT OPERATIONS

1983 DAY	TIME OF DAY		TIME TO OPERATION MIN	CONDENSER, °F			SUBCOOLER, °F			W, KLBH WARMUP
	STEAM TO COND	REACHED OPERATING PRESSURE		T IN	T OUT	ΔT MAX	T IN	T OUT	ΔT MAX	
123	0750	0825	35	*	*	*	*	*	*	0
125	0815	0840	25	600	430	170	580	360	220	200
131	0800	0815	15	580	280	300	580	310	270**	0
137	*	1005	--	*	*	*	580	350	230**	0
155	0825	0925	60	500	150	350	570	320	250	0
174	0820	0945	85	640	470	170**	530	350	180	65
182	0845	0935	50	*	*	*	*	*	*	60
192	0936	1244	188	640	400	240**	580	310	270**	70
193	0830	0920	50	650	440	210	530	290	240	70

---

\*DAS NOT ON DURING START-UP

\*\*MAX DURING "STEADY STATE" (NOT START-UP)



on the condenser (day 192) and subcooler (day 192) respectively. The maximum temperature differences were not necessarily associated with start-up.

The maximum subcooler temperature difference, 270°F, occurred during day 131 and day 192 after reaching operating conditions. This resulted from water leaving the condenser at saturation conditions, the subcooler doing all of the subcooling and with relatively low temperature oil coming from the TSU. The data from day 192 are shown in Figure 2.13. During this period, the heat exchangers were cyclicly operating over a range of heat duty.

During charging system start-up, from a period of cold soak, it was important to provide a warm-up period of oil circulation before steam entry where the oil and water in the lines and heat exchangers were warmed to the temperature of the oil leaving the lower manifold in the TSU. Normally, oil leaving the TSU was 250°F or higher. Figures 2.14 and 2.15 present data from two comparable days with and without warm-up.

Charging on day 125 (Figure 2.14) was performed with an oil circulation warm-up that resulted in maximum condenser and subcooler temperature differences of 170°F and 220°F, respectively, which were within the prescribed limits. Prior to steam entry, oil from the lower manifold was circulated through the charging circuit which warmed the equipment and lines to approximately 350°F. Full operating steam pressure at the condenser was achieved 25 minutes after steam entry resulting in a total start-up time of 45 minutes.

Day 155 (Figure 2.15) is representative of a start without warm-up and condenser and subcooler temperature differences reached 350°F and 250°F,

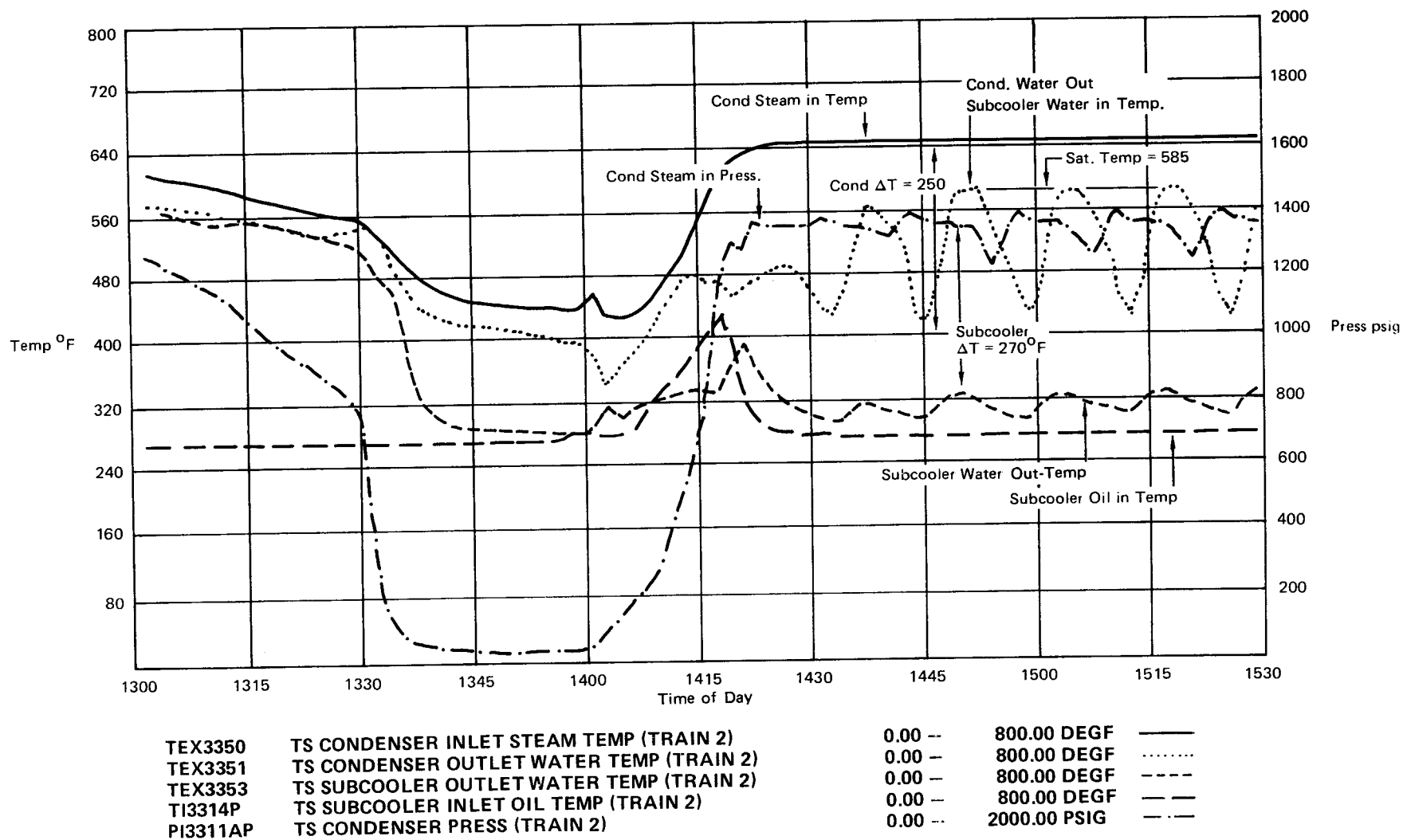
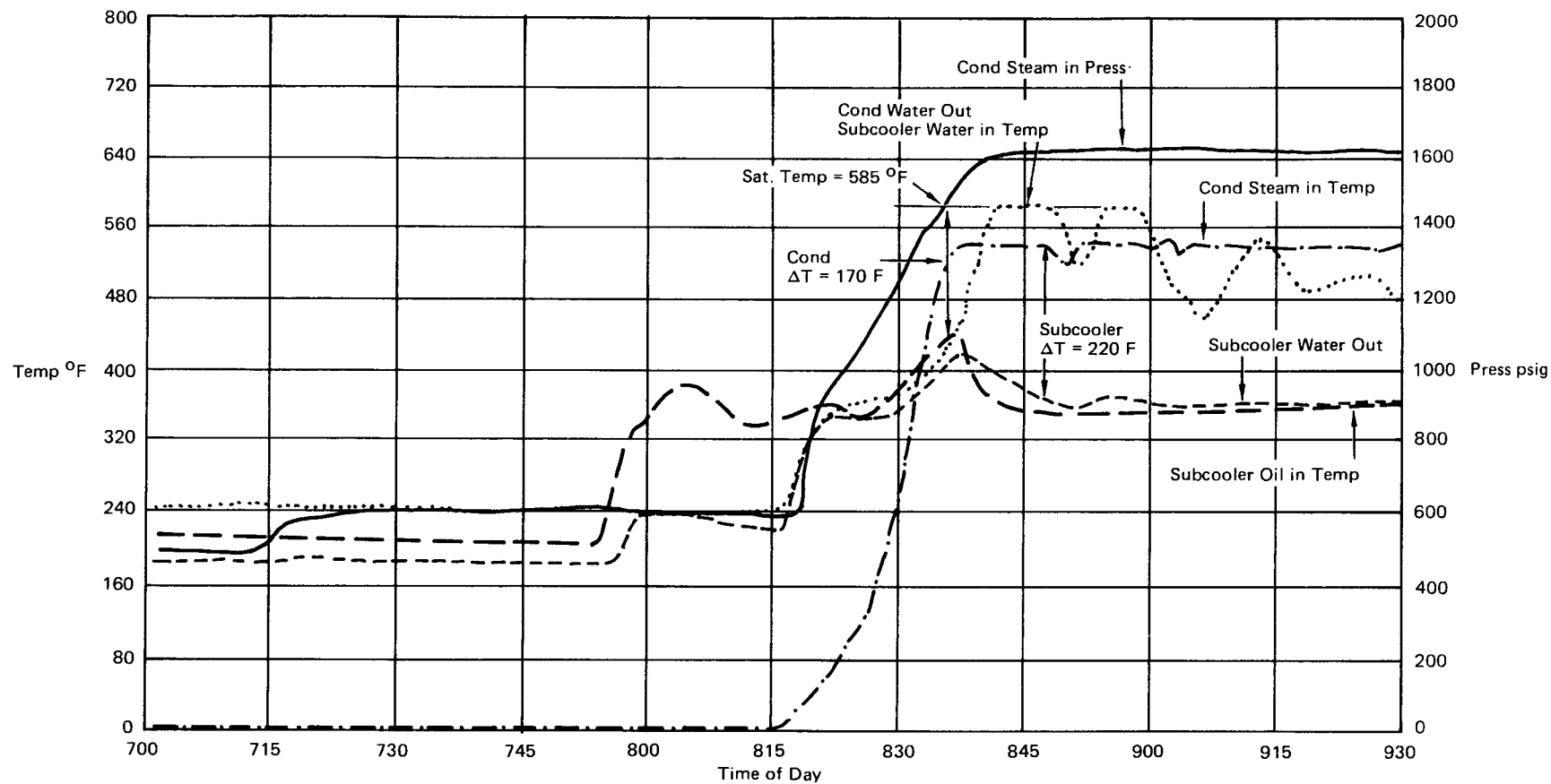


Figure 2.13. Day 192 (7/11/83) Charging Operation



TEX3250	TS CONDENSER INLET STEAM TEMP (TRAIN 1)	0.00	—	800.00 DEGF	——
TEX3251	TS CONDENSER OUTLET WATER TEMP (TRAIN 1)	0.00	—	800.00 DEGF	.....
TEX3253	TS SUBCOOLER OUTLET WATER TEMP (TRAIN 1)	0.00	—	800.00 DEGF	----
TI3214P	TS SUBCOOLER INLET OIL TEMP (TRAIN 1)	0.00	—	800.00 DEGF	-.-.-
PI3210P	TS CONDENSER PRESS (TRAIN 1)	0.00	—	2000.00 PSIG	----
*					

Figure 2.14. Day 125 (5/5/83) Charging Start-Up, with Warm-Up

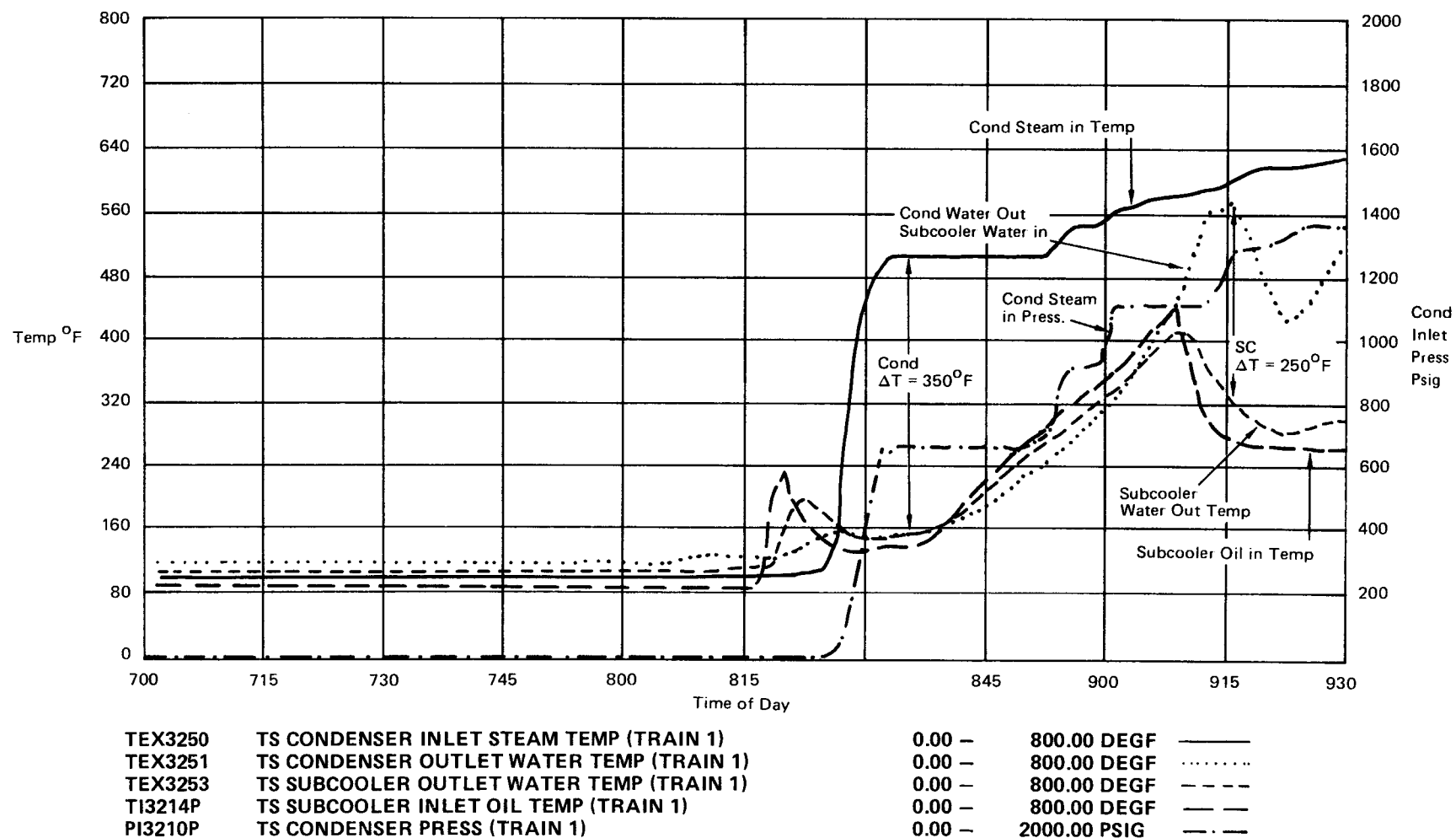


Figure 2.15. Day 155 (6/4/83) Charging Start-up, No Warm-Up

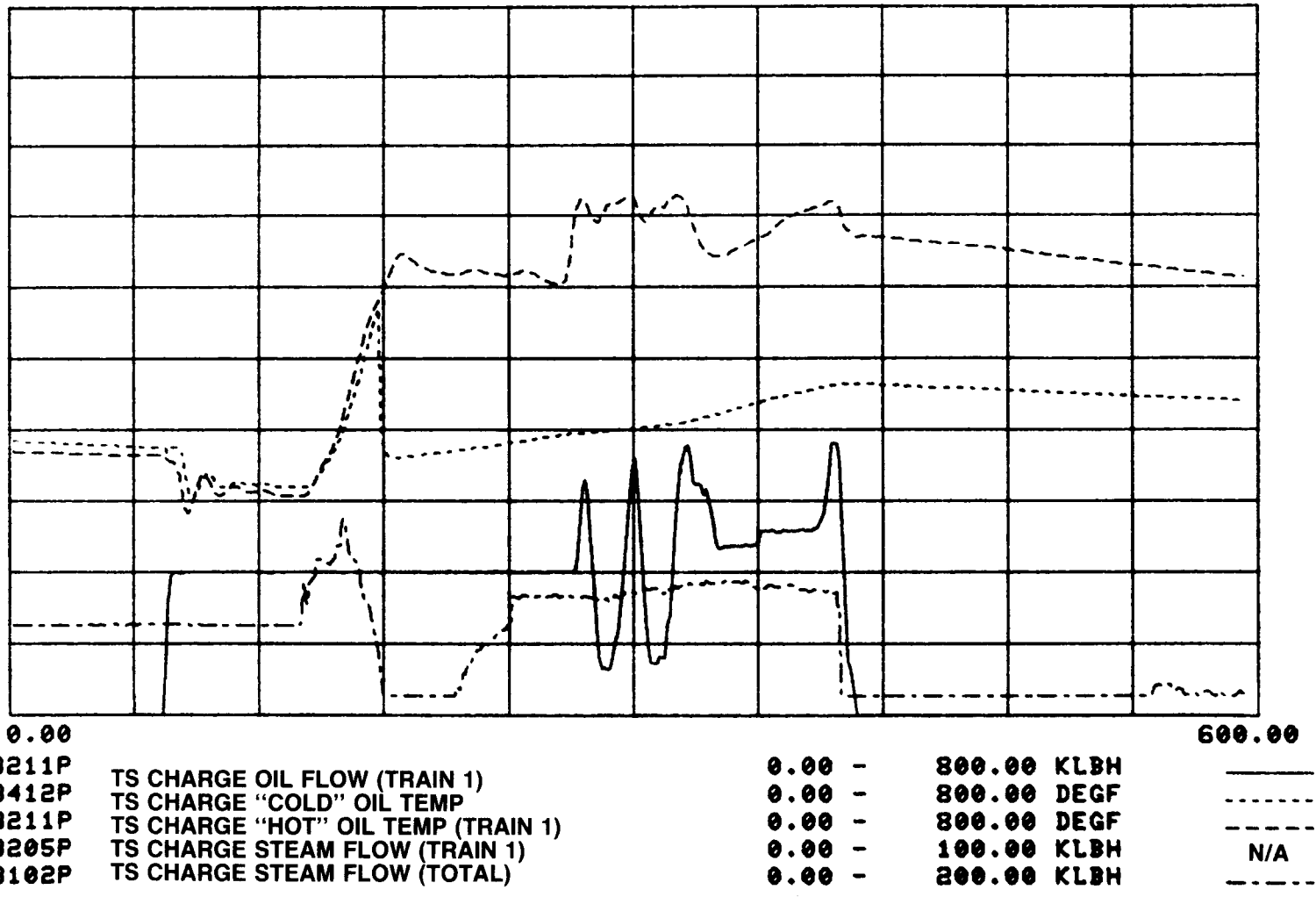
respectively. Even with a relatively long steam pressure ramp (60 minutes), higher equipment temperature differences existed compared to day 125 (which had a warm-up period and a much shorter start-up time). In addition to the warm-up oil circulation, control of the condenser steam inlet pressure rise ramp was implemented. During the initial start into a cool system, the steam temperature into the condenser would be equal to the saturation temperature corresponding to the steam pressure (a linear temperature ramp would require a non-linear pressure ramp since the saturation temperature changes much more rapidly at low pressure than at high pressure).

The sequence of events for plant start-up from steam dump operation to Mode 5 was developed during the Mode 5 test program. SDPC automation routines were developed to implement the sequence while minimizing operator initiated activities. Charging train warm-up and gradual system pressurization were implemented to minimize heat exchanger overall temperature differences during start-up (thereby minimizing thermal stresses). The start-up sequence developed, combining activities discussed in Section 2.1.2, is as follows:

1. Verify receiver total flowrate. If flow is greater than 90 KLBH, two charging trains must be operated.
2. Check/establish proper steam conditions for charging pressurization (receiver temperature setpoint nominally 775° to 850°F, steam dump pressure nominally 1000 psig).
3. Check the pressure differential across the charging inlet steam valve(s). If the differential pressure is greater than 100 psi, open the appropriate drain valve to reduce the differential pressure to less than 100 psi.
4. Execute a "run" cycle on the selected charging train(s). Prewarm and start the charging oil pump appropriate to the selected train (P301/P302). The TSU valves will be aligned to route oil flow from the bottom manifold, through the charging heat exchangers, and back into the TSU through the auxiliary manifold.

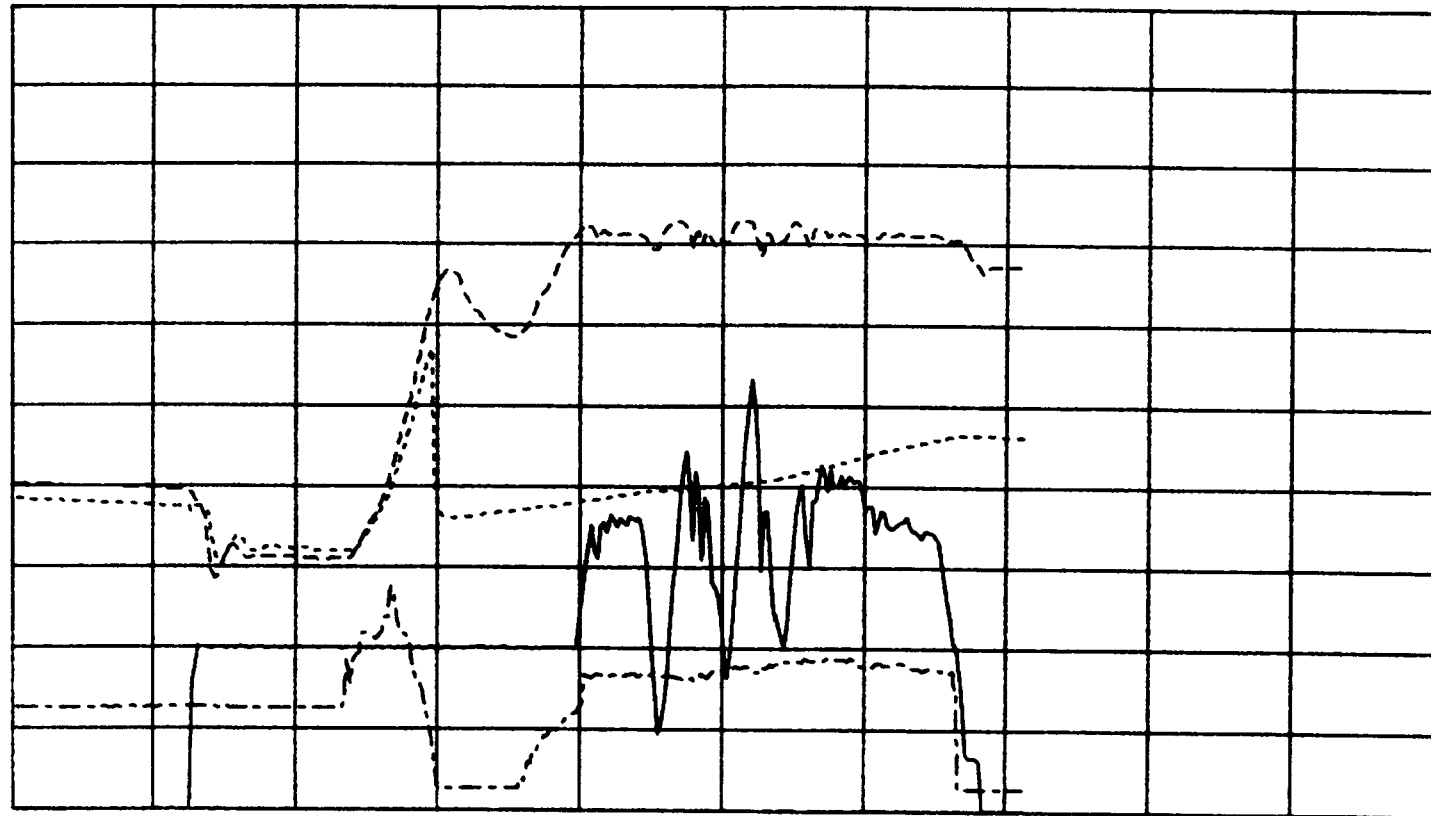
5. Initiate the auto pressurization sequence to pressurize the charging train(s) at a rate of approximately 30 psi per minute.
6. Following completion of the pressurization sequence, place the main charging steam inlet valve (UV3102) controller to manual and increase the steam dump pressure to 1400 psig.
7. Gradually open UV3102 (by 2 percent increments) until the steam dump valve is fully closed. Then switch the UV3102 controller to pressure control and increase the steam dump pressure setpoint to 1425 psig. When the charging train outlet oil temperature reaches 500°F, the TSU valves will automatically be realigned to route oil from the bottom manifold to the upper manifold. When the outlet oil temperature reaches 570°F, the oil system will automatically switch to temperature control.

Figure 2.16 (a thru e) illustrates the startup, transition to Mode 5, Mode 5 and shutdown for dual charging train operation on 9/16/83. Figures 2.16 (a) and (b) show charging system oil flows, "hot" and "cold" oil temperatures, and total charging steam flow (both individual train steam flowmeters were inoperative on this day). As shown in these figures, the charging oil flows were started at approximately 8:10 AM (solid lines) and run for some period prior to introducing charging steam. The starting point for the oil system during testing was arbitrary and carried out by the operators at a time when their work load permitted activating the oil pumps. The intent was to circulate warm oil through the heat exchangers and to allow them to warm up for a period of at least 30 minutes prior to the introduction of charging steam. During this period of initial oil circulation, the oil would bypass the thermal storage tank resulting in equal "cold" and "hot" oil temperatures (as indicated on the plots).



**Figure 2.16(a). Day 259 Dual Charging Train Operation – Train 1 Oil Parameters**

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)



0.00		600.00	
FI3310P	TS CHARGE OIL FLOW (TRAIN 2)	0.00 -	800.00 KLBH
TI3412P	TS CHARGE "COLD" OIL TEMP	0.00 -	800.00 DEGF
TI3310P	TS CHARGE "HOT" OIL TEMP (TRAIN 2)	0.00 -	800.00 DEGF
FI3305P	TS CHARGE STEAM FLOW (TRAIN 2)	0.00 -	80.00 KLBH
FI3102P	TS CHARGE STEAM FLOW (TOTAL)	0.00 -	200.00 KLBH

**Figure 2.16(b). Day 259 Dual Charging Train Operation – Train 2 Oil Parameters**



SOLAR DATA PLOT PLOT # P209  
 REFERENCE TIME: 259 07 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
 600.0000 MINUTE(S)

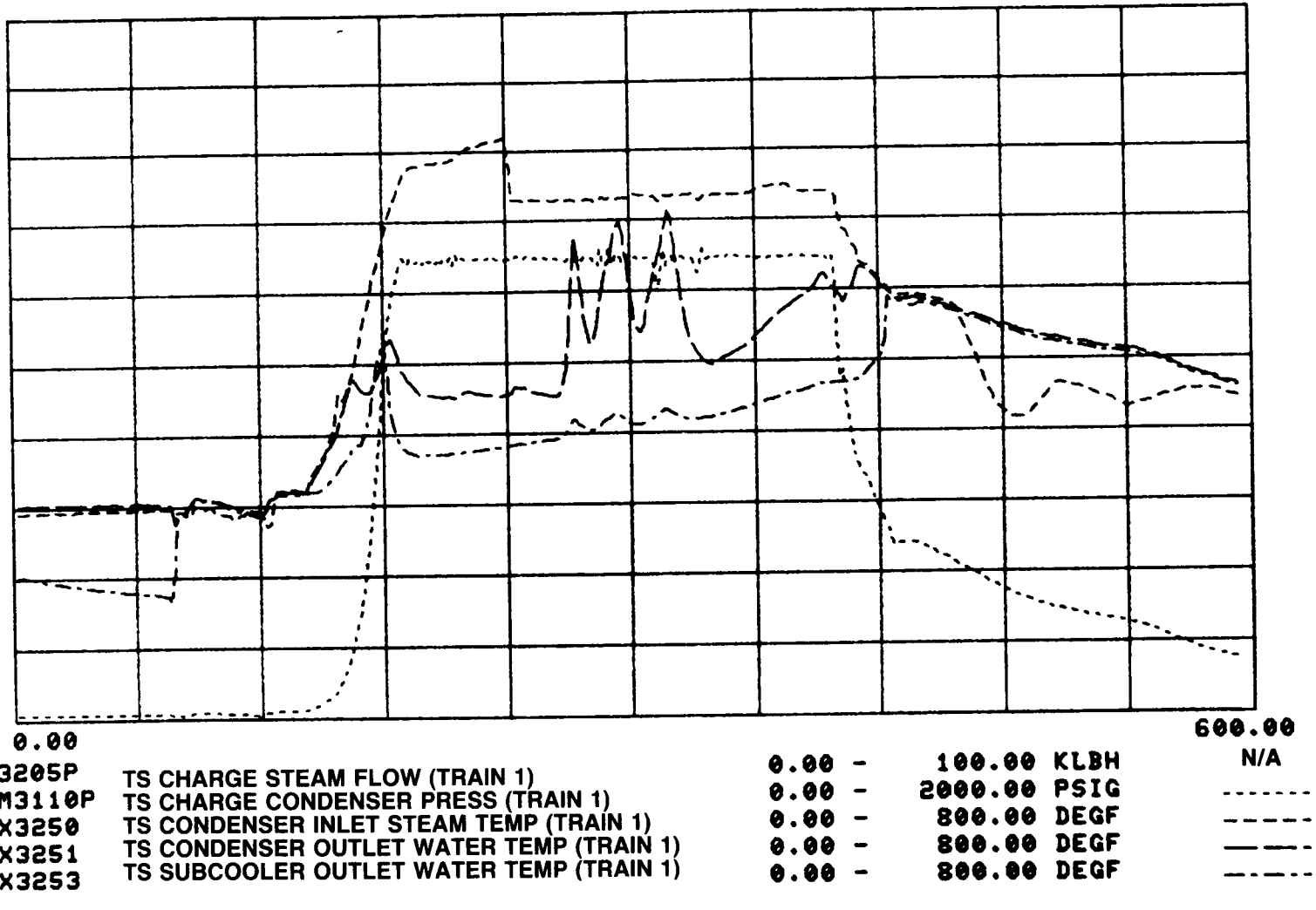


Figure 2.16(c). Day 259 Dual Charging Train Operation – Train 1 Water/Steam Parameters

SOLAR DATA PLOT PLOT # P210 NTH SAMPLE AVERAGE = 10  
REFERENCE TIME: 259 07 00 00.000 FOR 600.0000 MINUTE(S)

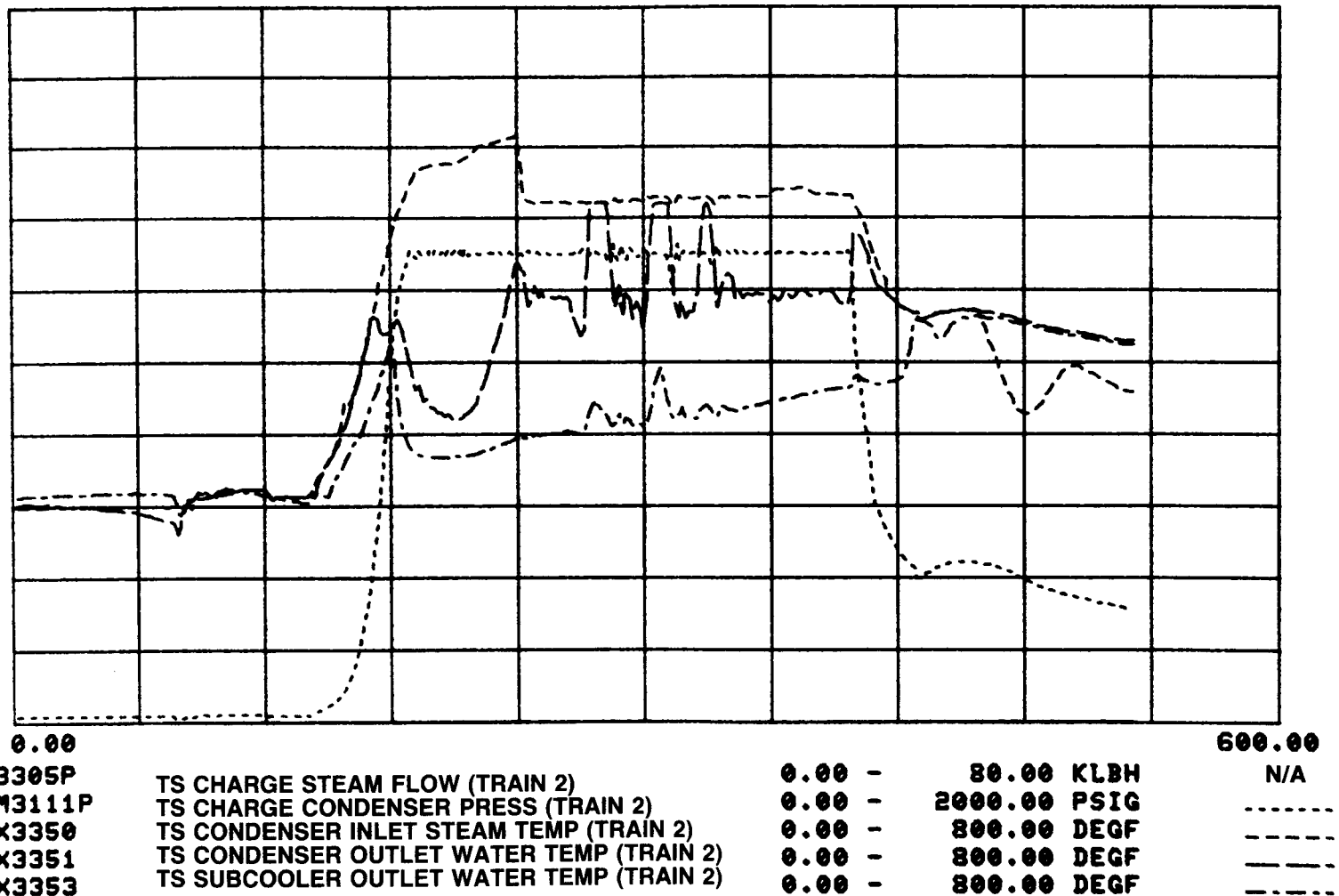
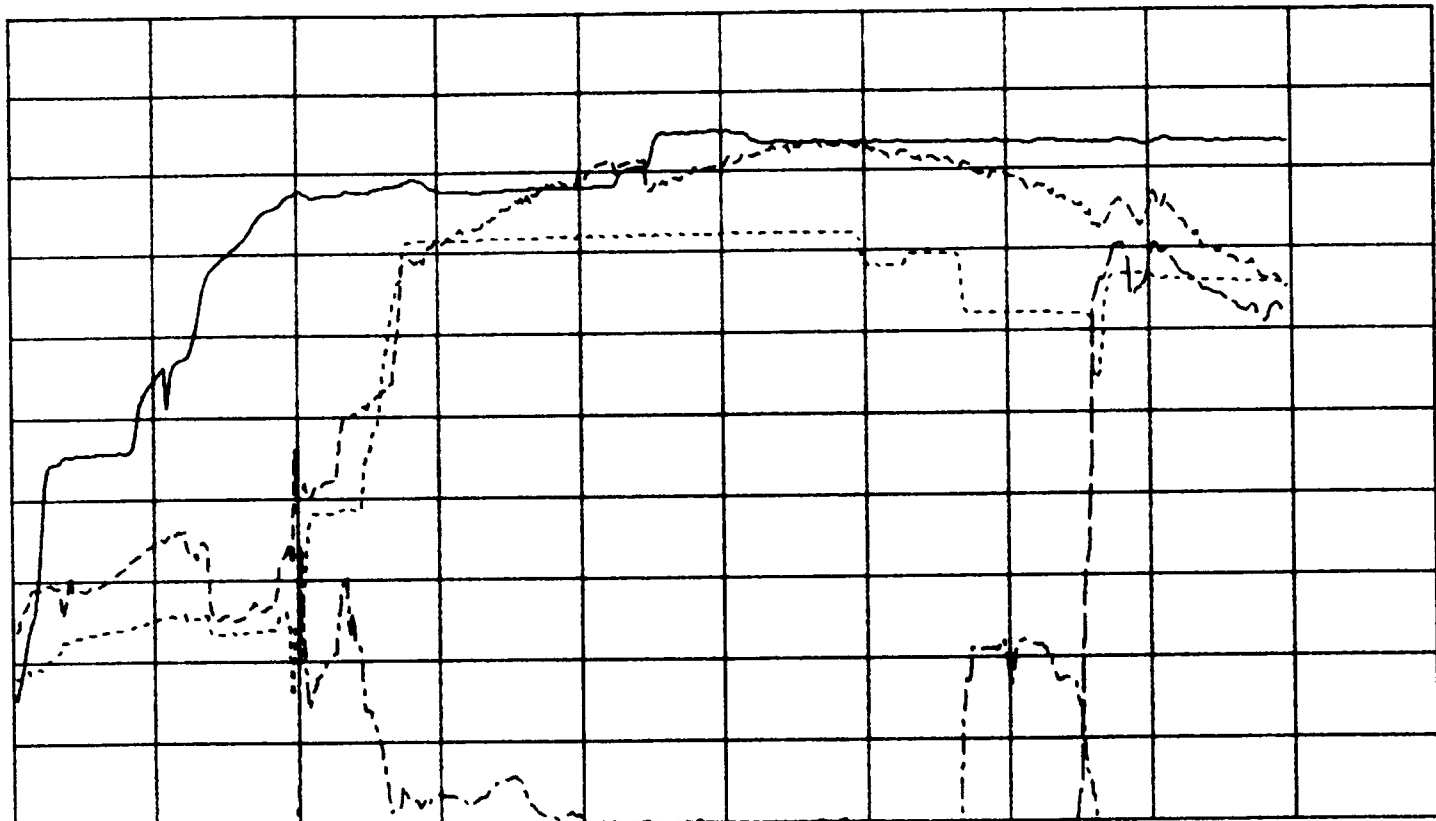


Figure 2.16(d). Day 259 Dual Charging Train Operation – Train 2 Water/Steam Parameters

SOLAR DATA PLOT PLOT # P206  
REFERENCE TIME: 259 07 00 00.000 FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)



0.00					600.00
TI2903P	REC DISCHARGE STEAM TEMP	0.00 -	1000.00	DEGF	_____
PI2902P	REC DISCHARGE STEAM PRESS	0.00 -	2000.00	PSIG	-----
FI2233P	REC FEEDWATER FLOW	0.00 -	100.00	KLBH	-----
JIC5100P	GROSS ELECTRICAL POWER	0.00 -	10000.00	KW	_____
ZI1001P	STEAM DUMP VALVE POSITION	0.00 -	100.00	PCT	-----

Figure 2.16(e). Day 259 Dual Charging Train Operation – Receiver Parameters

At approximately 9:18 AM, the charging system auto pressurization sequence was initiated and steam flow was introduced into both charging trains. The gradual system pressure increase to the final operating condition is shown in Figures 2.16 (c) and (d). The charging steam flowmeter (FI3102P) indicated response to the steam flow although the meter output was not correct in magnitude. Once the steam flow was introduced into the charging system, the "hot" oil temperatures (TI3211P, TI3310P) began to rise. Since the oil continued to bypass the thermal storage tank until the "hot" oil temperature exceeded 500°F, the "cold" oil temperatures (TI3412P) tracked the upward trend of the "hot" oil temperatures. Once the "hot" oil temperature in Train 2 exceeded 500°F, the "hot" oil flow was automatically diverted to the top of the thermal storage tank and "cold" oil was withdrawn from the bottom of the tank. At that time (approximately 9:55 AM), the data plots for the "hot" and "cold" oil temperatures diverged to their steady state values with the "hot" oil temperatures being set by the controlled oil flowrate through the charging heat exchangers and the "cold" oil temperature being set by the bottom temperature being withdrawn from the thermal storage tank.

At approximately 10:30 AM the charging steam flow was gradually increased until (at 11:00 AM) all the receiver steam was flowing to the charging heat exchangers and the plant was operating in Mode 5. This is seen on Figure 2.16(e) as the steam dump valve became fully closed (the steam dump valve had opened at 9:00 AM as the receiver steam downcomer was pressurized during receiver startup). In response to the increased charging steam flow, the "hot" oil temperature in Train 2 (Figure 2.16(b) increased to 570°F and the oil flow controller switched to temperature control. This event can be seen as the rapid increase in Train 2 oil flow at approximately 11:00 AM. At approximately 11:30 AM, Train 1 switched to temperature control initiating a series of flow/temperature oscillations which were typical of the majority of dual charging train operation days.

Prior to Train 1 temperature control operation, oil and steam flows were relatively stable. With the rapid increase in Train 1 oil flow, the system flow stability was upset and more steam flow was diverted to Train 1 with resultant decrease in steam/oil flow to Train 2. The change in heat exchange duty in the Train 2 condenser can be seen on Figure 2.16(d) as the condenser steam/water outlet temperature approached the steam inlet temperature and the condensing duty was transferred to the subcooler. As the Train 2 "hot" oil temperature decreased to the lower limit of the control band, the Train 2 oil flow rapidly increased with resultant increase in Train 2 steam flow and decrease in Train 1 steam flow. This flow oscillation process would continue as long as the controllers were in AUTO. On this particular operating day, the Train 1 oil temperature controller was put into manual at approximately 12:20 PM, thereby eliminating the instability. Subsequent to the Mode 5 test program, the dual train flow instability problem was solved by changing the control scheme such that both charging train condensate drain valves were controlled by a single controller. This forced the steam flow in each train to be nearly identical and prevented train-to-train flow instability.

At approximately 13:35 PM, the thermal storage tank was fully charged and Mode 5 shutdown was initiated by terminating charging steam flow (FI3102P, Figures 2.16 (a) and (b)). Then, as the "hot" oil temperatures decayed to 540°F (Train 1) and 536°F (Train 2), the charging oil pumps were automatically shutoff and the TSU manifold valves realigned concluding the Mode 5 shutdown sequence. As the steam flow to the charging trains was terminated, the steam dump valve automatically opened to accept the receiver steam (see Figure 2.16 (e)).

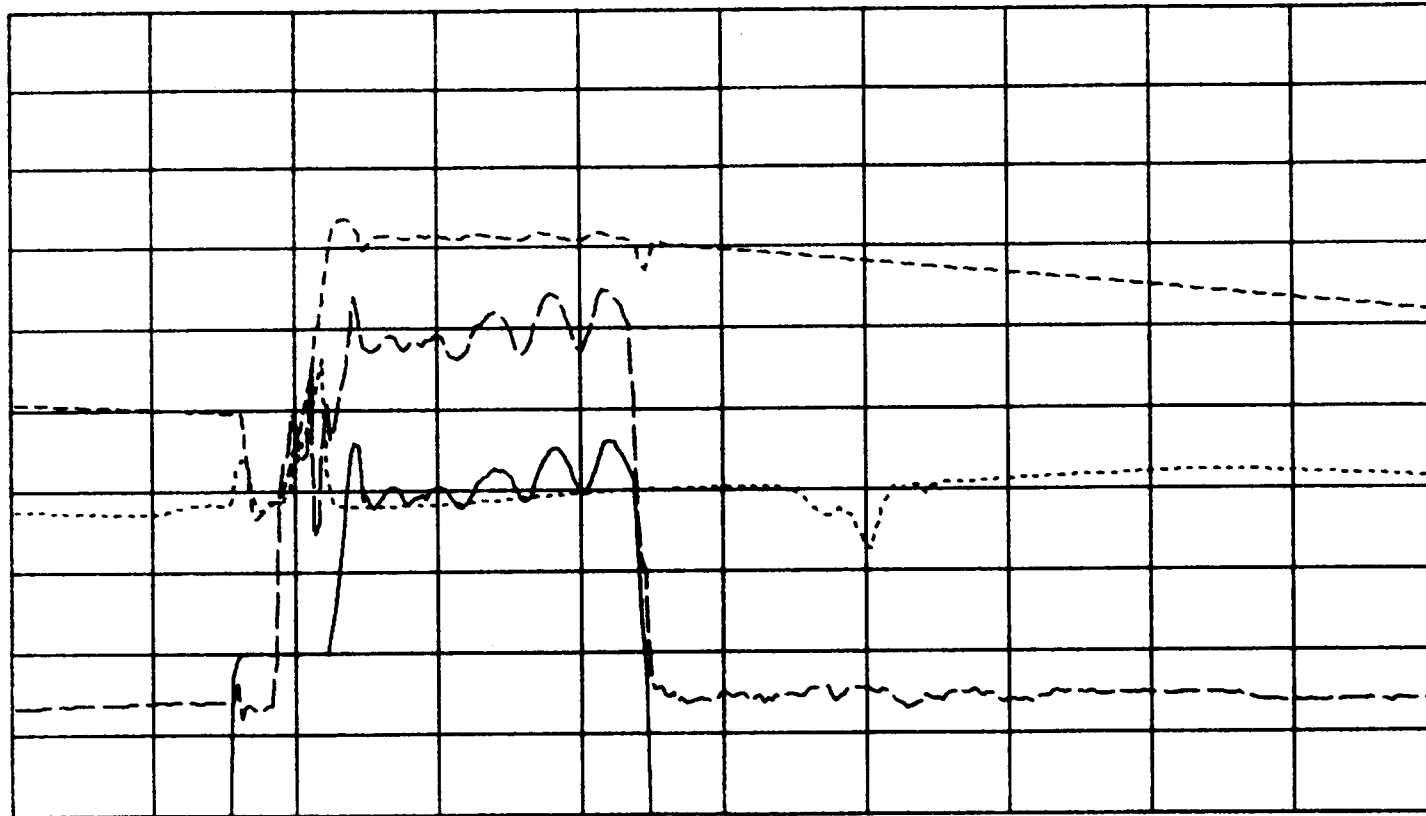
Data from day 333 (11/29/83) are presented in Figure 2.17 (a thru f) for a 10 hour period starting at 7:00 AM. Plant operation during this period included dual train Mode 5, transition to single train and low-to-high flow single train operation. Startup and dual train pressurization occurred as per the previous discussion with the charging system in pressure control (Mode 5) at approximately 9:15 AM (steam dump valve closed, Figure 2.17 (e), and the charging system accepting all the receiver steam).

At approximately 11:20 AM, the charging system was placed into FLOW control and the total charging steam flow reduced to 40 KLBH in preparation for a dual-to-single train transition test. The excess receiver-generated steam was introduced into the steam dump system and the steam dump valve re-opened (ZI1001P, Figure 2.17 (e)). At approximately 11:25 AM Charging Train 1 was shutdown and all charging steam was accepted by Train 2. The resultant upset in Train 2 condenser/subcooler process conditions can be seen in Figure 2.17(d).

The increase in condenser steam outlet temperature (TEX3351) to the saturated steam level and the "spike" in subcooler outlet temperature (TEX3353) indicated a period of time when the steam inlet rate to Train 2 exceeded the condensing rate. The excess steam flowed through the subcooler and into the TSS flash tank resulting in a peak flash tank pressure of approximately 148 psig (just below the relief level of 165 psig). Although a significant process upset occurred, only slight perturbations in the Train 2 charging oil outlet temperature occurred (TI3310P, Figure 2.17(b)). The process upset indicated that care must be exercised in the dual-to-single train transition such that the transition would only occur at a total charging steam flow of less than approximately 45 KLBH in order to prevent excessive flash tank pressures.

SOLAR DATA PLOT PLOT # P207  
REFERENCE TIME: 333 07 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)



0.00										600.00
FI3211P	TS CHARGE OIL FLOW (TRAIN 1)	0.00 -	800.00	KLBH		_____				
TI3412P	TS CHARGE "COLD" OIL TEMP	0.00 -	800.00	DEGF		-----				
TI3211P	TS CHARGE "HOT" OIL TEMP (TRAIN 1)	0.00 -	800.00	DEGF		-----				
FI3205P	TS CHARGE STEAM FLOW (TRAIN 1)	0.00 -	100.00	KLBH		-.-.-.-				
FI3102P	TS CHARGE STEAM FLOW (TOTAL)	0.00 -	200.00	KLBH		_____				N/A
*										

Figure 2.17(a). Day 333 Charging Train Transitions – Train 1 Oil Parameters

SOLAR DATA PLOT PLOT # P208  
 REFERENCE TIME: 333 07 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
 600.0000 MINUTE(S)

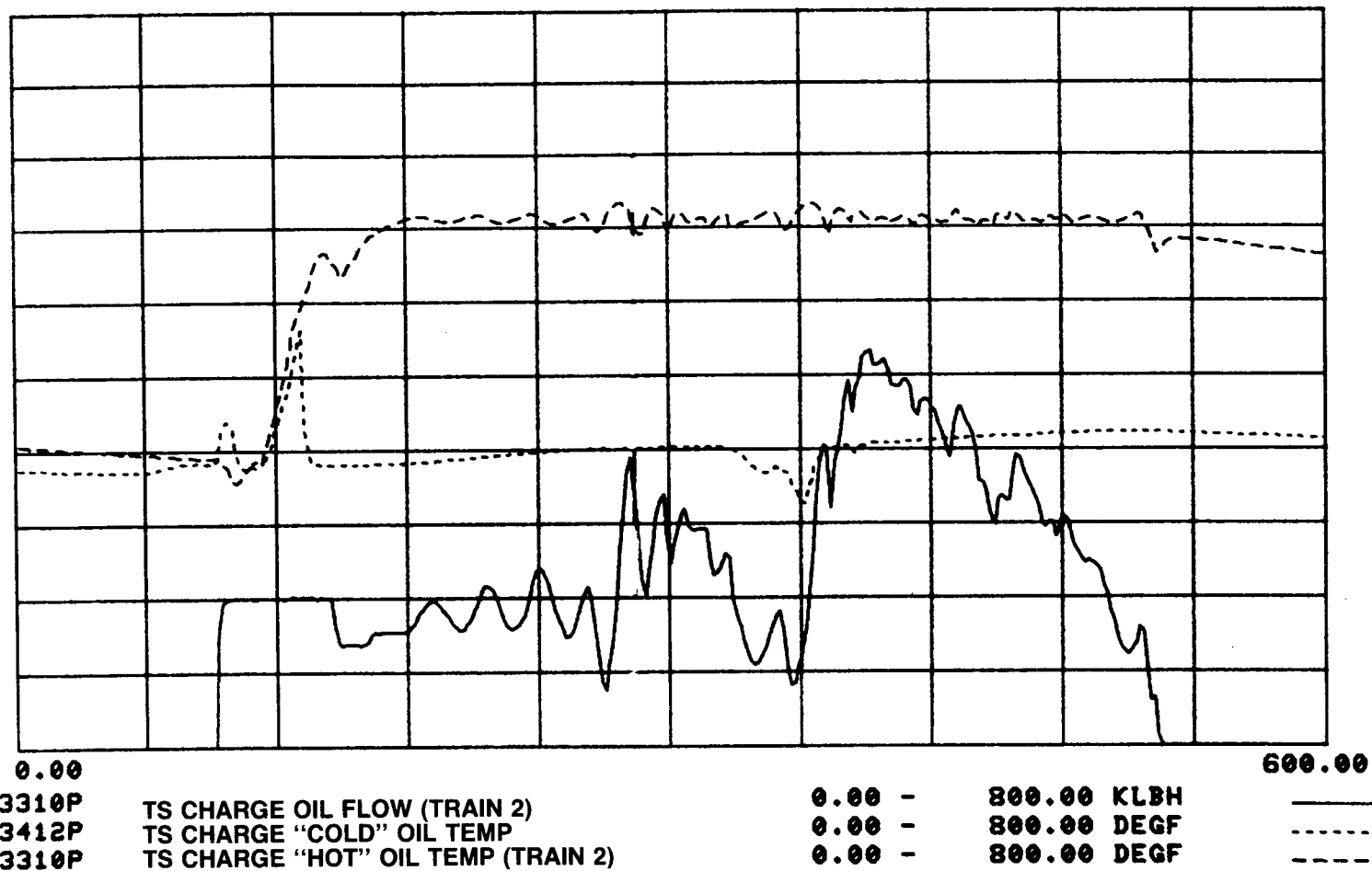


Figure 2.17(b). Day 333 Charging Train Transitions – Train 2 Oil Parameters



SOLAR DATA PLOT PLOT # P209 NTH SAMPLE AVERAGE = 10  
 REFERENCE TIME: 333 07 00 00.000 FOR 600.0000 MINUTE(S)

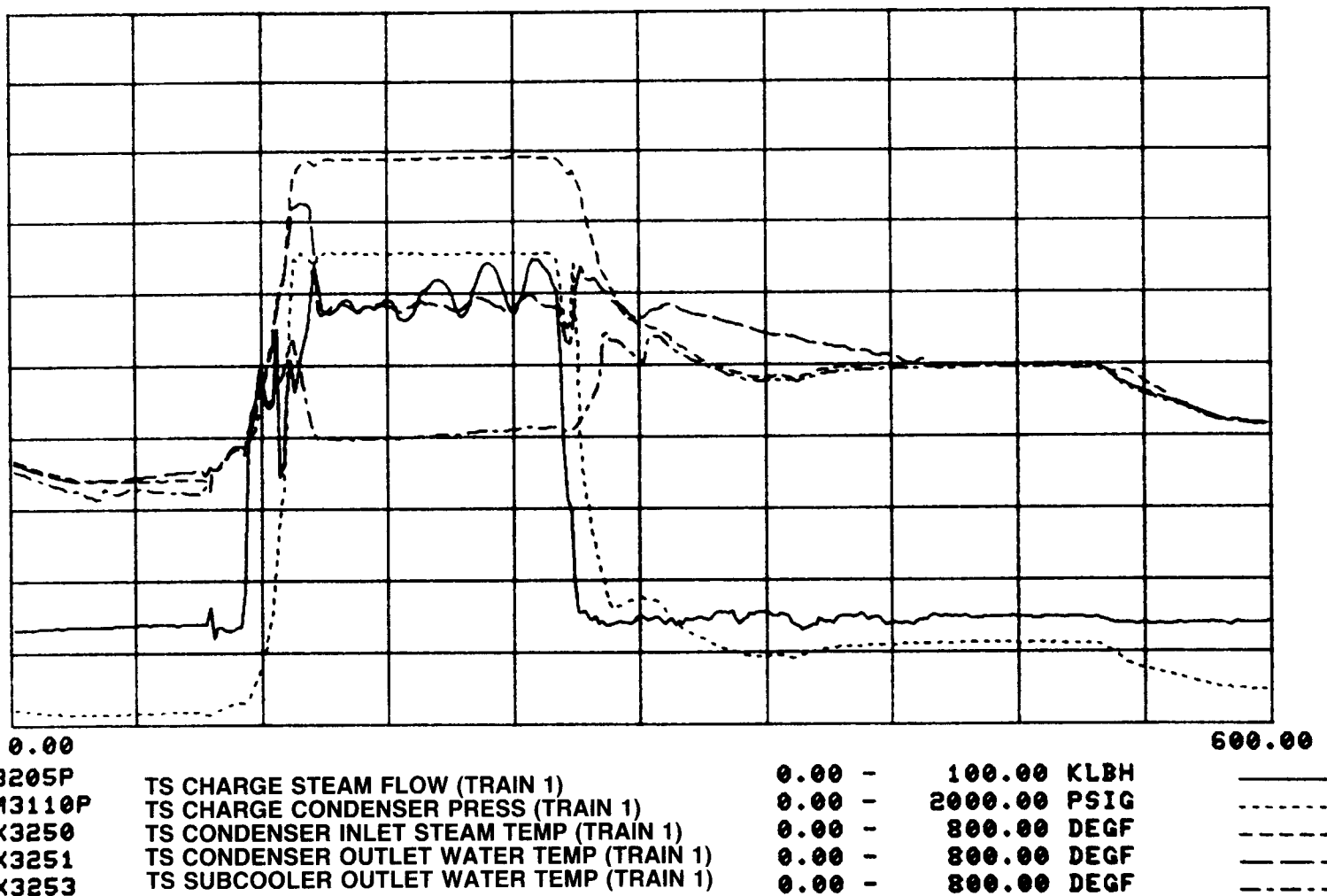
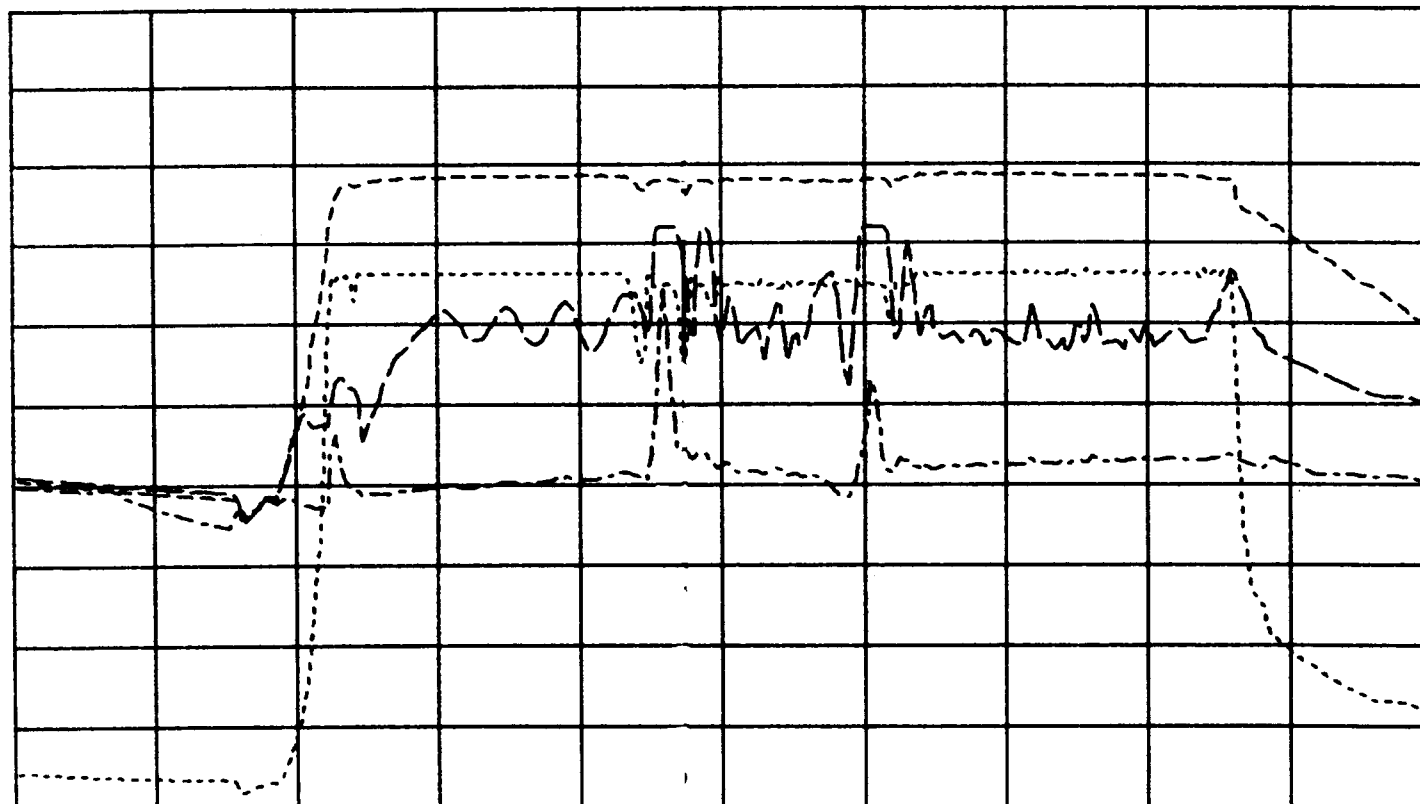


Figure 2.17(c). Day 333 Charging Train Transitions – Train 1 Water/Steam Parameters

SOLAR DATA PLOT PLOT # P210  
REFERENCE TIME: 333 07 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)

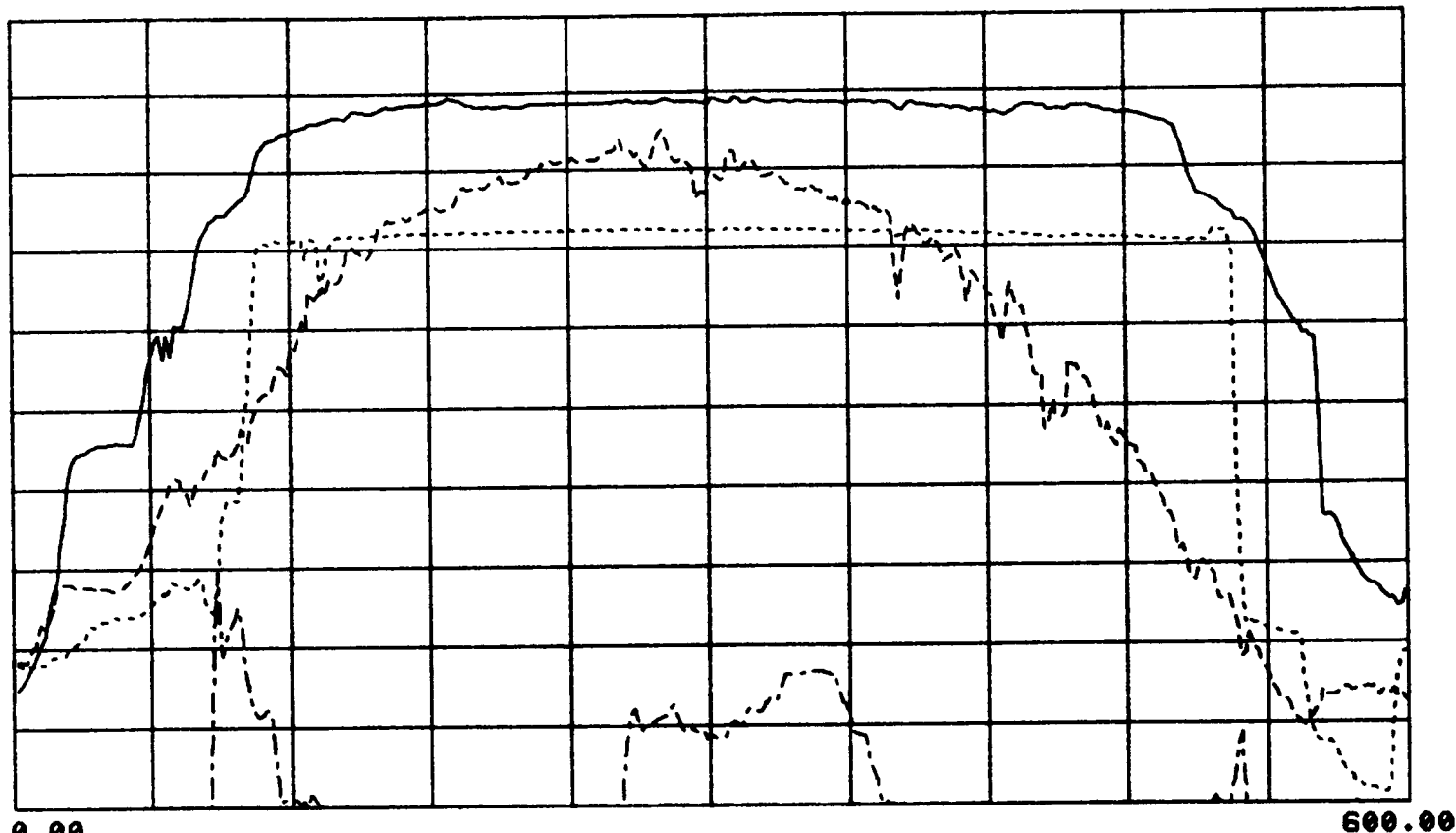


0.00									600.00
FI3305P	TS CHARGE STEAM FLOW (TRAIN 2)	0.00 -	80.00	KLBH				N/A	
PCM3111P	TS CHARGE CONDENSER PRESS (TRAIN 2)	0.00 -	2000.00	PSIG				-----	
TEX3350	TS CONDENSER INLET STEAM TEMP (TRAIN 2)	0.00 -	800.00	DEGF				-----	
TEX3351	TS CONDENSER OUTLET WATER TEMP (TRAIN 2)	0.00 -	800.00	DEGF				-----	
TEX3353	TS SUBCOOLER OUTLET WATER TEMP (TRAIN 2)	0.00 -	800.00	DEGF				-----	

Figure 2.17(d). Day 333 Charging Train Transitions – Train 2 Water/Steam Parameters

SOLAR DATA PLOT PLOT # P206  
REFERENCE TIME: 333 07 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)



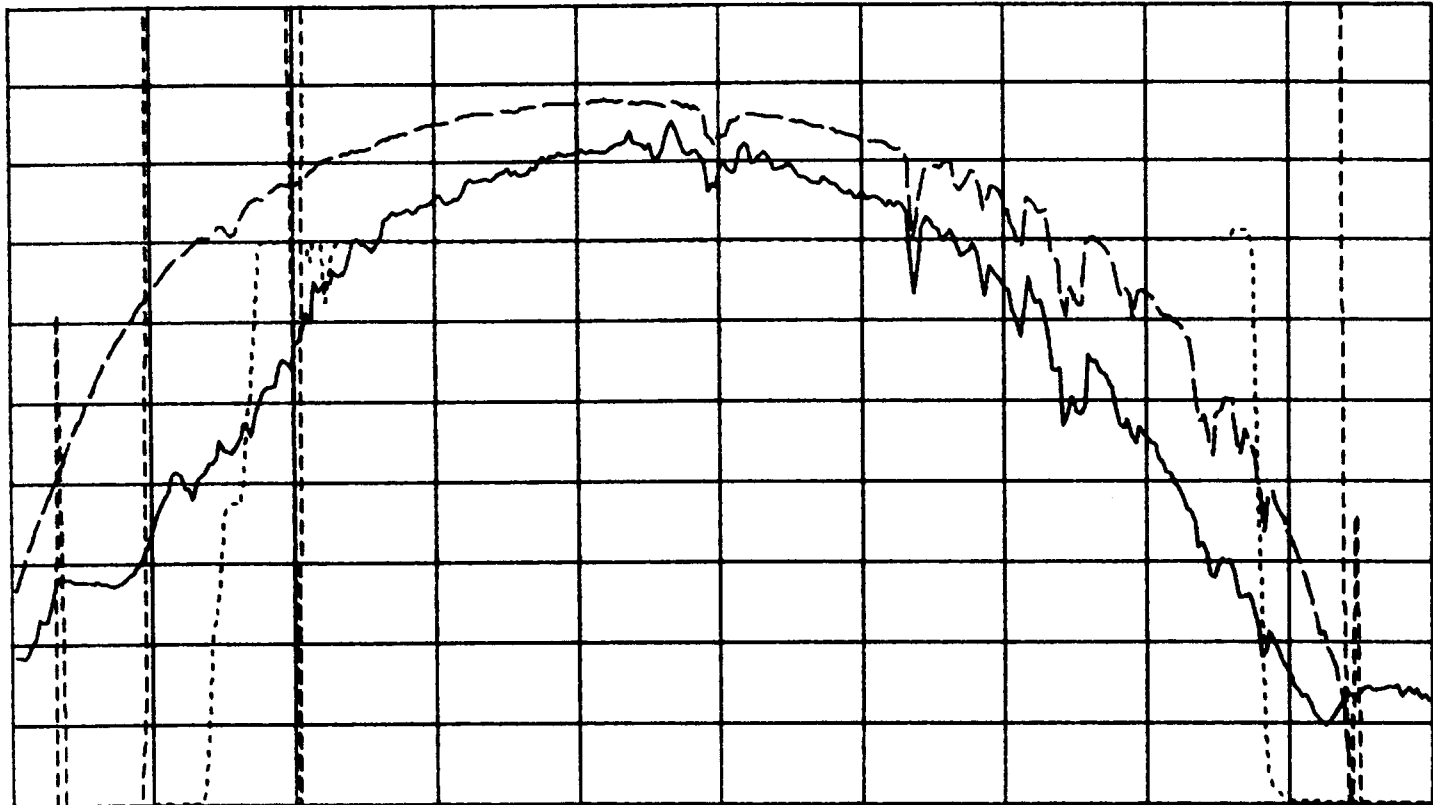
0.00  
TI2903P REC DISCHARGE STEAM TEMP  
PI2902P REC DISCHARGE STEAM PRESS  
FI2233P REC FEEDWATER FLOW  
JIC5100P GROSS ELECTRICAL POWER  
ZI1001P STEAM DUMP VALVE POSITION

0.00 - 1000.00 DEGF  
0.00 - 2000.00 PSIG  
0.00 - 100.00 KLBH  
0.00 - 10000.00 KW  
0.00 - 100.00 PCT  
N/A

Figure 2.17(e). Day 333 Charging Train Transitions – Receiver Parameters

SOLAR DATA PLOT PLOT # R2  
REFERENCE TIME: 333 07 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)



0.00						600.00
FI2233P	REC FEEDWATER FLOW	0.00 -	100.00	KLBH	_____	
PI1001P	MAIN STEAM PRESS	0.00 -	2000.00	PSIG	-----	
TI2904P	REC DISCHARGE STEAM TEMP	0.00 -	1000.00	DEGF	-----	
**ATX1817A	DIRECT INSOLATION	0.00 -	1000.00	W/M2	-----	
JIC5100P	GROSS ELECTRICAL POWER	0.00 -	10000.00	KW	-----	N/A
*						

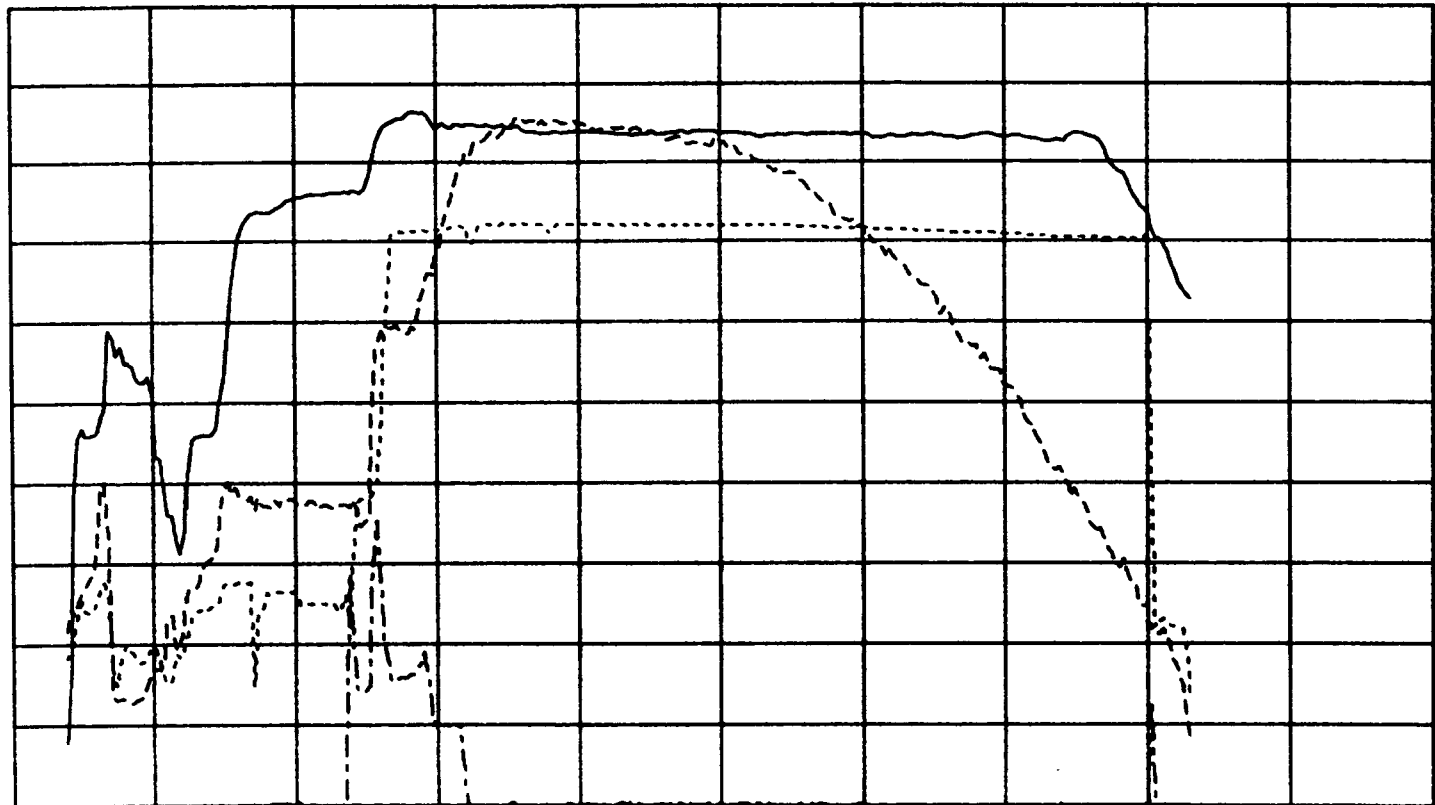
Figure 2.17(f). Day 333 Charging Train Transitions – Receiver/NIP Parameters

Following stabilization of Train 2 charging operation, Train 2 steam flow was decreased to obtain low-flow performance data. Then, at approximately 12:55 PM, steam flow was gradually increased such that Charging Train 2 was accepting all receiver generated steam and the steam dump valve was closed (1:15 PM, Figure 2.17(e)). During these periods of decreasing and increasing steam flow, condenser/subcooler process modifications occurred with only minor changes in charging oil outlet temperature (Figure 2.17(b)) and oil flow adjustments to process conditions. Following this period, the charging steam rate was only modified by decreasing insolation and minor cloud transients (see Figure 2.17(f)). Again, the charging oil flow adjusted to changes in steam flow with only minor changes in outlet oil temperature. Charging Train 2 was shutdown at approximately 3:42 PM due to increasing cloud cover.

Data from day 306 (11/2/83) are presented in Figure 2.18 (a thru f) for a 10 hour period starting at 8:00 AM. Start-up of two charging trains and transition to dual charging train Mode 5 operation was complete by approximately 11:15 AM with complete closure of the steam dump valve (Figure 2.18(a)). During Mode 5 operation, pressure control of both trains was provided by Train 2, thus "slaving" the two condensate drain valves together (see Figure 2.18(f)). This was done to "de-couple" the pressure controllers such that significant steam flow shifts from train-to-train would not occur.

At approximately 3:10 PM, the charging train pressures began to decay (see Figures 2.18 (d and e)). Charging train pressure control was normally provided by balancing the condenser inlet energy rate (steam) with the outlet energy rate (oil) at the desired pressure value. This was accomplished by controlling the condenser water level and thus the condensing surface area available. In a case of decreasing steam flow, the situation could arise

SOLAR DATA PLOT PLOT # P206 NTH SAMPLE AVERAGE = 10  
REFERENCE TIME: 306 08 00 00.000 FOR 600.0000 MINUTE(S)



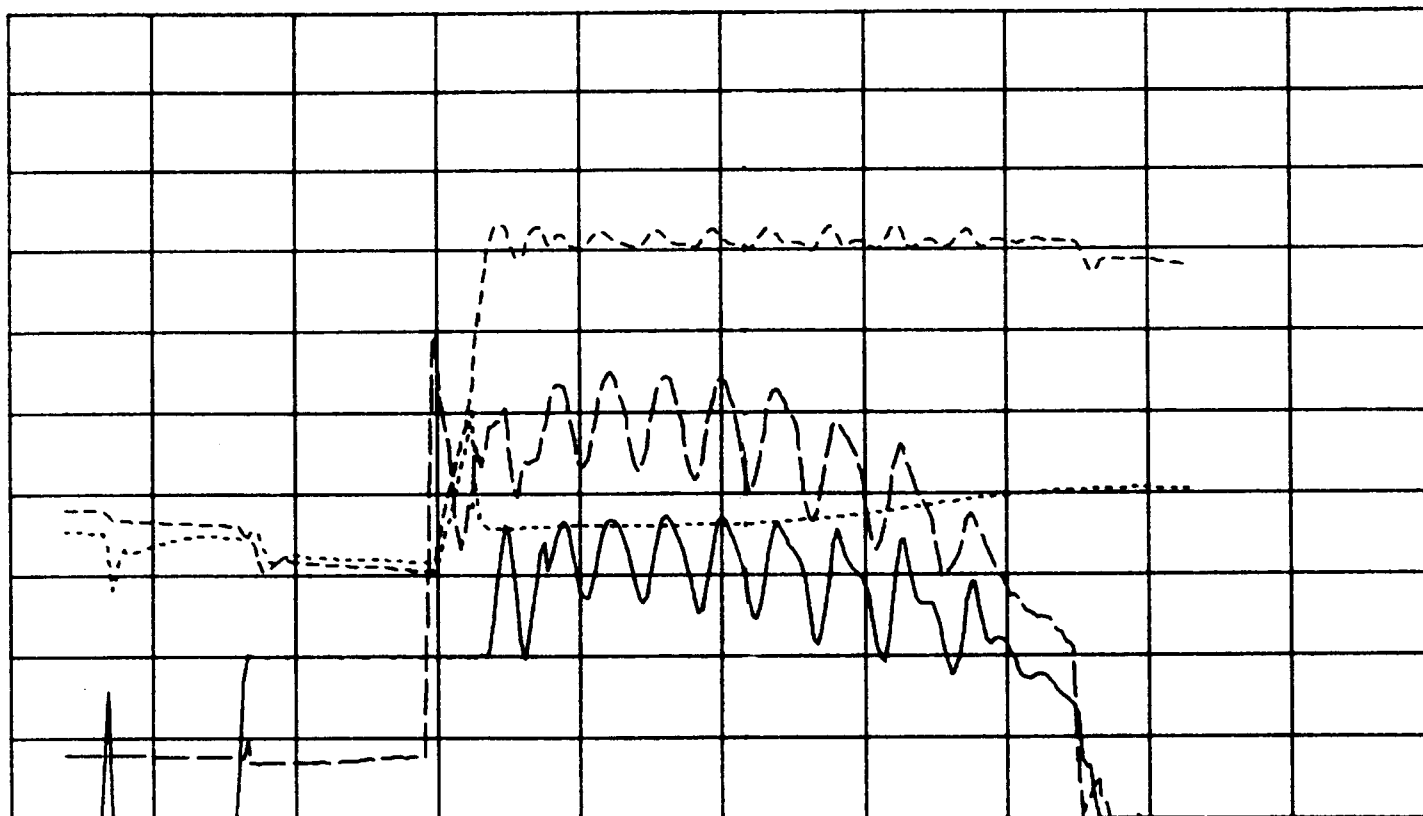
0.00						600.00
T12903P	REC DISCHARGE STEAM TEMP	0.00 -	1000.00	DEGF	———	
P12902P	REC DISCHARGE STEAM PRESS	0.00 -	2000.00	PSIG	-----	
F12233P	REC FEEDWATER FLOW	0.00 -	100.00	KLBH	.....	
J1C5100P	GROSS ELECTRICAL POWER	0.00 -	10000.00	KW	N/A	
Z11001P	STEAM DUMP VALVE POSITION	0.00 -	100.00	PCT	-----	

Figure 2.18(a). Day 306 Dual-Single Charging Train Transition – Receiver Parameters

SOLAR DATA PLOT  
REFERENCE TIME: 306 08 00 00.000

PLOT # P207

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)

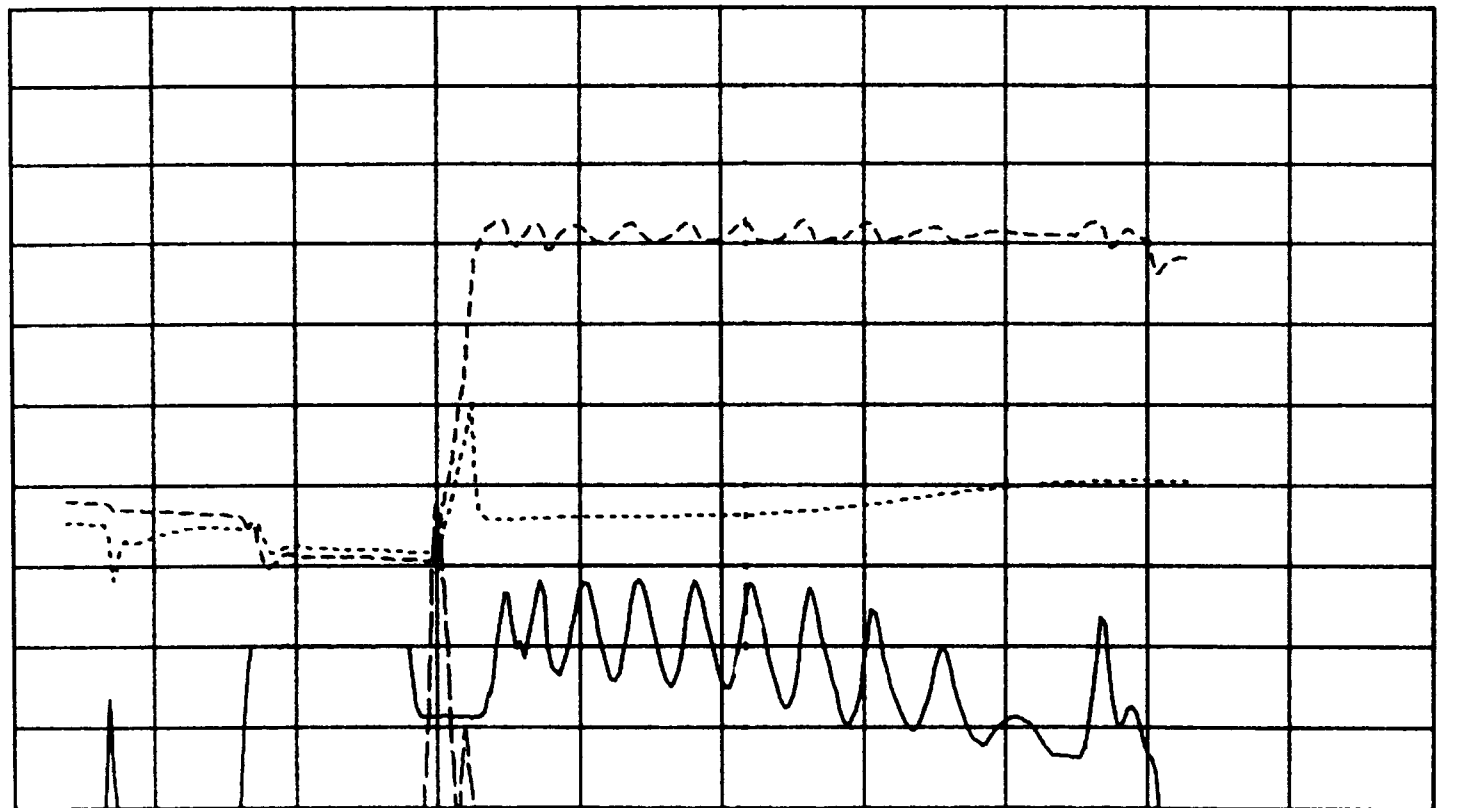


0.00					600.00
FI3211P	TS CHARGE OIL FLOW (TRAIN 1)	0.00 -	800.00	KLBH	_____
TI3412P	TS CHARGE "COLD" OIL TEMP	0.00 -	800.00	DEGF	-----
TI3211P	TS CHARGE "HOT" OIL TEMP (TRAIN 1)	0.00 -	800.00	DEGF	.....
FI3205P	TS CHARGE STEAM FLOW (TRAIN 1)	0.00 -	100.00	KLBH	-----
FI3102P	TS CHARGE STEAM FLOW (TOTAL)	0.00 -	200.00	KLBH	-.-.-.-
*					N/A

Figure 2.18(b). Day 306 Dual-Single Charging Train Transition – Train 1 Oil Parameters

SOLAR DATA PLOT PLOT # P208  
REFERENCE TIME: 306 08 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)



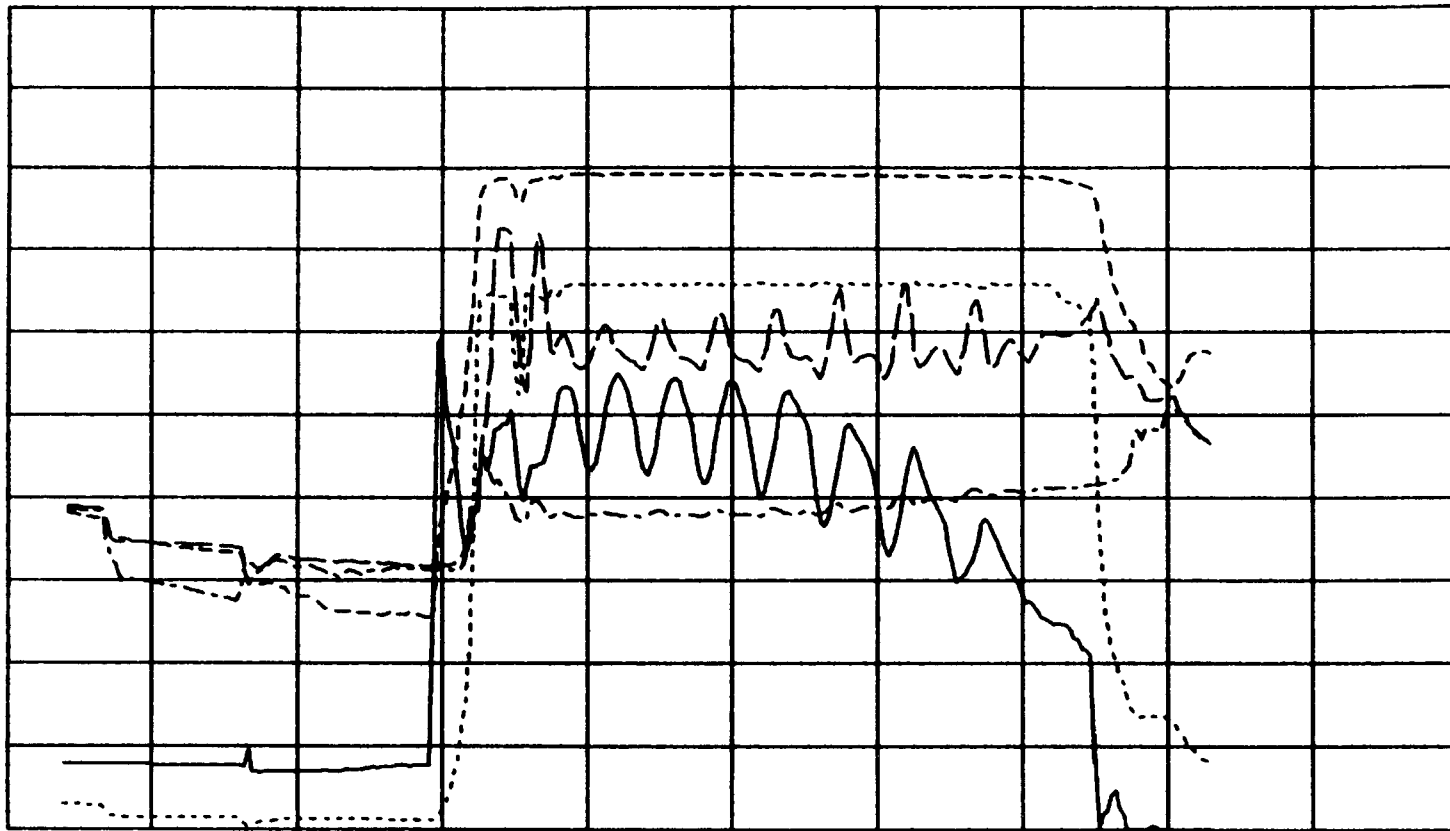
0.00						600.00
FI3310P	TS CHARGE OIL FLOW (TRAIN 2)	0.00 -	800.00	KLBH	_____	
TI3412P	TS CHARGE "COLD" OIL TEMP	0.00 -	800.00	DEGF	-----	
TI3310P	TS CHARGE "HOT" OIL TEMP (TRAIN 2)	0.00 -	800.00	DEGF	-----	
FI3305P	TS CHARGE STEAM FLOW (TRAIN 2)	0.00 -	80.00	KLBH	-----	
FI3102P	TS CHARGE STEAM FLOW (TOTAL)	0.00 -	200.00	KLBH	-----	N/A

Figure 2.18(c). Day 306 Dual-Single Charging Train Transition – Train 2 Oil Parameters



SOLAR DATA PLOT PLOT # P209  
REFERENCE TIME: 306 08 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)

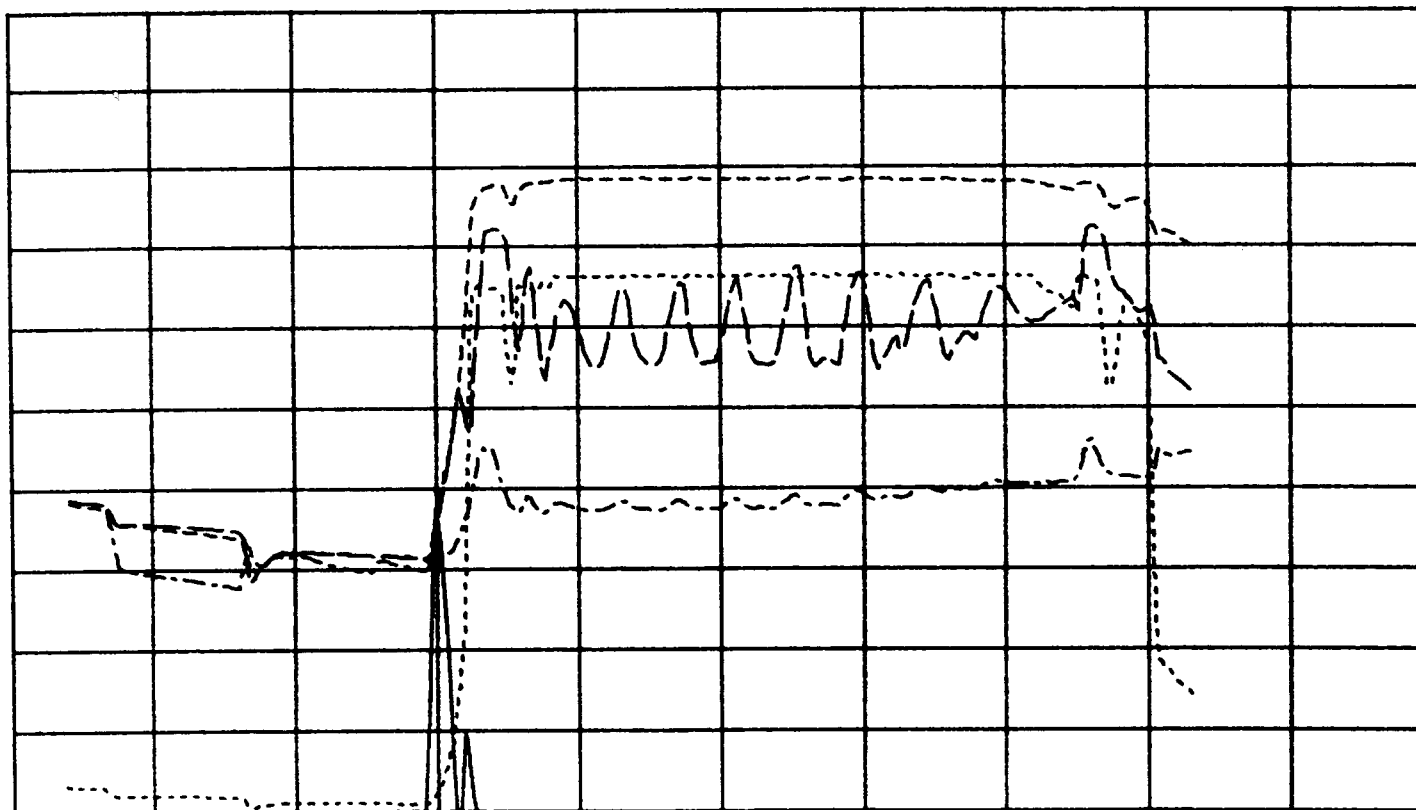


0.00					600.00
FI3205P	TS CHARGE STEAM FLOW (TRAIN 1)	0.00 -	100.00 KLBH	_____	
PCM3110P	TS CHARGE CONDENSER PRESS (TRAIN 1)	0.00 -	2000.00 PSIG	-----	
TEX3250	TS CONDENSER INLET STEAM TEMP (TRAIN 1)	0.00 -	800.00 DEGF	-----	
TEX3251	TS CONDENSER OUTLET WATER TEMP (TRAIN 1)	0.00 -	800.00 DEGF	-----	
TEX3253	TS SUBCOOLER OUTLET WATER TEMP (TRAIN 1)	0.00 -	800.00 DEGF	-----	

Figure 2.18(d). Day 306 Dual-Single Charging Train Transition – Train 1 Water/Steam Parameters

SOLAR DATA PLOT PLOT # P210  
REFERENCE TIME: 306 08 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)



0.00									600.00
FI3305P	TS CHARGE STEAM FLOW (TRAIN 2)	0.00 -	80.00	KLBH	_____				
PCM3111P	TS CHARGE CONDENSER PRESS (TRAIN 2)	0.00 -	2000.00	PSIG	-----				
TEX3350	TS CONDENSER INLET STEAM TEMP (TRAIN 2)	0.00 -	800.00	DEGF	-----				
TEX3351	TS CONDENSER OUTLET WATER TEMP (TRAIN 2)	0.00 -	800.00	DEGF	-----				
TEX3353	TS SUBCOOLER WATER TEMP (TRAIN 2)	0.00 -	800.00	DEGF	-----				

Figure 2.18(e). Day 306 Dual-Single Charging Train Transitions – Train 2 Water/Steam Parameters

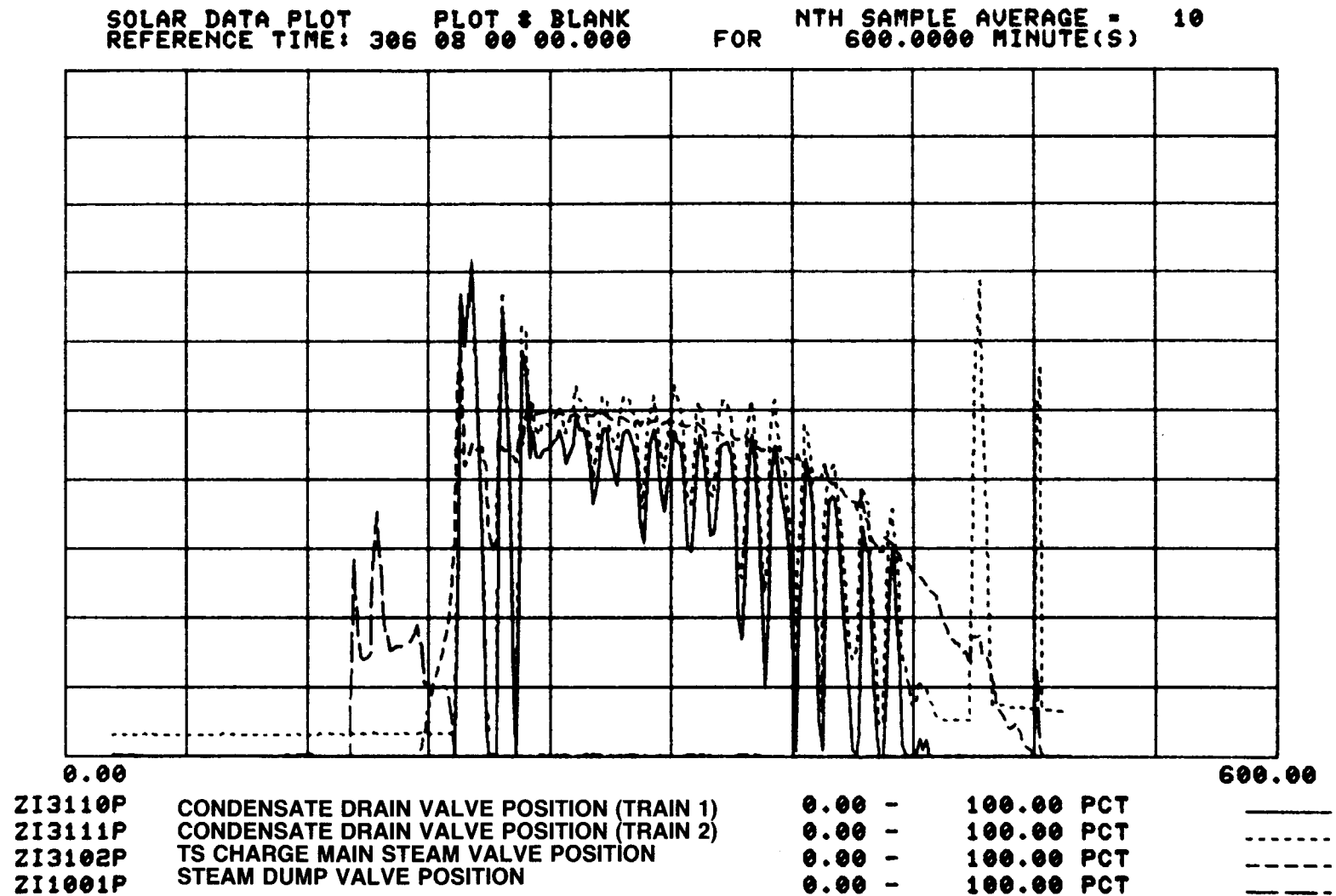


Figure 2.18(f). Day 306 Dual-Single Charging Train Transition – Valve Positions

where the steam flow (condensation rate) was low enough such that the rate of level rise was too slow to adjust the condensation rate to balance the oil energy rate (and "over-condensation" would occur). This would result in a decrease in train pressure such as occurred on day 306. At this point, the steam flow was too low (see Figure 2.18 (a), FI2233P) for stable dual-train operation (approximately 45 KLBH receiver flow).

At approximately 3:32 PM, charging Train 1 was shutdown and the transition from dual-train to single train Mode 5 occurred. System pressure recovered but the Train 2 process upset, which occurred due to the significant increase in steam flow when Train 1 was shutdown, only recovered just prior to Train 2 shutdown (4:00 PM). The data indicated that dual-to-single train transition could be used to extend Mode 5 but the transition should occur at a higher total steam flowrate (possibly 50-60 KLBH total receiver flow).

Figure 2.19 (a thru d) presents data from Mode 5 operation during severe cloud transients. The data are shown for a 10 hour time period starting at 7:30 AM on day 101 (4/11/83). Charging Train 1 was started at 8:47 AM (Figure 2.19 (c)), with the transition to Mode 5 completed by 9:30 AM (steam dump valve closed, Figure 2.19 (b)). Steam flow to the charging system was terminated for a period of time (10:05 - 10:30) as a result of low insolation and the charging oil flow decreased to the start-up level. Mode 5 was re-established and operation continued for the rest of the day.

At approximately 11:10 AM, loss of insolation occurred of sufficient magnitude to cause charging power to be reduced such that oil outlet temperature could not be maintained (Figure 2.19 (c)). As the oil temperature (TI3211P) decayed to 540°F, the oil pump flowrate was automatically "run back" to the start-up level.

SOLAR DATA PLOT      PLOT # BLANK      NTH SAMPLE AVERAGE = 1  
REFERENCE TIME: 101 07 30 00.000      FOR      600.0000 MINUTE(S)

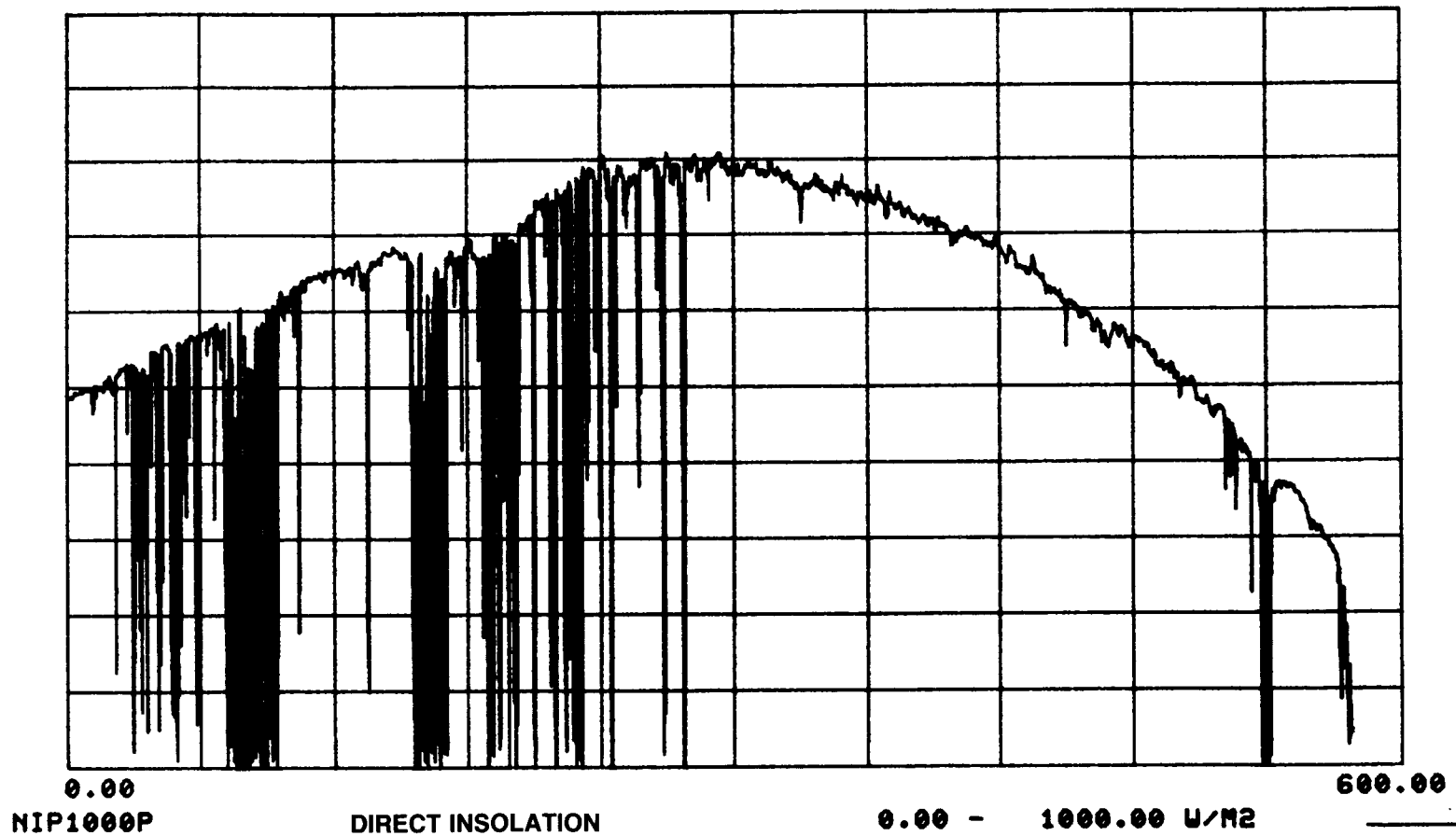
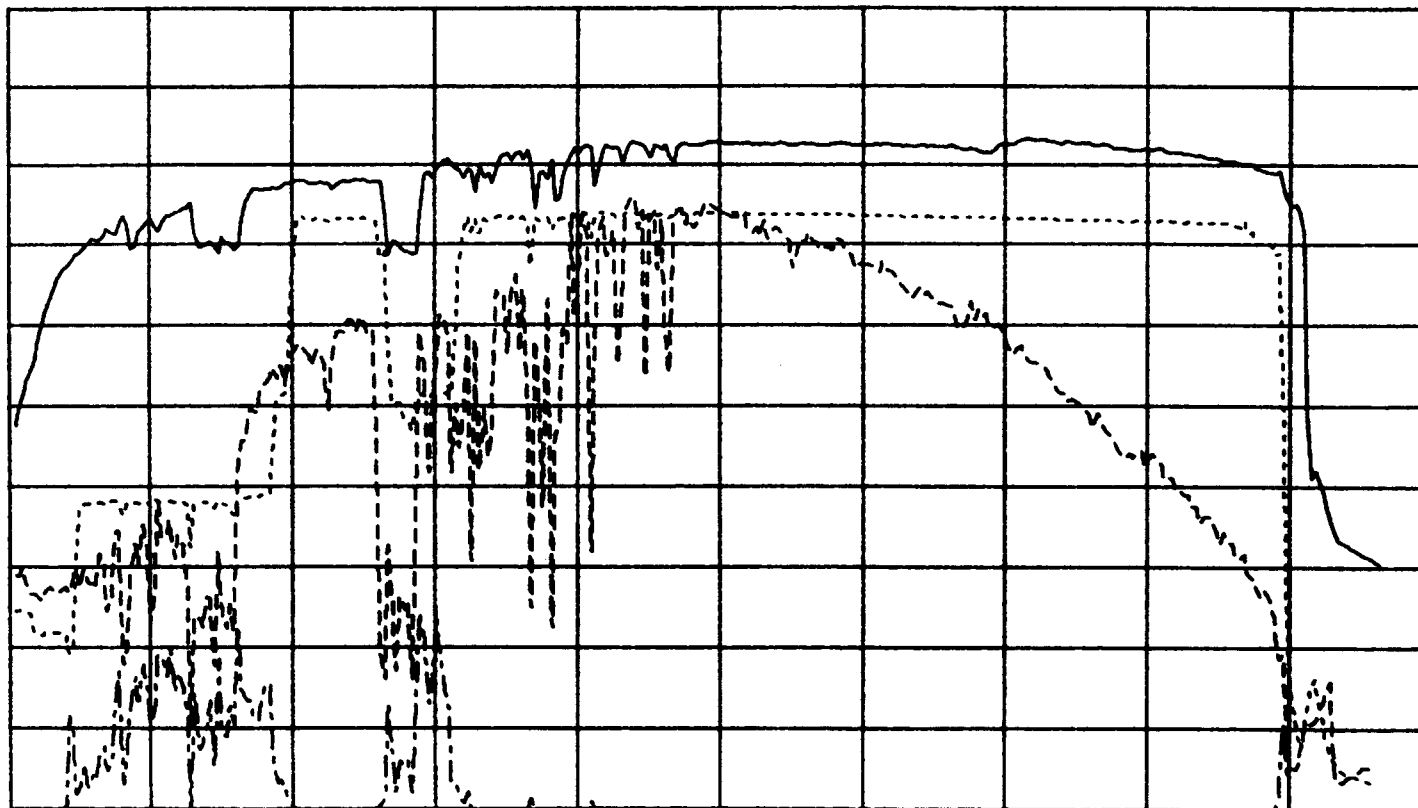


Figure 2.19(a). Day 101 Mode 5 Cloud Transients – Insolation

SOLAR DATA PLOT PLOT # P206  
 REFERENCE TIME: 101 07 30 00.000

FOR NTH SAMPLE AVERAGE = 10  
 600.0000 MINUTE(S)



0.00					600.00
TI2903P	REC DISCHARGE STEAM TEMP	0.00 -	1000.00	DEGF	_____
PI2902P	REC DISCHARGE STEAM PRESS	0.00 -	2000.00	PSIG	-----
FI2233P	REC FEEDWATER FLOW	0.00 -	100.00	KLBH	.....
JIC5100P	GROSS ELECTRICAL POWER	0.00 -	10000.00	KW	N/A
ZI1001P	STEAM DUMP VALVE POSITION	0.00 -	100.00	PCT	-----

Figure 2.19(b). Day 101 Mode 5 Cloud Transients – Receiver Parameters

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)

SOLAR DATA PLOT PLOT # P209  
REFERENCE TIME: 101 07 30 00.000

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)

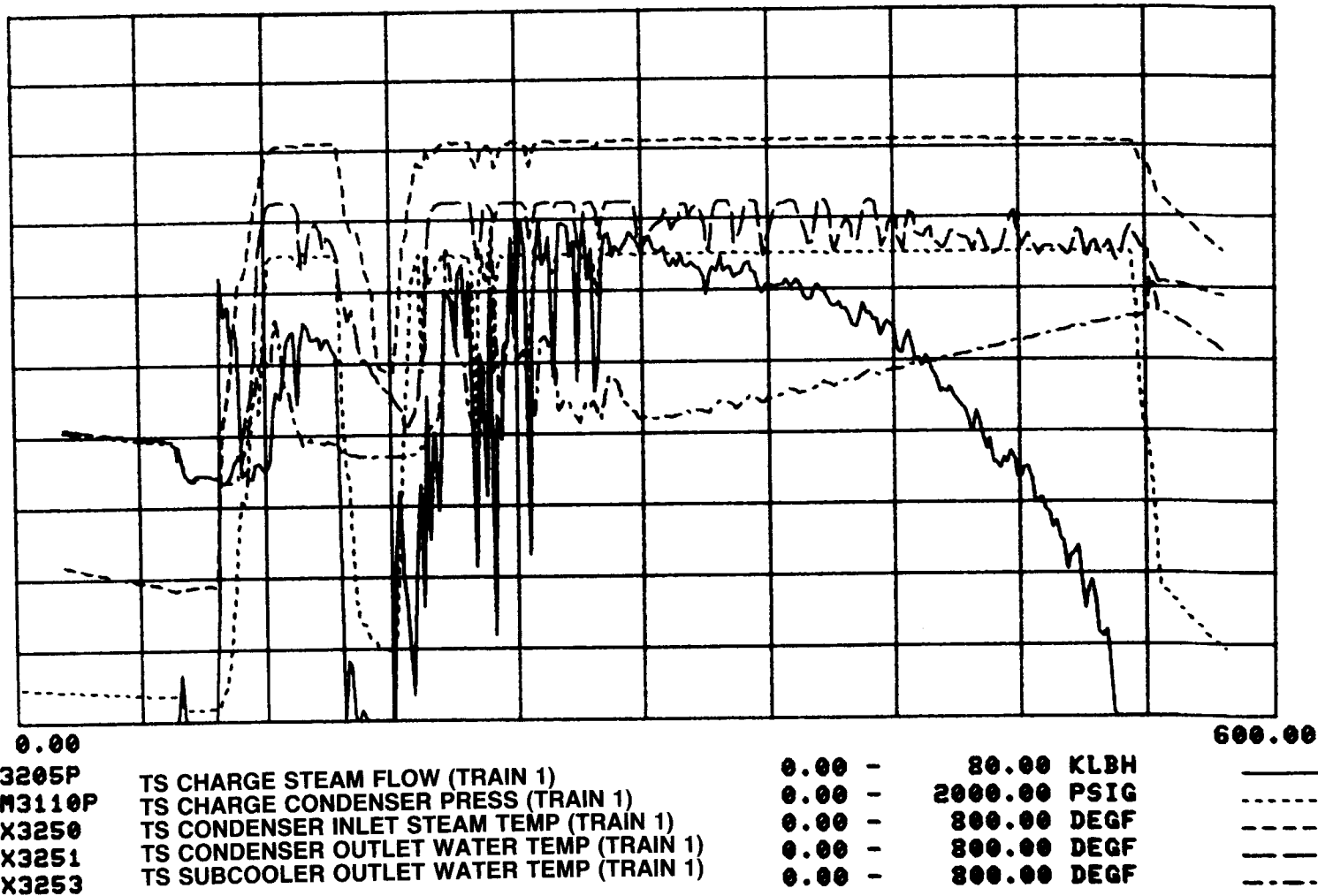


Figure 2.19(d). Day 101 Mode 5 Cloud Transients – Train 1 Water/Steam Parameters



Normal flow was re-established as insolation (and oil temperature) recovered. Operation continued through severe cloud transients and, although significant process upsets in the condenser/subcooler occurred (Figure 2.19 (d)), outlet oil temperature remained relatively constant (Figure 2.19 (c)). The plant was operated in Mode 5 until 4:25 PM when shutdown occurred at a receiver total flow of approximately 25 KLBH (Figure 2.19 (b)).

The transitions between Mode 5 and Mode 2 involve phasing in or phasing out turbine operation using main steam while continuing to charge the Thermal Storage Unit (TSU). The transitions between Mode 5 and Mode 4 involve phasing in or phasing out turbine operation using admission steam while continuing to charge the TSU. The operational characteristics of these transitions are discussed in Reference 3.

#### 2.5.2 Steady-State Operation

As stated in Section 2.2.1, the goal of steady-state Mode 5 operation was to investigate the range of Mode 5 operating conditions, gather data for estimation of performance, determine first-order performance-related sensitivities and to establish operational limits. Also, the establishment and movement of the thermocline (see Section 1.2) through the TSU was of interest in the determination of the effectiveness of large-scale dual media energy storage. The majority of the data used to establish "instantaneous" performance were obtained from time-averaged five minute data samples (see Table 2.1) occurring during periods of steady-state operation. The numbers on the data points on figures in this section correspond to the particular data samples in Table 2.1.

### 2.5.2.1 Charging Efficiency

Charging efficiency calculations were based on receiver absorbed energy due to the uncertainties in receiver incident energy and receiver losses. Also, as discussed in Section 2.4, steam flowrate to the charging heat exchangers was calculated from the thermal storage desuperheater spray water flowrate and desuperheater thermodynamic state points.

Mode 5 test data indicated that there were two primary factors which effected charging efficiency; charging inlet ("cold") oil temperature and the use of heat recovery in the feedwater system. The "cold" oil which is pumped through the charging heat exchangers does not enter at a constant temperature. The temperature level is reflective of the type of extraction operations which had occurred at some earlier time. Typically, high flow extraction operations (to generate admission steam) resulted in "cold" oil temperatures on the order of 400°F. Low flow extraction operations (for the purpose of generating auxiliary or blanketing steam) typically resulted in "cold" oil temperatures of 250 to 280°F. The effect of these variations in "cold" oil temperature directly influenced the plant charging efficiency. The colder the inlet oil temperature to the charging heat exchangers, the greater the fraction of available energy which was transferred to the thermal storage oil system (with a correspondingly smaller quantity of waste heat leaving the flash tank).

Figure 2.20 depicts charging steamside power as a function of charging heat exchanger steam flow for a number of Mode 5 steady-state operating points. The steamside power, assumed to be equal to the oil-side power under steady-state conditions, was calculated from charging heat exchanger inlet and outlet conditions and steam flow determined from the desuperheater energy balance. The result of increasing steamside power with decreasing "cold" oil temperature may be seen from this figure.

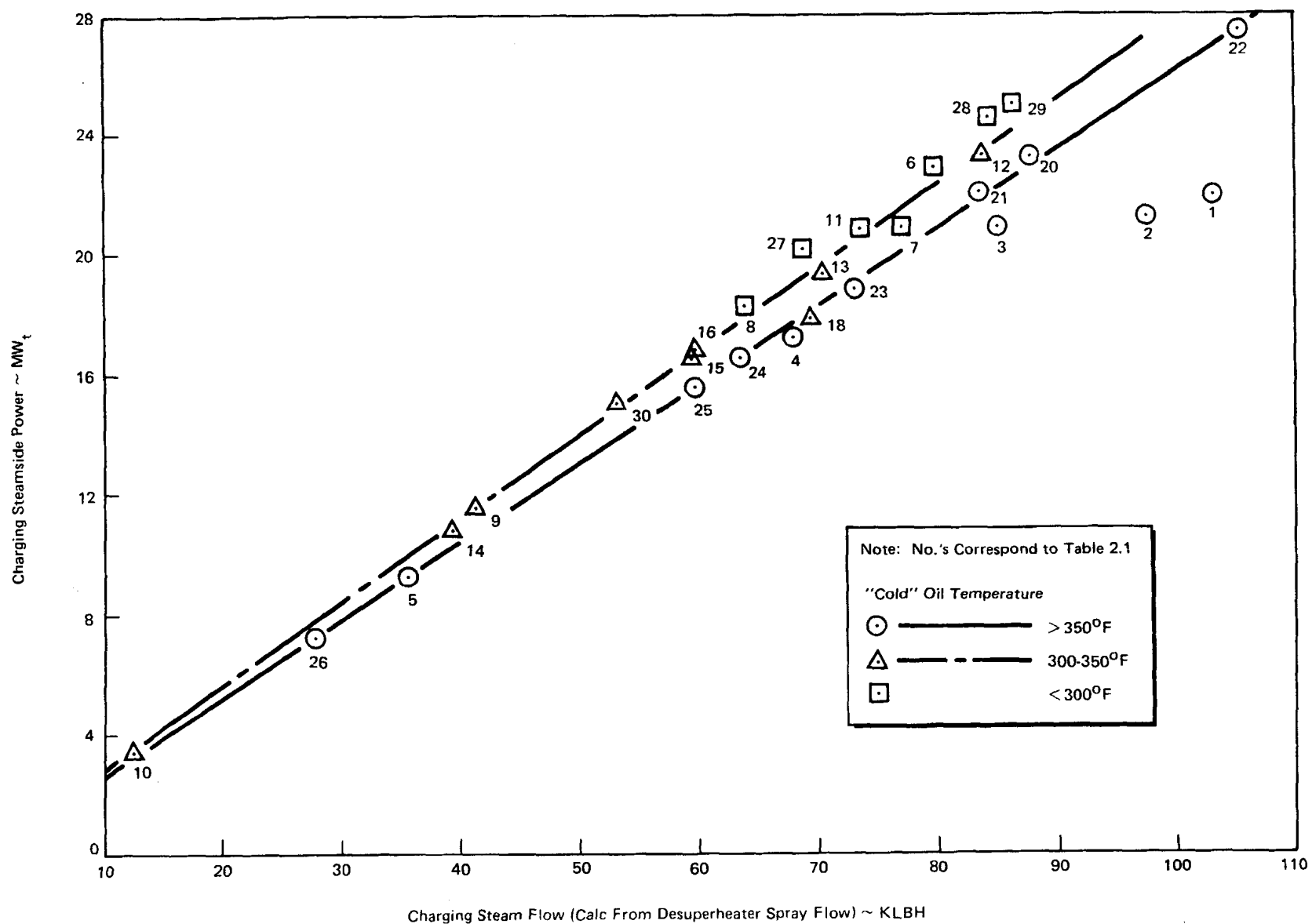


Figure 2.20. Effect of "Cold" Oil Inlet Temperature on Charging Steamside Power

The second primary factor influencing charging efficiency involved use of heat recovery paths (see Section 2.3 for a discussion of the thermal storage heat recovery system). Thermal energy which was not absorbed into the thermal storage oil system would flow from the flash tank to the condenser or feedwater system in the form of high temperature condensate and waste steam. The actual flowpaths in service during Mode 5 testing depended on the condensate and steam chemistry (as it left the flash tank), hardware availability, and operator choice. As a general rule it was determined to be better to utilize waste heat for feedwater heating, when the flash tank steam and condensate chemistry were within acceptable limits, instead of using additional auxiliary steam (which would draw main steam away from the charging system). Auxiliary steam during Mode 5 was supplied from the steam downcomer through PV1003 (Figure 2.1) and would enter the deaerator through PV647A (Figure 2.7). The auxiliary steam was used to pressurize the deaerator for the deaeration process.

Calculated auxiliary steam flow as a function of total receiver flow is shown in Figure 2.21. The auxiliary steam flow was not measured, therefore it was calculated based on the design flow coefficient for PV1003 and the commanded valve (PV1003) position. The data on this figure indicate qualitatively (due to the limited data available) the effects of heat recovery and deaerator pressure on auxiliary steam demand during Mode 5 operation. The band of data for operation without heat recovery paths in service represents a range in deaerator pressure from 23 psia (minimum auxiliary steam flow demand) to 29 psia. The data band for operation with heat recovery (from the thermal storage flash tank) in service represents a range in deaerator pressure from 24 psia to 36 psia. The lower auxiliary steam demand for operation with heat recovery represents increased steam flow to the charging heat exchangers (for a given receiver flow) and thus higher charging efficiency.

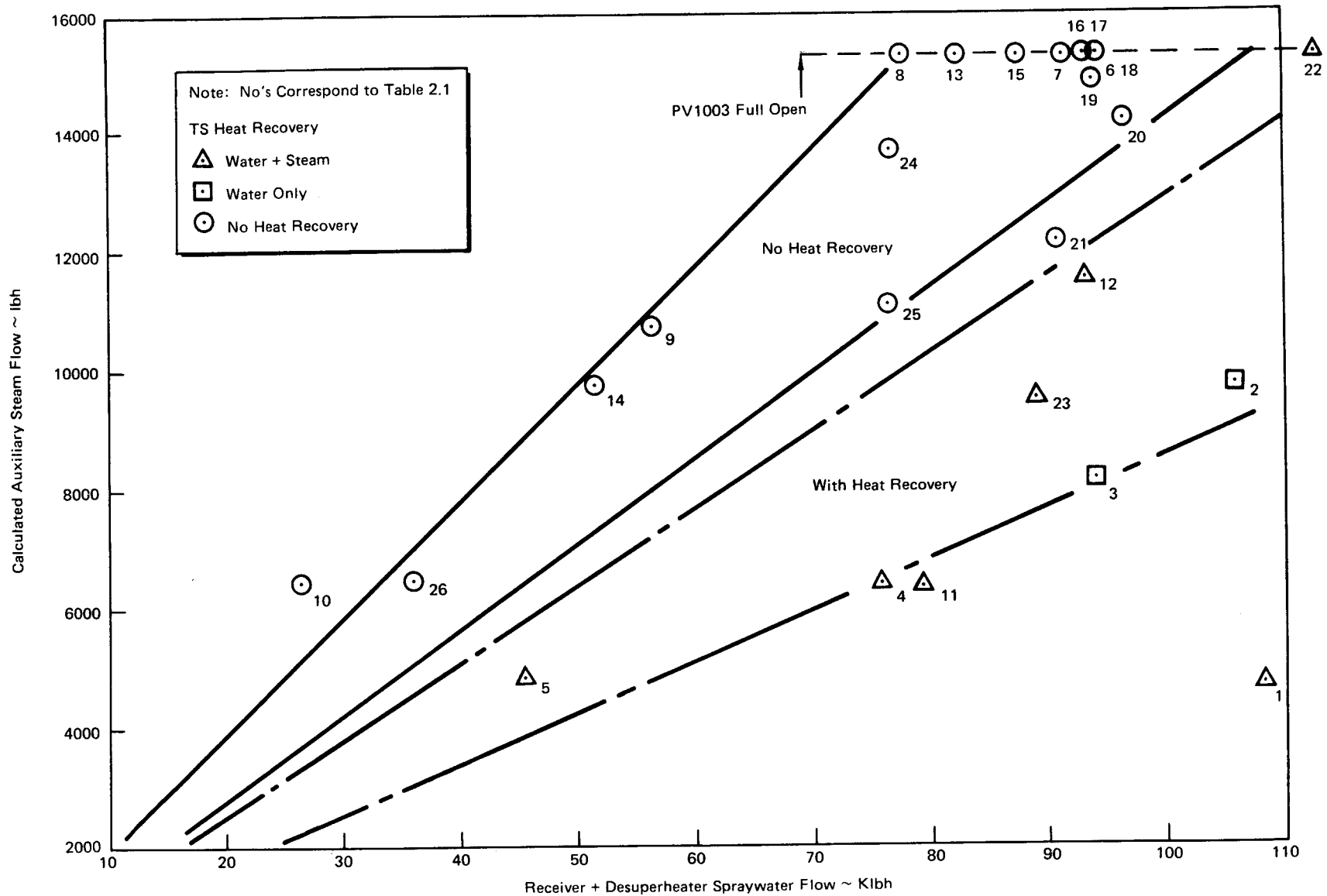


Figure 2.21. Effect of TS Heat Recovery on Auxiliary Steam Flow – Mode 5

The maximum auxiliary steam flow indicated on Figure 2.21 represents the condition of PV1003 wide open. With this condition, and increasing receiver flow, either the deaerator pressure setpoint must be reduced (since the increased demand for auxiliary steam at higher feedwater flow cannot be met) or heat recovery paths must be placed in service. The results of testing in several operating modes indicated that there was no discernable advantage in operating with deaerator pressures above approximately 25 psia, and this was the nominal pressure setpoint for normal operation. An increase in pressure from 25 psia to 36 psia would only result in an increase in water temperature from 240°F to 260°F, having little effect on the deaeration process.

The combined effect of "cold" oil temperature and heat recovery on charging power can be seen in Figure 2.22. Although "cold" oil temperature was not a directly controllable factor, heat recovery could be used to minimize the auxiliary steam demand and thus maximize charging power for given receiver conditions. The ratio of charging power to receiver absorbed power is a measure of plant-level charging efficiency. Charging efficiency as a function of total feedwater flow is shown in Figure 2.23. The data bands showing the effects of "cold" oil temperature and heat recovery are taken from Figure 2.22. The majority of the data points are between 65 and 80 percent. As indicated before, thermal energy which is not absorbed into the thermal storage oil flows from the flash tank to the condenser or feedwater system in the form of high temperature condensate or waste steam or as heat loss from the steam piping and heat exchangers.

#### 2.5.2.2 Operational Limits

The plant was operated in Mode 5 over a range of operating conditions within the limits specified in Figures 2.3 and 2.4. As stated in Section 2.1.2,

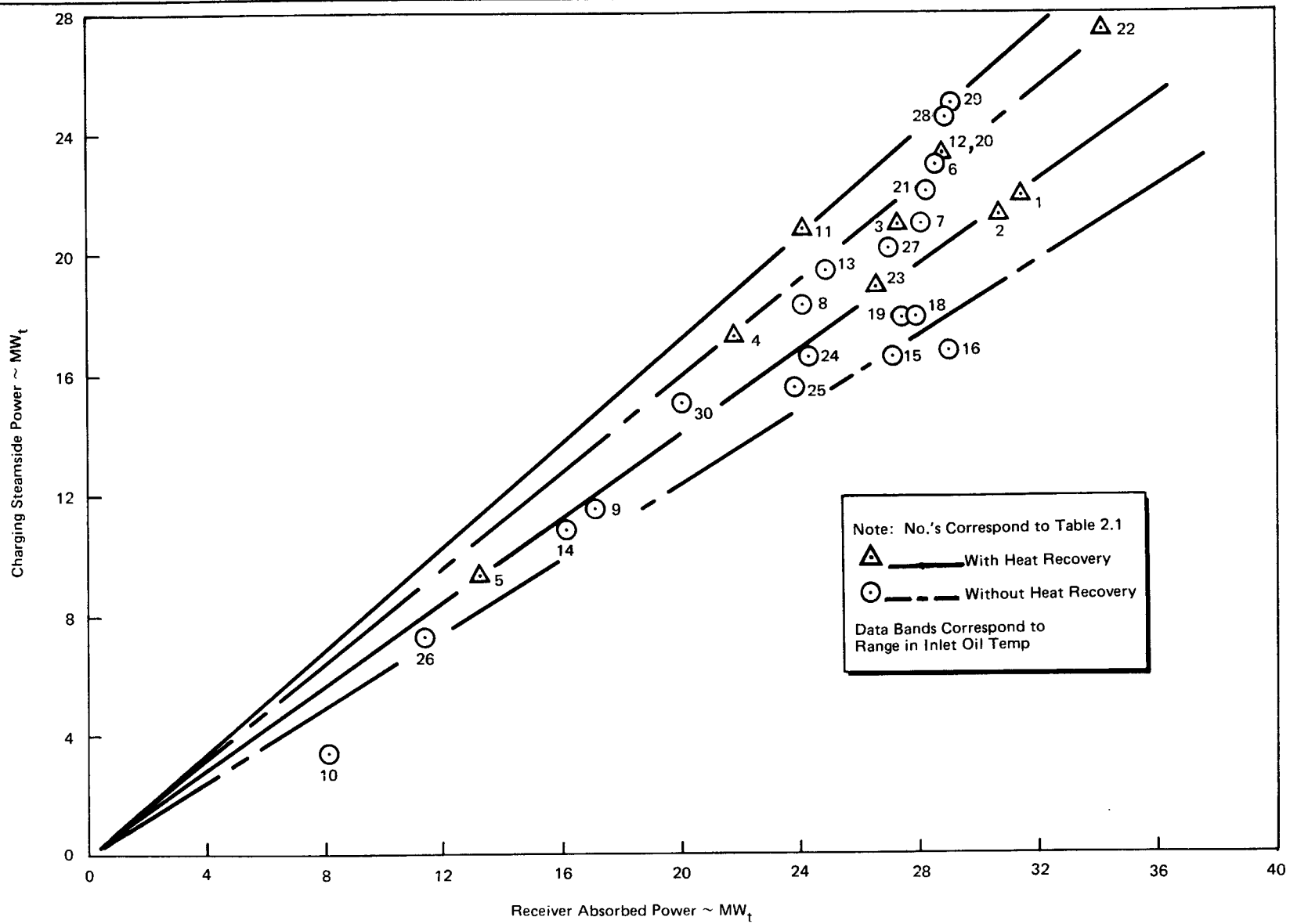


Figure 2.22. Charging Steamside Power

$$\text{Charging Efficiency} = \frac{\text{Charging Steamside Power}}{\text{Receiver Absorbed Power}}$$

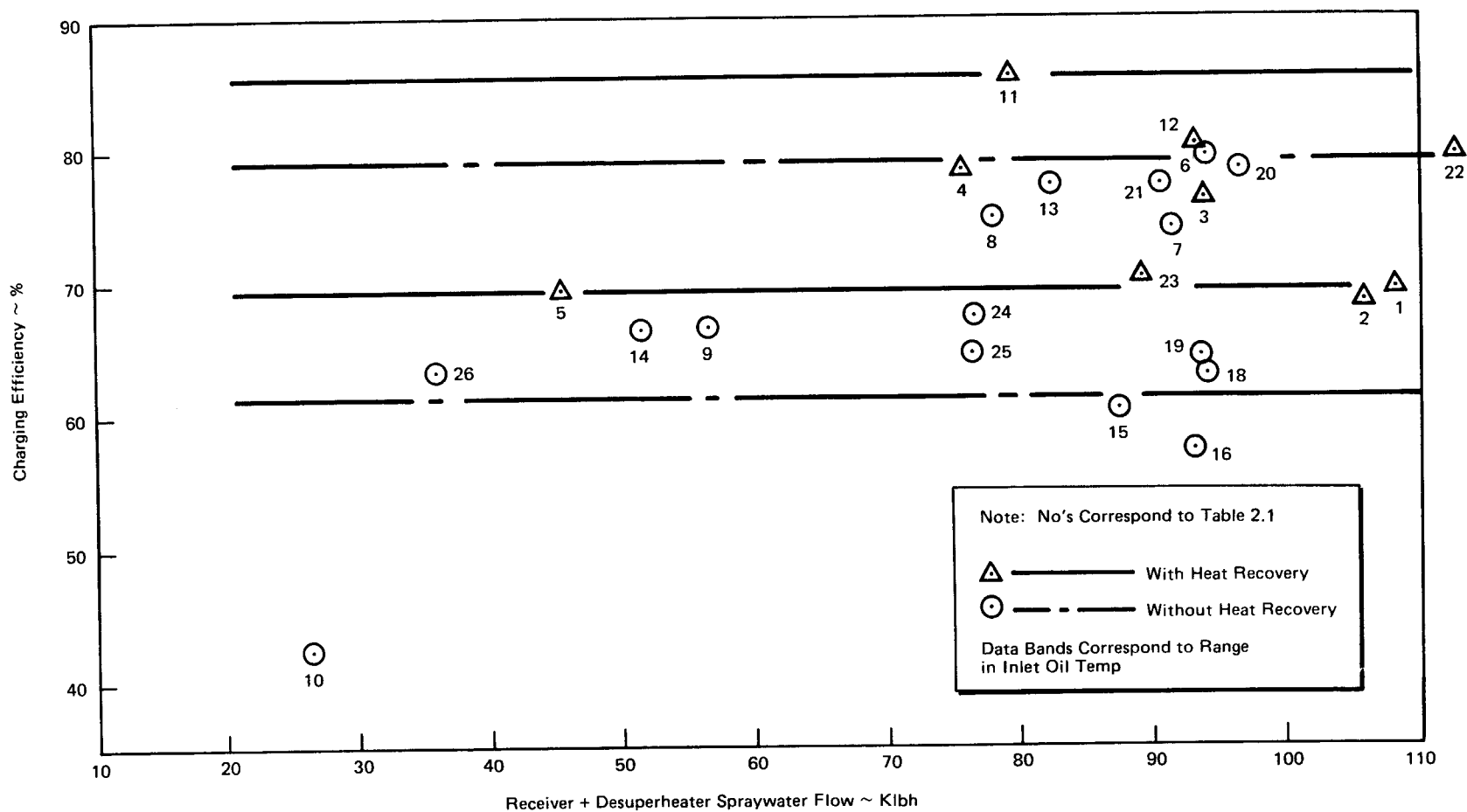


Figure 2.23. Charging Efficiency — Mode 5



typical receiver steam temperature setpoints of between 775°F and 850°F were used during Mode 5 operation. Higher receiver steam temperatures would result in increased receiver energy losses (and reduced receiver absorbed power) and require additional desuperheater spraywater flow. Lower temperatures would result in reduced steam superheat and lower margin for Mode 5 operation during cloud transients. The low flow characteristics of both one and two charging trains were investigated and the steam flow limit for single charging train operation was established. The steam flow limit for dual charging train Mode 5 operation was not reached due to the limit in maximum attainable receiver flow. Design maximum receiver steam flow was not achieved during the Mode 5 test program due to several factors; heliostats off-line, reduced heliostat reflectivity, reduced receiver absorptivity, etc. Charging steam pressure was typically set at 1400 psi. This provided a margin on the high side for receiver pressure excursions (during flow/flux excursions) and a margin on the low side for minimum steam condensation temperature (see Section 2.3).

An example of maximum single charging train steam flow is seen from the data for day 139 (5/19/83). Data points 1-5 on Figure 2.20 are for day 139 and represent receiver steam flows of 94.3 KLBH, 92.7KLBH, 82.1KLBH, 67.9KLBH, and 41.5KLBH, respectively. As can be seen, a point is reached where increased steam flow results in very little increase in charging steam power. This is the result of reaching the condensing rate limit for a single charging train. Flow and temperature data for day 139, starting at 9:00 AM for a 10-hour period, are shown in Figure 2.24 (a-c). Over a range of receiver flows (Figure 2.24a), the condenser steam outlet temperature (TEX3251) remained constant at the saturation temperature (no condenser subcooling). Also, the subcooler differential temperature (inlet-outlet) was only 60°F during this

SOLAR DATA PLOT PLOT # P206  
REFERENCE TIME: 139 09 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)

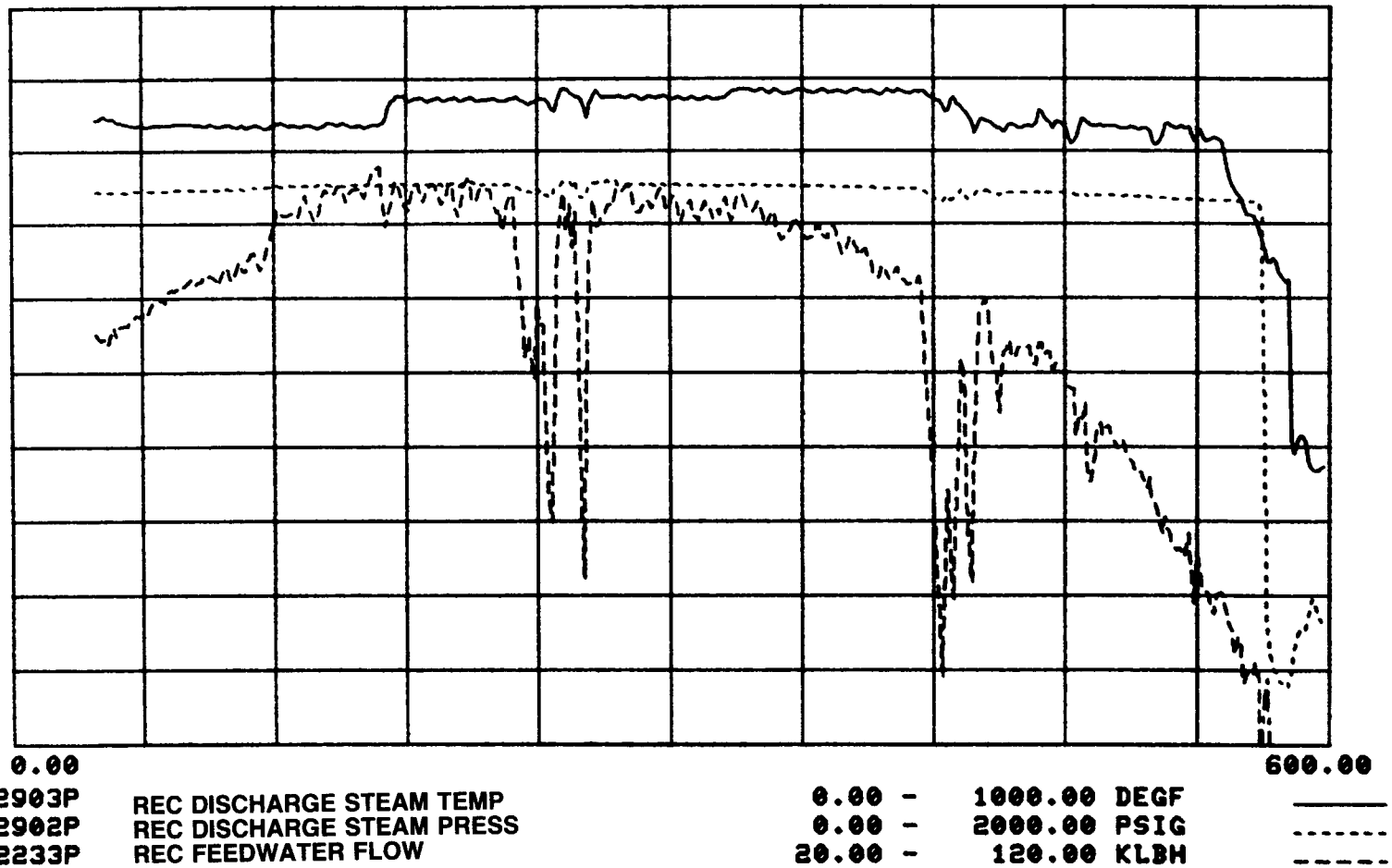


Figure 2.24(a). Day 139 Maximum Single Train Charging Rate – Receiver Parameters

SOLAR DATA PLOT PLOT # P207 NTH SAMPLE AVERAGE = 10  
REFERENCE TIME: 139 09 00 00.000 FOR 600.0000 MINUTE(S)

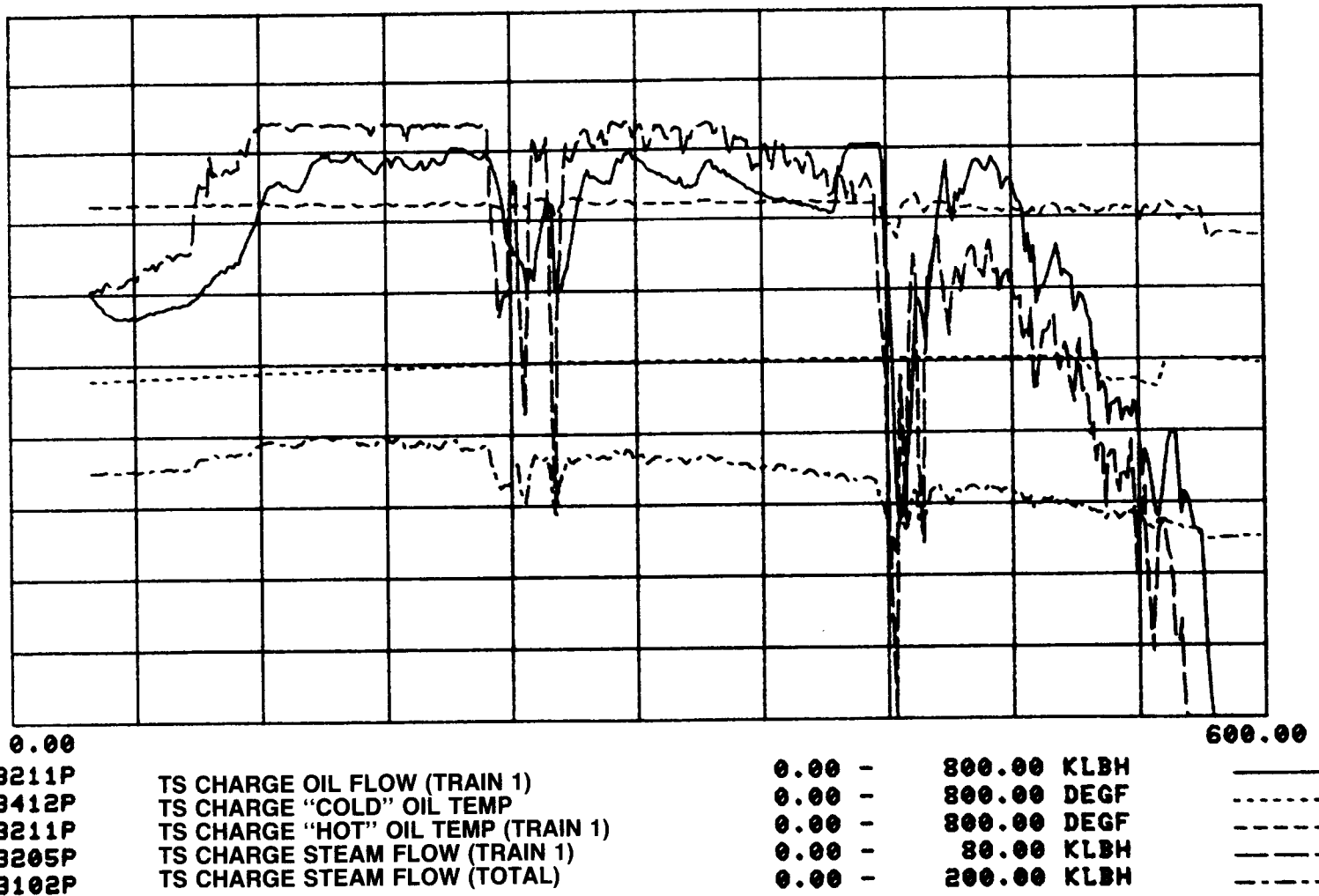


Figure 2.24(b). Day 139 Maximum Single Train Charging Rate – Train 1 Oil Parameters

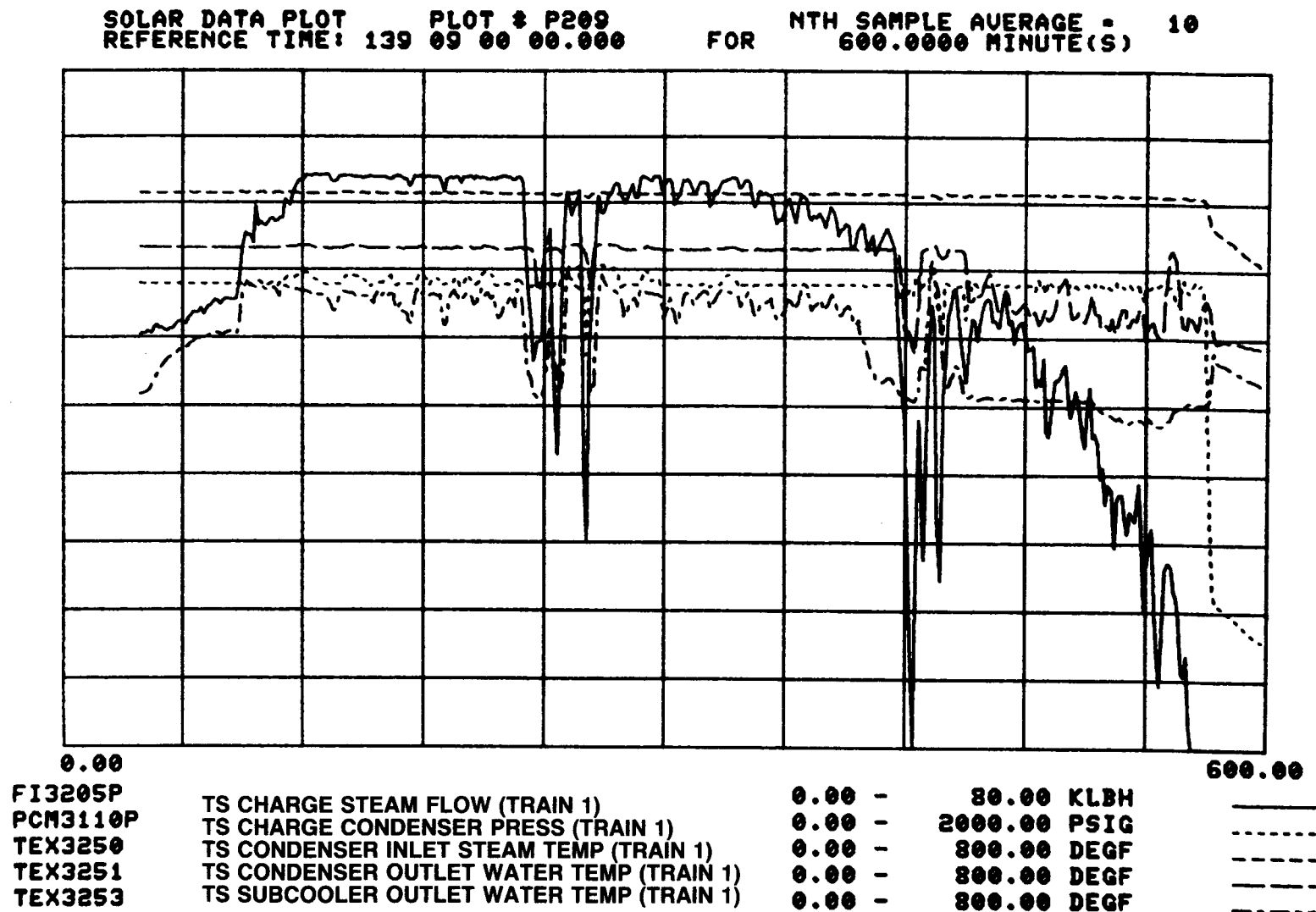


Figure 2.24(c). Day 139 Maximum Single train Charging Rate – Train 1 Water/Steam Parameters

period. Not until a cloud transient at approximately 4:00 PM did the condenser outlet temperature drop below saturation temperature (accompanied with a large decrease in subcooler outlet temperature). This was indicative of the steam flow dropping below the condensation flow limit for the single train. The reduced performance during limiting operation can be seen on Figure 2.23, where data points 1 and 2 show charging efficiencies substantially below comparable dual-train (non-limiting) values represented by data points 20 and 22.

The maximum charging steam flow for a single charging train was determined to be a function of the charging inlet oil temperature. Data points 28 and 29 on Figure 2.20 represent high flow, single train operation at an inlet oil temperature of 272°F whereas the inlet oil temperature for the limiting case discussed above was 400°F (Figure 2.24b). Based on additional Mode 5 operating experience, the 90 KLBH receiver flow limit for single charging train operation was established (see Section 2.5.1).

The low flow limit for both single and dual charging trains was also investigated. As discussed in Section 2.5.1, the minimum receiver flow for stable dual-train Mode 5 operation was determined to be approximately 50 KLBH (see discussion for day 306); this value was then set as a guideline for transitioning from dual-to-single train operation. The low flow limit for single train operation was determined to be approximately 30 KLBH which was also the approximate low flow limit for stable receiver operation. On day 306, after the transition from dual to single train operation, Mode 5 continued down to a receiver flow of 25.2 KLBH (see Figure 2.18 and discussion). The performance penalty for operation at this low flow may be seen from Figure 2.23 (day 306, 3:55 - 4:00 PM), data point 10.

### 2.5.2.3 TSU Thermocline

Sizing and performance estimates of the TSU were dependent on the characteristics of the thermocline, heat loss to the environment, and strength capability of the supporting foundation. The characteristic shape of the thermocline was established both by a detailed analysis and testing of a full-scale (height) model during the preliminary design contract phase. The shape of the thermocline was determined to be relatively insensitive to the tank shape or volume. A region will exist between the lower and upper manifolds that can be considered the active portion of the bed. When thermal energy is extracted from the TSU, the thermocline will move upward and oil will leave the upper manifold at the upper temperature (575° to 580°F) and return to the lower manifold at the lower temperature (425°). The outlet oil temperature will remain constant until the thermocline reaches the upper manifold. At this point the thermocline will "enter" the upper manifold, and the oil outlet temperature will begin to drop. Oil flow will continue until the temperature drops to a value below which it cannot further generate the required heat energy. At this point, the TSU will be fully discharged of energy for electrical power generation purposes. During charging, hot oil (580°F) will enter the upper manifold, cold (425°F) oil will leave the lower manifold, and the thermocline will move in a downward direction. The TSU is considered fully charged when the cool oil leaving the lower manifold reaches the inlet temperature limit of the charging heat exchangers.

Figure 2.25 shows the approximate location of the thermocouples used to establish the shape of the TSU thermocline. Figure 2.26 shows the movement of the thermocline through the TSU during two consecutive days of dual-train Mode 5 charging operation. The thermocline is shown at 11:00 AM, 3:00 PM and 5:00

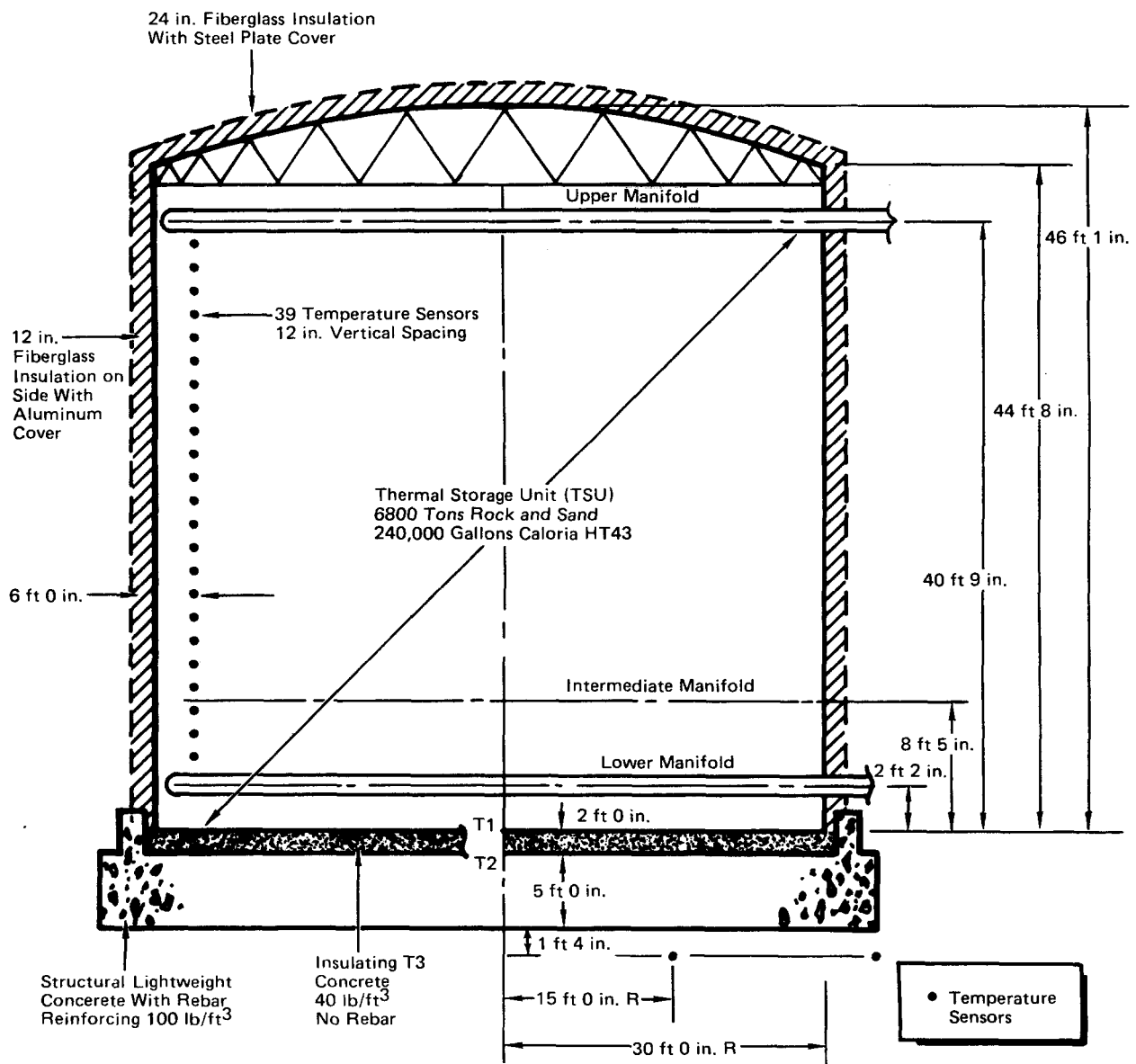


Figure 2.25. Thermal Storage Unit Schematic

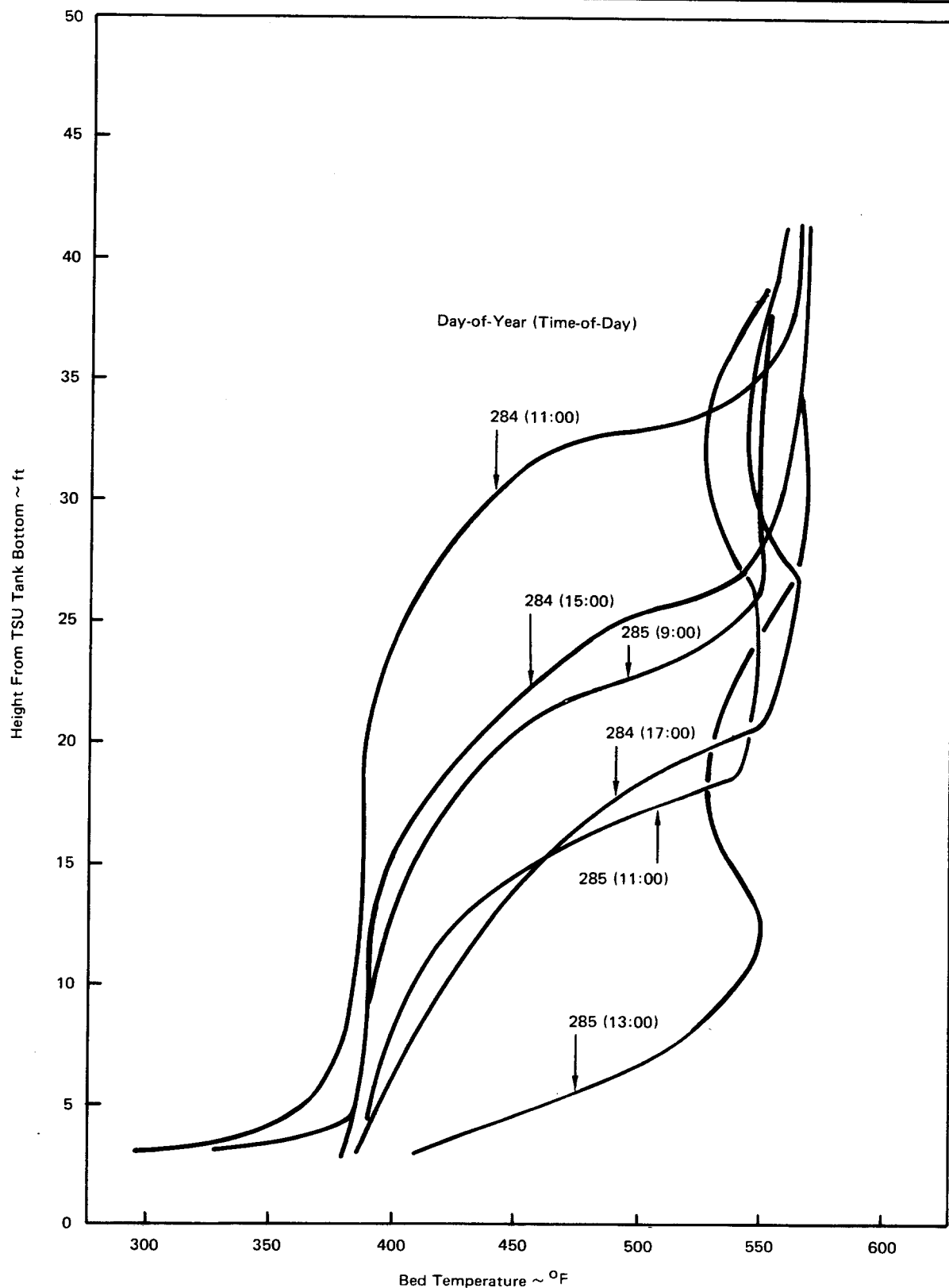


Figure 2.26. TSU Thermoclines – Dual Train Charging on Days 284, 285



PM on day 284 and at 9:00 AM, 11:00 AM and 1:00 PM on day 285. The loss of energy between 5:00 PM (day 284) and 9:00 AM (day 285) is reflective of TSU heat loss plus energy extracted for overnight blanketing/seal steam generation. Figure 2.27 shows the thermocline motion through the TSU during an extended period of single-train Mode 5 operation. An energy balance conducted on the TSU indicated that during this period 156 MWhT were added to the TSU.

### 2.5.3 Mode 5 Trips

The plant trip system is designed to protect plant equipment by sensing key parameters and automatically shutting down plant equipment when the key parameters are significantly out of limits. The parameters which monitor the TSS and which would "trip" the TSS charging system are:

1. High desuperheater outlet steam temperature.
2. High charging oil pressure.
3. High charging oil temperature.
4. High charging steam pressure.
5. High TSU oil level.
6. High flash tank condensate level.
7. High flash tank pressure.
8. High or low TSU ullage pressure.

Also, the plant operator can initiate a charging system trip (pushbutton) or a receiver trip will initiate a charging trip. A trip of the charging system will close the charging steam valve (UV3102), shutoff the oil pumps and close the charging train steam inlet valves (AOV3206/3306).

During normal plant operation, charging system trips occurred which demonstrated each of the above conditions and the plant was automatically

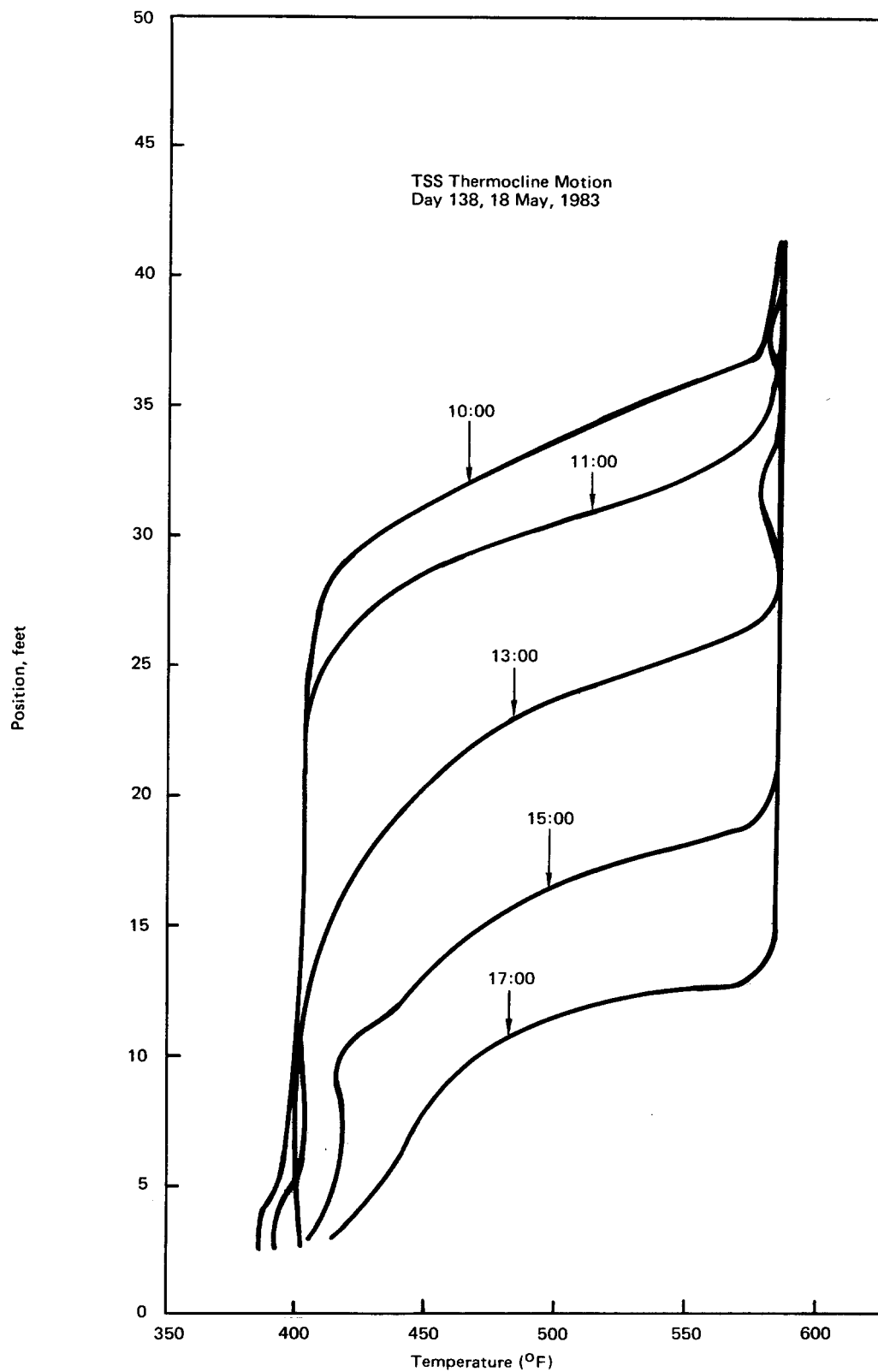


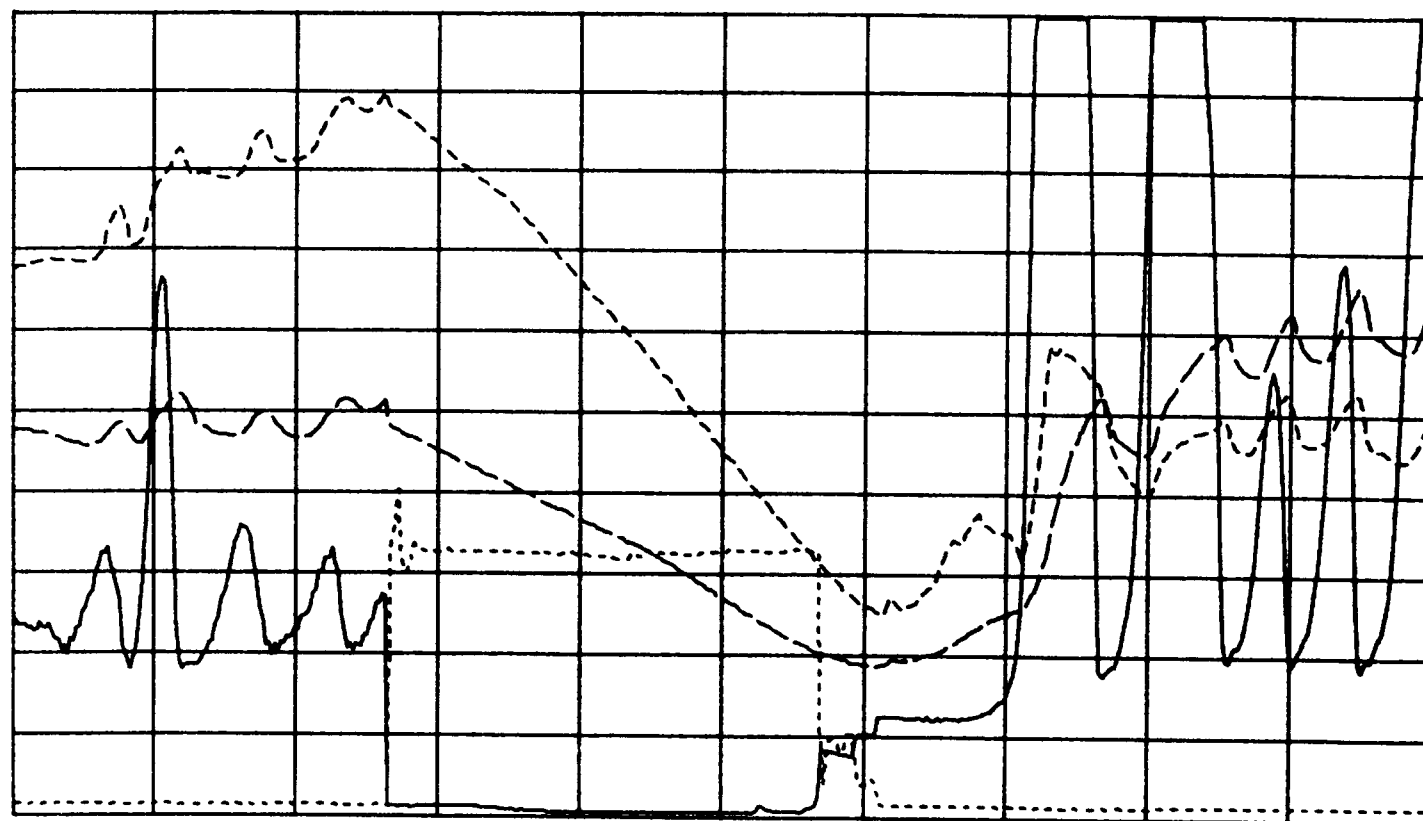
Figure 2.27. TSU Thermoclines -- Single Train Charging on Day 138

transitioned from Mode 5 to a lower level of plant operation (steam dump system operation or Mode 8). No specific trip tests were planned as a part of Mode 5 testing. The following examples of trips occurring during Mode 5 demonstrate satisfactory transition from Mode 5 to steam dump operation.

Figure 2.28 (a-f) presents data during dual-train Mode 5 operation on day 4 (1/4/83) including a charging system trip due to high flash tank condensate level. Figure 2.28a shows the level (LI3112P) increasing to the trip value (54 in.) with a trip and closure of UV3102 (ZI3102P). The key element of operation following the trip is the transition of receiver steam flow from the charging system to the steam dump system without a significant perturbation in receiver operation. Figures 2.28a and 2.28b show the immediate response of the steam dump valve and the slight increase in receiver pressure (PI2902) as the pressure setpoint was increased from charging pressure control to steam dump pressure control. Steam dump operation continued until the operators re-initiated Mode 5 charging, with no interruption of receiver operation. The oil system response to the trip is shown in Figures 2.28c and 2.28d and the steam system response is shown in Figures 2.28e and 2.28f.

On day 171 (6/20/83), charging train 1 was started using controlled warmup procedures. Just following the completion of the transition to Mode 5 operation, the charging system was tripped due to high charging oil outlet temperature. The increase in oil temperature to the trip level of 600°F is shown in Figure 2.29a, with subsequent shutdown of the charging oil pump and termination of steam flow to the charging system. The oil system response is shown in Figure 2.29a and the steam system response is shown in Figure 2.29b. Overall receiver parameters are shown on Figure 2.29c including the response of the steam dump valve to the trip-initiated transition. Subsequent to the trip, successful operation in Mode 5 was re-initiated.

FOR NTH SAMPLE AVERAGE = 1  
60.0000 MINUTE(S)



					60.00
ZI3102P	TS CHARGE MAIN STEAM VALVE POSITION	0.00 -	100.00 PCT		
ZI1001P	STEAM DUMP VALVE POSITION	0.00 -	100.00 PCT		
LI3112P	TS FLASH TANK FLUID LEVEL	10.00 -	60.00 INCH		
PI3114P	TS FLASH TANK PRESSURE	0.00 -	100.00 PSIG		

**Figure 2.28(a). Mode 5 Trip – High Flash Tank Level – Flash Tank Parameters**

SOLAR DATA PLOT PLOT # P206  
 REFERENCE TIME: 004 07 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
 600.0000 MINUTE(S)

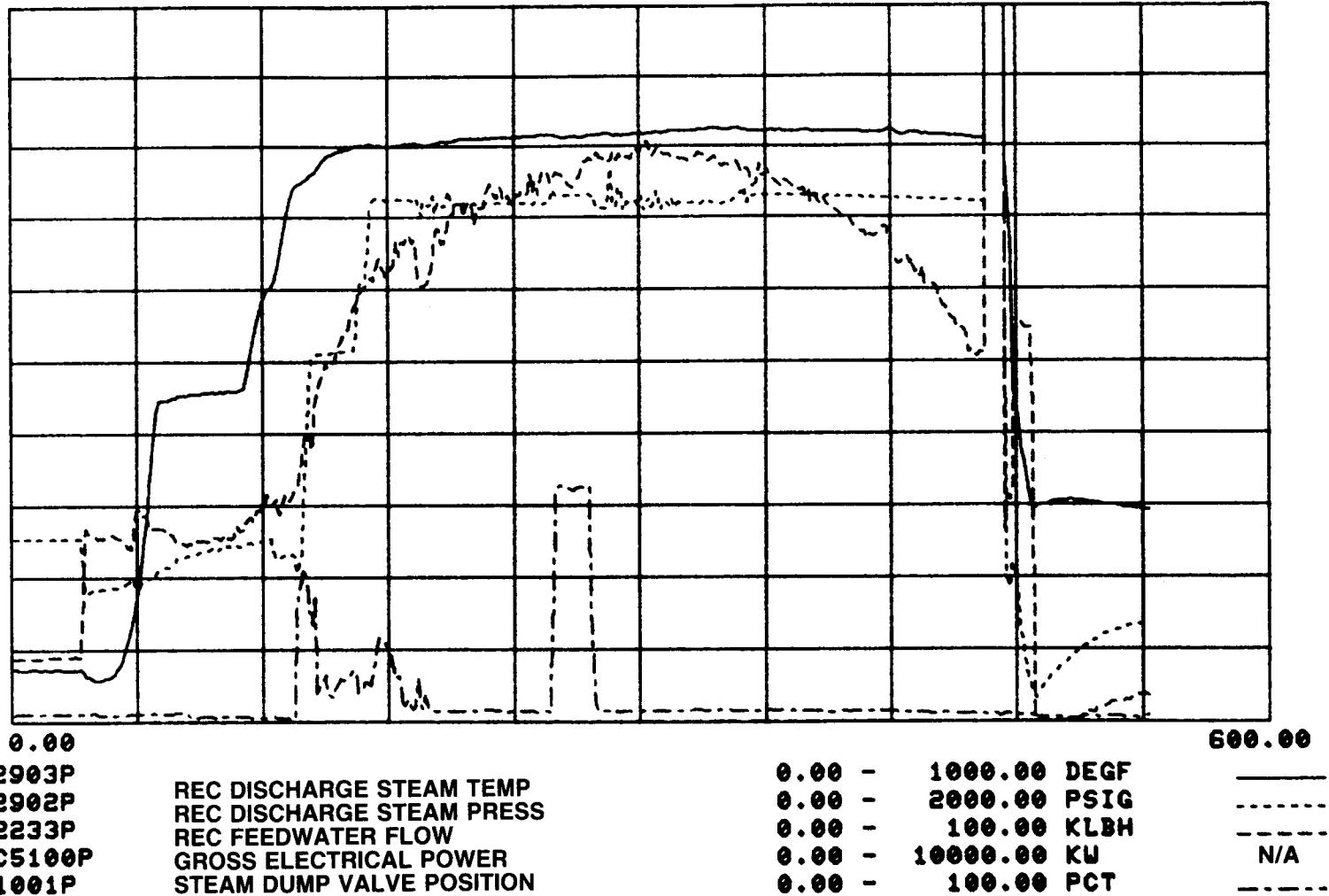
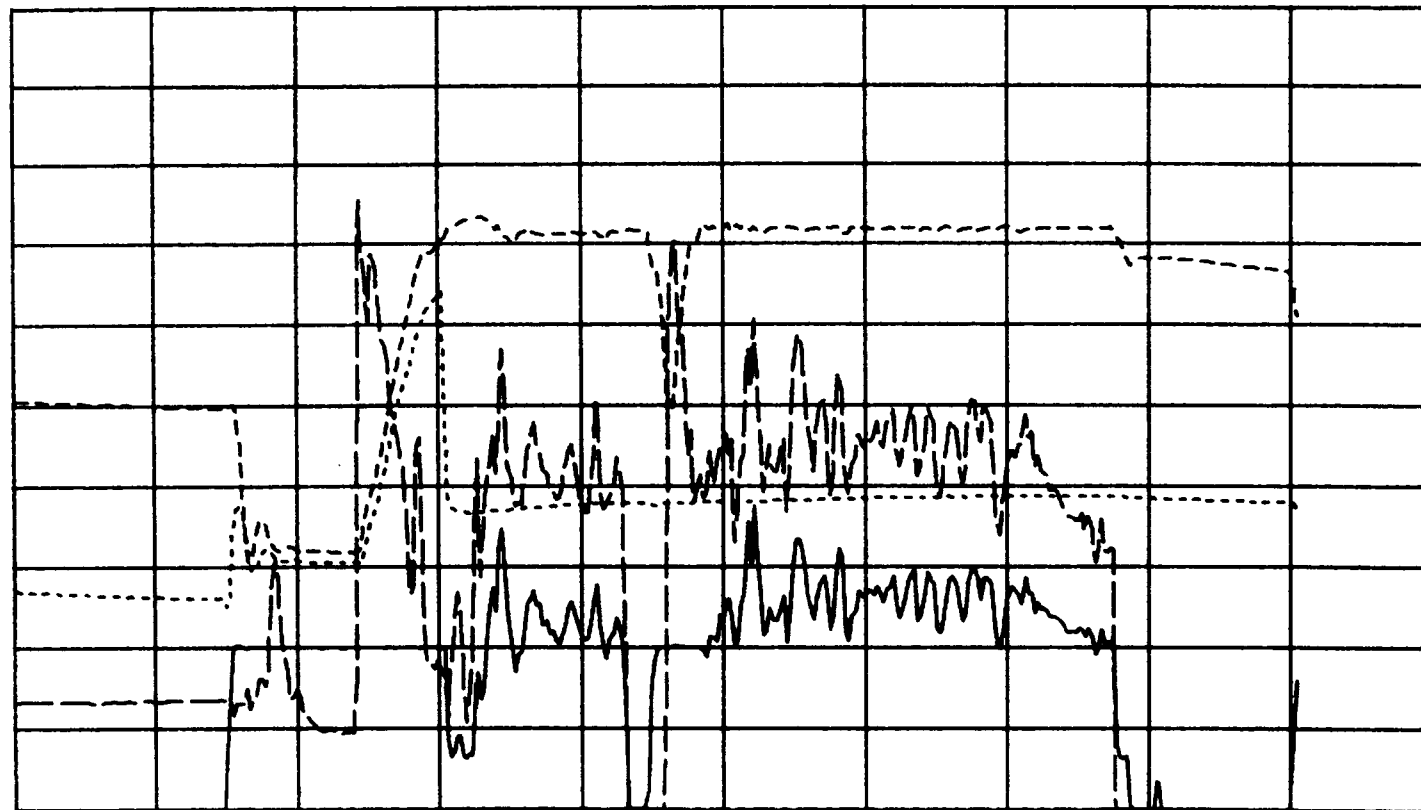


Figure 2.28(b). Mode 5 Trip – High Flash Tank Level – Receiver Parameters

SOLAR DATA PLOT PLOT # P207  
 REFERENCE TIME: 004 07 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
 600.0000 MINUTE(S)



0.00				600.00
FI3211P	TS CHARGE OIL FLOW (TRAIN 1)	0.00 -	800.00 KLBH	_____
TI3412P	TS CHARGE "COLD" OIL TEMP	0.00 -	800.00 DEGF	.....
TI3211P	TS CHARGE "HOT" OIL TEMP (TRAIN 1)	0.00 -	800.00 DEGF	-----
FI3205P	TS CHARGE STEAM FLOW (TRAIN 1)	0.00 -	80.00 KLBH	----

Figure 2.28(c). Mode 5 Trip – High Flash Tank Level – Train 1 Oil Parameters

SOLAR DATA PLOT PLOT # P208  
 REFERENCE TIME: 004 07 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
 600.0000 MINUTE(S)

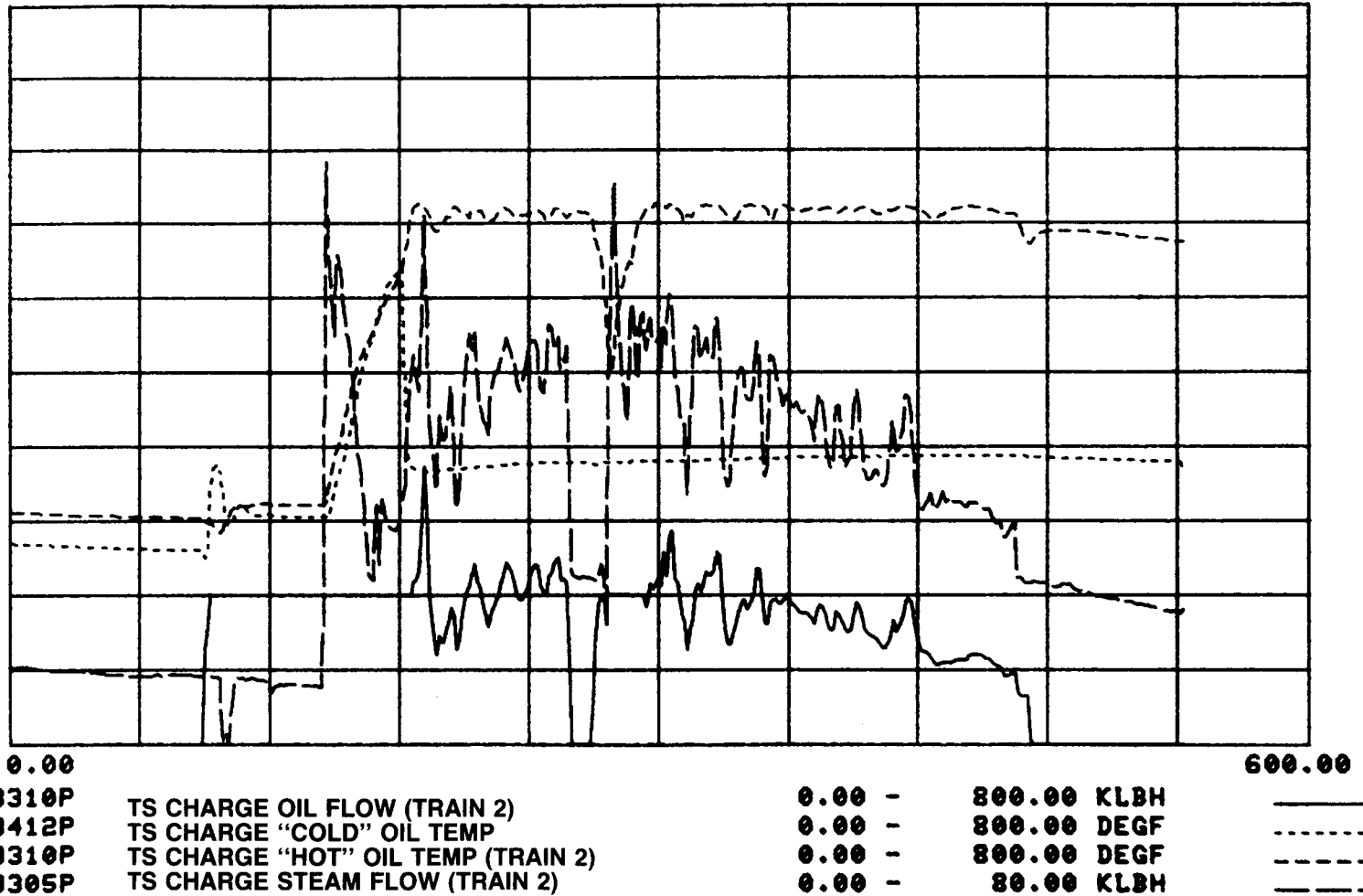


Figure 2.28(d). Mode 5 Trip – High Flash Tank Level – Train 2 Oil Parameters

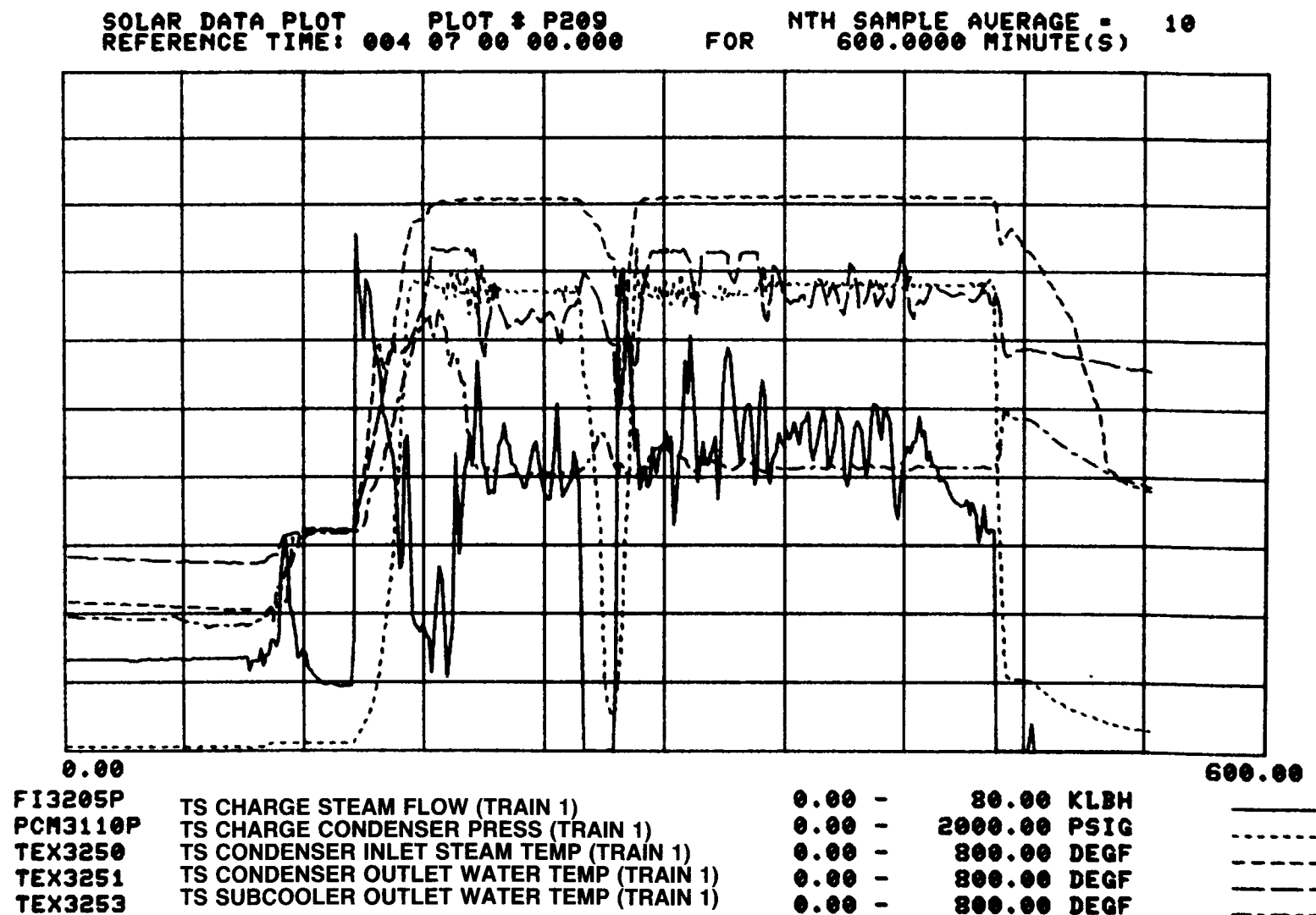


Figure 2.28(e). Mode 5 Trip – High Flash Tank Level – Train 1 Water/Steam Parameters



SOLAR DATA PLOT PLOT # P210  
REFERENCE TIME: 004 07 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)

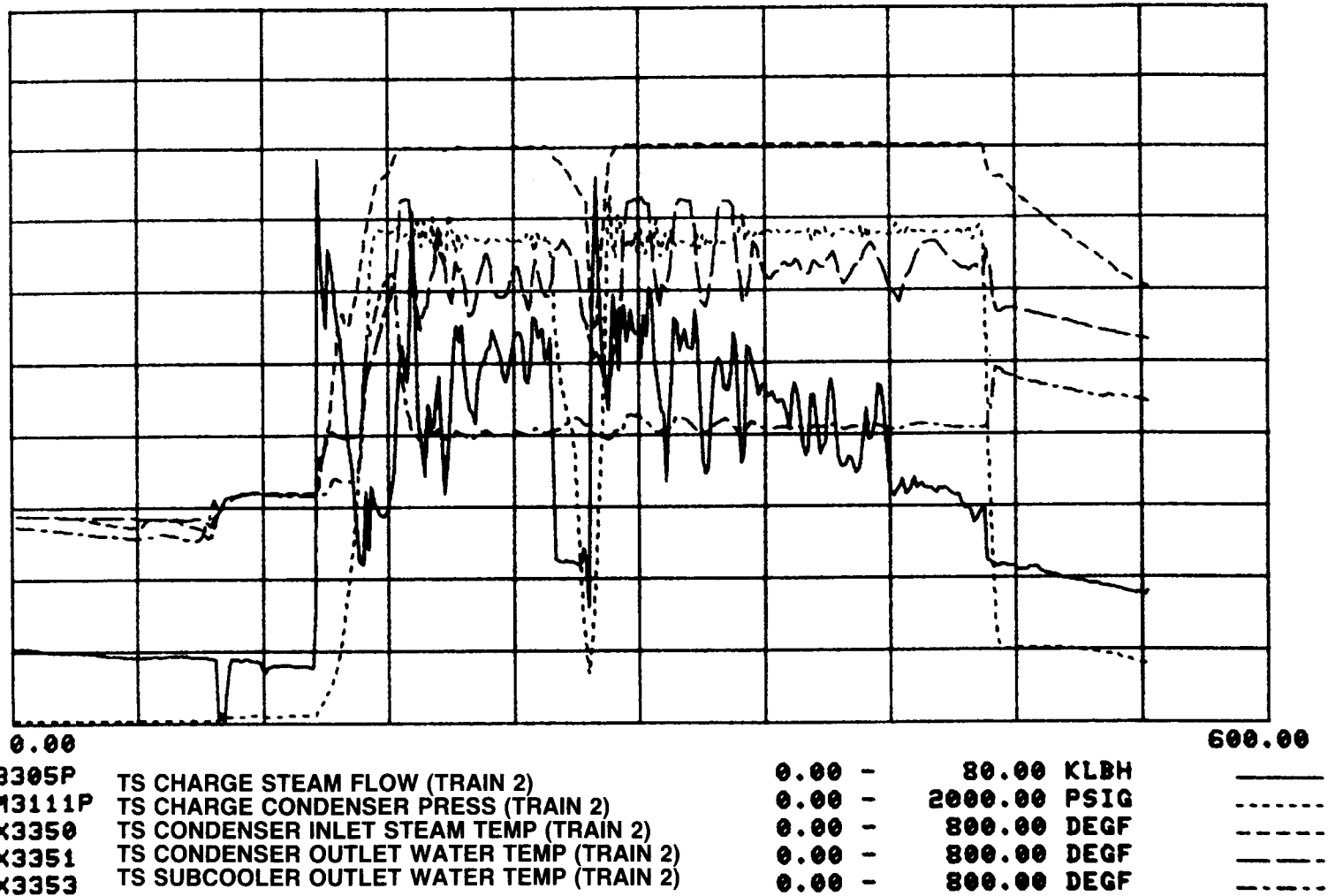
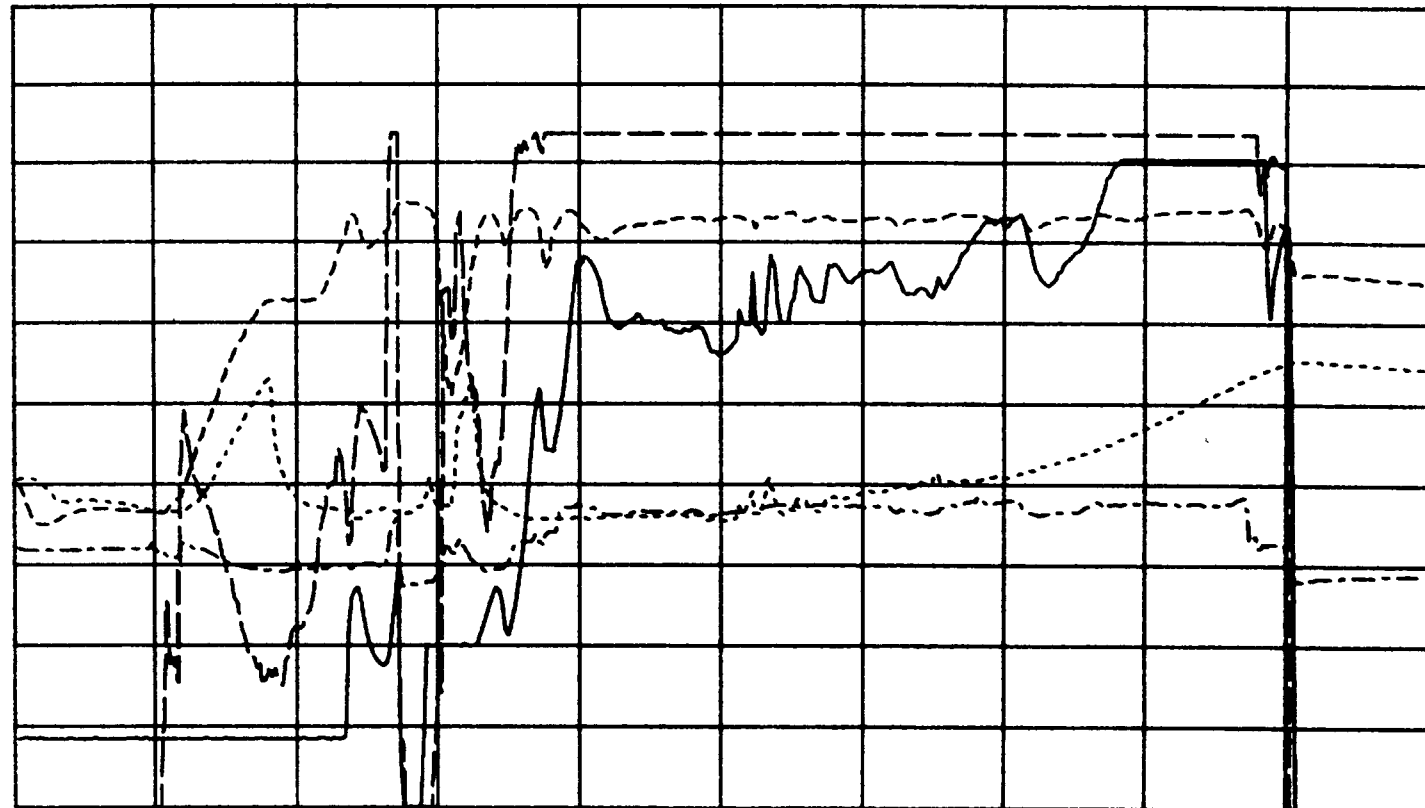


Figure 2.28(f). Mode 5 Trip – High Flash Tank Level – Train 2 Water/Steam Parameters

SOLAR DATA PLOT PLOT # P207  
 REFERENCE TIME: 171 07 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
 600.0000 MINUTE(S)



0.00					600.00
FI3211P	TS CHARGE OIL FLOW (TRAIN 1)	0.00 -	800.00	KLBH	———
TI3412P	TS CHARGE "COLD" OIL TEMP	0.00 -	800.00	DEGF	-----
TI3211P	TS CHARGE "HOT" OIL TEMP (TRAIN 1)	0.00 -	800.00	DEGF	-----
FI3205P	TS CHARGE STEAM FLOW (TRAIN 1)	0.00 -	100.00	KLBH	———
FI3102P	TS CHARGE STEAM FLOW (TOTAL)	0.00 -	200.00	KLBH	-----
*					

Figure 2.29(a). Mode 5 Trip – High Oil Temperature – Train 1 Oil Parameters

SOLAR DATA PLOT PLOT # P209  
 REFERENCE TIME: 171 07 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
 600.0000 MINUTE(S)

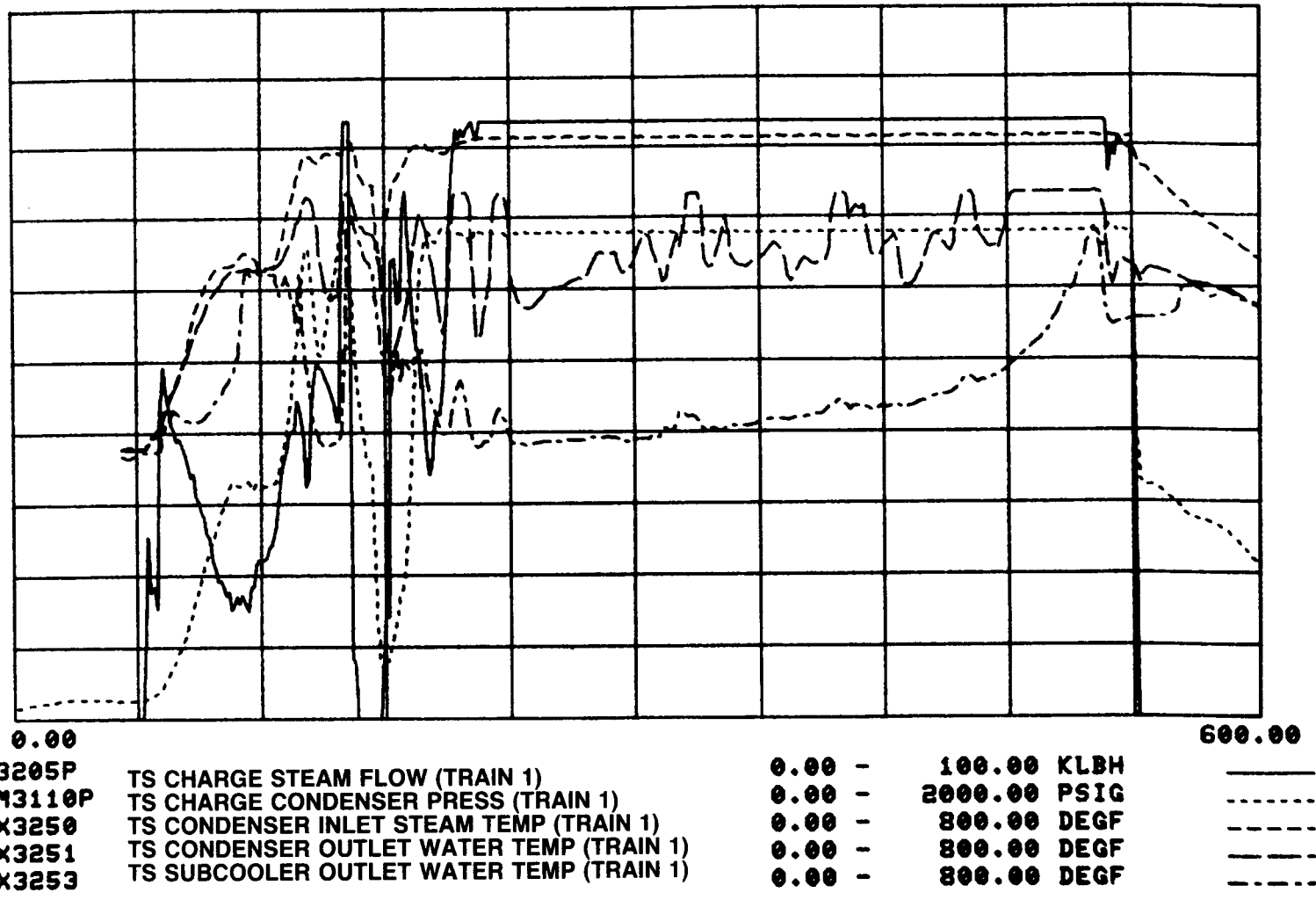
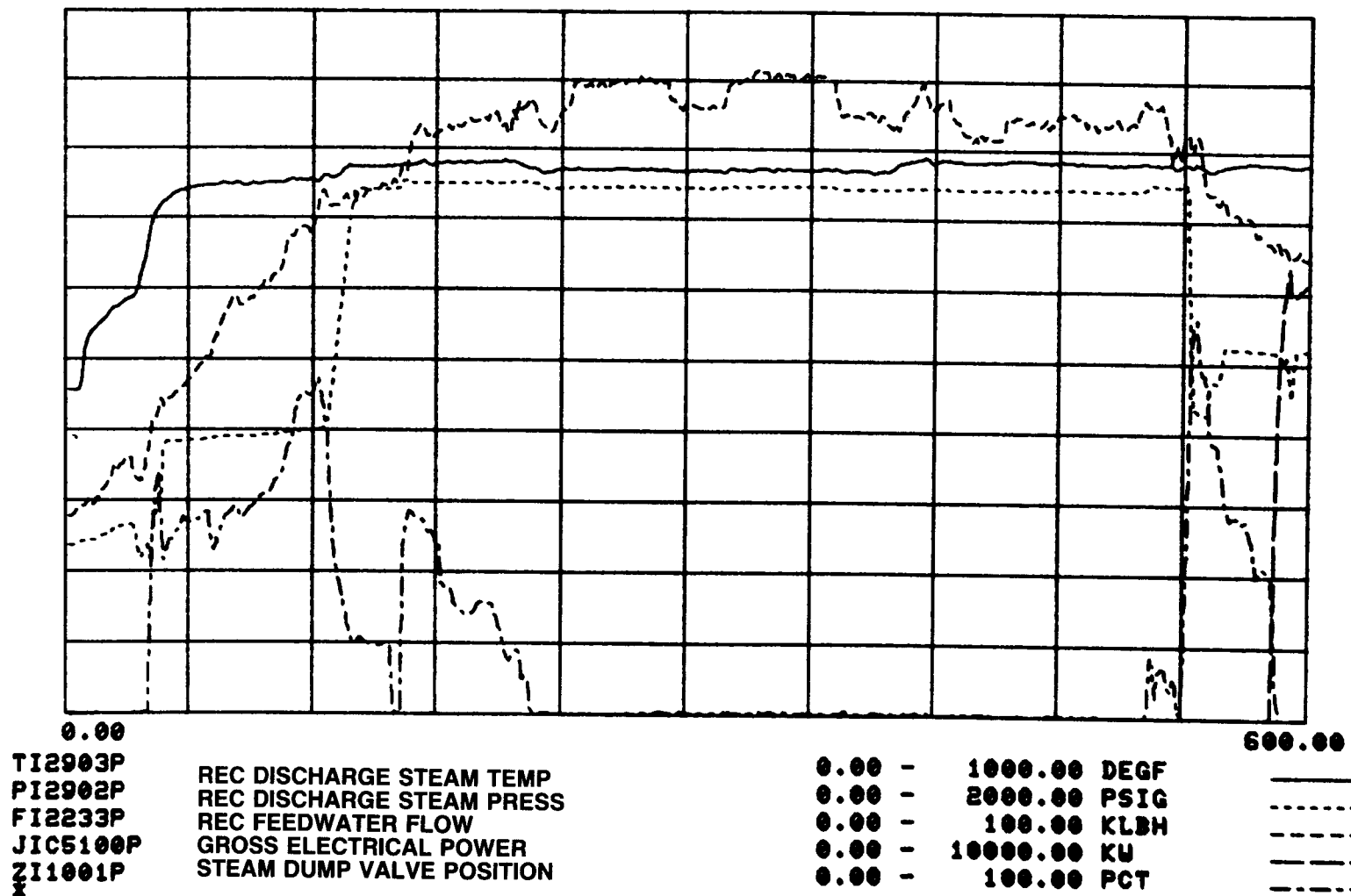


Figure 2.29(b). Mode 5 Trip – High Oil Temperature – Train 1 Water/Steam Parameters



**Figure 2.29(c). Mode 5 Trip – High Oil Temperature – Receiver Parameters**

A TSS charging system trip due to high TSU pressure occurred on day 3(1/3/83) during the initiation of dual-train Mode 5 operation. Charging system data for this period are presented in Figure 2.30 (a-f). The increase in TSU pressure (PI4008P) to the trip level of 16 IN-H<sub>2</sub>O is shown in Figure 2.30a, with closure of the charging steam valve (ZI3102P) as the trip occurred. Figure 2.30b shows the immediate response of the steam dump system (ZI1001P) as steam flow is diverted from the charging system. The responses of the charging oil systems and steam systems are shown for both charging trains in Figures 2.30c/d and 2.30e/f, respectively.

## 2.6 CONCLUSIONS

The conclusions with regard to Mode 5 operations are both qualitative and quantitative in nature. The qualitative factors are with regard to overall plant operation, equipment characteristics and operating philosophy. The quantitative factors are with regard to performance evaluation and equipment limitations.

Plant operation with TSU charging only, and receiver pressure control provided by the charging steam system, was demonstrated over a wide range of operating conditions during the Mode 5 test program. Plant operation during cloud transients demonstrated the effectiveness of using Mode 5 when receiver operation for turbine-direct steam would not be practical. The sequence for start-up and transition of the plant to Mode 5 was developed during the test program (See Section 2.5.1). Gradual warm-up of the charging heat exchangers was implemented and the start-up sequence was automated to minimize required operator actions.

SOLAR DATA PLOT PLOT # BLANK  
REFERENCE TIME: 003 12 00 00.000

FOR NTH SAMPLE AVERAGE = 1  
60.0000 MINUTE(S)

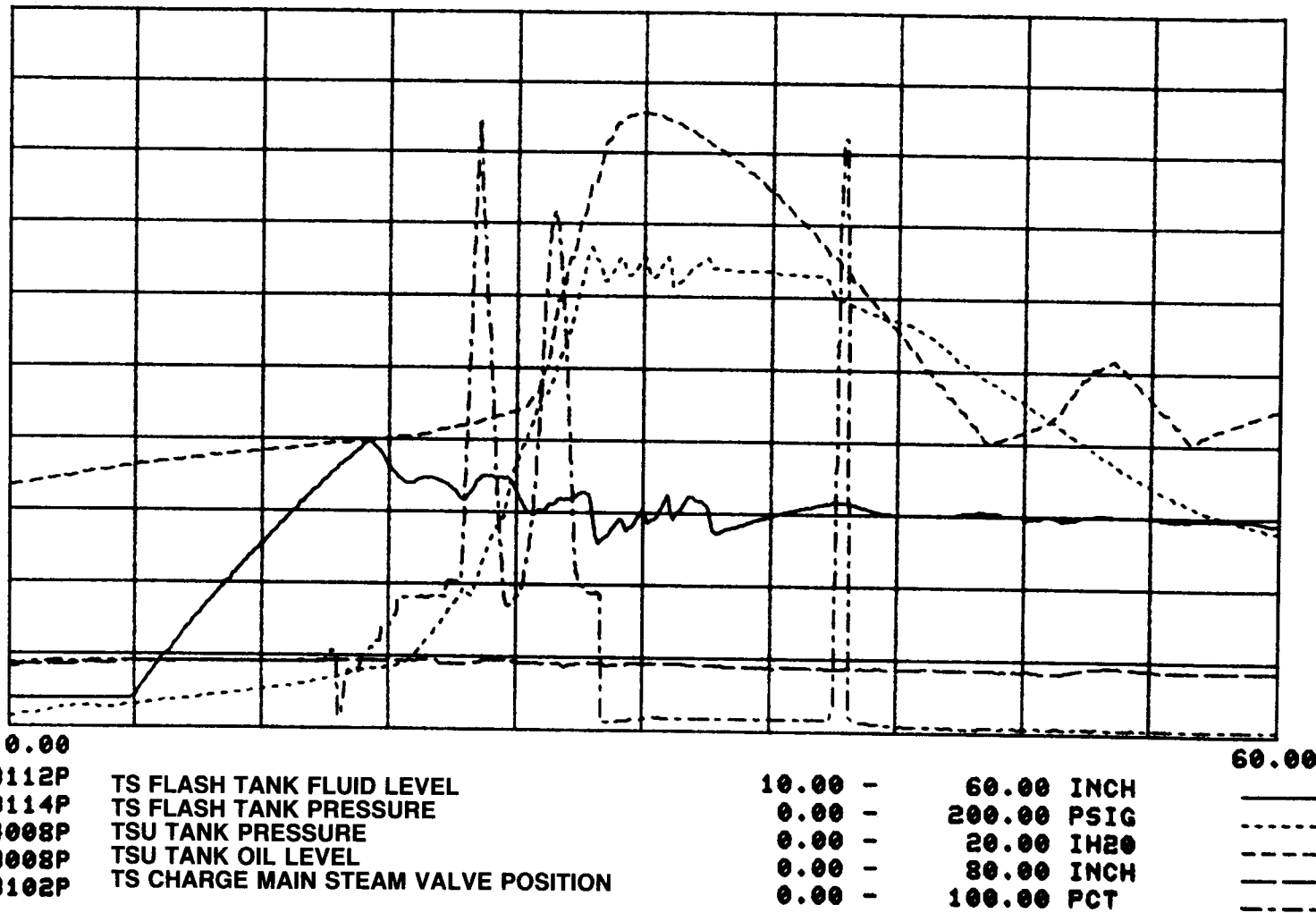
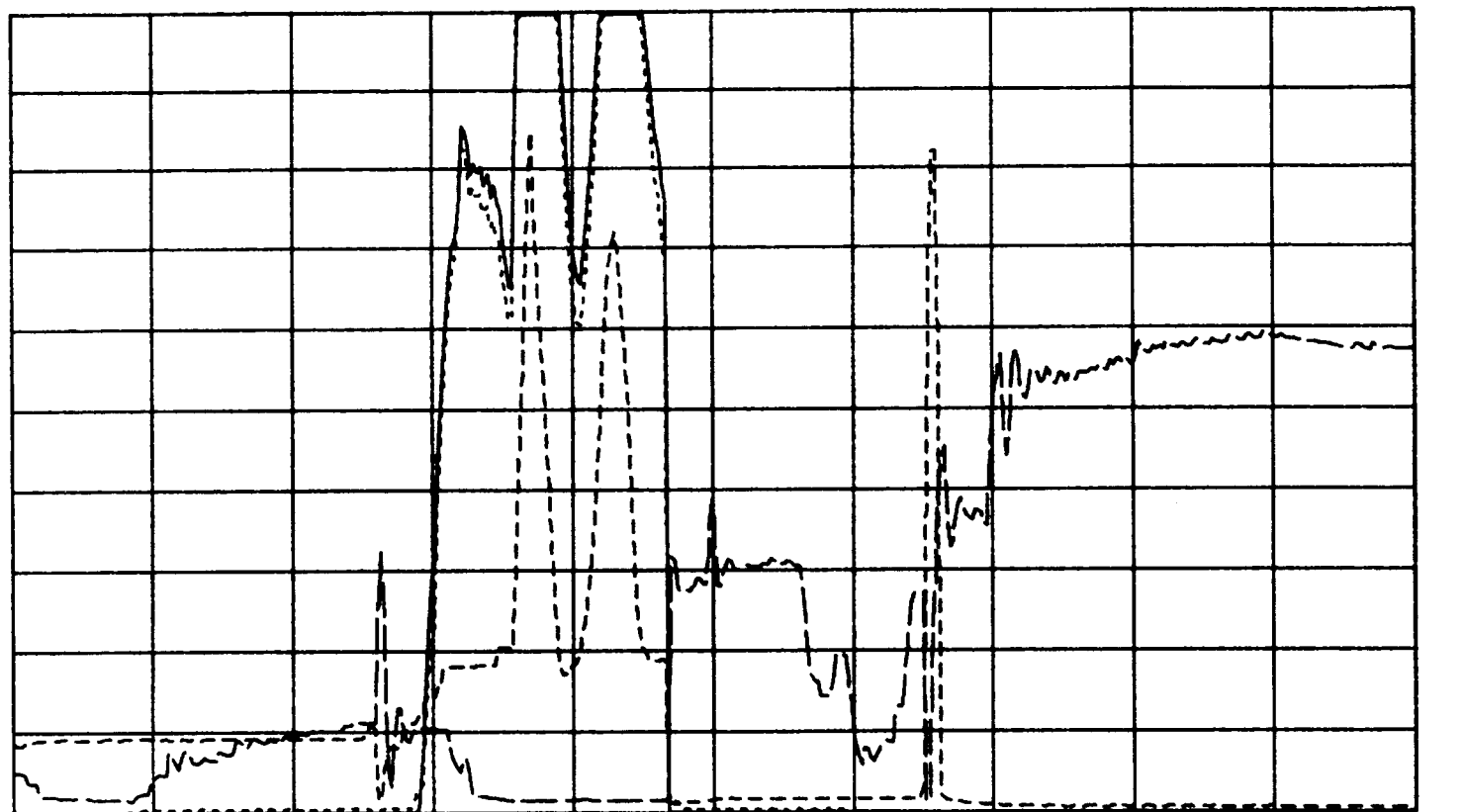


Figure 2.30(a). Mode 5 Trip – High TSU Pressure – TSU Parameters

SOLAR DATA PLOT PLOT # BLANK  
 REFERENCE TIME: 003 12 00 00.000

FOR NTH SAMPLE AVERAGE = 1  
 60.0000 MINUTE(S)



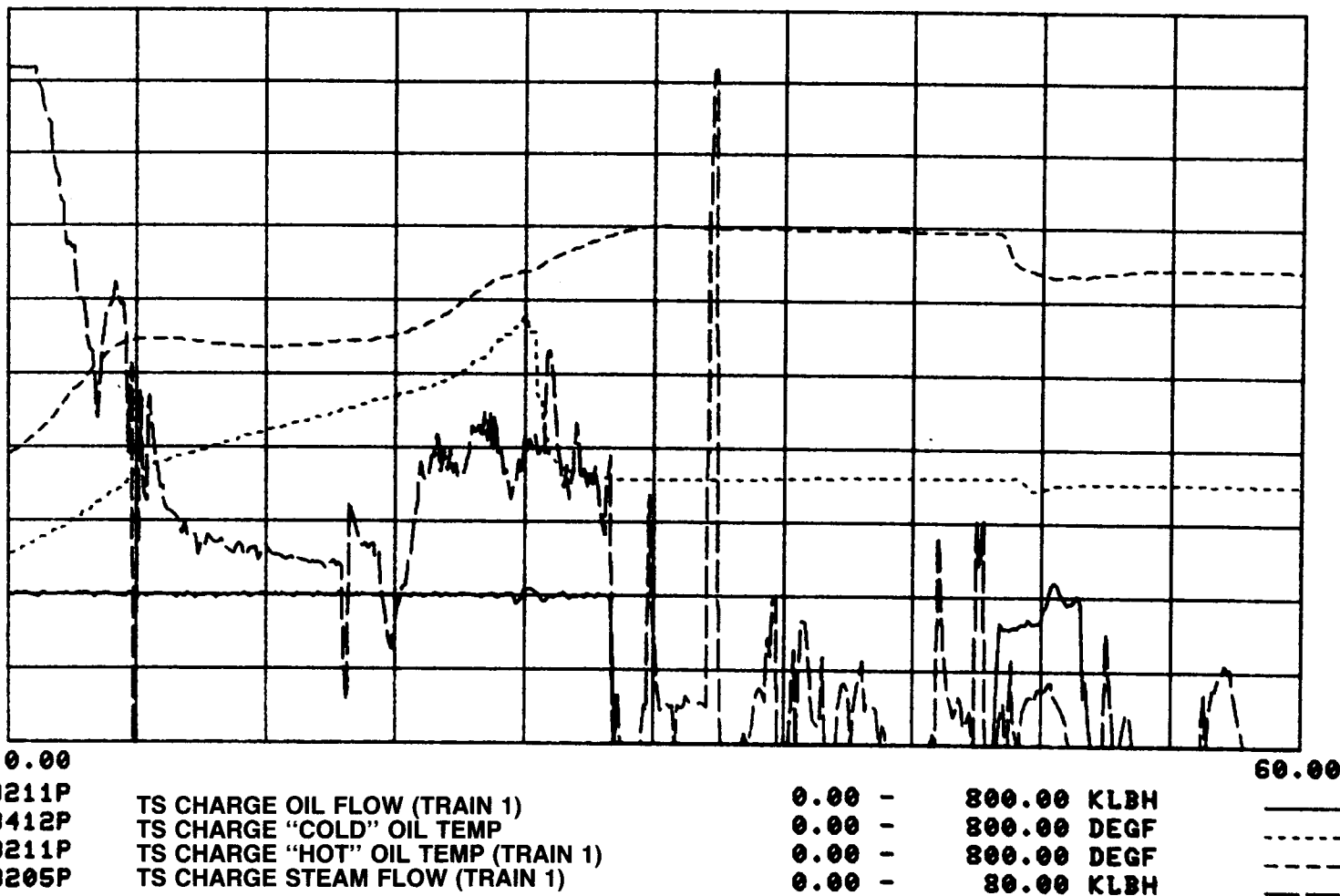
0.00				60.00
ZI3110P	CONDENSATE DRAIN VALVE POSITION (TRAIN 1)	0.00 -	100.00 PCT	_____
ZI3111P	CONDENSATE DRAIN VALVE POSITION (TRAIN 2)	0.00 -	100.00 PCT	-----
ZI3102P	TS CHARGE MAIN STEAM VALVE POSITION	0.00 -	100.00 PCT	.....
ZI1001P	STEAM DUMP VALVE POSITION	0.00 -	100.00 PCT	-----

\*

Figure 2.30(b). Mode 5 Trip – High TSU Pressure – Valve Positions

SOLAR DATA PLOT PLOT # P207  
 REFERENCE TIME: 003 12 00 00.000

FOR NTH SAMPLE AVERAGE = 1  
 60.0000 MINUTE(S)



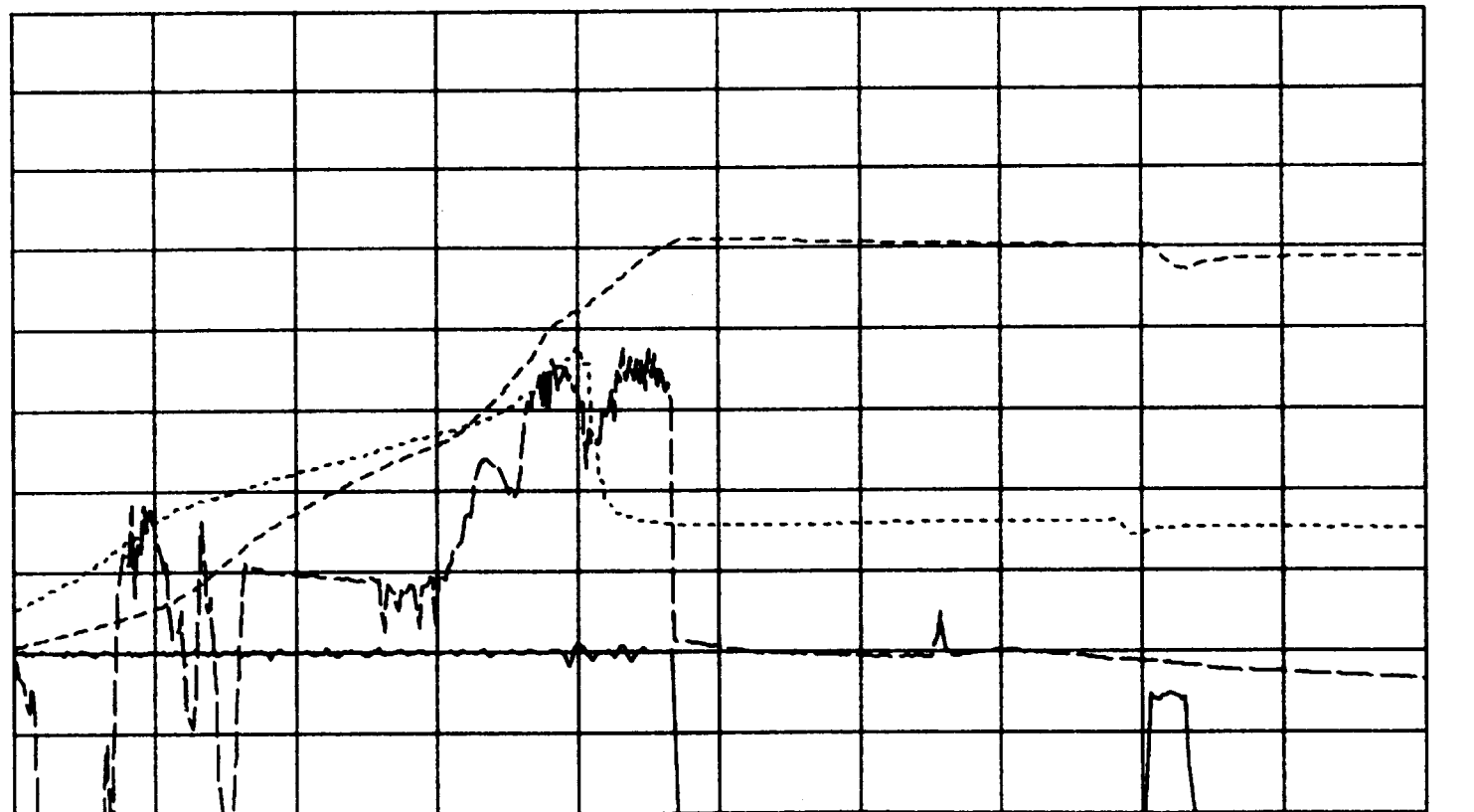
\*

Figure 2.30(c). Mode 5 Trip – High TSU Pressure – Train 1 Oil Parameters



SOLAR DATA PLOT PLOT # P208  
 REFERENCE TIME: 003 12 00 00.000

FOR NTH SAMPLE AVERAGE = 1  
 60.0000 MINUTE(S)



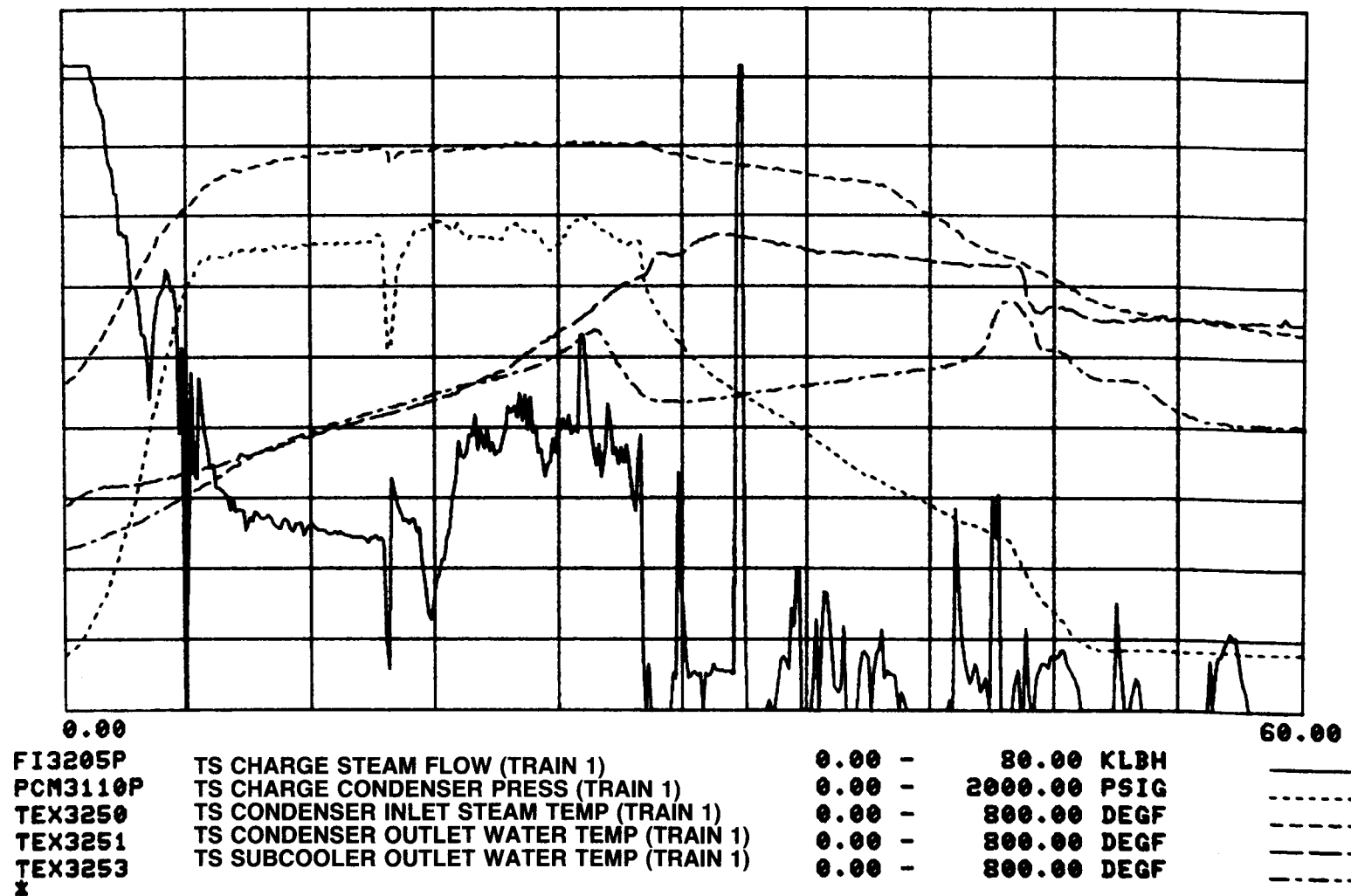
0.00				60.00
FI3310P	TS CHARGE OIL FLOW (TRAIN 2)	0.00 -	800.00 KLBH	_____
TI3412P	TS CHARGE "COLD" OIL TEMP	0.00 -	800.00 DEGF	-----
TI3310P	TS CHARGE "HOT" OIL TEMP (TRAIN 2)	0.00 -	800.00 DEGF	-----
FI3305P	TS CHARGE STEAM FLOW (TRAIN 2)	0.00 -	80.00 KLBH	-----

\*

Figure 2.30(d). Mode 5 Trip – High TSU Pressure – Train 2 Oil Parameters

SOLAR DATA PLOT PLOT # P209  
REFERENCE TIME: 003 12 00 00.000

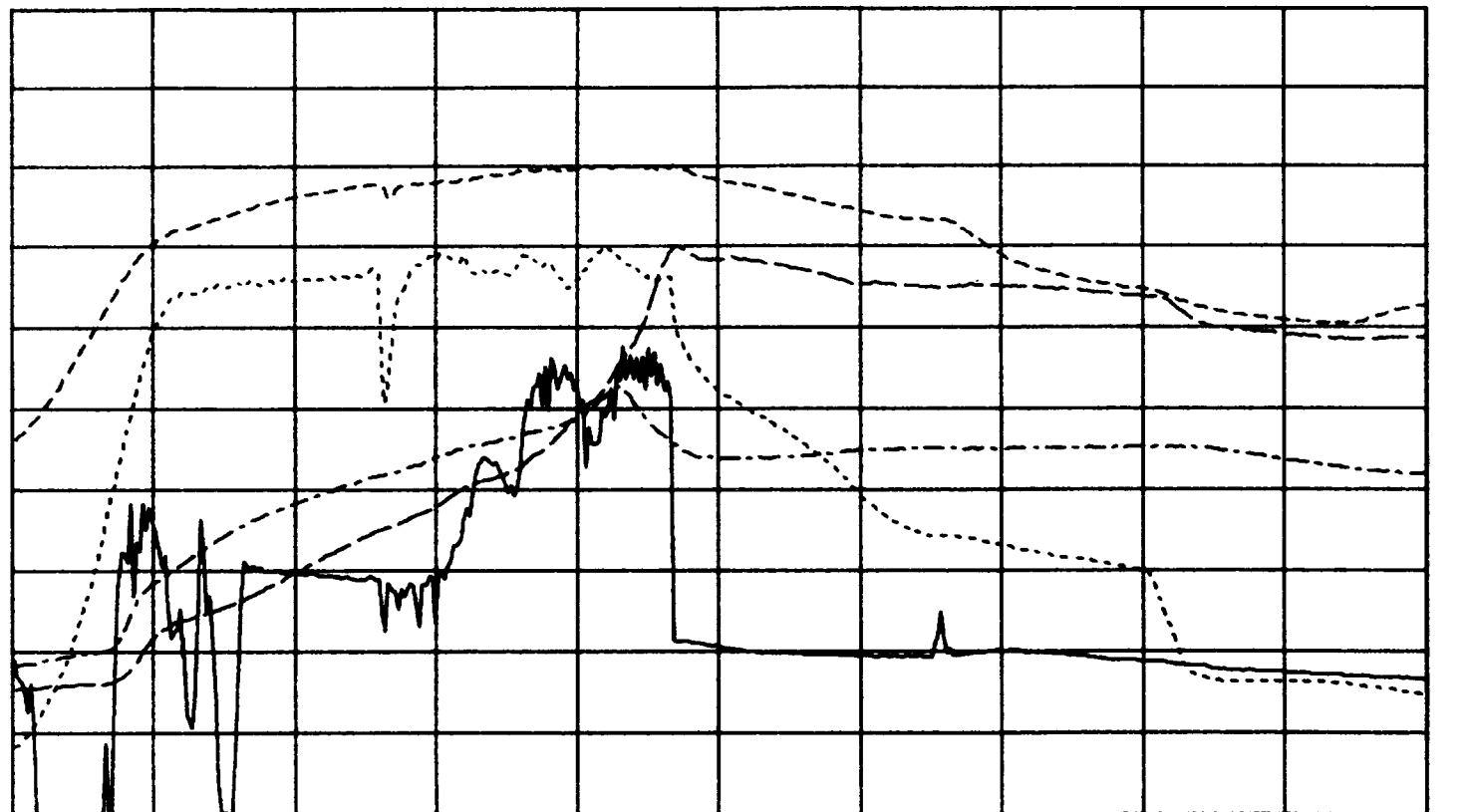
FOR NTH SAMPLE AVERAGE = 1  
60.0000 MINUTE(S)



**Figure 2.30(e). Mode 5 Trip – High TSU Pressure – Train 1 Water/Steam Parameters**

SOLAR DATA PLOT PLOT # P210  
REFERENCE TIME: 003 12 00 00.000

FOR NTH SAMPLE AVERAGE = 1  
60.0000 MINUTE(S)



0.00						60.00
FI3305P	TS CHARGE STEAM FLOW (TRAIN 2)	0.00 -	80.00	KLBH	_____	
PCM3111P	TS CHARGE CONDENSER PRESS (TRAIN 2)	0.00 -	2000.00	PSIG	-----	
TEX3350	TS CONDENSER INLET STEAM TEMP (TRAIN 2)	0.00 -	800.00	DEGF	-----	
TEX3351	TS CONDENSER OUTLET WATER TEMP (TRAIN 2)	0.00 -	800.00	DEGF	-----	
TEX3353	TS SUBCOOLER OUTLET WATER TEMP (TRAIN 2)	0.00 -	800.00	DEGF	-----	

Figure 2.30(f). Mode 5 Trip – High TSU Pressure – Train 2 Water/Steam Parameters

Based on the results of the Mode 1 (turbine-direct, Ref. 4), Mode 2 (turbine-direct and charging, Ref. 3) and Mode 5 test programs, it was determined that Mode 1 was best for electrical power generation and Mode 5 was best for TSU charging. Splitting the receiver steam between the turbine and charging systems (Mode 2) resulted in the operation of both systems far from their design points with associated performance penalties (reduced efficiencies and performance, increased parasitic loads, operating complexities, etc.). Since Mode 1 was determined to be the best mode for power generation, it is better to accomplish TSU charging as fast as possible in order to be able to return to Mode 1 for power production at or near the design point (instead of extended charging in Mode 2 with the turbine operated far from its design point).

Dual charging train operation was demonstrated during Mode 5 testing. Initially, coupling between the trains resulted in large "swings" in steam flow from one train to another. This was alleviated by first increasing the flow coefficients of the condensate valves (PV3110, PV3111) and then by "slaving" control of both condensate valves from a single controller. With the increase in condensate valve flow coefficient, along with the apparent lack of heat exchanger tube fouling, the actual single-train steam flow limit was approximately 90 KLBH (the design value was 65 KLBH). Thus, single train Mode 5 operation, when receiver flow was less than 90 KLBH, became the preferred operating configuration. This would result in high charging efficiencies, reduced parasitic power (compared to dual-train operation), and reduced operating complexity. When both trains were in operation, it was determined that the transition from dual-to-single train operation should occur at a total receiver flow of no less than 50 KLBH. With a single train in operation, it was determined that the charging operation should be terminated at a minimum receiver flow of approximately 30 KLBH.

Due to the lack of reliable charging steam flow instrumentation, steam flow to the charging heat exchangers was calculated from charging desuperheater spraywater flow and the desuperheater thermodynamic state points. Based on these calculations, charging efficiency was determined. Charging efficiency, defined as the ratio of charging power to receiver absorbed power, was generally higher at higher steam flows and also higher when TSS heat recovery was in service. Typical values of 65 to 80 percent were determined for charging efficiency which meant that 65 to 85 percent of the receiver absorbed power was delivered to the charging oil flow during Mode 5. The use of heat recovery paths resulted in lower auxiliary steam flow and thus higher charging steam flow for a given receiver flow. Deaerator pressure level also effected charging efficiency in that, for a given total feedwater flow, higher auxiliary steam flows would be required to maintain higher deaerator pressures. Deaerator pressures in excess of 25 psia were determined not to be advantageous in improving the deaeration process.

High volume, dual media energy storage was verified during the Mode 5 test program by the generation and maintenance of the TSU thermocline. The shape and motion of the thermocline were as predicted from analytical studies and scale test data.

## Section 3

### MODE 6 (STORAGE DISCHARGING)

During Mode 6 (Storage Discharging) operation, the plant is operated in a "Load following" or "flow" control strategy under manual control. All of the steam generated by the thermal storage extraction heat exchangers flows to the turbine to generate electrical power. The total steam/oil flow and resulting extraction rate may fluctuate depending on the amount of Thermal Storage Unit (TSU) charge, the flow setpoint, or the electrical demand (load). The thermal storage extraction rate is set to provide admission steam to the turbine at a level required to satisfy the electrical demand of the flow setpoint. As the TSU becomes fully discharged, the steam generator (steam) temperature and pressure will gradually decay until an admission steam condition trip occurs unless the operator transitions the plant into another operating mode.

#### 3.1 Summary of Mode 6 Operation

Mode 6 is used to generate electrical power after sunset, or during other non-sunshine periods, when thermal energy is available in the thermal storage subsystem. The thermal storage extraction rate is set to provide admission steam to the turbine at a level required to satisfy the electrical demand. The thermal storage steam generation equipment is capable of producing admission steam over the range of 5,500 to 110,000 LBH at a turbine inlet condition of 525°F and 385 psia. The plant design condition for Mode 6 operation is 7 MWe (net) for four hours. The principal components, flow paths, and process sensors associated with this operating mode are highlighted in Figures 3.1 and 3.2.

The number of extraction trains selected for operation depended on the desired plant electrical output to be generated from admission steam, the state of



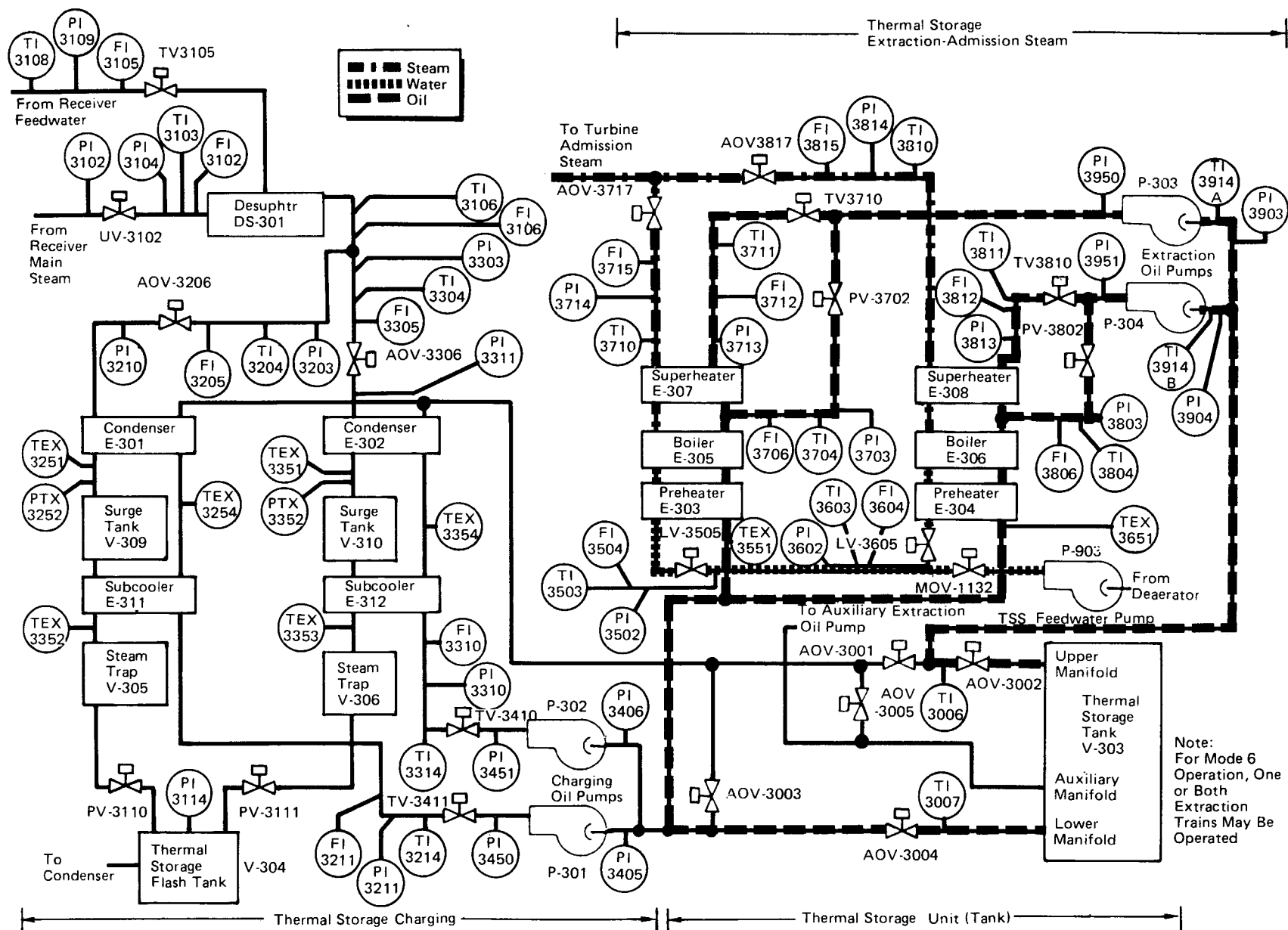


Figure 3.2. Major Thermal Storage Flow Paths Active During Mode 6 Operation



charge of the thermal storage tank, operational constraints and equipment availability. During the Mode 6 test program, tests were conducted primarily with a single extraction train in order not to rapidly expend the stored energy in the thermal storage tank and to ease the operating burden both in the control room (with its limited number of CRT terminals) and out in the field. Extended periods of equipment outage in the extraction oil systems, usually associated with pump (motor) inverter and winding temperature indication problems, heat exchanger leaks, and improper boiler water chemistry usually resulted in one of the two trains being unavailable for service. A limited amount of thermal storage two train extraction and turbine admission steam testing was accomplished as a part of the Mode 6 test program.

Within Mode 6 operation, there are two control strategies which were employed to regulate the thermal storage steam generator(s). In "flow" control, the thermal storage steam generator supplies a fixed admission steam flow to the turbine. Turbine generator electrical output then varies in response to changes in setpoints. In "load" control, the admission steam flow from the steam generator is modulated to produce a fixed electrical output. In this strategy, if two extraction trains are in service, one train would be operating in "flow" control while the second train would be operating the "load" control.

For either of the control strategies, the turbine admission steam control valves modulate to control admission steam pressure. In actuality, they control both the thermal storage steam generator pressure and the steam pressure leaving the last turbine high pressure stage (immediately upstream of the turbine admission control valves) enroute to the low pressure turbine stages. Admission steam temperature is controlled by diverting hot Caloria to

the dedicated superheater (see Figure 3.2). Oil flow is modulated in direct response to discharge steam temperature. The balance of the Caloria flows directly to the steam generator in response to either steam flow or electrical load control signals.

The process conditions appropriate to Mode 6 are an admission steam temperature of approximately 525°F and a pressure of 370 psi at the admission steam pressure control sensor immediately upstream of the admission steam stop valve. By maintaining the pressure at or near the design operating value of 370 psi, the turbine admission steam control valves have their greatest possible control range. If lower admission steam pressures are selected, the turbine control valves rapidly reach a full open condition and can no longer control pressure. In order to maintain admission steam flow in either "flow" control or "load" control strategy under this condition, the thermal storage steam generator pressure would "float" in an uncontrolled manner.

#### 3.1.1 Mode 6 Control

The TSS extraction subsystem is controlled by one of three different control schemes: "flow" control, "pressure" control, or gross electrical generator "load" control. In addition, auxiliary blanket steam can be provided by using the auxiliary extraction oil pump loop. The amount of steam generated is regulated by the amount of oil circulated through the boiler. Temperature control is maintained by the amount of oil circulated through the superheater section of the steam generator. Two separate trains are required to provide the turndown ratio over the operating range. Associated with each train are oil fluid pumps to control the oil circulation, controls for the steam flow, pressure, and temperature, controls for the boiler condensate level, and controls for generating auxiliary blanket steam. "Pressure" control is used

during the transition to Mode 6 operation and for generating auxiliary blanket steam, but, during Mode 6 operation, pressure control is provided by the turbine.

The extraction boiler oil control valves (PV3702, PV3802) can be operated in any of 3 control modes. The 3 control modes are "flow," "pressure," and turbine electrical "load" control. The control mode can be selected by the operator. In the "flow" control mode, the steam flowrate out of the extraction superheater for each train is controlled by modulating the oil control valve PV3702/PV3802. The flow loop feedback is calculated from the measured steam flowrate (FI3715/FI3815) out of the extraction superheater and the enthalpy of the superheated steam. In the "pressure" control mode, redundant measurements of the extraction boiler outlet pressure are high selected to provide the single feedback signal (PI3702/PI3802) to the pressure controller. This signal is also used in the auxiliary oil flow - pressure controller. In the turbine "load" control mode, the turbine load, JT5100 is fed back for comparison to the load setpoint by the load controller to position the extraction oil control valve.

The outlet steam temperature of each extraction train is controlled by regulating the amount of oil circulated through each superheater. The controller consists of an inner flow loop with the superheater oil flow (FT3712/FT3812) fed back to the flow loop controller which positions the temperature control valve (TV3710/TV3810). The outer temperature loop feeds back the high select (TI3710/TI3810) of the steam outlet temperature for comparison to the steam temperature setpoint (nominally 540°F). The temperature error is acted upon by the temperature controller and multiplied by a variable gain which is a function of superheater oil flow. The commanded

oil flow due to the temperature error is combined with the feed forward commanded oil flow which is approximately 35 percent of the main oil flow (FI3706/FI3806) to provide the cascaded oil flowrate setpoint. The main oil flow and the superheater oil flow are both fed through function generators to remove the flow bias at zero flow for monitoring purposes only (FI3712, adjusted superheater oil flow and FI3706, adjusted main oil flow).

The water level in each extraction boiler is controlled to a constant level by modulating the feedwater control valve (LV3505, LV3605). The valve is positioned in response to the level error and the difference between the extraction steam flow (FI3715/FI3815) exiting the boiler and the flow of water into the boiler (FI3504/FI3604). The extraction oil pump speed for each train is varied in response to oil flow demand to maintain either the main oil valve, PV3702/PV3802, or the superheater steam temperature control valve, TV3710/TV3810, at a command position of 80 percent open. The commanded positions of the main oil valve and the superheater temperature control valve are high selected so that the flow path with the highest demand will control the pump. This control scheme reduces pump pressure losses and parasitic loads.

### 3.1.2 Mode 6 Initiation

Mode 6 operation is typically initiated by transitions from Mode 8 (inactive) through steam generator start up and turbine generator start up, although transitions from Mode 3 or Mode 4 are also possible. The sequence of events and equipment operation were developed during the Mode 6 test program. Thermal storage extraction system start up may be initiated by SDPC automation sequences, while turbine start up and generator synchronization is an operator controlled, manual procedure.

### 3.1.2.1 Extraction System Start Up

The extraction train WARM sequence is used to begin initial heat up of the superheater and boiler using the auxiliary oil pump, P305. The WARM sequence is similar to the auxiliary steam sequence except it does not implement the auxiliary feedwater pump, P904. Initiating the WARM sequence aligns the extraction main oil valve controllers and commands the valve 30 percent open, commands the superheater steam temperature control valve to manual 30 percent open, puts the extraction oil pump controllers in manual and outputs two analog commands to ILS. ILS will align the extraction train block valves and start the auxiliary oil pump P305. ILS sends an analog command of 85 percent which puts the auxiliary oil flow steam pressure controller in manual, open 85 percent to allow the steam pressure to rise. When the superheater outlet pressure PI3714/PI3814 exceeds 205 psi, ILS sends an analog command of 100 percent to switch PCM3910 to auto. The pressure setpoint for PCM3910 will be set to the operating pressure with the PV tracking option.

The RUN sequence will interface with ILS to properly align the valves for using the main oil pump, P303/P304, and shutdown the auxiliary oil pump P305. Initiating the run sequence will align the main oil valve (PV3702/PV3802) and the superheater steam temperature control valve (TV3710/TV3810) 30 percent open and 70 percent open, respectively, and maintain the extraction oil pump controllers in manual until the superheater oil flow and boiler outlet pressure increase. When the superheater oil flow rate FI3712/FI3812 exceeds 50K LBH and the boiler outlet pressure PI3702/PI3802 exceeds 220 psig, the main oil controller will be switched to auto in pressure control with PV tracking. The oil pump controller is switched to auto and the superheater steam outlet temperature flow loop to auto with the temperature controller in manual with an output of 30 percent. At this point the extraction train is in

pressure control supplying admission steam and ready for turbine roll. When admission steam flow increases to 17.7 KLBH, and the superheater steam outlet temperature reaches 510°F, the steam temperature controller will switch to automatic temperature control and the RUN sequence logic outputs an analog signal of 99 percent to notify ILS to close the vent valves AOV3118/AOV3117 to the TSS flash tank.

### 3.1.2.2 Turbine Generator Start Up

During the course of the two year plant test and evaluation program, the turbine exhibited a series of operational problems which involved rolling the unit on admission steam. These problems emerged as part of the startup transition to Mode 6 as well as the transition from Mode 5 to Mode 4. In both cases, the transitions involved bringing the turbine generator online.

In order to understand the nature of these problems as well as both the corrective actions attempted during the course of the test program and their operational impacts, it is appropriate to review the basic features of the turbine as well as the initially intended operating procedure. Figure 3.3 shows a simplified schematic of the turbine. It shows the relative locations of the main and admission steam line penetrations as well as the locations of the stop and control valves for each steam line. The schematic also shows that the turbine is internally divided into a high pressure (HP) and low pressure (LP) section by an internal barrier. The shaft runs the entire length of the turbine and penetrates through the internal barrier. A shaft seal is provided at the barrier to minimize steam leakage between the high and low pressure sections and a packing steam dump valve is included to divert packing leakage to the condenser. This valve is intended to open in the event of a turbine trip to dump trapped steam which would otherwise continue to

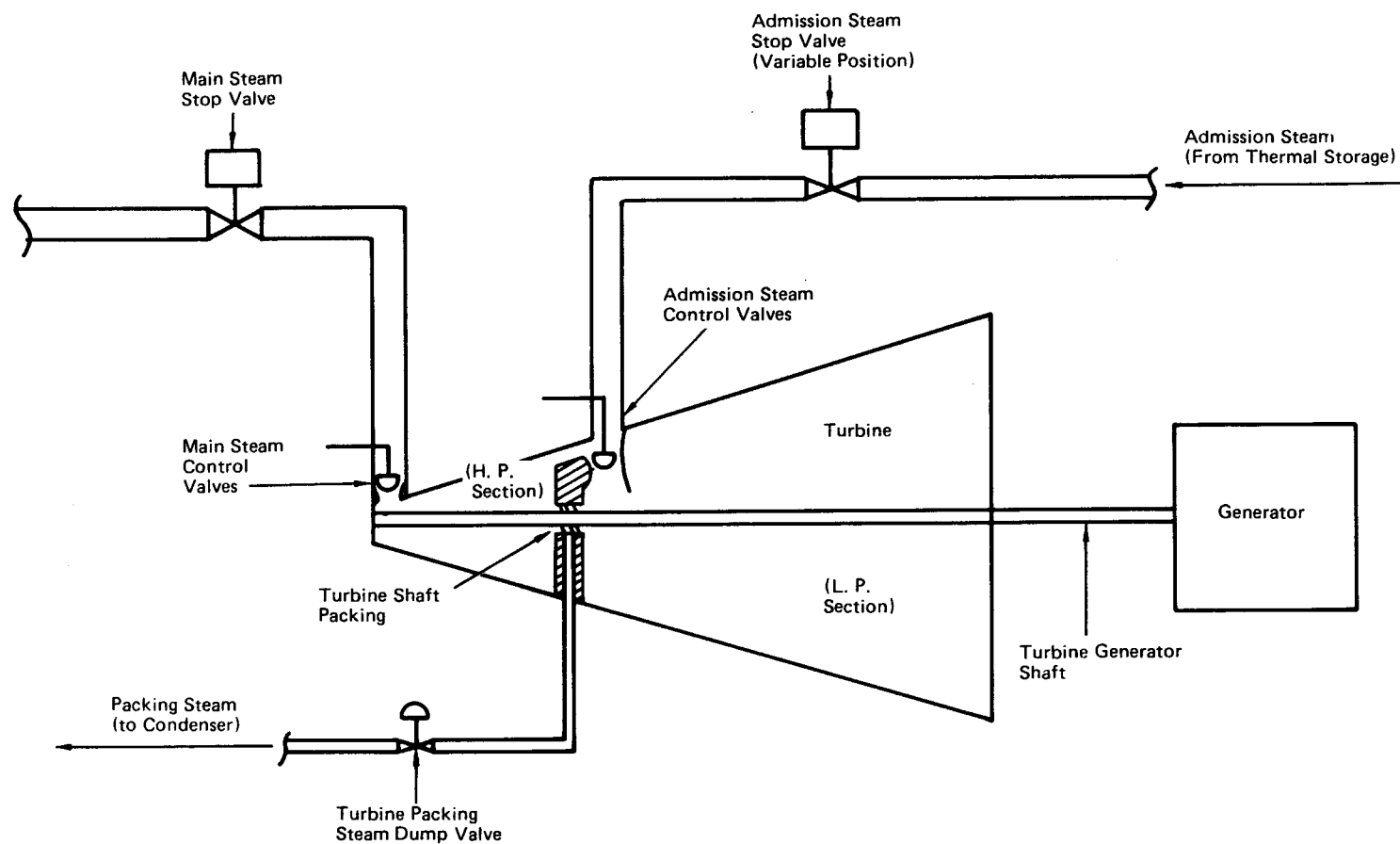


Figure 3.3. Simplified Schematic of Turbine Valves, Steam Flow Paths, and Shaft

expand through the turbine and could potentially cause a turbine over speed condition. The dump valve is triggered open by closure of the admission steam control valves.

It is also important to note the internal steam flow path through the turbine. All steam contained in the turbine high pressure section flows to the upstream side of the admission steam control valves. The steam then passes through the control valves and into the low pressure section of the turbine. Since the admission steam line enters the turbine on the upstream side of the admission steam control valves, the high pressure section of the turbine is pressurized to full admission steam pressure when the turbine is operating exclusively on admission steam.

When rolling and synchronizing the turbine on admission steam, the turbine was designed to utilize the admission steam control valves to maintain turbine speed control. At that time, the turbine high pressure section is pressurized to admission steam pressure while flow into the low pressure section is regulated by the control valves. This is a period of maximum differential pressure between the upstream and downstream side of the internal separation barrier. During this operation, the variable position admission steam stop valve is commanded to a full open position.

When the first turbine roll on admission steam was attempted in August 1982, a significant operating problem emerged. As the admission steam stop valve was opened allowing steam pressure to build in the turbine high pressure section, the turbine accelerated off the turning gear in an uncontrolled fashion even though the control valves were fully closed. After verifying that the control valves were in fact closed and seated, the cause of the problem was identified



as leakage past the shaft seal and into the low pressure section of the turbine. The influence of the leakage could be reduced somewhat by opening the packing dump valve to the condenser. The dominant effect of this action however was to significantly increase the consumption of admission steam.

After attempting a series of alternate operating procedures, it was concluded that rolling the turbine using the variable position stop valve for speed control presented the best hope for solving this problem short of redesigning the seal and disassembling the turbine for its installation. In this revised approach, the admission steam control valves were opened prior to turbine roll and the turbine was accelerated by gradually opening the stop valve. In this way, the majority of the steam pressure drop occurred across the stop valve with a substantially reduced pressure existing in the turbine high pressure section and virtually no pressure differential occurring across the shaft seal.

As the turbine approached synchronous speed, one of two approaches could be used. Manual operation of the stop valve could continue through the synchronization and initial loading phases followed by a transfer of the turbine control to the admission steam control valves. The second approach involved transferring control to the admission steam control valves immediately prior to synchronizing and loading the turbine. In this way normal turbine speed/load control functions could be utilized which were inherently superior in maintaining turbine control over strictly manual operation of the admission steam stop valve.

Several problems and concerns were identified pertaining to this alternate turbine startup procedure. First, the large size of the stop valve plug (50 sq in cross-section) presented significant difficulty in providing the fine

steam flow control necessary for precise turbine speed control. Second, it is in general not a normal practice to use a stop valve for control primarily out of concern for plug and seat erosion which could damage the valve and prevent it from providing the necessary tight shutoff in the event of a turbine trip.

In order to alleviate these concerns, an alternate stop valve plug design was developed which incorporated three 1 sq in poppet valves into the 50 sq in plug. As the stop valve began to open, the valve stem would first lift the poppet valves followed by a lifting of the main plug. The poppet valves were designed to provide sufficient steam flow to roll, synchronize, and initially load the turbine. Control of the valve position and resulting turbine speed/load continued however to be a manual (operator controlled) operation. This revised stop valve design was installed and ready for checkout during the first week of March 1983.

Initial testing revealed that turbine speed control was feasible using the revised stop valve design but that the manual control dial located in the control room (10 turn potentiometer) was far too sensitive. Typical dial settings were 0.94 (turbine roll off), 0.96 (1000 rpm hold), 0.975 (2000 rpm), and 1.25 (3000 rpm). This coarse response to very small changes in dial position forced the operators to approach this operation with a great deal of caution and required them to develop substantial finesse. It was not unusual for operators to tap the control knob slightly to achieve a change of 50 to 100 rpm in turbine speed.

During this test time, data were gathered regarding the relative merits of synchronizing and loading the turbine with the stop valve versus first transferring control to the control valves and synchronizing and loading the

unit as originally planned. Due to the extreme sensitivity in controlling speed with the stop valve, it became the preferred approach to transfer control to the control valves as soon as possible (approximately 3500 rpm) and move the stop valve to a full open position. Since the control valves operated at a nearly full closed position once the transfer was made, the packing steam dump valve would be triggered open thereby significantly increasing the admission steam demand to maintain turbine speed. This required that the control valves move to a more open position which released the dump valve to reclose. This reclosure caused the control valves to close back down which in turn reopened the packing dump valve. This cyclic valve operation caused substantial boiler flow and pressure oscillations to the point where boiler or turbine (low superheat) trips were common occurrences immediately prior to synchronization. The cyclic behavior continued until a sufficient load was assumed by the turbine so that the admission steam control valves were operating in a more open position relative to the opening trigger point for the packing steam dump valve.

As a result of these additional problems, General Electric engineers revised both the stop valve control characteristics and the activation of the packing steam dump valve. The revised nonlinear stop valve control characteristics resulted in much better turbine speed control at low flow. The revised control settings resulted in turbine rolloff at a dial position of approximately 3 and a 1/2-in total steam travel by dial position 9. This would only affect the poppet valve operation while not yet lifting the full stop valve plug. The remaining dial rotation from position 9 to 10 accomplished the balance of the stem travel to the full open 3-15/16 in position. Adjustments made to the packing steam dump valve logic required that the admission steam control valves be driven to a slightly "over closed"

condition prior to activating the dump valve. This prevented the mutual cycling between the control valves and the packing dump valve. These changes were accomplished during mid-December 1983.

As a result of these changes, fairly well behaved turbine roll, synchronization, and loading operations using admission steam were demonstrated. The baseline operating approach continued to involve transfer to admission steam control valve operation prior to synchronization of the unit and motion of the stop valve to a full open position. Unfortunately these final changes were made well after most of the Mode 6 and Mode 4 transition testing and operator training had been completed.

At the time of this writing, a dialogue continues between Southern California Edison and General Electric regarding the ultimate resolution of this turbine seal issue. In addition, since the original procurement contract specified an automatic admission steam roll and acceleration control feature, discussions also focus on how this capability may be transferred to the admission steam stop valve position controller.

### 3.1.3 Mode 6 Termination

#### 3.1.3.1 Extraction System Shutdown

To shutdown the extraction trains when supplying admission steam, the stop sequence automation is initiated. This commands the superheater steam temperature control valve (TV3710/TV3810) and the extraction main oil valve (PV3702/PV3802) closed to cool the boiler(s), and commands the boiler level control valve (LV3505/LV3605) closed and the oil pump controllers to manual. Analog commands are also sent to ILS to shutdown the main oil pumps P303/P304 and to close the extraction train block valves. When P305 is off and the

block valves 3906 and 3905 are closed, an analog command is sent to put the auxiliary steam pressure controller in manual, 85 percent open, to allow for oil expansion. As the pressure decays in the train, ILS will close AOV3717/AOV3817 and AOV3117/AOV3118 when the pressure decreases to 100 psi.

#### 3.1.3.2 Turbine Generator Shutdown

As the extraction trains are shutdown (above), and the admission steam flow is allowed to decrease, the turbine load will gradually decay. Continued decay in turbine load will result in a low-load turbine trip and the unit will come off-line.

### 3.2 Mode 6 Test Goals and Objectives

The goals and objectives of the Mode 6 test program were to gather test data in three areas of plant operation for subsequent analysis and comparison to design requirements as well as to provide recommendations for overall plant operation (specific operating conditions within the Mode or Mode-to-Mode performance comparisons). The three areas were steady-state operation, start-up and transitions, and trips.

#### 3.2.1 Steady-State Operation

The goal of the steady-state operational testing involved gathering sufficient data in order to make Mode 6 performance estimates. Attempts were made to gather performance related data over a range of plant operating conditions, subject to reasonable plant operating limits in order to identify any first order sensitivities. Measured performance values could then be used to make comparisons between Mode 6 and other operating modes as well as identifying the preferred Mode 6 operating conditions. Both single and dual train tests were conducted, including a determination of the maximum Mode 6 electrical power and total energy capacity of the TSU.

### 3.2.2 Start-Up and Transitions

The goal of Mode 6 start up tests was to develop an operational timeline, based on equipment operational characteristics and limitations, which would minimize the time required from establishment of oil flow through the steam generators to steady state Mode 6 turbine operation. This involved both single and dual extraction train operation.

The transition testing involved transitions both to and from Mode 6, from two train to one train operation, and varying steam flows either through flow set point changes or as a result of load set point changes. The mode transitions to Mode 6 involved initial operation in either Mode 4 (in line flow) or Mode 3 (storage boosted) and shutting down the thermal storage charging system or turbine operation on main steam, respectively, to reach Mode 6. The transition from Mode 6 involved shutting down the thermal storage extraction system to return to Mode 8 (inactive - plant shutdown), phasing in main steam flow to initiate Mode 3 (storage boosted), or phasing in TSU charging operation to initiate Mode 4 (in-line flow).

Transitioning testing within Mode 6 involved varying the quantity of admission steam to the turbine by increasing or reducing the flow or load set points or by allowing the extraction system energy in the TSU to naturally decay. The objectives of these tests were to gain insight into the overall plant response and controllability as well as identifying operational thresholds and limitations of individual components and systems.

The critical mode transition issues involved demonstrating the necessary manual operation sequences (through the Subsystem Distributed Process Control System) and developing timeline data which could be used in the evaluation of

Mode 6. It was beyond the scope of the Mode 6 test program to test any automatic control sequences which were initiated and controlled by the Operational Control System (OCS) to accomplish transitions to or from Mode 6.

### 3.2.3 Trips

The goal of the trip evaluation was to verify that the plant would continue to operate in a lower level mode following a trip condition. A trip of a single extraction train during dual train operation should result in continued Mode 6 operation whereas a TSS trip should result in a transition to plant shutdown. In the event of a turbine trip during Mode 6 operation, both the extraction system and the turbine would shutdown resulting in a non operating plant.

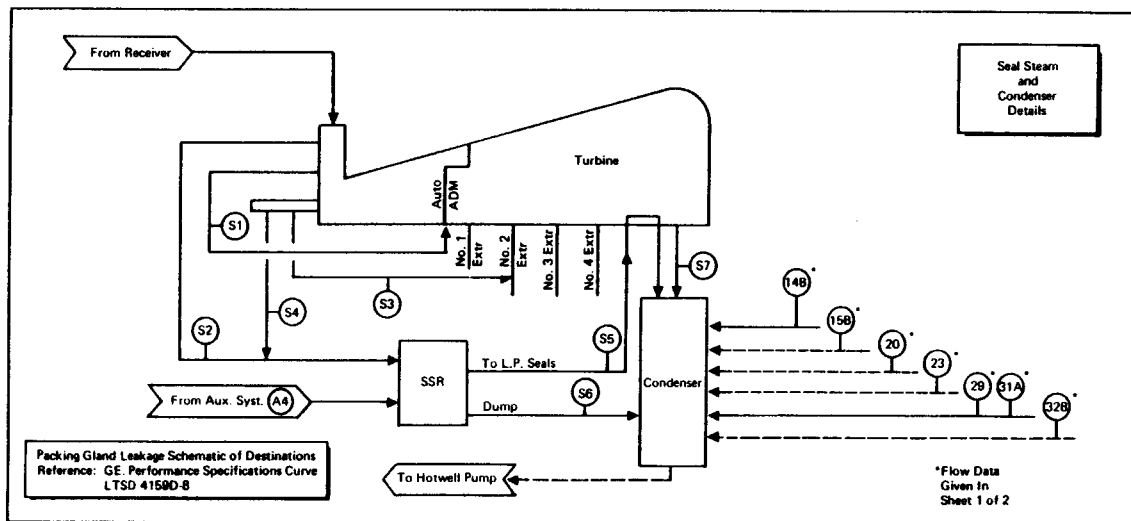
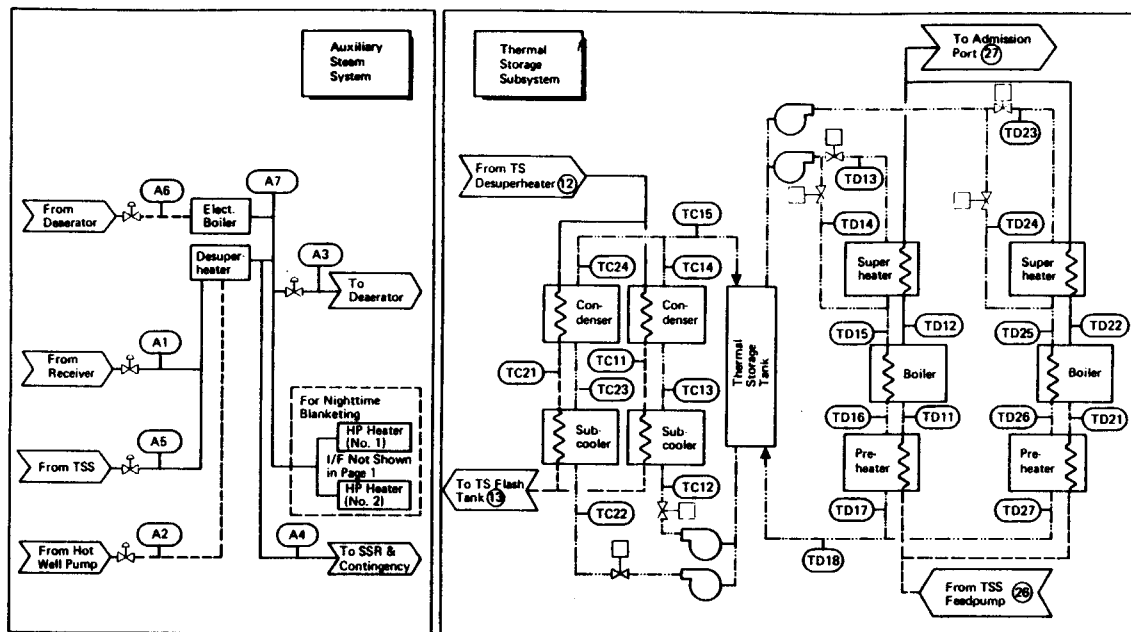
### 3.3 Mode 6 Design Summary

Before discussing plant test results for Mode 6 operation, a review of the basic operating range and performance predictions, which were developed as part of the initial plant sizing and overall design activities, will be provided. With this information, it is possible to make direct comparisons to actual operating data and to identify areas of discrepancy or uncertainty. The Mode 6 design summary addresses the water/steam and thermal storage oil portions of the plant.

Detailed design data involving actual state point conditions at various locations in the water/steam and extraction oil systems are shown in Figures 3.4 and 3.5. The data contained in Figure 3.4 (a and b) represent the predicted plant operating characteristics at maximum admission steam flowrate. Note that this case represents the maximum design steam flow for the system using two extraction trains. The design data shown in Figure 3.5 (a and b) correspond to minimum design turbine load during Mode 6 operation at

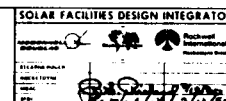






Location Identification	Flow Rate (lb/hr)	Enthalpy (Btu/lb)	Temperature (°F)	Pressure (psia)
Auxiliary Steam System	A1			
	A2			
	A3			
	A4			
	A5			
	A6			
	A7			
Thermal Storage System	TC11			
	TC12			
	TC13			
	TC14			
	TC15			
	TC21			
	TC22			
	TC23			
	TC24			
	TD11	96000.0	427.7	447.8
	TD12	96000.0	1206.5	447.8
	TD13	144488.0	575.0	71.5
	TD14	460000.0	575.0	88.7
	TD15	804488.0	567.3	84.4
	TD16	804488.0	467.7	51.2
	TD17	804488.0	429.8	41.9
	TD18	1188872.0	429.8	26.7
	TD21	96000.0	427.7	447.8
	TD22	96000.0	1206.5	447.8
	TD23	144488.0	575.0	71.5
	TD24	460000.0	575.0	88.7
	TD25	804488.0	567.3	84.4
	TD26	804488.0	467.7	51.2
	TD27	804488.0	429.8	41.9
Seal Steam Condenser	S1			
	S2			
	S3	2708.5	1283.1	525.0
	S4	1448.3	1283.1	525.0
	S5	850.0	1283.1	449.3
	S6	798.3	1283.1	449.3
	S7	91681.7	969.0	108.7

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DEPARTMENT OF ENERGY  
 SOLAR TEN MEGAWATT PROJECT OFFICE  
 9350 BLAIR DRIVE, SUITE 210  
 SAN FRANCISCO, CALIFORNIA 94133

10 MW SOLAR PILOT PLANT, DAGUERRE, CALIFORNIA

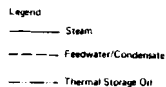
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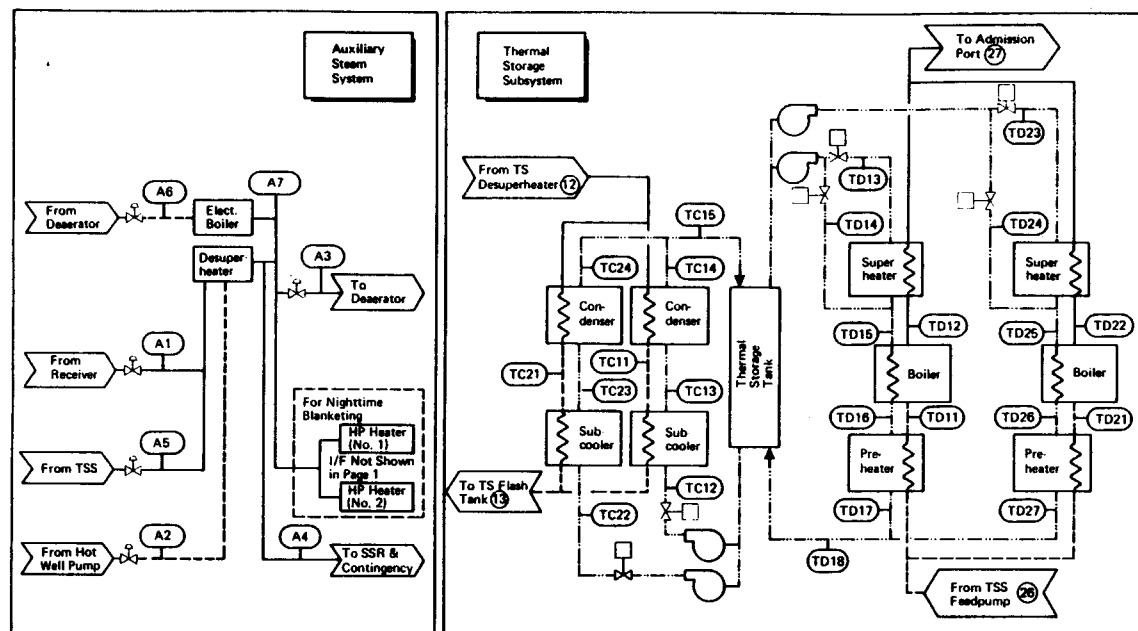
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Figure 3.4(b). Mode 6 Operation – High Admission Steam Flow



Location Number	Flowrate (lb/hr)	Enthalpy (Btu/lb)	Temperature (°F)	Pressure (psia)
1	30277.8	78.7	108.7	1.228
2	30138.8	77.3	108.8	140.0
2A				
3	30138.8	116.6	148.2	138.7
4				
5				
E				
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22	1218.0	1046.4	181.3	3.67
23	1218.0	77.9	188.0	30.0
24	32630.3	186.3	228.0	500.0
25	32630.3	186.4	228.0	490.0
26	32630.3	186.4	228.0	388.3
27	32630.3	1264.6	630.0	388.0
28	30000.0	1283.1	626.0	
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32B				
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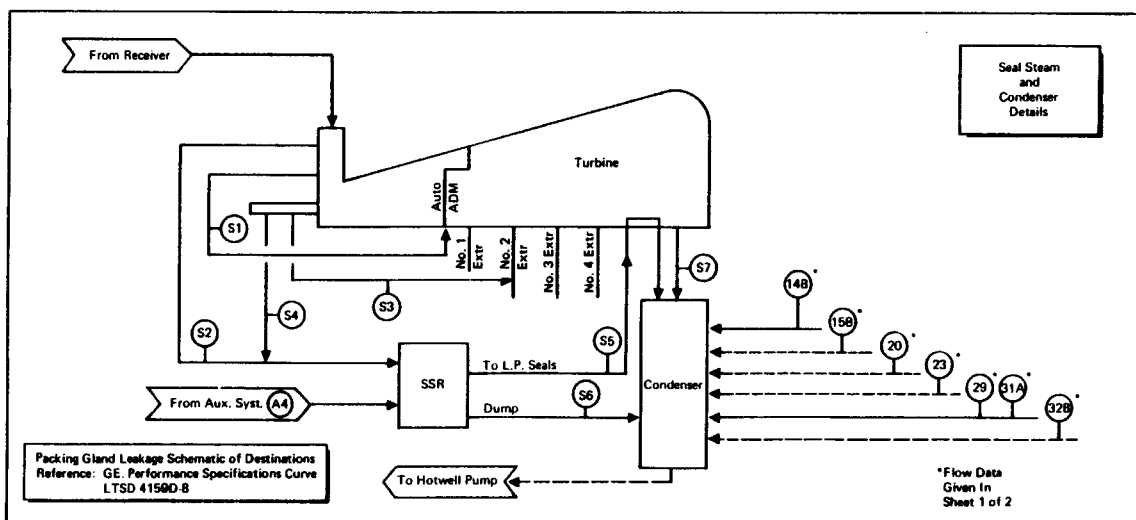


Legend

— Steam

- - - Feedwater/Condensate

- · - Thermal Storage Oil



Location Identification	Flow Rate (lb/hr)	Enthalpy (Btu/lb)	Temperature (°F)	Pressure (psia)
Auxiliary Steam System	A1			
	A2	140.7	77.3	108.9
	A3	2263.5	1204.7	345.0
	A4	277.4	1204.7	345.0
	A5	2630.3	1263.1	481.0
	A6			
	A7			
Thermal Storage System	TC11			
	TC12			
	TC13			
	TC14			
	TC15			
	TC21			
	TC22			
	TC23			
	TC24			
	TD11	32830.3	427.7	447.8
	TD12	32830.3	1206.6	447.8
	TD13	80282.2	876.0	41.0
	TD14	288888.0	876.0	40.1
	TD15	328191.2	567.0	38.7
Seal Steam and Condenser	TD16	328191.2	461.6	34.5
	TD17	328191.2	416.4	31.5
	TD18	328141.2	416.4	28.7
	TD21			
	TD22			
	TD23			
	TD24			
	TD25			
	TD26			
	TD27			
	S1			
	S2			
	S3	3784.2	1263.1	625.0
	S4	372.6	1263.1	625.0
	S5	860.0	1238.6	392.9
	S6			
	S7	28408.4	1008.3	108.7

Packing Gland Leakage Schematic of Destinations  
Reference: GE Performance Specifications Curve  
LTSD 4158D-8

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DEPARTMENT OF ENERGY  
SOLAR TEN MEGAWATT PROJECT OFFICE  
9550 LAIR DRIVE, SUITE 210  
SAN FRANCISCO OPERATIONS OFFICE  
EL MONTE, CALIFORNIA 91731

10 MW SOLAR PILOT PLANT - DAGGETT, CALIFORNIA

FILE  
HEAT AND MASS BALANCE  
MODE 6-3

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2 of 2

Figure 3.5(b). Mode 6 Operation – Low Admission Steam Flow

low admission steam flow. This case corresponds to the use of a single thermal storage extraction heat exchanger train. The relative locations within the predicted Mode 6 operating characteristics for both of these design cases are shown in Figure 3.6. They are referred to as "Mode 6-1" and "Mode 6-2", respectively. It should also be noted that these design data cases correspond to admission steam conditions of 525°F and 385 psia at the turbine inlet.

Figure 3.6 shows the predicted variation in gross cycle heat rate over the Mode 6 operating range. These predictions were based on the assumptions listed in the figure. Deviations from these assumptions would alter these predictions. Due to the multitude of possible combinations of these assumptions to represent off-design operation, no effort was made to analyze off-design cases as part of the plant design activity.

The primary factor which influenced the predicted cycle heat rate variation at low admission steam flow involved the use of the auxiliary steam system. The design analysis assumed that the deaerator would be "pegged" at a pressure of 15 psi. During moderate to high turbine flow operation, this "pegging" of the deaerator could be accomplished naturally with the normal turbine extraction functions. At low turbine flows, however, insufficient extraction pressure would be available to supply turbine steam to the deaerator. As a result, the auxiliary steam system was assumed to be activated to supply this "pegging" steam with a corresponding penalty (increase) in cycle heat rate. This effect is shown in Figure 3.6 (upper curve). A simplified schematic of the auxiliary steam system is shown in Figure 3.7. Without steam from heat recovery systems or turbine extractions, "pegging" steam must be supplied by the auxiliary steam system through valve PV1005 thereby reducing the steam generator steam flow to the turbine.

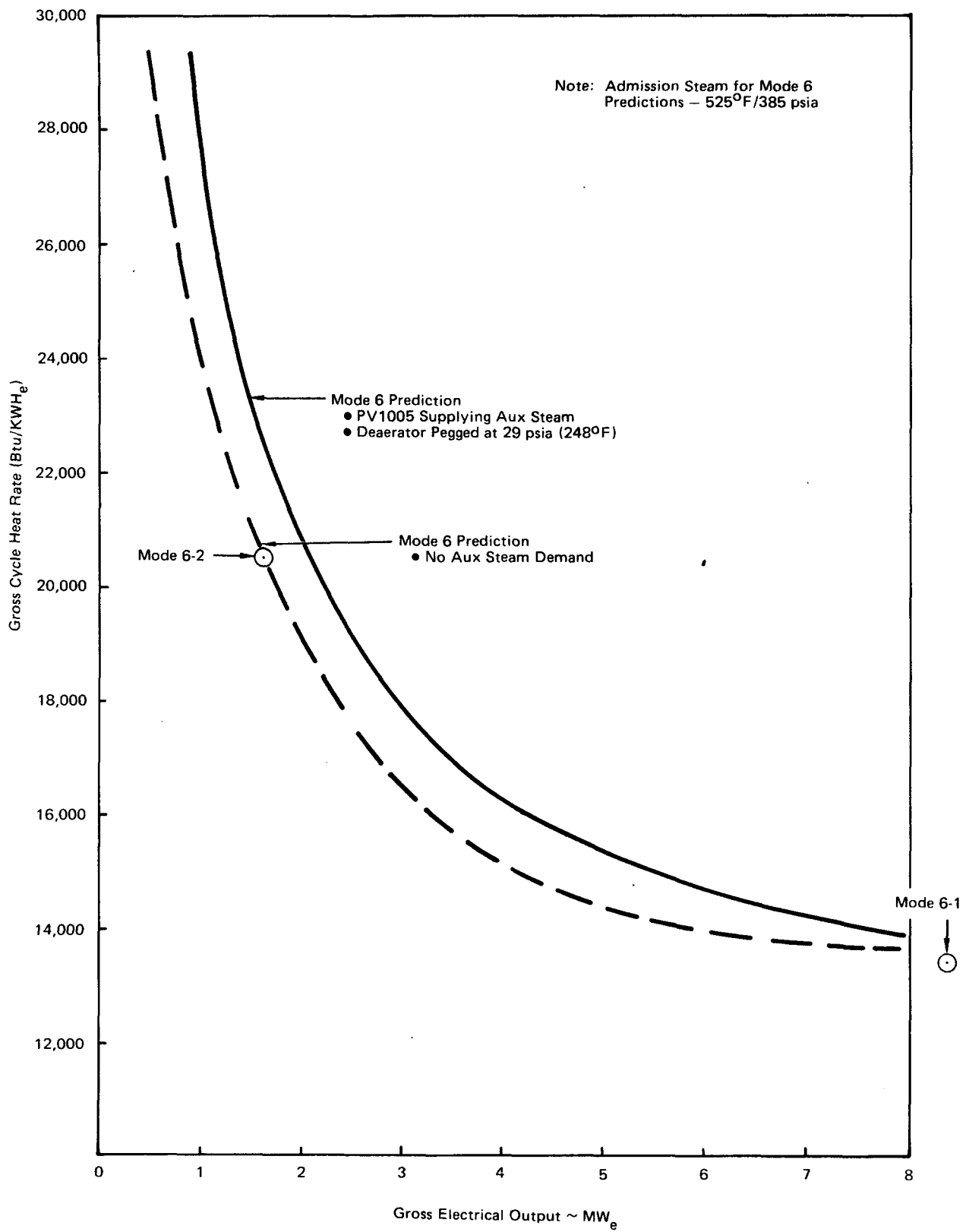


Figure 3.6. Predicted Mode 6 Gross Cycle Heat Rate

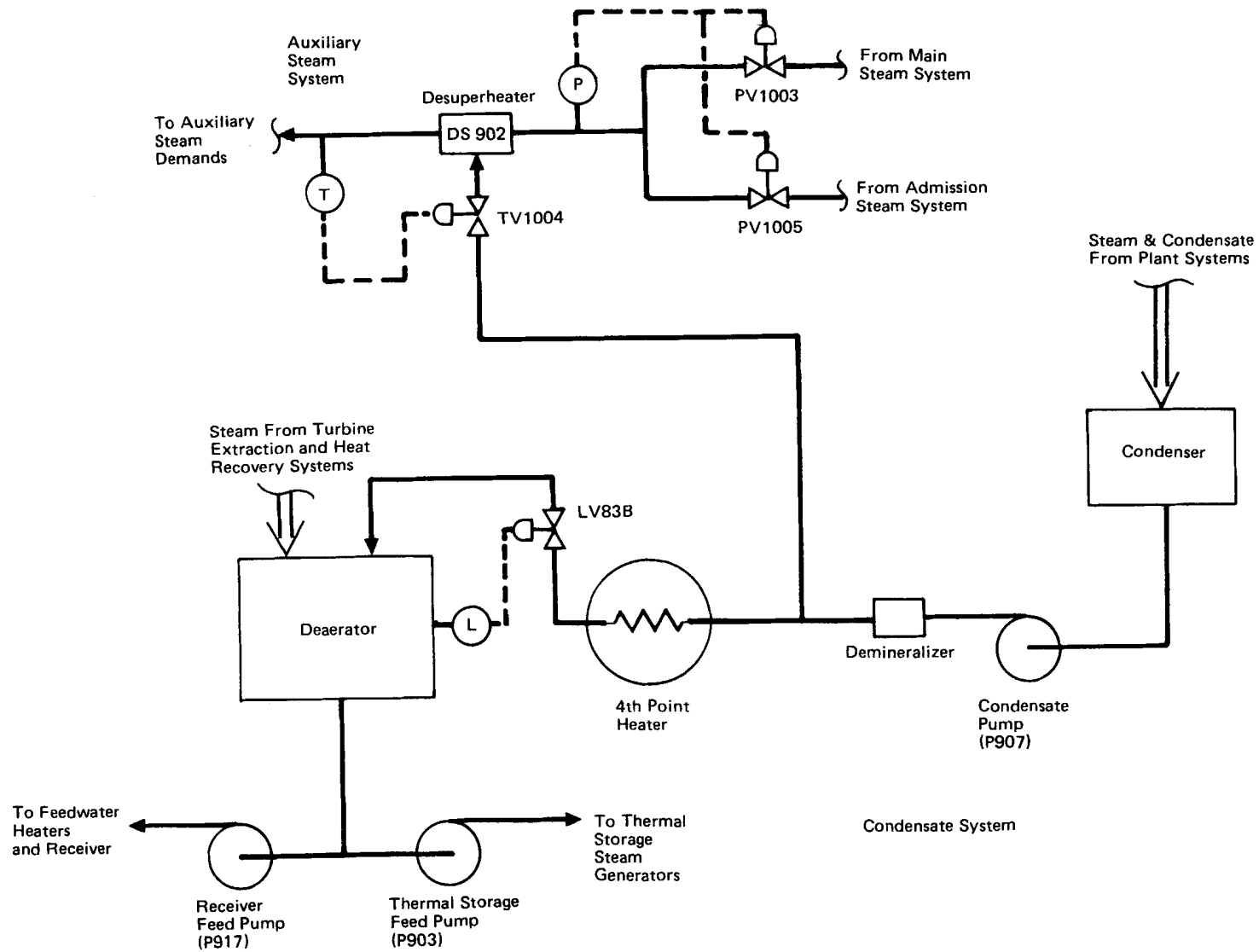


Figure 3.7. Simplified Schematic of Condensate and Auxiliary Steam Systems

Implicit in the preparation of the (Figure 3.6) was a constant deaerator operating pressure and temperature. This assumption was based on concern for the proper operation of the thermal storage extraction system which would draw its feedwater supply directly from the deaerator. This concern is illustrated in Figure 3.8. This figure shows the heat transfer process assumed to occur between the Caloria and the water/steam in an extraction train. The plot exhibits the "pinch point" characteristic of a heat transfer process involving a phase change such as (in this case) feedwater conversion to superheated steam.

In order to satisfy the laws of thermodynamics involving the heat transfer process, a positive temperature difference must exist between the Caloria (rejecting heat) and the water/steam (absorbing heat). It is clear that the "pinch point" is the zone where the temperature difference is of greatest concern. If the feedwater entered the preheater at a temperature much above the 250°F assumed value, the pinch point would approach a zero temperature differential. In reality, the Caloria could not be cooled down to the 425°F minimum operating temperature. This would correspondingly increase the Caloria flow required for the same heat transfer process and diminish the effective heat storing capacity of the thermal storage system.

The operating experience with Solar One showed that the requirement of holding a fixed deaerator temperature was not necessary. Instead, the deaerator pressure (and resulting saturation temperature) was permitted to float and seek its own value based on natural cycle operations. There are two primary reasons for this. First, the actual heat transfer processes do not exactly follow the idealized counterflow process shown in Figure 3.8. Second, the individual heat exchangers were specified to include fouling factors in the

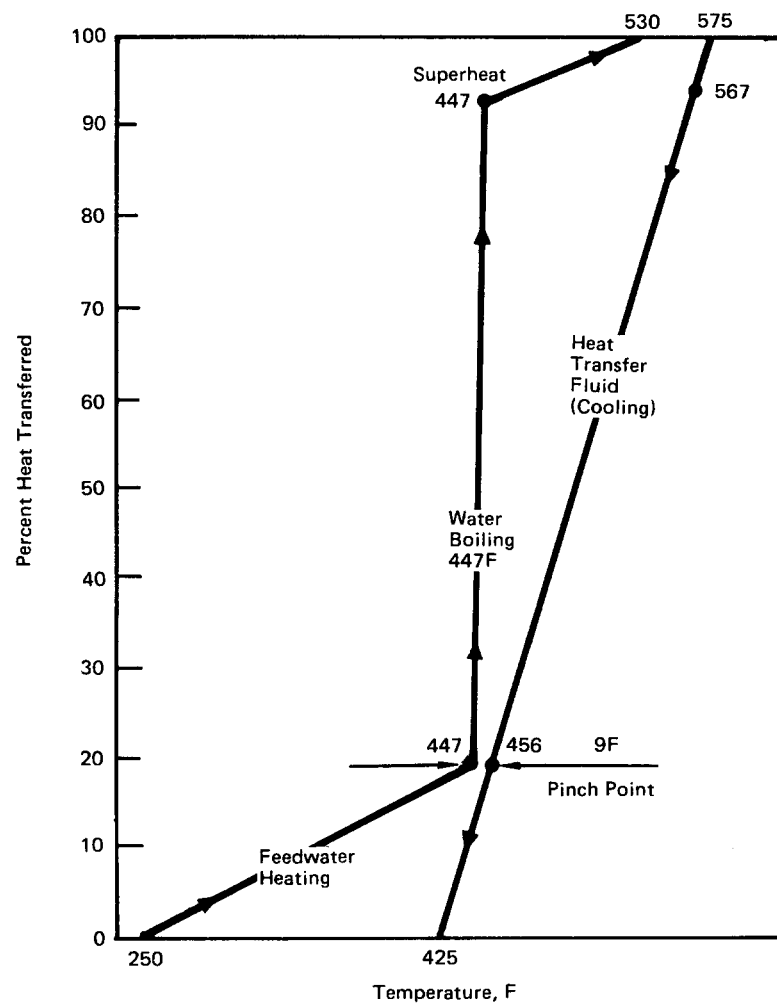


Figure 3.8. Thermal Storage Discharging (Extraction) Characteristics



event of deposition from the Caloria system. The fact that there was no evidence of such deposition resulted in heat exchangers with higher effectiveness or greater capacity than required by the original plant design. In fact, it was possible to cool the Caloria down to approximately 405°F during routine extraction operation.

#### 3.4 Test Approach and Critical Instrumentation

The approach to Mode 6 testing involved gathering sufficient operational data such that both the steady state and transition related test objectives described in Section 3.2 could be analyzed. Test time within each of the operating modes was necessarily limited by other plant operating activities such as tuning of control systems, developing operating procedures, gathering test data in other operating modes, developing requirements for automatic software, and testing plant automation functions. Therefore, efforts were made to utilize Mode 6 operating time as efficiently as possible.

As a prerequisite to any Mode 6 testing (also appropriate to Modes 3, 4, and 7, which involved admission steam operation), it was necessary to first establish a sufficient charge in the thermal storage tank. This required that some type of charging operation be accomplished prior to planned extraction tests. As a result, extensive extraction tests, such as those which involved Mode 6 operation, required a minimum of two days when the necessary charging operation was considered. This issue was further complicated by the competition for stored energy from other operating modes involving extraction operation and the demand for stored energy to support the blanketing functions required during nighttime or cloudy periods. In fact, during the limited sunshine days of fall and winter, which were normally interspersed with cloudy periods, many days were often dedicated to the establishment of a sufficient

charge to conduct a meaningful test involving thermal storage extraction operation (such as required for Mode 6).

As a result of the limited time specifically dedicated to Mode 6 testing, the majority of the test time was spent in those areas where the plant could reasonably be expected to operate. For Mode 6 operation, this primarily meant the use of a single extraction train.

Dedicated trip testing was not carried out as part of Mode 6 test program due to other plant operating priorities and the need to gather meaningful Mode 6 test data for reasonable time periods once Mode 6 operations were established. Instead, plant responses were noted during naturally occurring trips involving Mode 6. These separate trip events included trips of the thermal storage system (both single and dual extraction trains simultaneously) and the turbine generator. In this way all possible trip transition logic paths short of complete plant trip were demonstrated by naturally occurring events.

The Mode 6 data base was gathered during 16 days of plant operation extending from December 1982 to October 1983. These were days during which dedicated operation in Mode 6 occurred. This excluded periods when the plant may have been briefly in Mode 6 as part of a transition to other operating modes. Of the 16 operating day data base for Mode 6, the majority of the data used for this report were gathered on 12 test days. The rejection of the remaining operating days was based on too brief an operating period to gather meaningful data, control system troubleshooting and tuning which impacted the meaningfulness of the data, or missing data due to problems with the Data Acquisition System. The 12 test days which served as the basis of the Mode 6 data base are shown in Table 3.1.

TABLE 3.1    MODE   6 OPERATING DATA BASE

<u>DATE</u>	<u>DAY OF YEAR</u>	<u>MODE 5 DATA PERIOD</u>	<u>COMMENT</u>
12/20/82	354	16:30 - 16:35 (1)	High power - dual train
2/25/83	056	13:35 - 13:40 (2) 14:04 - 14:09 (3)	Maximum power - dual train
4/7/83	097	20:00 - 20:05 (4) 20:12 - 20:17 (5) 20:30 - 20:35 (6)	Single train
4/13/83	103	17:30 - 17:31 (7) 18:00 - 18:01 (8) 18:30 - 18:31 (9)	Single train
4/14/83	104	19:05 - 19:10 (10) 20:05 - 20:10 (11)	Single train
5/4/83	124	17:55 - 18:00 (12) 19:40 - 19:45 (13) 21:00 - 21:05 (14)	Maximum power - single train
5/11/83	131	19:00 - 19:05 (15) 19:18 - 19:21 (16)	Single train
5/18/83	138	15:30 - 15:35 (17) 16:30 - 16:35 (18) 17:30 - 17:35 (19) 18:30 - 18:35 (20) 19:30 - 19:35 (21) 20:30 - 20:35 (22)	High power - dual train (maximum extraction)
6/27/83	178	17:00 - 17:05 (23) 19:00 - 19:05 (24) 21:25 - 21:30 (25) 23:55 - 24:00 (26)	Single train
6/28/83	179	02:00 - 02:05 (27) 04:00 - 04:05 (28) 06:00 - 06:05 (29) 08:00 - 08:05 (30)	Low power - all night run (maximum time turbine on-line)
9/7/83	250	14:30 - 14:35 (31) 14:40 - 14:45 (32) 14:55 - 15:00 (33) 15:12 - 15:14 (34) 15:16 - 15:18 (35) 15:28 - 15:33 (36) 15:55 - 16:00 (37) 16:10 - 16:15 (38) 17:14 - 17:19 (39)	Single train
10/14/83	277	16:15 - 16:20 (40) 16:45 - 16:50 (41) 17:25 - 17:30 (42) 17:55 - 18:00 (43) 18:25 - 18:30 (44) 19:00 - 19:05 (45) 19:45 - 19:50 (46)	Single train

The critical instrumentation monitored during Mode 5 tests is shown in Figures 3.1 and 3.2 as appropriate to the indicated "active" flow paths. For reference purposes, the following tag identification prefix conventions are used in these figures:

FI	Flow indication
JI	Electrical power
JIC	Electrical power
PCM	Pressure indication
PE	Plant electrical load (power)
PI	Pressure indication
PTX	Pressure indication
TEX	Temperature indication
TI	Temperature indication

The fact that there are multiple designations for temperature indications, pressure indications, and electrical power is due to the function being served by a particular sensor and the computer system responsible for receiving and processing the data.

From a data quality and measurement accuracy standpoint, the comments pertaining to Mode 5 operation (as presented in Section 2.4) are also appropriate to this operating mode. The exception involves the thermal storage extraction steam flowmeters (target type meters). Unlike the charging steam flowmeters described in Section 2.4, the extraction flowmeters exhibited much greater durability and higher operational reliability. This was probably due to the lower operating steam pressures and temperatures of the extraction system. The exception involved an extraction steam flowmeter (target shaft) which was bent backwards on several occasions due to a failure of an adjacent steam check valve. As in Mode 5 though, the accuracy of the steam flowmeters was questionable.

Before determining overall Mode 6 performance factors, it was also necessary to evaluate the thermal storage extraction process and identify the flow instrumentation to be used as the reference standard for these performance calculations. If all flow instrumentation (see Figure 3.9) was working properly, a good correlation should exist between the extraction oil, extraction (admission) steam, and boiler feedwater flow (power) measurements.

In reviewing the data, it was observed that the extraction oil flows experienced more significant disturbances (even at or near steady state steaming operations) than either the steam or boiler feedwater flow. This was because significant changes in input thermal powers to the steam generator and superheater were required to cause a significant boiler/superheater reaction due to the high thermal inertia of the extraction system. Also, because of the flow split between the boiler and superheater, an increase in oil flow to one element could be offset by a decrease in flow to the other element with no net change in thermal power delivered to the extraction train and no change in steam flow. This tendency for the oil flows (measured downstream of the split) to vary continuously made it difficult to achieve a reasonable steady-state oil flow condition (and thus makes the oil flowmeter data a questionable reference for engineering performance calculations).

Using the available oil side steady state data, power correlation comparisons were made against the measured extraction steam and boiler makeup water flows. Figure 3.10 (reproduced from Reference 3) shows the resulting thermal power correlation between the measured oil and steam side flows. The steam flowmeter data are shown with (darkened symbols) and without (open symbols) a "zero" shift being applied to the data. The "zero" shift is defined as the indicated steam flow after the extraction train was shutdown. It is also

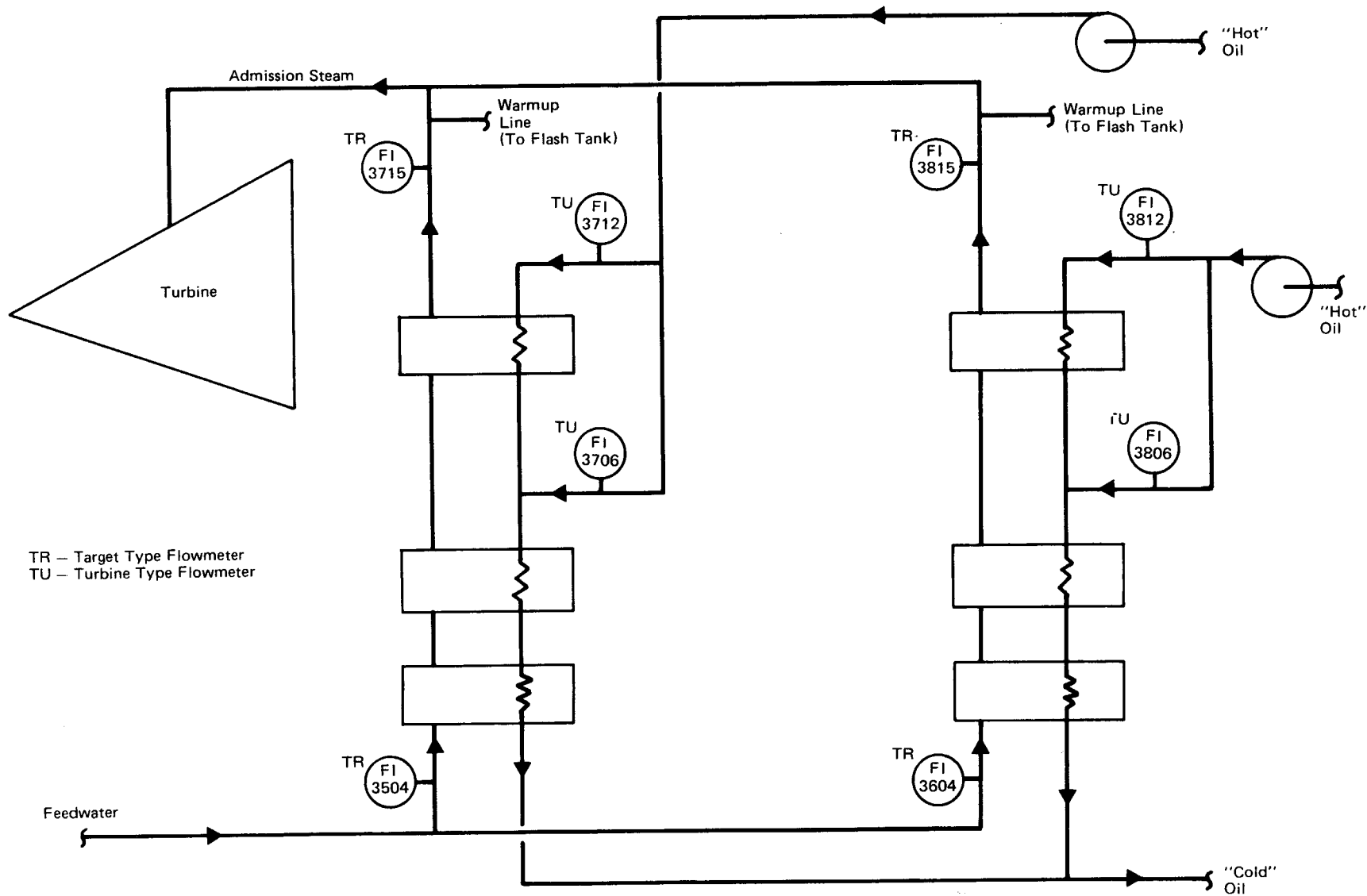


Figure 3.9. Flowmeter Arrangement for Thermal Storage Extraction and Admission Steam Systems

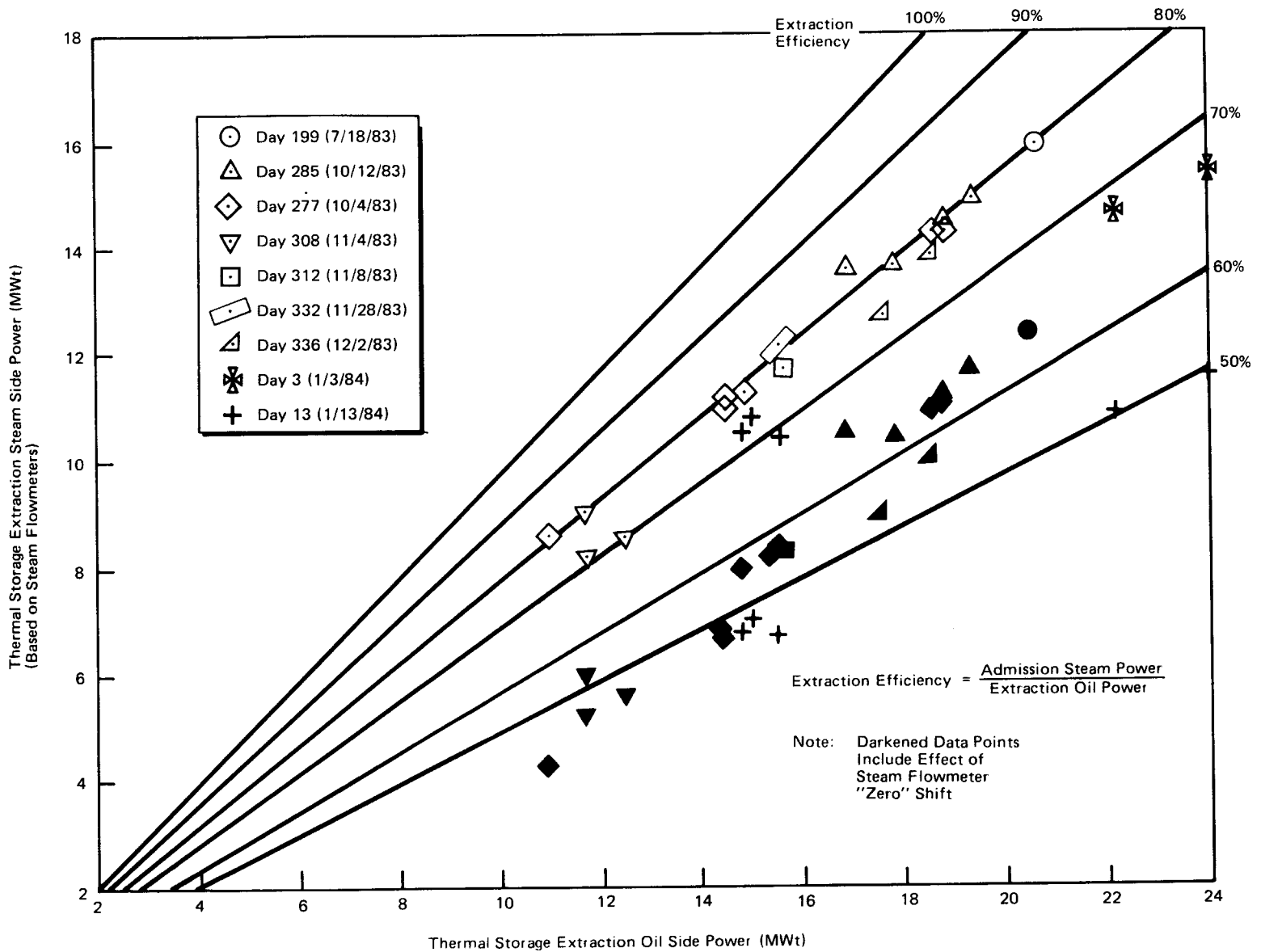


Figure 3-10. Extraction System Correlation Between Admission Steam and Oil Side Power (Based on Steam Flowmeters)

assumed that the same shift in meter output existed during flow conditions. Due to the residual thermal energy contained in the steam generators, and the possibility of steam flow due to leakage following shutdown, it was difficult to isolate an electronic signal shift from actual residual flow. The correlation shows that a moderate amount of data scatter existed and that, if the zero shift was applied to reduce the steady state indicated flow, an extraction efficiency of 50 to 60 percent would be calculated (based on these measurements). If the zero shift was not applied, an extraction efficiency of 75 to 80 percent would be calculated.

Based on experience with insulated heat exchangers, both of these two extraction efficiency levels are well below the level that would be expected. If these results were correct, 20 to 50 percent of the thermal power was rejected while the balance was used to drive the turbine. This fraction represents an excessive amount of "lost" power which is inconsistent with the energy losses expected from the thermal storage extraction system. A more likely explanation is that either the steam flowmeters were indicating low or that the oil flowmeters were indicating high.

The steam flowmeters (target type) and data system were calibrated for an assumed nominal steam density corresponding to 530°F and 395 psi. For steam conditions different from this reference condition, the indicated flow values needed to be corrected by the square root of the density ratio. Since most admission steam operations were carried out at pressures of 250 to 370 psi, substantial data corrections were required. In addition, during operations at low pressure (low density), the flowmeter output could reach a full scale condition when the actual "corrected" flow was significantly less. Because of this factor, it was not unusual to have the extraction steam flowmeters



saturated (indicating full-scale), making resulting data of no use for engineering evaluation.

As an alternate approach to estimating the thermal power transferred from the thermal storage extraction system to the admission steam system, correlation data were prepared between the extraction oil system and the steam system, using steam flow calculations based on extraction boiler makeup feedwater flow. During steady state operation, the boiler feedwater flow should equal admission steam flow (since the boiler water level was maintained at a fixed set point value).

Figure 3.11 (also reproduced from Reference 3) shows the correlation between steam side power based on boiler feedwater flow and oil side power. These data indicate, in agreement with the data in Figure 3.10 without the "zero" shift applied, that the extraction efficiency was approximately 80 percent. The low extraction efficiency (~ 80 percent) again makes the validity of the indicated measurements questionable, with the possibility that the oil flow measurements were too high or the feedwater flow measurements were too low.

In order to calculate thermal power, and perform subsequent Mode 6 performance analyses, it was necessary to select a reference steam flow. The reference selected, based on the above discussions, was the boiler feedwater flow. This decision was reached based on the fact that these measurements were, in general, more steady than the oil flow indications and their use eliminated the "zero" shift issue associated with the operation of the steam flowmeters. In addition, since the widely varying admission steam pressures had little influence on feedwater density, and the deaerator temperature (source of the feedwater) was reasonably constant, the density corrections for the boiler feedwater measurements were small in comparison to the corrections required

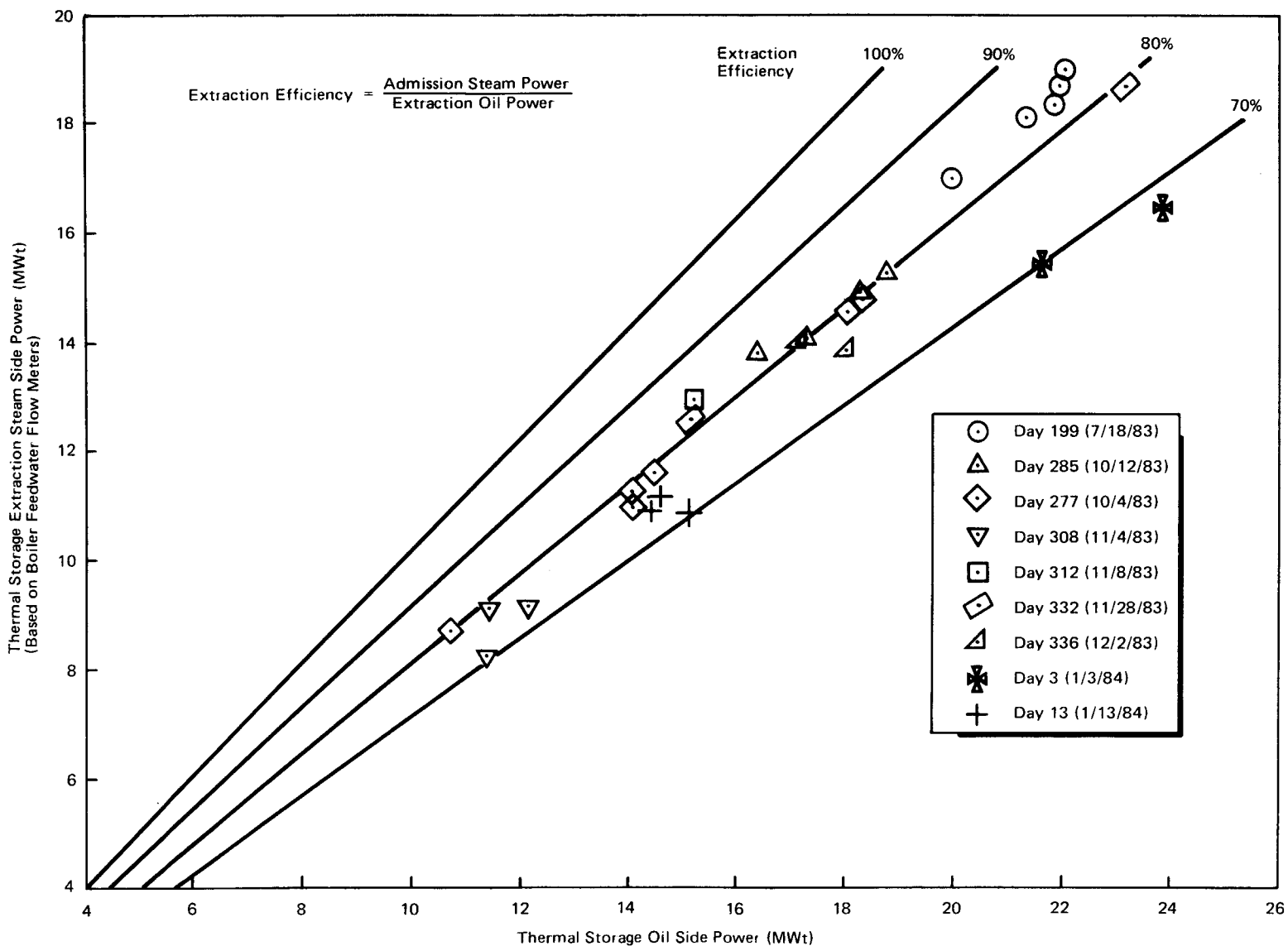


Figure 3.11. Extraction System Correlation Between Admission Steam and Oil Side Power (Based on Boiler Feedwater Flowmeters)

for the steam flow measurements. Also, the problem of the flowmeter reaching a full-scale indication (which occurred with the steam flowmeters) was not a factor with the boiler feedwater measurements.

The fact that the calculated extraction efficiency was low, based on either the feedwater or steam flow measurements (Figures 3.10 and 3.11), indicates that the oil flow indications could have been high by approximately 15 to 20 percent. This same conclusion was reached (see Section 2.4) in analyzing the charging oil flow measurements. A review was conducted of the calibration data for the individual turbine (rotor) flowmeters, the electronic set-up in the field, and the full scale data base values contained in the control and data system computers (which were used to convert signal levels to data in engineering units). At the present time no explanation exists for the apparent bias in the oil flowmeter data.

### 3.5 Mode 6 Test Results

The test results and supporting discussions in this section address the three areas of plant operation discussed in Section 3.2; plant start-up to Mode 6 as well as transitions to and from Mode 6 and transitions within Mode 6 (dual to single train, power steps, flow steps), performance aspects of steady-state plant operation in Mode 6 including a comparison of measured to predicted performance, and the effects of trips which occurred while operating in Mode 6.

#### 3.5.1 Start-up and Transitions

The sequence of events for plant start-up from Mode 8 (Inactive) to Mode 6 was developed during the Mode 6 test program. SDPC automation routines were developed to minimize operator activities, although the turbine operations continued to be manually initiated (as discussed in Section 3.1.2.2). The

start-up sequence, combining activities discussed in Section 3.1.2, was as follows:

1. Prewarm and start the thermal storage feedwater pump (P903).
2. Execute a "warm" cycle on the selected thermal storage extraction train using "hot" oil circulated by the auxiliary oil pump (P305).
3. Open admission steam line isolation valves, drains, and freeblow vents (if required) to warm steam line and establish at least 50°F superheat at the turbine admission steam stop valve.
4. Sample admission steam and verify compliance with steam chemistry specifications.
5. Execute a "run" cycle on the selected thermal storage extraction train. Prewarm and start the main extraction oil pump appropriate to the selected train (P303/P304).
6. Roll the turbine by manually controlling the admission steam stop valve position (control valves wide open).
7. Transfer turbine roll control to the control valves and completely open the stop valve at a turbine speed of approximately 3500 rpm.
8. Synchronize and load the generator.
9. Transfer the turbine to admission steam pressure control.

Start-up of a single extraction train and transition into Mode 6, using the above sequence, is illustrated in Figure 3.12 (a, b, and c). These figures depict a five hour time period, starting at 12:30 PM on 7 September 1983, during which the plant was operated in Mode 6 with a number of power steps (transitions). Figure 3.12 (a), the primary train 2 oil system parameters, shows the flow and temperature responses to the initial warm-up operation (pump P305) followed by a shutdown of P305 and start-up of pump P304 (run

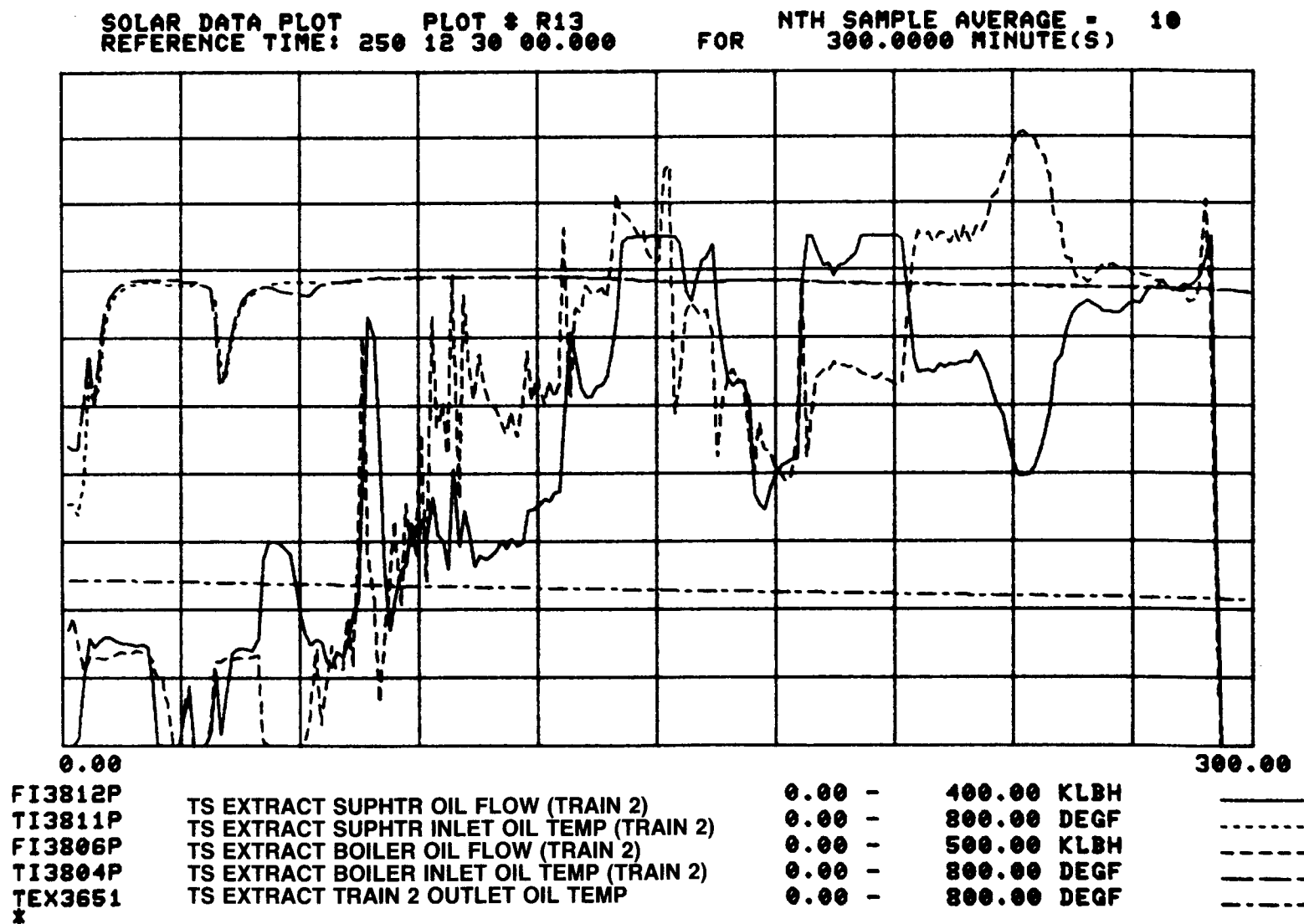


Figure 3.12(a). Mode 6 Start-Up and Transitions – Train 2 Oil Parameters

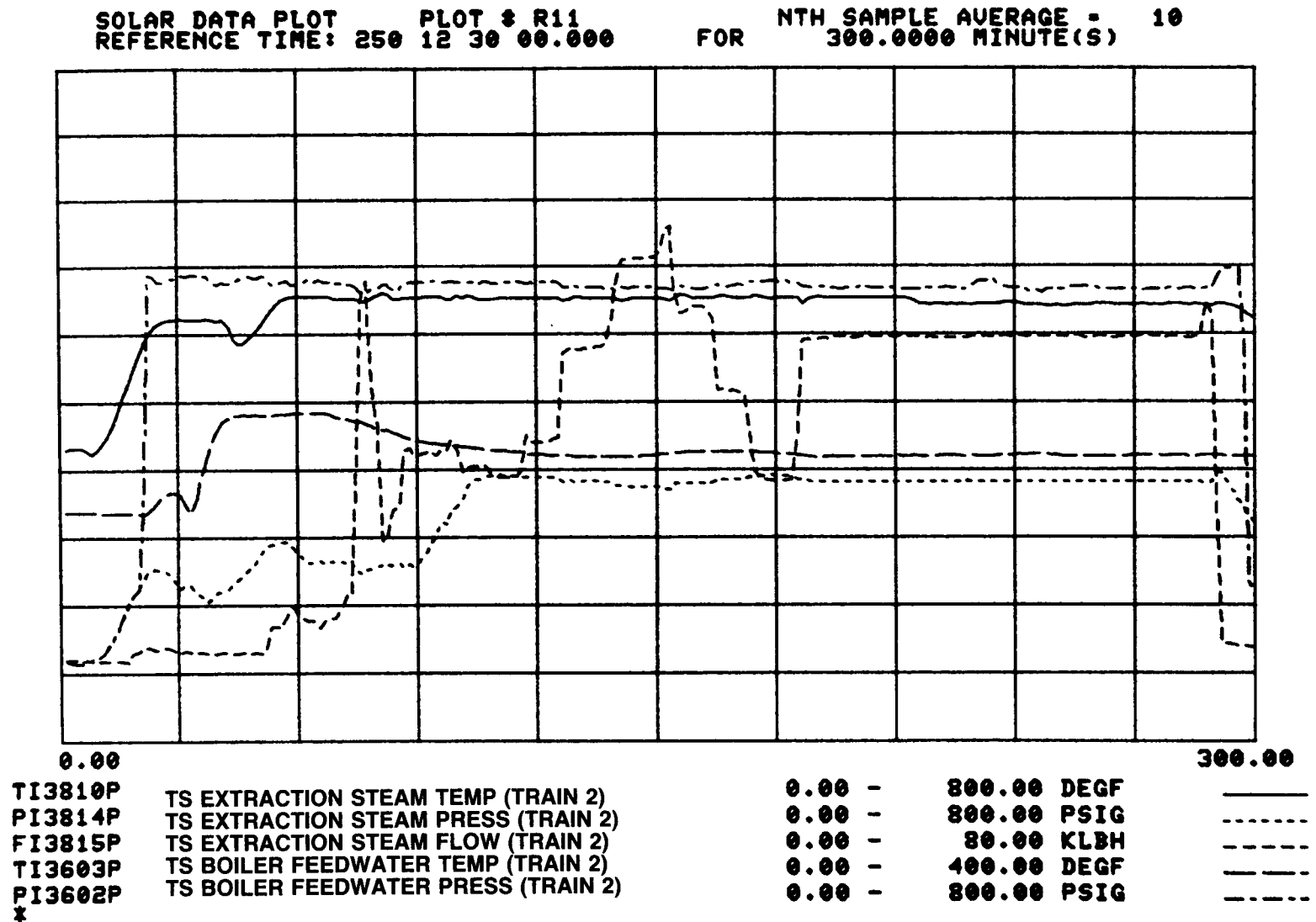
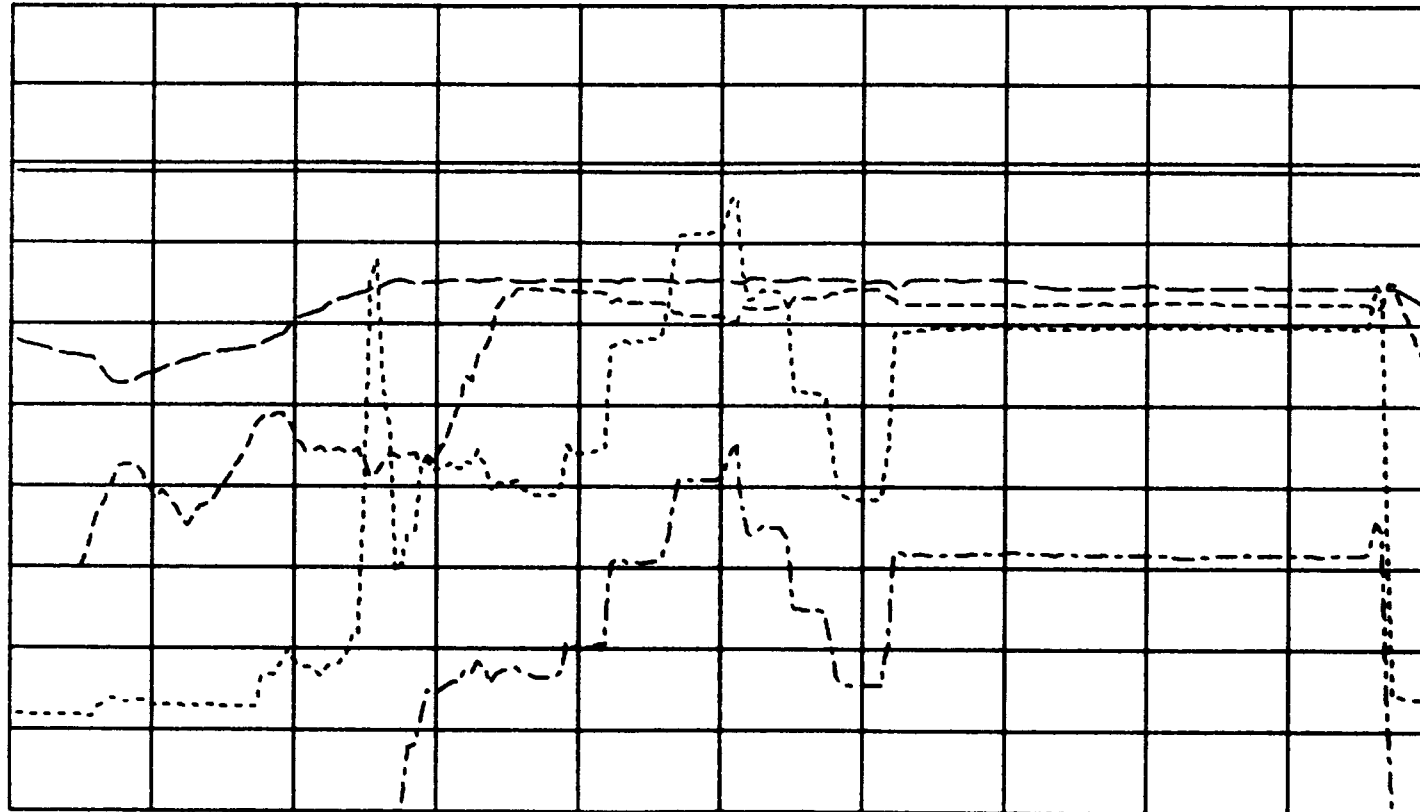


Figure 3.12(b). Mode 6 Start-Up and Transitions – Train 2 Water/Steam Parameters

SOLAR DATA PLOT PLOT # R9  
REFERENCE TIME: 250 12 30 00.000

FOR NTH SAMPLE AVERAGE = 10  
300.0000 MINUTE(S)



0.00										300.00
FI3715P	TS EXTRACTION STEAM FLOW (TRAIN 1)	0.00 -	80.00	KLBH	_____					
FI3815P	TS EXTRACTION STEAM FLOW (TRAIN 2)	0.00 -	80.00	KLBH	-----					
PI937P	ADMISSION STEAM PRESSURE	0.00 -	500.00	PSIG	-----					
TI1025P	ADMISSION STEAM TEMPERATURE	0.00 -	800.00	DEGF	-----					
JIC5100P	GROSS ELECTRICAL POWER	0.00 -	10000.00	KW	-----					

Figure 3.12(c). Mode 6 Start-Up and Transitions - Turbine Parameters

sequence initiated at approximately 12:56 PM). The "spike" in oil flows at approximately 1:45 PM was due to the steam flow transient during turbine start (see subsequent discussion) while the other oil flow transients were the result of Mode 6 power steps.

Figure 3.12 (b) illustrates the primary steam/condensate parameters during the same time period. The "spike" in admission steam flow (FI 3815P) at approximately 1:45 PM was the result of the turbine packing dump valves cycling open and closed immediately prior to synchronizing the turbine generator (the turbine had been rolled on admission steam at approximately 1:27 PM). The approach used to roll the turbine on admission steam involved opening the turbine admission steam control valves and rolling the unit by modulating the admission steam stop valve position. Manual stop valve position control was used during the periods of turbine acceleration and hold (at 1000 rpm) until a speed of approximately 3500 rpm was reached. At this time, the control valves would come into service to assume turbine speed control responsibility while the stop valve was gradually moved to a fully open position. The turbine would then be brought to synchronous speed and synchronized and loaded through the operation of the admission steam control valves.

As the admission steam control valves would move into service, they would also activate the turbine packing dump valve which would allow steam to be bled from the turbine shaft seal (which separates the turbine high and low pressure sections). Since the activation of the packing dump valve was tied to the position of the control valves, a severe oscillatory pattern would normally result in which the packing dump valve would open when the control valve moved to a nearly closed position. With the opening of the dump valve, the turbine



steam demand to maintain constant speed would increase dramatically which would result in motion of the control valves to a much more open position. This movement would cause the packing dump valve to close which, in turn, would force the control valves to close back down in order to maintain the turbine at constant speed. This action would reopen the packing dump valve and the cycle would be repeated. These valve operating cycles would cause severe oscillations in steam generator flow and occasionally result in turbine or thermal storage extraction trips.

The problem involving the cycling of the packing dump valve was ultimately corrected by General Electric engineers (following the completion of the Mode 6 testing), although the overall turbine roll procedure was significantly different from the originally planned approach (which involved turbine speed control by exclusively using the admission steam control valves). As a part of the original plans, the turbine control console was fitted with a speed/load control device connected to the admission steam control valves. By using the stop valve to roll the turbine, however, no such automatic speed control feature could be used. As a result, turbine start-up and synchronization was on a strictly manual control basis.

Figure 3.12 (c) illustrates the turbine admission steam conditions and gross electrical power (JIC 5100P) during Mode 6 operation involving power steps. During Mode 6 operation, the turbine was in pressure control while the extraction train was operated in load control. As can be seen, relatively large changes in flow and power did not have a significant effect on admission pressure (PI 937P).

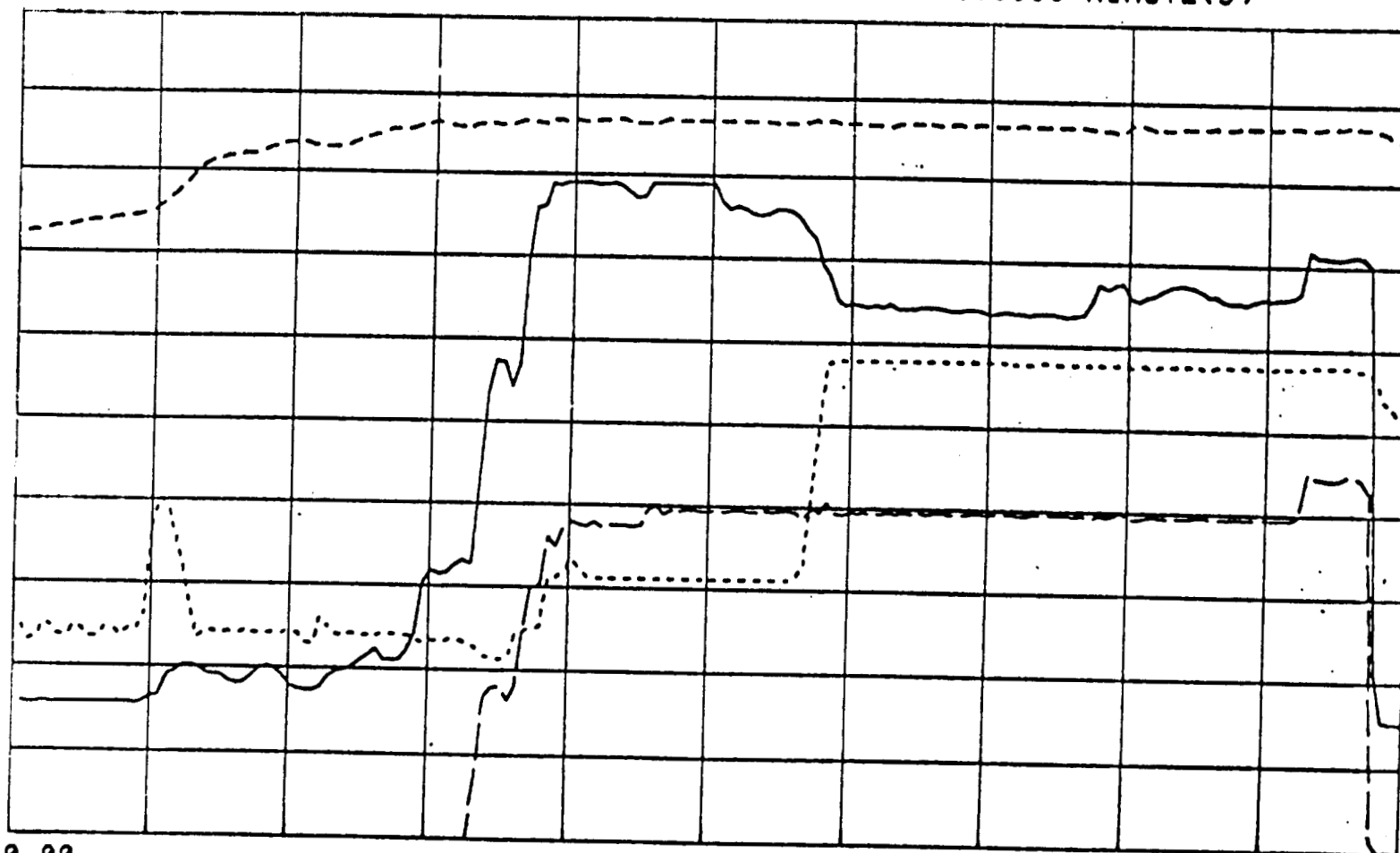
As stated previously, the issue of severe admission steam flow oscillations

during turbine roll on admission steam was ultimately resolved by General Electric engineers. Following adjustments to the packing dump valve operations, much more consistent relationships existed between the steam flow required to roll and load the turbine and that flow required from the thermal storage steam generator. Figure 3.13 (1/3/84) shows the principal thermal storage admission steam and turbine parameters during a turbine startup following packing dump valve operational modifications. The well behaved relationship between steam flow and turbine startup and load is apparent and certainly superior to the highly dynamic fluctuations discussed earlier.

Mode 6 shutdown (transition to Mode 8) involved stopping the thermal storage extraction system, with the turbine-generator automatically going off-line when a low load condition was reached. This transition typically was completed within a 1 to 2 minute time span although it could be intentionally lengthened by operator action. This would involve a continual reduction in the turbine admission steam pressure set point once the thermal storage extraction system had been stopped. In this way, a greater portion of the residual thermal energy contained in the steam generator at the time of shutdown would be converted to steam and consumed by the turbine. Mode 6 shutdown, accomplished by simple shutdown of the extraction system, is shown at the end of the Mode 6 operating period in Figure 3.12 (a, b, and c).

Figure 3.14 (a, b, c, d, and e) presents data for start-up, steady-state, Mode 6, and shutdown (transition to Mode 8) for dual extraction train operation. The data are for 5/18/83, the day that the design point extraction test was performed. Power production of approximately 43 MWHe (net) exceeded the design point value of 7 MWHe for 4 hours (28 MWHe). The test was initiated at 07:00 AM, but two thermal storage trips delayed activities. The warm sequence

SOLAR DATA PLOT PLOT # R9  
REFERENCE TIME: 003 12 00 00.000 FOR NTH SAMPLE AVERAGE = 10  
300.0000 MINUTE(S)



0.00

300.00

FI3815P  
PI937P  
TI1025P  
JIC5100P

TS EXTRACTION STEAM FLOW (TRAIN 2)  
ADMISSION STEAM PRESSURE  
ADMISSION STEAM TEMPERATURE  
GROSS ELECTRICAL POWER

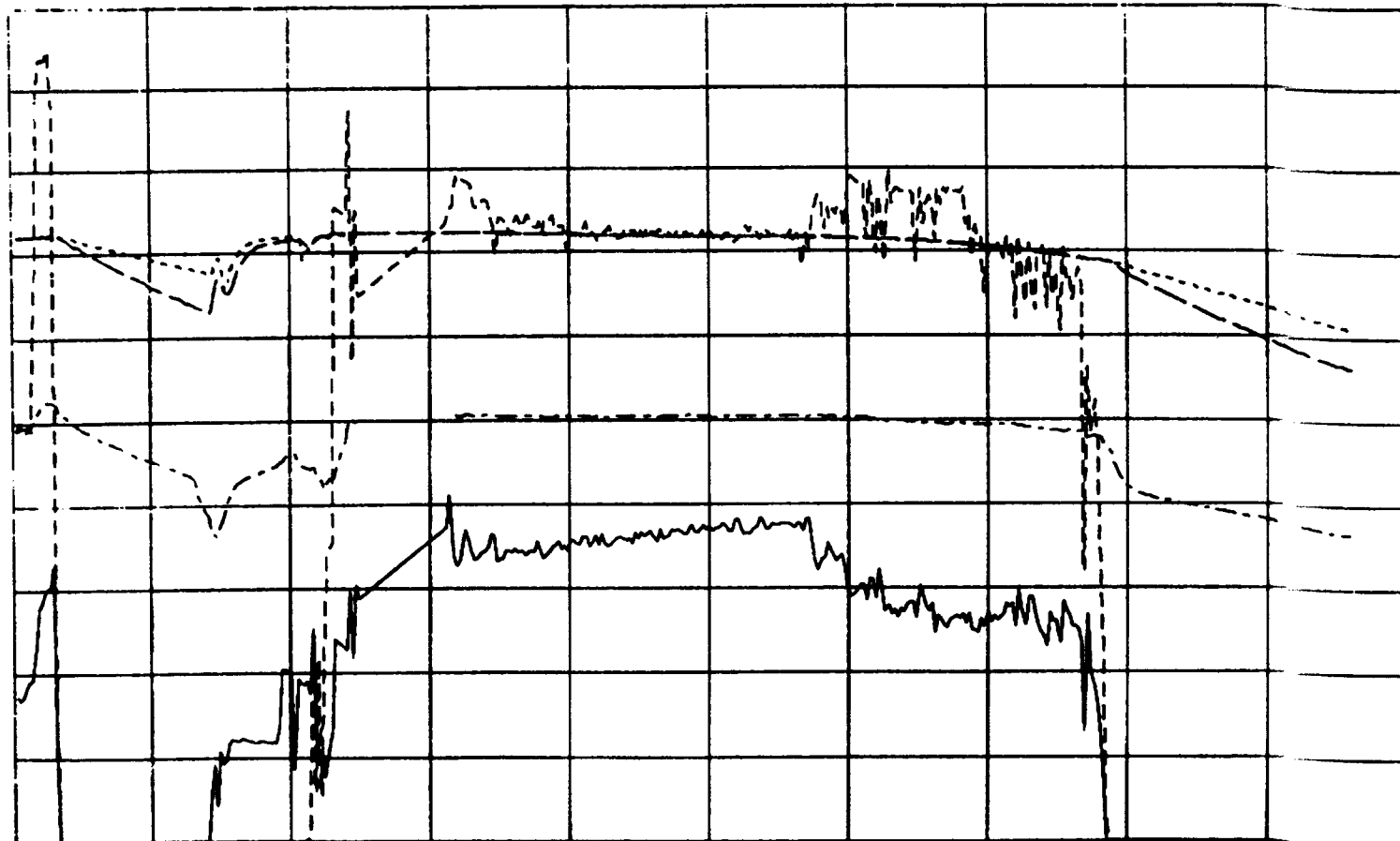
0.00 - 80.00 KLBH  
120.00 - 520.00 PSIG  
0.00 - 600.00 DEGF  
0.00 - 10000.00 KW

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Figure 3.13. Admission Steam Parameters During Turbine Roll and Loading Operations

SOLAR DATA PLOT PLOT # R12  
REFERENCE TIME: 138 12 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)



0.00

600.00

FI3712P TS EXTRACT SUPHTR OIL FLOW (TRAIN 1)  
TI3711P TS EXTRACT SUPHTR INLET OIL TEMP (TRAIN 1)  
FI3706P TS EXTRACT BOILER OIL FLOW (TRAIN 1)  
TI3704P TS EXTRACT BOILER INLET OIL TEMP (TRAIN 1)  
TEX3551 TS EXTRACT TRAIN 1 OUTLET OIL TEMP

0.00 - 400.00 KLBH  
0.00 - 800.00 DEGF  
0.00 - 500.00 KLBH  
0.00 - 800.00 DEGF  
0.00 - 800.00 DEGF

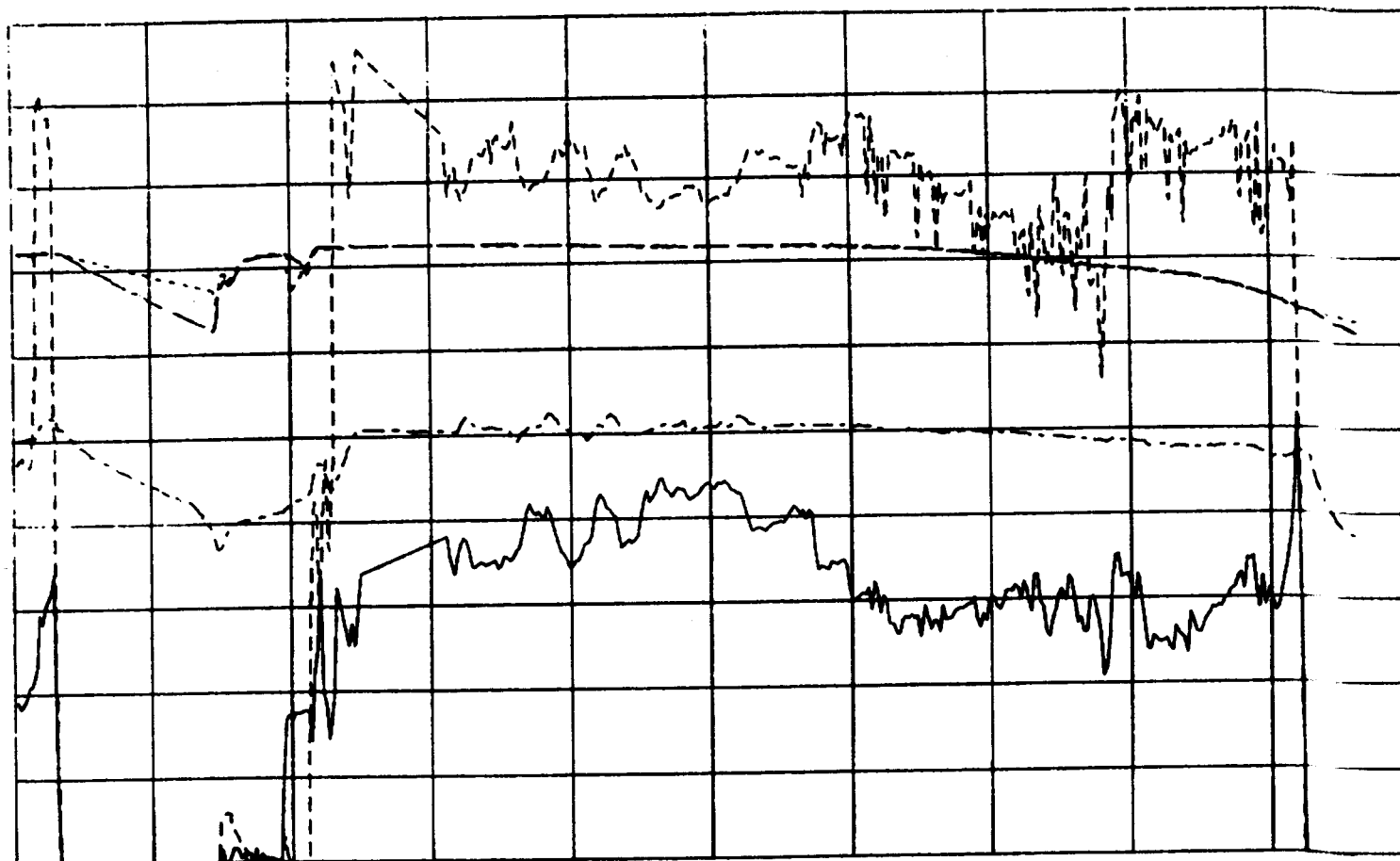
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Figure 3.14(a). Dual Train Mode 6 Transitions – Train 1 Oil Parameters

SOLAR DATA PLOT  
REFERENCE TIME: 138 12 00 00.000

PLOT # R13

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)



0.00

600.00

FI3812P TS EXTRACT SUPHTR OIL FLOW (TRAIN 2)  
TI3811P TS EXTRACT SUPHTR INLET OIL TEMP (TRAIN 2)  
FI3806P TS EXTRACT BOILER OIL FLOW (TRAIN 2)  
TI3804P TS EXTRACT BOILER INLET OIL TEMP (TRAIN 2)  
TEX3651 TS EXTRACT TRAIN 2 OUTLET OIL TEMP

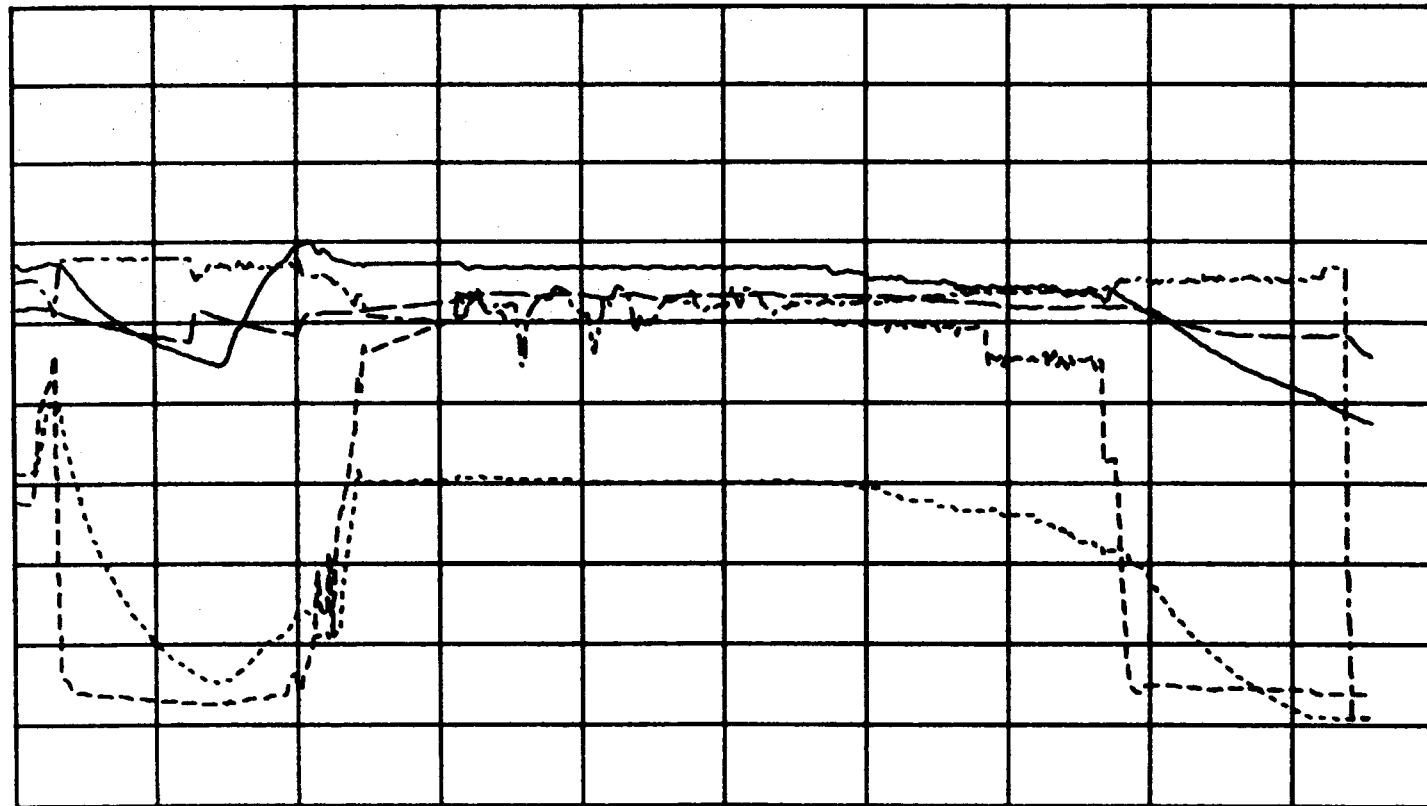
0.00 - 400.00 KL BH  
0.00 - 800.00 DEGF  
0.00 - 500.00 KL BH  
0.00 - 800.00 DEGF  
0.00 - 800.00 DEGF

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Figure 3.14(b). Dual Train Mode 6 Transitions - Train 2 Oil Parameters

SOLAR DATA PLOT PLOT # R10  
REFERENCE TIME: 138 12 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)

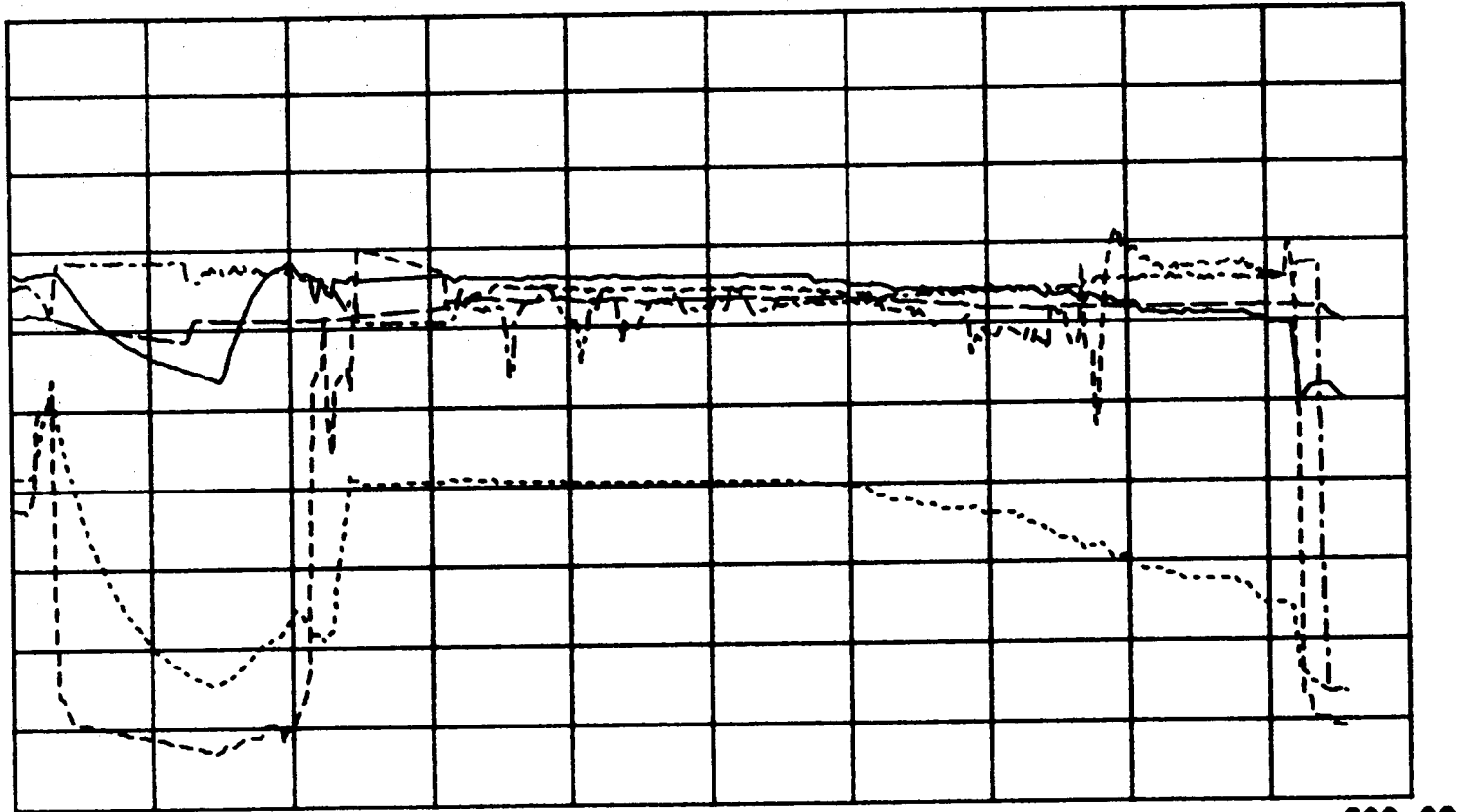


0.00							600.00
TI3710P	TS EXTRACTION STEAM TEMP (TRAIN 1)	0.00 -	800.00	DEGF		_____	
PI3714P	TS EXTRACTION STEAM PRESS (TRAIN 1)	0.00 -	800.00	PSIG		-----	
FI3715P	TS EXTRACTION STEAM FLOW (TRAIN 1)	0.00 -	80.00	KLBH		-----	
TI3503P	TS BOILER FEEDWATER TEMP (TRAIN 1)	0.00 -	400.00	DEGF		_____	
PI3502P	TS BOILER FEEDWATER PRESS (TRAIN 1)	0.00 -	800.00	PSIG		-----	
*							

Figure 3.14(c). Dual Train Mode 6 Transitions – Train 1 Water/Steam Parameters

SOLAR DATA PLOT PLOT # R11  
 REFERENCE TIME: 138 12 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
 600.0000 MINUTE(S)

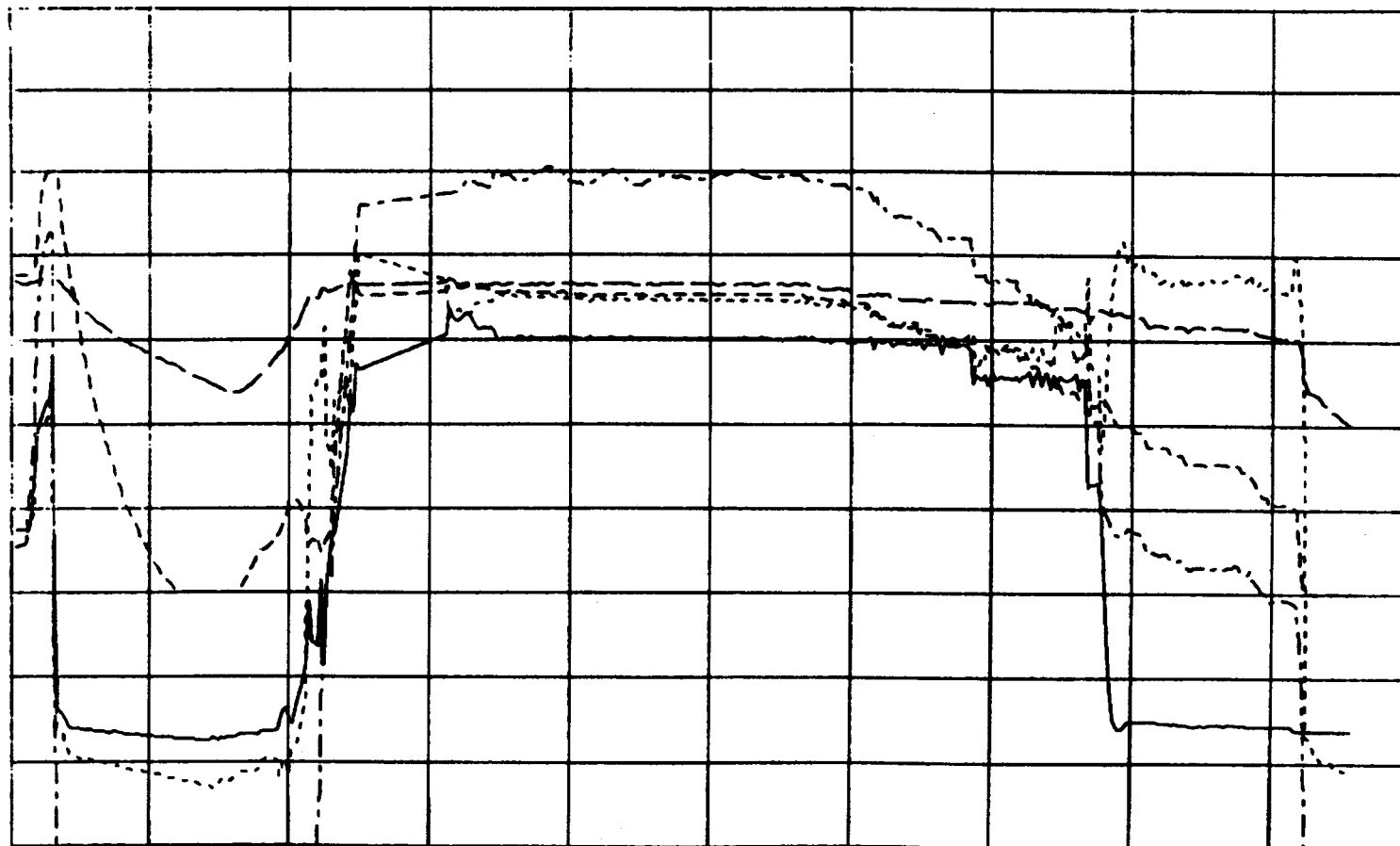


0.00						600.00
TI3810P	TS EXTRACTION STEAM TEMP (TRAIN 2)	0.00 -	800.00	DEGF	———	
PI3814P	TS EXTRACTION STEAM PRESS (TRAIN 2)	0.00 -	300.00	PSIG	.....	
FI3815P	TS EXTRACTION STEAM FLOW (TRAIN 2)	0.00 -	30.00	KLBH	----	
TI3603P	TS BOILER FEEDWATER TEMP (TRAIN 2)	0.00 -	400.00	DEGF	— · — ·	
PI3608P	TS BOILER FEEDWATER PRESS (TRAIN 2)	0.00 -	300.00	PSIG	-----	
*						

Figure 3.14(d). Dual Train Mode 6 Transitions – Train 2 Water/Steam Parameters

SOLAR DATA PLOT PLOT # R9  
REFERENCE TIME: 138 12 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)



0.00

600.00

FI3715P  
FI3815P  
PI937P  
TI1025P  
JIC5100P

TS EXTRACTION STEAM FLOW (TRAIN 1)  
TS EXTRACTION STEAM FLOW (TRAIN 2)  
ADMISSION STEAM PRESSURE  
ADMISSION STEAM TEMPERATURE  
GROSS ELECTRICAL POWER

0.00 - 80.00 KLBH  
0.00 - 80.00 KLBH  
0.00 - 500.00 PSIG  
0.00 - 800.00 DEGF  
0.00 - 10000.00 KW

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Figure 3.14(e). Dual Train Mode 6 Transitions – Turbine Parameters



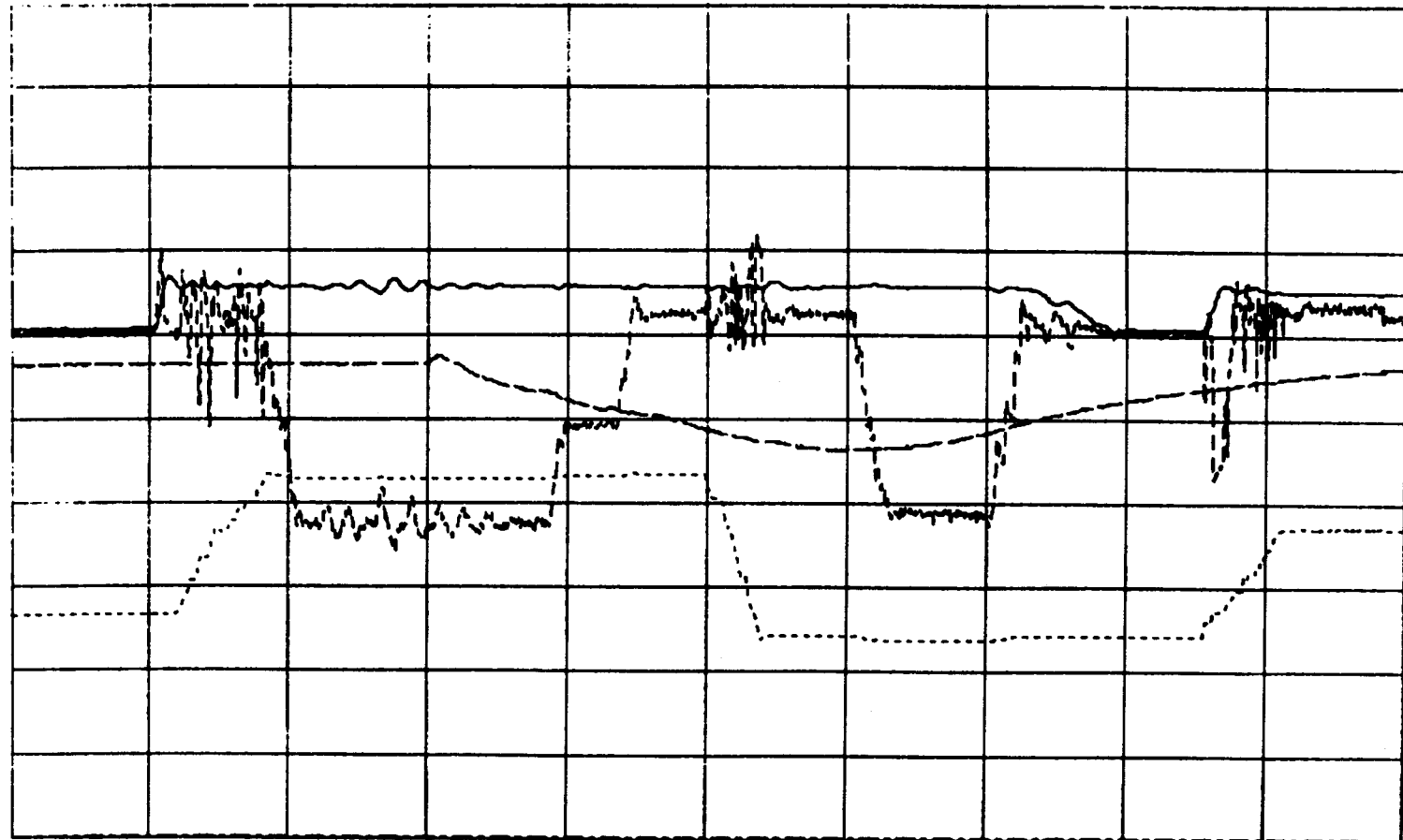
was reinitiated at approximately 1:24 PM followed by initiation of the run sequences; main oil pump P304 start at 1:55 PM and P303 start at 1:58 PM), Figures 3.14 (a) and 3.14 (b). Turbine roll on admission steam occurred at approximately 1:55 PM with synchronization at approximately 2:10 PM. The admission steam flow oscillations (previously discussed) were also evident during turbine roll, Figures 3.14 (c) and (d). During the subsequent Mode 6 operation, extraction Train 1 was operated in flow control while Train 2 was operated in pressure control.

As the extraction inlet oil temperature began to decrease (TI3711/3811, TI3704/3804, Figures 3.14 (a) and (b)), reductions in the steam pressure setpoint (at 5:40 PM) and steam temperature setpoint (at 6:17 PM) were begun to maintain admission steam superheat and extend operations - see Figures 3.14 (c) and (d). The flow setpoint in Train 1 was reduced twice, Figure 3.14 (c), with resulting reduction in power, and, at approximately 7:45 PM, Train 1 was shut down and Mode 6 operation was transitioned from dual train to single train operation. The subsequent readjustment in Train 2 operation is apparent in Figures 3.14 (b) and (d). Finally, at approximately 9:12 PM, Train 2 was shut down and the plant transitioned from Mode 6 to Mode 8.

On 10/4/83, a series of off-design turbine inlet condition operating points were investigated to determine turbine sensitivity. The data are shown in Figure 3.15 (a, b, and c) for a five hour period starting at 3:00 PM. The plant was initially operated in Mode 4, and transition to Mode 6 occurred at approximately 4:17 PM as the charging system was shut down. A discussion of the turbine-generator and plant performance during this test period is presented in Section 3.5.2.

SOLAR DATA PLOT PLOT # R11  
REFERENCE TIME: 277 15 00 00.000

FOR NTH SAMPLE AVERAGE = 1  
300.0000 MINUTE(S)



0.00

300.00

TI3810P  
PI3814P  
FI3815P  
TI3603P

TS EXTRACTION STEAM TEMP (TRAIN 2)  
TS EXTRACTION STEAM PRESS (TRAIN 2)  
TS EXTRACTION STEAM FLOW (TRAIN 2)  
TS BOILER FEEDWATER TEMP (TRAIN 2)

0.00 - 800.00 DEGF  
0.00 - 800.00 PSIG  
0.00 - 80.00 KLBH  
0.00 - 400.00 DEGF

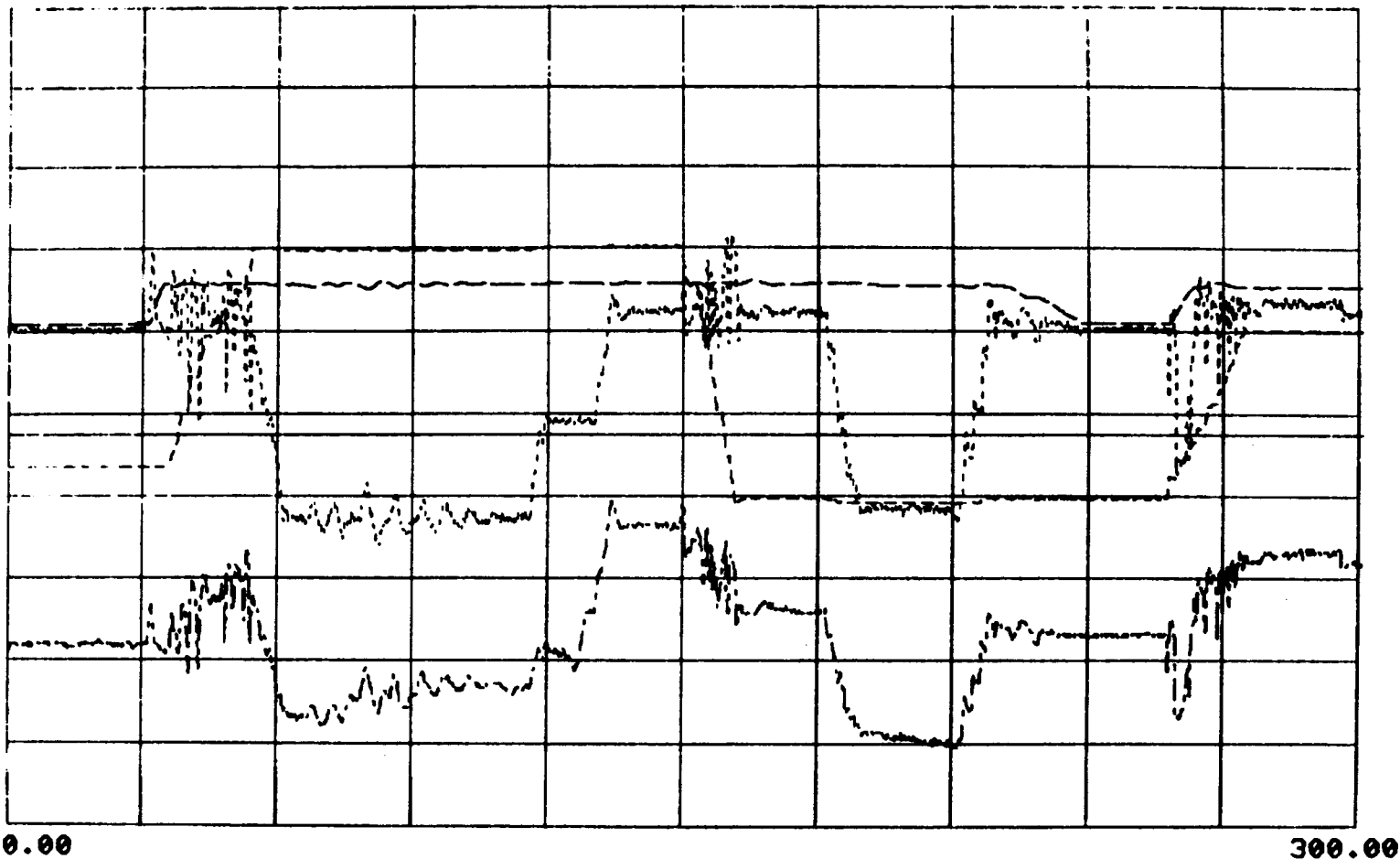
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Figure 3.15(a). Turbine Inlet Condition Variations – Mode 6 – Train 2 Water/Steam Parameters

SOLAR DATA PLOT PLOT # R9  
REFERENCE TIME: 277 15 00 00.000

FOR NTH SAMPLE AVERAGE = 1  
300.0000 MINUTE(S)



0.00  
FI3715P TS EXTRACTION STEAM FLOW (TRAIN 1)  
FI3815P TS EXTRACTION STEAM FLOW (TRAIN 2)  
PI937P ADMISSION STEAM PRESSURE  
TI1025P ADMISSION STEAM TEMPERATURE  
JIC5100P GROSS ELECTRICAL POWER

0.00 - 80.00 KLBH  
0.00 - 80.00 KLBH  
0.00 - 500.00 PSIG  
0.00 - 800.00 DEGF  
0.00 - 10000.00 KW

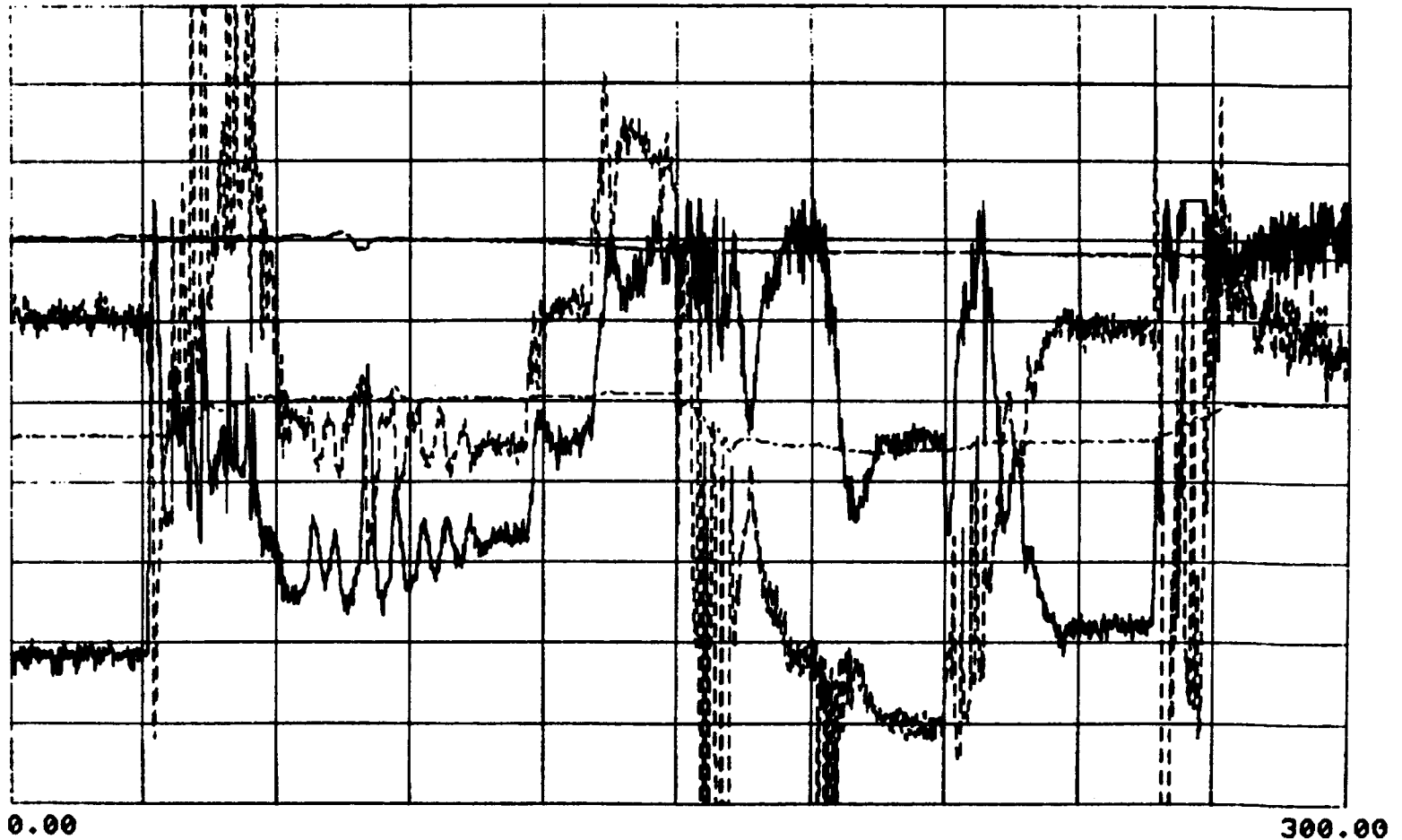
300.00

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Figure 3.15(b). Turbine Inlet Condition Variations - Mode 6 - Turbine Parameters

SOLAR DATA PLOT PLOT # R13  
 REFERENCE TIME: 277 15 00 00.000

FOR NTH SAMPLE AVERAGE = 1  
 300.0000 MINUTE(S)

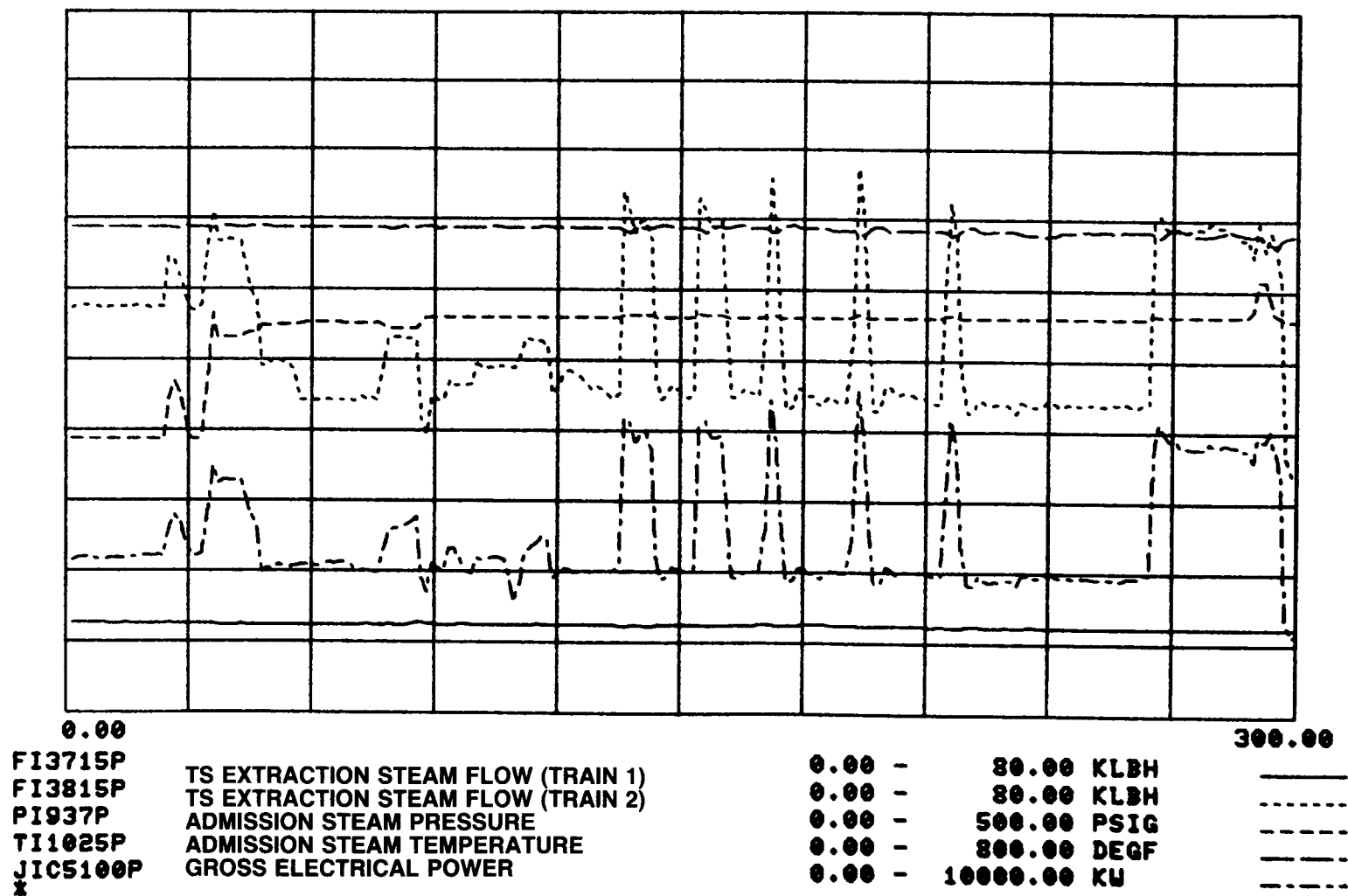


0.00						300.00
FI3812P	TS EXTRACT SUPHTR OIL FLOW (TRAIN 2)	0.00 -	400.00	KLBH	_____	
TI3811P	TS EXTRACT SUPHTR INLET OIL TEMP (TRAIN 2)	0.00 -	800.00	DEGF	-----	
FI3806P	TS EXTRACT BOILER OIL FLOW (TRAIN 2)	0.00 -	500.00	KLBH	-----	
TI3804P	TS EXTRACT BOILER INLET OIL TEMP (TRAIN 2)	0.00 -	800.00	DEGF	-----	
TEX3651	TS EXTRACT OUTLET OIL TEMP (TRAIN 2)	0.00 -	800.00	DEGF	-----	

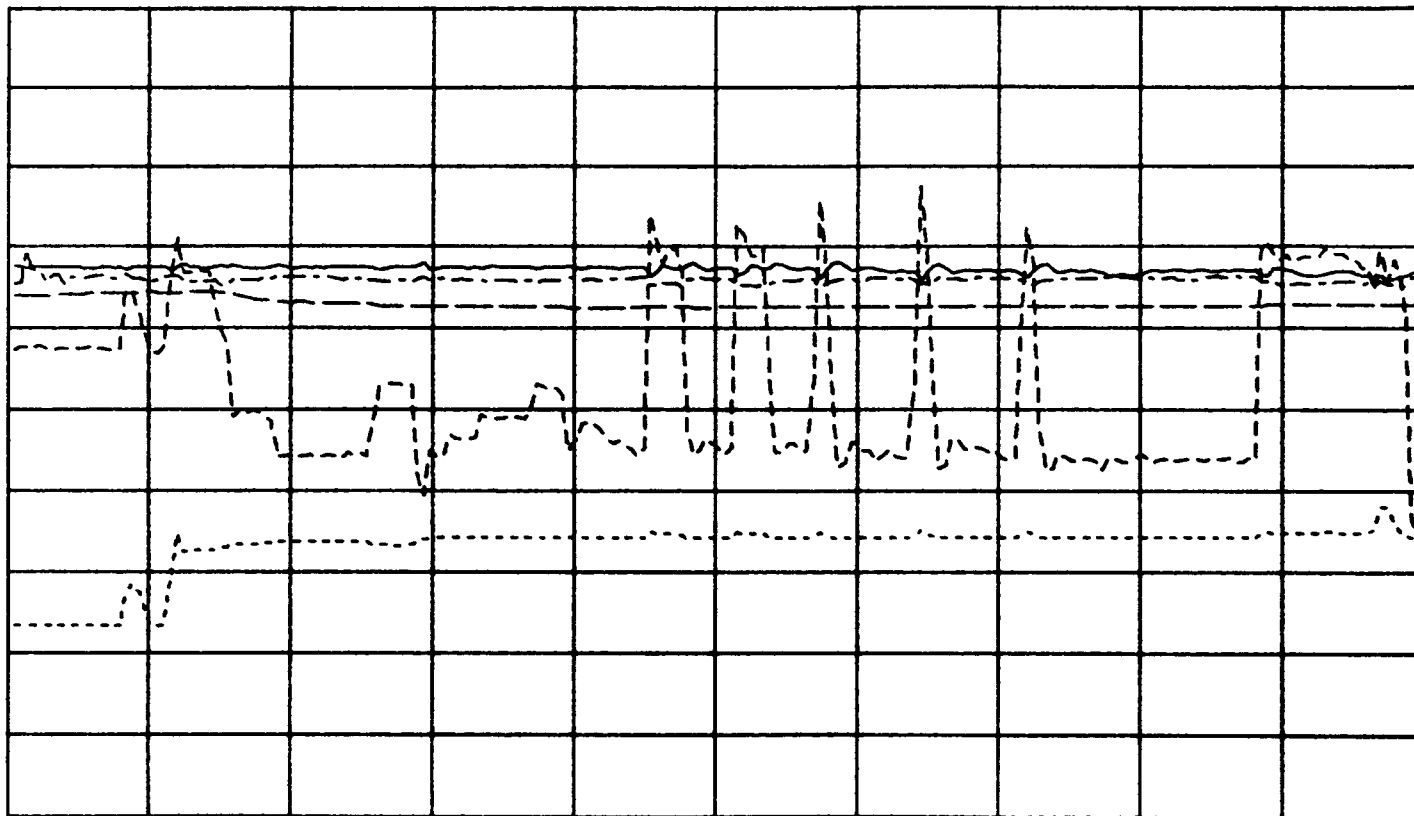
Figure 3.15(c). Turbine Inlet Condition Variations - Mode 6 - Train 2 Oil Parameters

Figure 3.15 (a) shows the TSS extraction Train 2 steam generator parameters as the system was transitioned between operating points. The significant disturbances in steam flow during the pressure transitions were the result of adjustments in the boiling heat transfer process which occurred when the heat of vaporization and the total enthalpy difference changed (due to boiler pressure change). These disturbances were also reflected in turbine load (JIC 5100P), Figure 3.15 (b) and TSS oil flows, Figure 3.15 (c). The most significant process upset occurred when both the boiler pressure and temperature were increased simultaneously (approximately 7:18 PM). Flow transitions which occurred without changes in pressure or temperature setpoints (at 4:57, 5:10, 6:02 and 6:32 PM) resulted in no process upsets.

On 5/11/83, response to load, flow and pressure steps was evaluated while the plant was operating in Mode 6. The data are shown in Figure 3.16 (a, b, and c) for a five hour period starting at 5:00 PM. The plant was initially operated in Mode 4, and transition to Mode 6 occurred at approximately 6:28 PM (as the charging operation was terminated). The control system was set up with the turbine in pressure control and extraction Train 2 set to load control (at 6:57 PM) with a 2 MWe set point. Figure 3.16 (a) shows the system response to load setpoint changes from 1.0 MWe to 4.0 MWe back to 2.0 MWe (at 7:15 PM and 7:33 PM), steam flow setpoint changes from 35 KLBH to 55 KLBH back to 35 KLBH (at 7:49 PM, 8:10 PM, and 8:33 PM, after the extraction train had been switched to flow control), and turbine pressure setpoint changes from 283 psig to 307 psig back to 283 psig (at 9:48 PM). Figures 3.16 (b) and 3.16 (c) show the extraction system steam and oil system parameters (respectively) during the same time period. Note that in spite of the significant variations in oil and steam flows due to the setpoint changes, the admission steam temperature and pressure were relatively constant (Figure 3.16 (a)).



SOLAR DATA PLOT PLOT # R11 NTH SAMPLE AVERAGE = 10  
REFERENCE TIME: 131 17 00 00.000 FOR 300.0000 MINUTE(S)

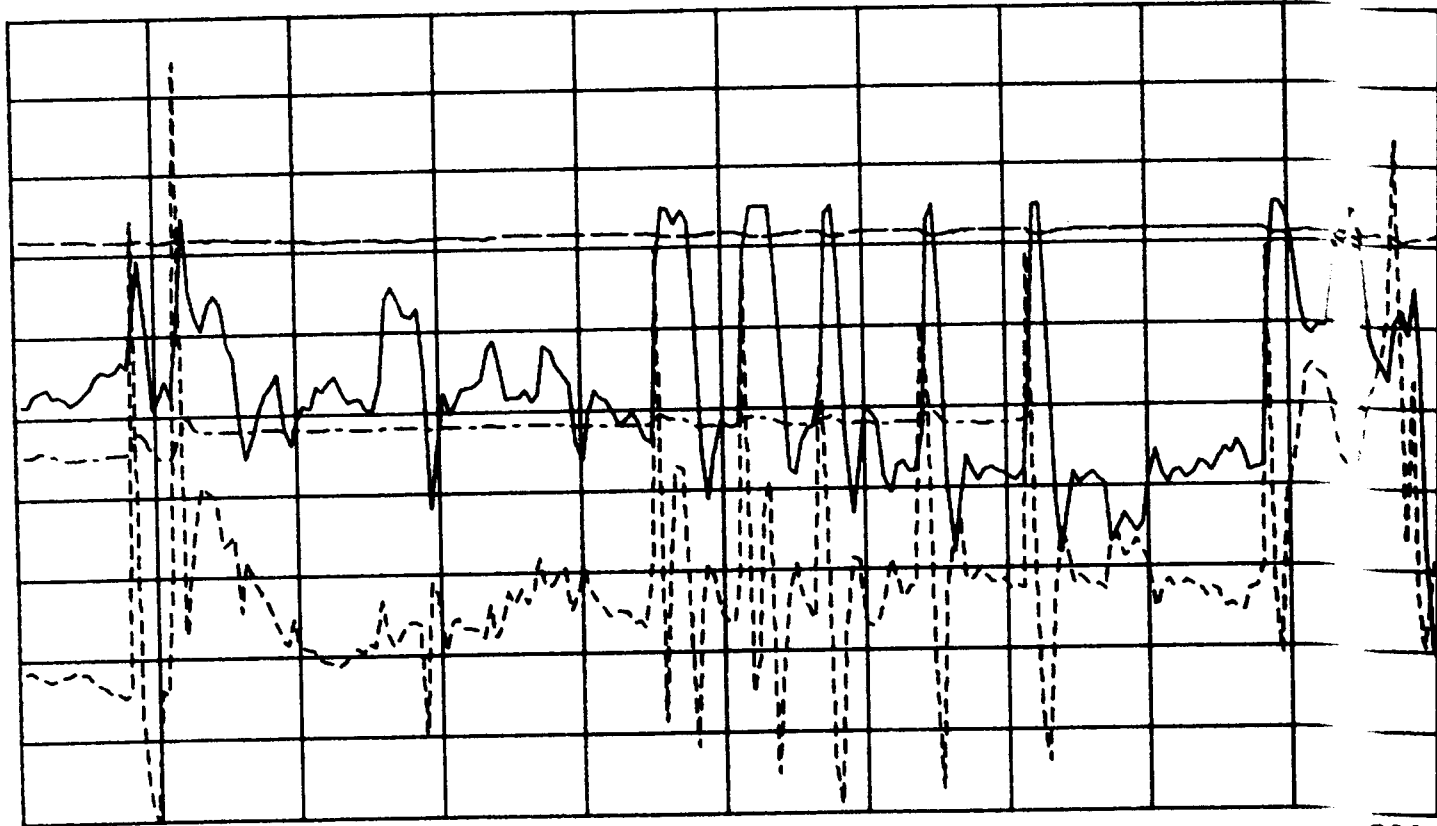


0.00										300.00
T13810P	TS EXTRACTION STEAM TEMP (TRAIN 2)	0.00	-	800.00	DEGF					_____
P13814P	TS EXTRACTION STEAM PRESS (TRAIN 2)	0.00	-	800.00	PSIG					-----
F13815P	TS EXTRACTION STEAM FLOW (TRAIN 2)	0.00	-	80.00	KLBH					-----
T13603P	TS BOILER FEEDWATER TEMP (TRAIN 2)	0.00	-	400.00	DEGF					_____
P13602P	TS BOILER FEEDWATER PRESS (TRAIN 2)	0.00	-	800.00	PSIG					-----
*										

Figure 3.16(b). Single Train Mode 6 Transitions – Train 2 Water/Steam Parameters

SOLAR DATA PLOT PLOT # R13  
REFERENCE TIME: 131 17 00 00.000

FOR NTH SAMPLE AVERAGE = 1\*  
300.0000 MINUTE(S)



0.00  
FI3812P  
TI3811P  
FI3806P  
TI3804P  
TEX3651  
X

TS EXTRACT SUPHTR OIL FLOW (TRAIN 2)  
TS EXTRACT SUPHTR INLET OIL TEMP (TRAIN 2)  
TS EXTRACT BOILER OIL FLOW (TRAIN 2)  
TS EXTRACT BOILER INLET OIL TEMP (TRAIN 2)  
TS EXTRACT OUTLET OIL TEMP (TRAIN 2)

0.00 - 400.00 KLBH  
0.00 - 800.00 DEGF  
0.00 - 500.00 KLBH  
0.00 - 800.00 DEGF  
0.00 - 800.00 DEGF

300.00  
\_\_\_\_\_  
-----  
-----  
-----  
-----

Figure 3.16(c). Single Train Mode 6 Transitions – Train 2 Oil Parameters



On 6/21/83, a maximum power run (Mode 3) was made with the peak load reaching 13.1 MWe (gross). Mode 3 operation continued until approximately 6:47 PM when main steam flow to the turbine was terminated and the plant was transitioned to Mode 6. As a result of the extended admission steam operation, the Thermal Storage Unit charge became depleted and the extraction train inlet oil temperature began decreasing. This condition is shown on Figure 3.17 (a); oil temperatures at the inlet to the superheater (TI 3711P) and the boiler (TI 3704P). The operational procedure for this condition was to periodically reduce the superheater steam temperature setpoint (in order to maintain admission superheat) - see Figure 3.17 (b). Nominally, the turbine would operate at approximately 100°F superheat, but by reducing the temperature/pressure setpoints and allowing admission steam superheat levels as low as 70°F (50°F is the trip level), Mode 6 operation could be extended. The performance penalty for off-design turbine operation is discussed in Section 3.5.2.

The transitions between Mode 6 and Mode 3 involved phasing in or phasing out main steam operation while continuing to run the turbine on admission steam. The transitions between Mode 6 and Mode 4 involved initiating or terminating thermal storage charging operations while continuing to run the turbine on admission steam. The operational characteristics of these transitions are discussed in Reference 3.

### 3.5.2 Steady-State Operation

The goal of steady-state Mode 6 operation (see Section 3.2.1) was to investigate the range of Mode 6 operating conditions, gather data for estimation of performance, determine first-order performance related sensitivities and to establish operational limits. Also, the movement of the

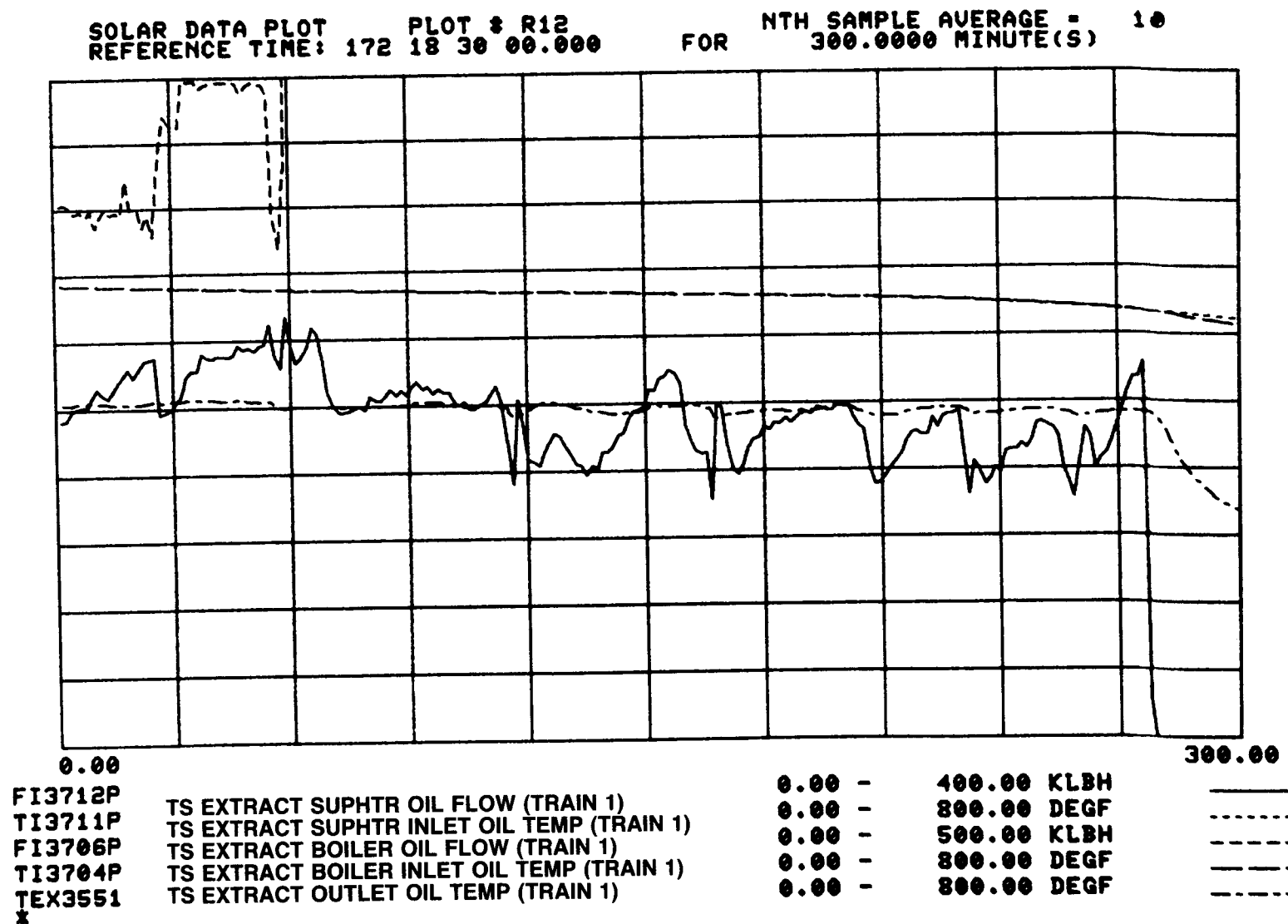
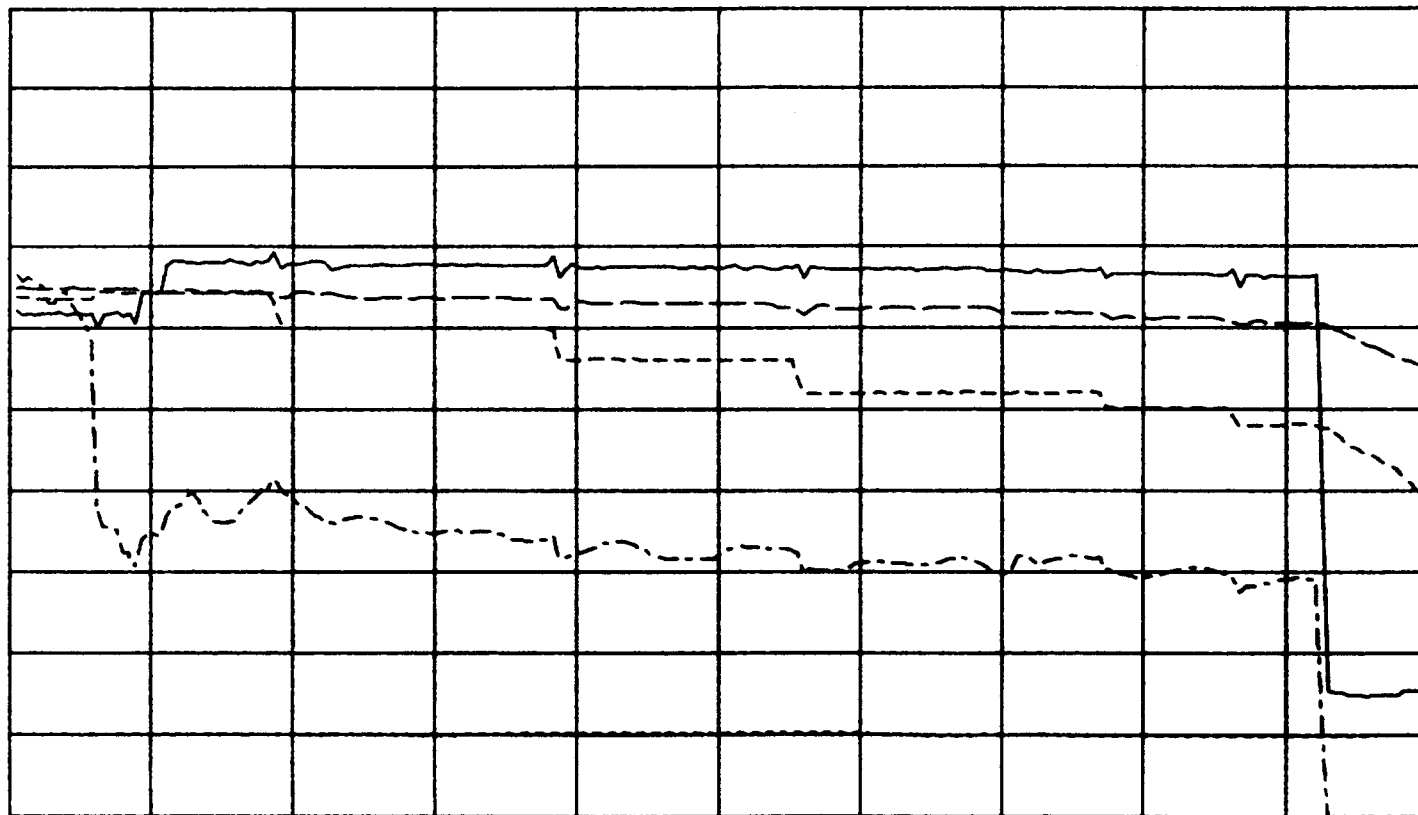


Figure 3.17(a). Extended Mode 6 Operation – Train 1 Oil Parameters

SOLAR DATA PLOT PLOT # R9  
REFERENCE TIME: 172 18 30 00.000

FOR NTH SAMPLE AVERAGE = 10  
300.0000 MINUTE(S)



0.00									300.00
FI3715P	TS EXTRACTION STEAM FLOW (TRAIN 1)	0.00 -	80.00	KLBH					
FI3815P	TS EXTRACTION STEAM FLOW (TRAIN 2)	0.00 -	80.00	KLBH				N/A	
PI937P	ADMISSION STEAM PRESSURE	0.00 -	500.00	PSIG				-----	
TI1025P	ADMISSION STEAM TEMPERATURE	0.00 -	800.00	DEGF				-----	
JIC5100P	GROSS ELECTRICAL POWER	0.00 -	10000.00	KW				-----	
*									

Figure 3.17(b). Extended Mode 6 Operation – Turbine Parameters

thermocline (see Section 1.2) through the TSU was of interest in the determination of the total amount of energy available for steam generation in Mode 6. The majority of the data used to establish "instantaneous" performance were obtained from time-averaged five minute data samples (see Table 3.1) occurring during periods of steady-state operation. The numbers on the data points on figures in this section correspond to the particular data samples in Table 3.1.

#### 3.5.2.1 Plant Performance

Calculated plant cycle performance during Mode 6 operation was based on extraction heat exchanger steam generation rate and turbine-generator gross electrical power. As discussed in Section 3.4, the basis for the determination of the steam generation rate was the extraction boiler feedwater flow measurement (corrected for actual feedwater density). Mode 6 data and performance calculations are compared in this section to predicted values developed during the original plant heat and mass balance analysis. The predicted values were based on a single set of turbine admission steam conditions (370 psig, 525°F) and a feedwater temperature of 250°F. Since the data presented in this section cover a wide range of admission steam conditions (196-396 psig, 485-540°F) and feedwater temperatures (100-255°F), the predicted values are presented for general comparison only.

As indicated by the constant feedwater temperature in the heat and mass balance analysis, a constant deaerator pressure was assumed. During moderate to high turbine admission steam flow operation, the deaerator could be maintained at this fixed level (30 psia) from normal turbine extraction flows. At low turbine flows, however, insufficient extraction pressure would be available to supply turbine steam to the deaerator. Therefore, it was

assumed (in the analysis) that the auxiliary steam system would be activated to supply the additional steam required, with a corresponding penalty (increase) in cycle heat rate. It was also assumed that a constant deaerator pressure would be required for proper operation of the extraction heat exchangers which were supplied with feedwater directly from the deaerator (see Section 3.3).

The operating experience at Solar One indicated that holding a fixed deaerator pressure (temperature) was not required. The deaerator pressure (and resulting saturation temperature) was permitted to "float" and seek its own value based on natural cycle operations. There were two primary reasons for this. First, the actual heat transfer processes did not exactly follow the idealized counterflow process shown in Figure 3.8. Second, the individual heat exchangers were specified to include fouling factors in the event of deposition from the Caloria system. The fact that there was no evidence of such deposition resulted in heat exchangers with higher effectiveness or greater capacity than required by the original plant design. It was determined to be possible to cool the Caloria down to approximately 405°F during routine TSU extraction operation. As a result of the "floating" deaerator pressure, the auxiliary steam demand at all turbine flows was reduced.

Mode 6 gross electrical power as a function of extraction boiler steam flow (calculated from boiler make up water flow) is presented in Figure 3.18. The data indicate that the Mode 6 performance was better than expected, with the data following the general trend of the predicted values. Since no previous manufacturers data were available for operation of the turbine in the admission steam mode (the admission port for other applications of the turbine

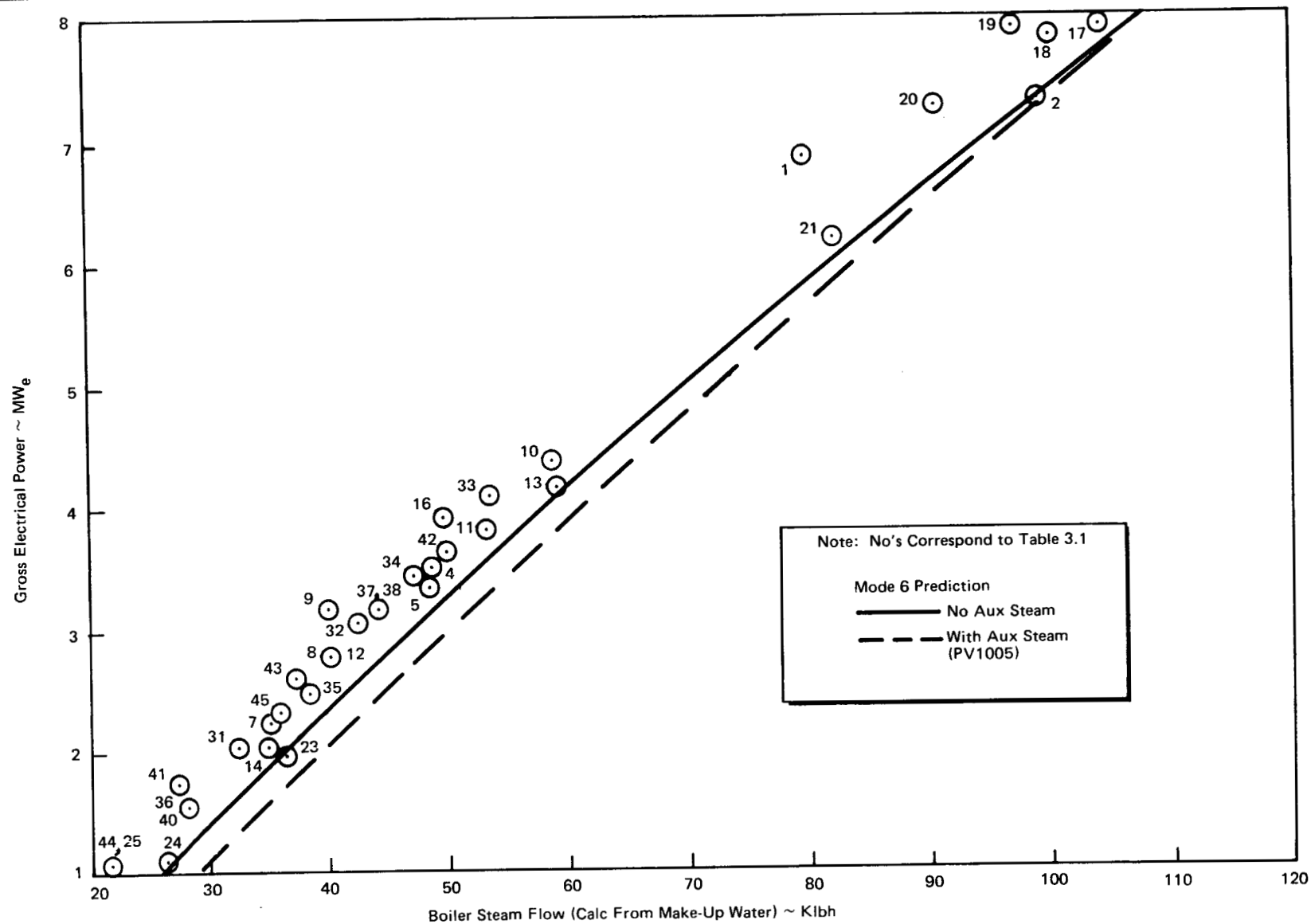


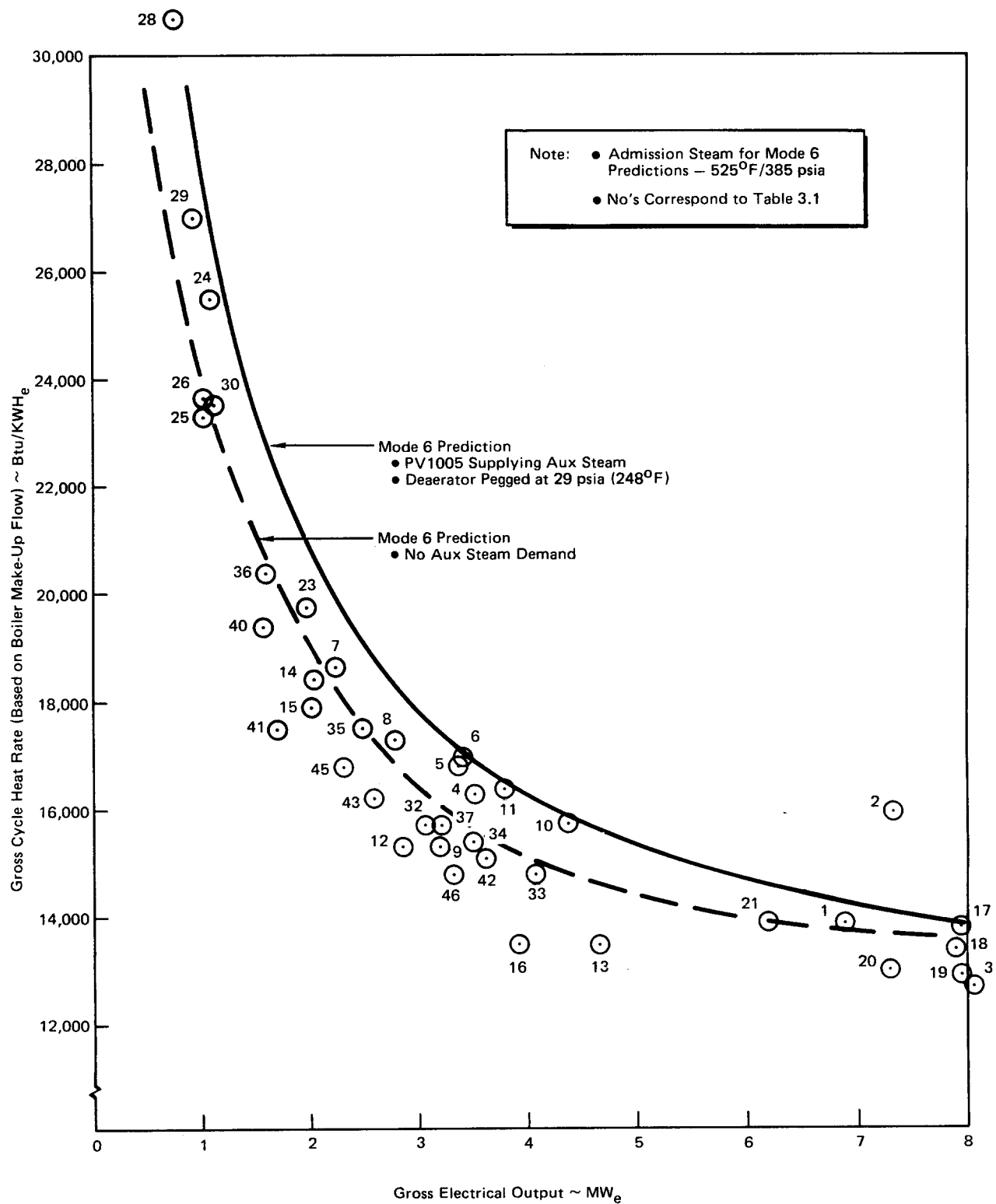
Figure 3.18. Predicted and Actual Mode 6 Performance — Gross Electrical Power

was normally an extraction port), the predicted performance was based only on turbine cycle analytical results. The corresponding Mode 6 gross cycle heat rate is shown in Figure 3.19. The gross cycle heat rate was calculated from thermal power delivered to the extraction heat exchanger water/steam and from turbine-generator delivered gross electrical power. As before, the data follow the trends of the predicted values with better (lower) than predicted cycle heat rates. The data clearly show the disadvantage of operating the turbine at low load, with a substantial increase in thermal energy required from the TSU for an equivalent number of MWe at low loads compared to high loads.

#### 3.5.2.2 Operational Limits

The plant was operated in Mode 6 over a range of turbine admission conditions and feedwater temperatures as discussed in the previous section. The low flow (load) characteristics using a single extraction train were investigated as well as the high flow (load) characteristics using both single and dual extraction trains. Also, the Mode 6 design point extraction case (7 MWe for 4 hours) was verified.

On 6/27/83 (day 178) and 6/28/83 (day 179) Solar One was on-line for 33.6 continuous hours as a demonstration of continuous and overnight operation. From 4:35 PM on 6/27/83 to 8:05 AM on 6/28/83 the plant was operated in Mode 6 at approximately 1 MWe (gross) output. Data from a portion of this time period are shown on Figure 3.20 (a-c). Stable operation continued until approximately 3:30 AM (6/28/83) when the receiver feedwater pump was started. The increased demand for auxiliary steam required for deaerator pressurization resulted in a reduction in turbine admission steam and turbine load (see Figure 3.20a). The load continued below 1 MWe (gross) until the steam



**Figure 3.19. Predicted and Actual Mode 6 Performance — Gross Cycle Heat Rate**



SOLAR DATA PLOT PLOT # R9 NTH SAMPLE AVERAGE = 10  
REFERENCE TIME: 178 23 00 00.000 FOR 600.0000 MINUTE(S)

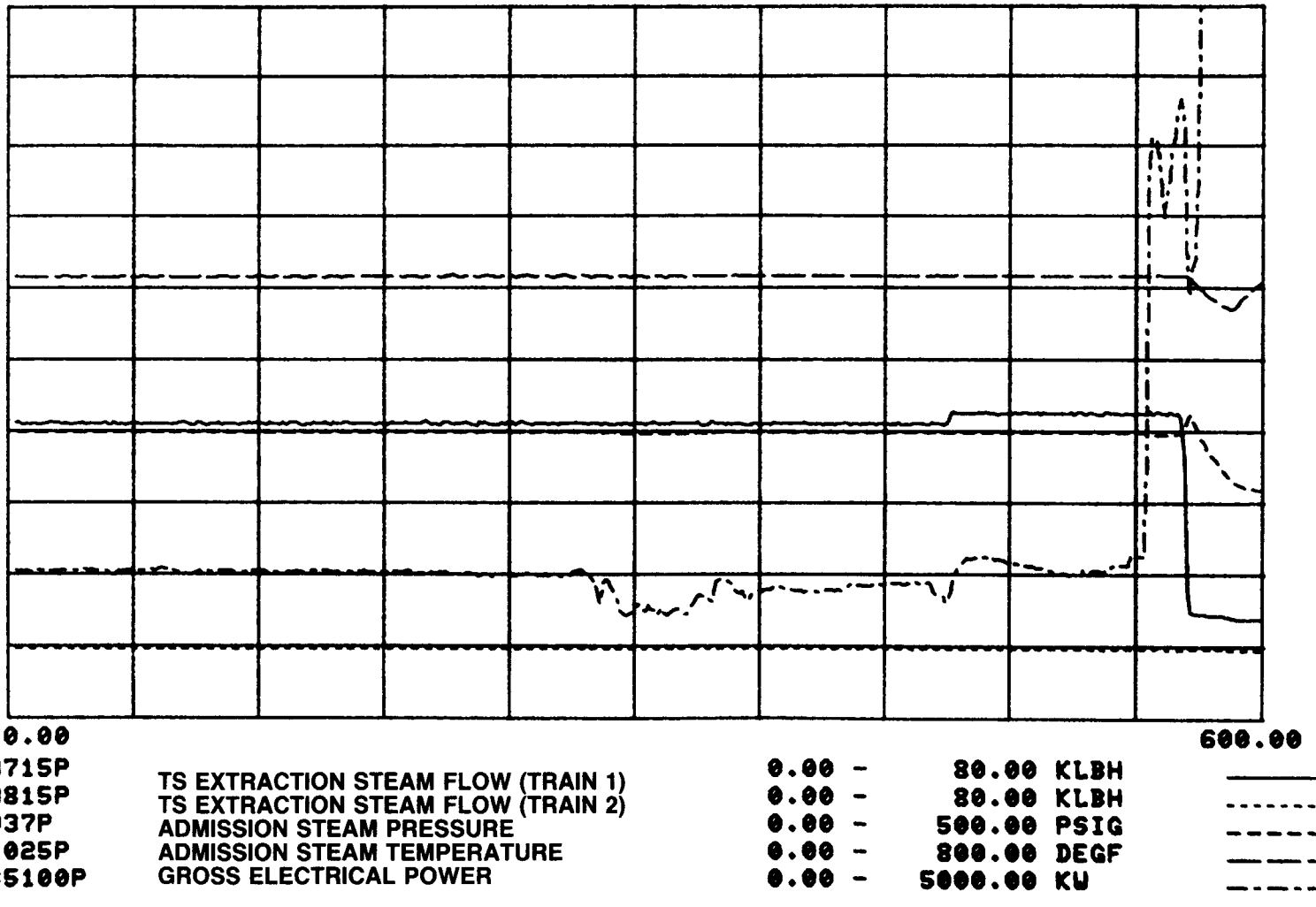


Figure 3.20(a). Low Load Mode 6 Operation – Turbine Parameters

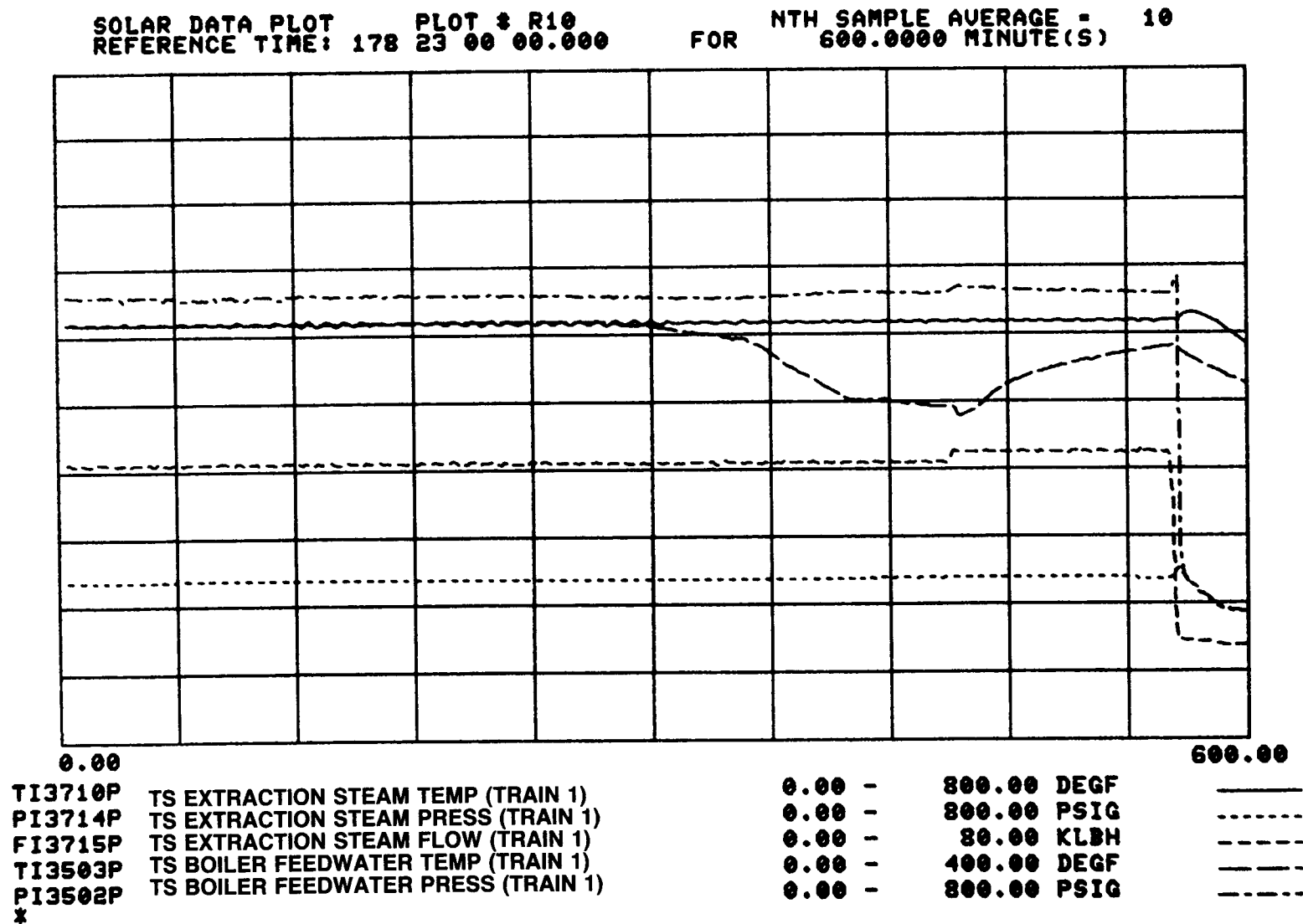


Figure 3.20(b). Low Load Mode 6 Operation – Train 1 Water/Steam Parameters

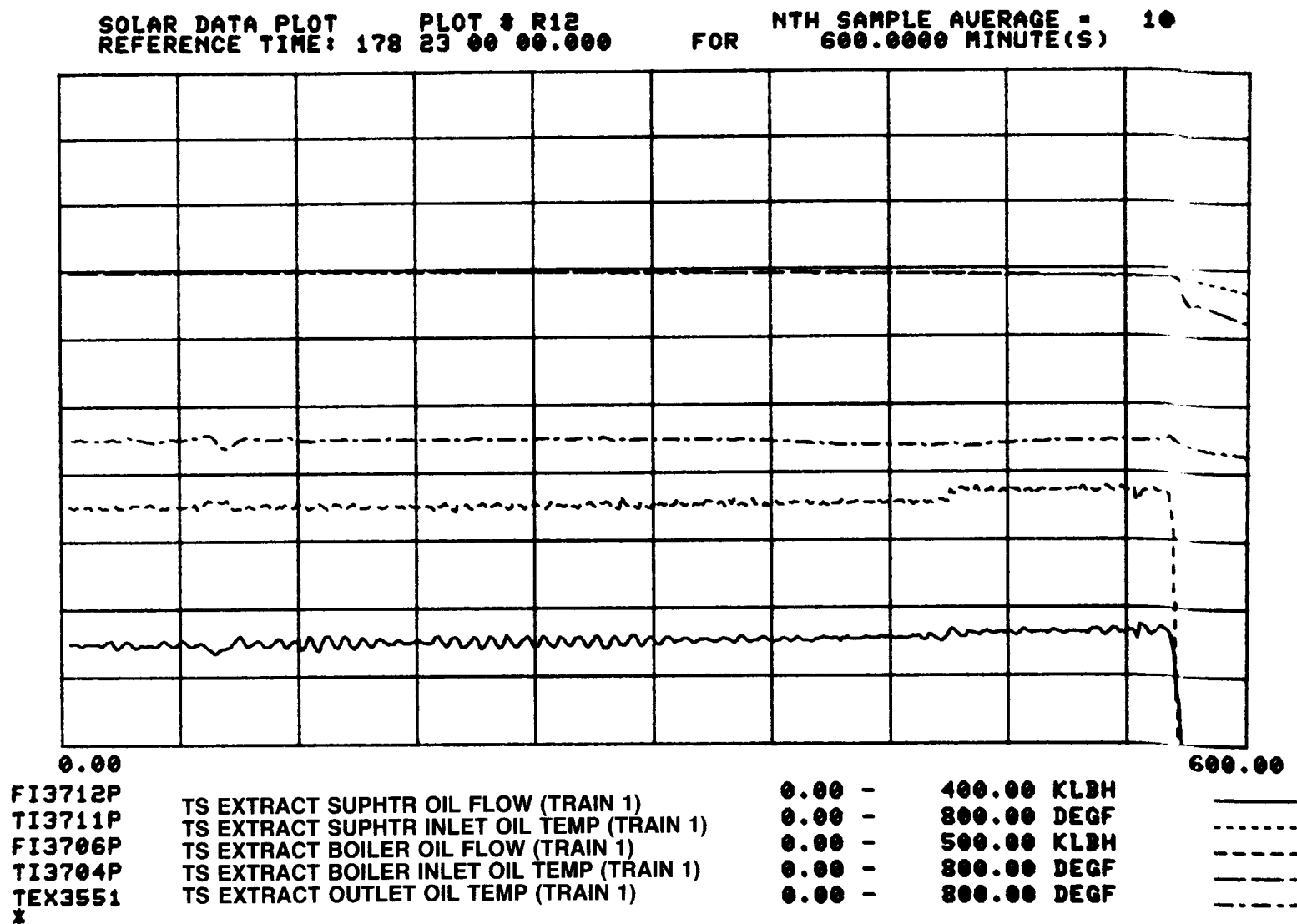


Figure 3.20(c). Low Load Mode 6 Operation – Train 1 Oil Parameters

generator flow was increased at 6:30 AM. A transition to Mode 3 operation occurred at 8:05 AM and the steam generator was shutdown at 8:24 AM.

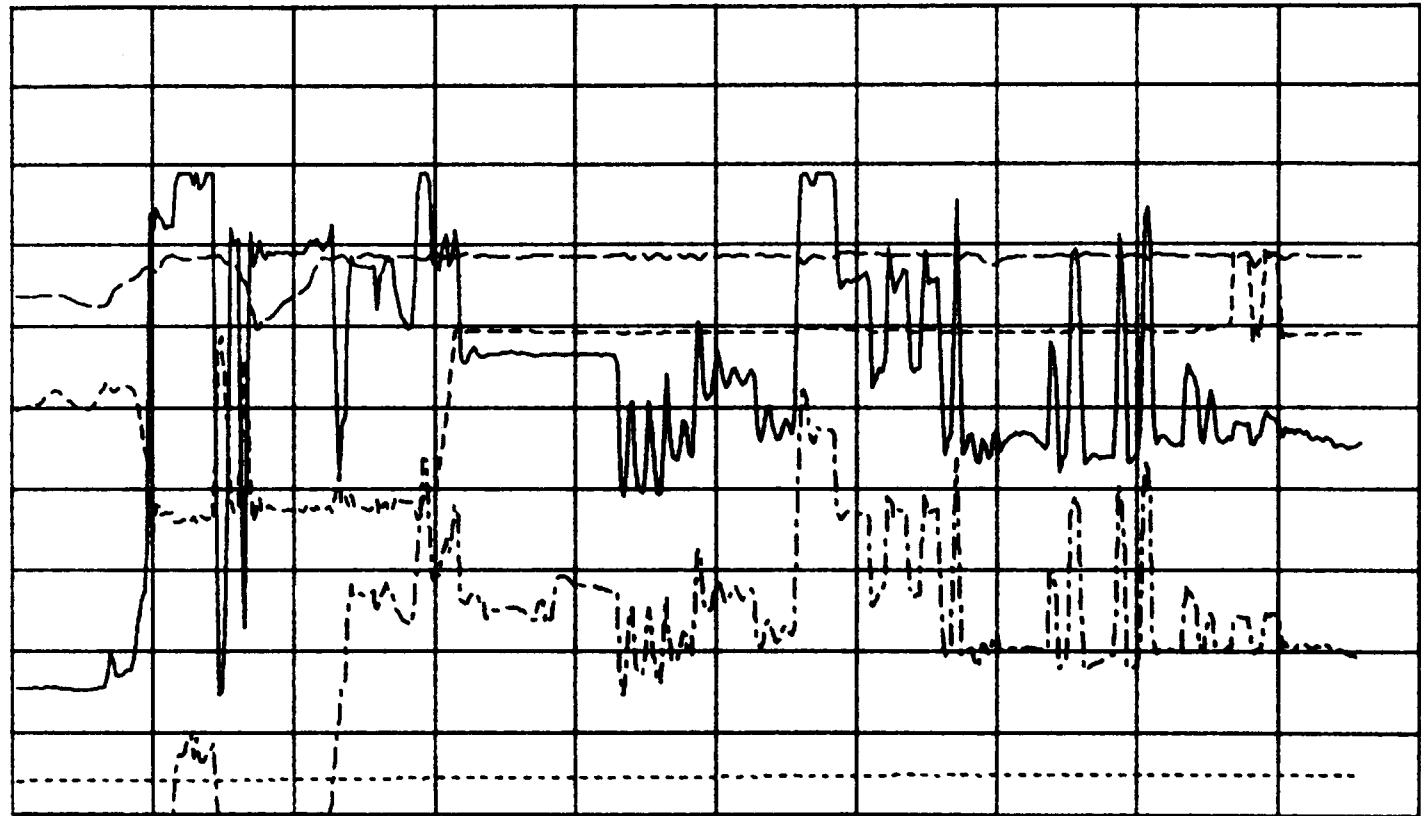
Water/steam system parameters are shown on Figure 3.20(b) and oil system parameters are shown on Figure 3.20(c) during this time period. Although continuous stable operation at low load was demonstrated, only 6:05 PM MWe (gross) were generated between midnight and 6:15 AM at considerable TSU energy expenditure (approximately 25,000 BTU/KWH gross cycle heat rate).

On 5/4/83 (day 124), the plant was operated in Mode 6 with a number of power cycles as the control system was being tuned (see Figure 3.21 a-d). At 7:30 PM, the turbine load was increased to the approximate maximum for a single extraction train (4.68 MWe gross). The turbine admission steam control valves were open 62 percent (ZI943P, Figure 3.21b) and the steam flowmeter output was maximum (FI3715P, Figure 3.21a). Also, the superheater oil flowmeter output was maximum (FI3712P, Figure 3.21c) and the boiler oil flow was at 350 KLBH (FI3706P, Figure 3.21c). Although the load peaked at 5.2 MWe during the power transient (boiler steam flow surge), this level was not maintainable during steady flow conditions.

On 2/25/83 (day 56), special Mode 6 testing was performed to verify the 7 MWe design point. Both extraction trains were started and the turbine was on-line at 11:25 AM (Figure 3.22a). After a period of low load operation, the steam generators were placed in LOAD control and the power was ramped at 1:12 PM to 7.3 MWe (gross), GE5100P (Figure 3.22a). At 1:42 PM, the turbine pressure set point was decreased to 325 psig. This resulted in a sudden surge in steam generation as the boiler saturation pressure decreased and the turbine load momentarily increased to 8.6 MWe (gross). Following pressure stabilization,

SOLAR DATA PLOT PLOT # R9  
REFERENCE TIME: 124 14 00 00.000

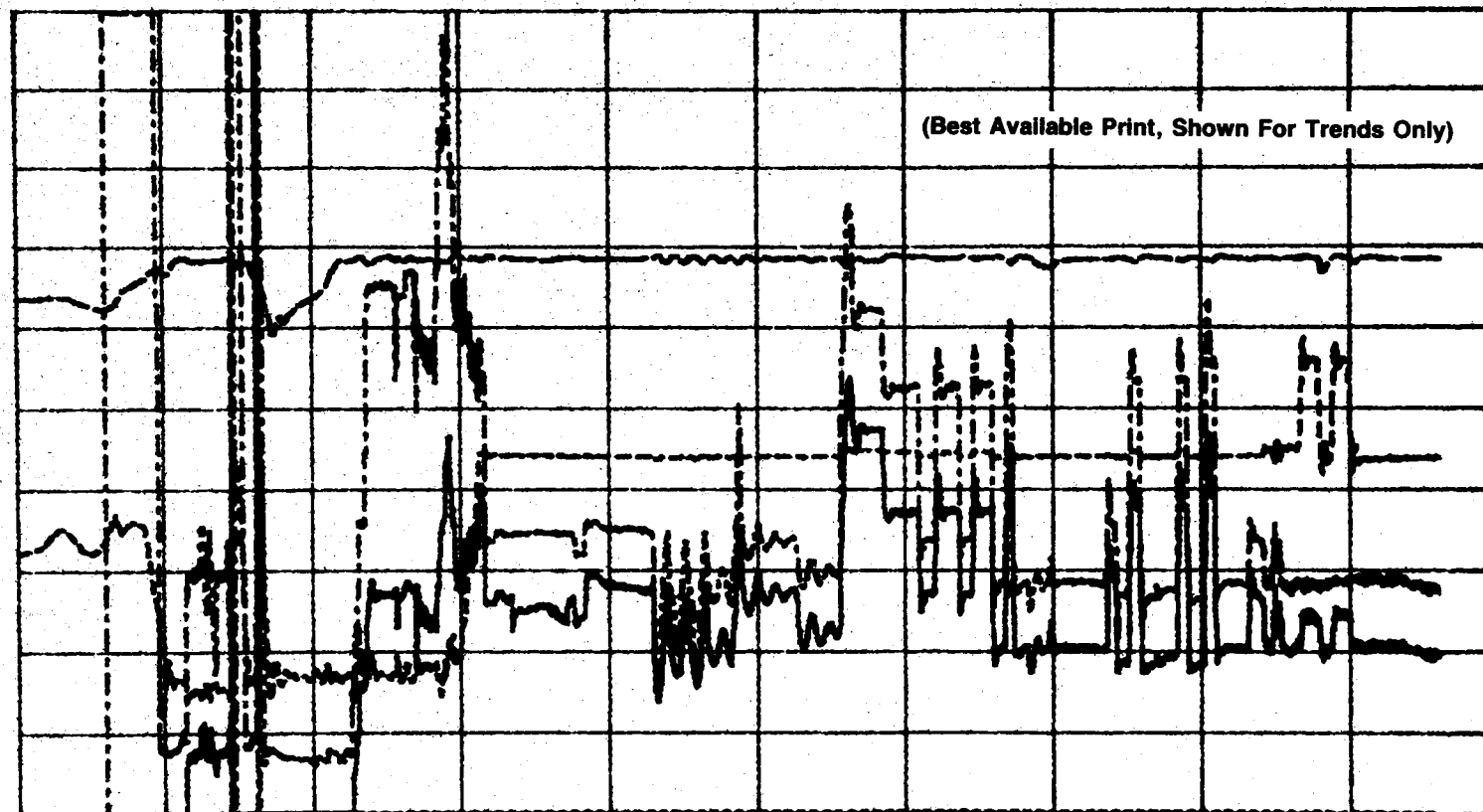
FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)



0.00									600.00
FI3715P	TS EXTRACTION STEAM FLOW (TRAIN 1)	0.00 -	80.00	KLBH					
FI3815P	TS EXTRACTION STEAM FLOW (TRAIN 2)	0.00 -	80.00	KLBH					
PI937P	ADMISSION STEAM PRESSURE	0.00 -	500.00	PSIG					
TI1025P	ADMISSION STEAM TEMPERATURE	0.00 -	800.00	DEGF					
JIC5100P	GROSS ELECTRICAL POWER	0.00 -	10000.00	KW					

Figure 3.21(a). Maximum Single Train Mode 6 Operation – Turbine Parameters

1 SOLAR DATA PLOT PLOT # BLANK NTH SAMPLE AVERAGE =  
 REFERENCE TIME: 124 14 00 00.000 FOR 600.0000 MINUTE(S)



0.00			600.00
GE5100P	GROSS ELECTRICAL POWER	0.00 -	10000.00 KW
NE5102AP	NET ELECTRICAL POWER	0.00 -	10000.00 KW
P1937P	ADMISSION STEAM PRESSURE	120.00 -	520.00 PSIG
TI1025P	ADMISSION STEAM TEMPERATURE	0.00 -	800.00 DEGE
ZI943P	TURBINE ADMISSION CONTROL VALVE POSITION	0.00 -	100.00 PCT

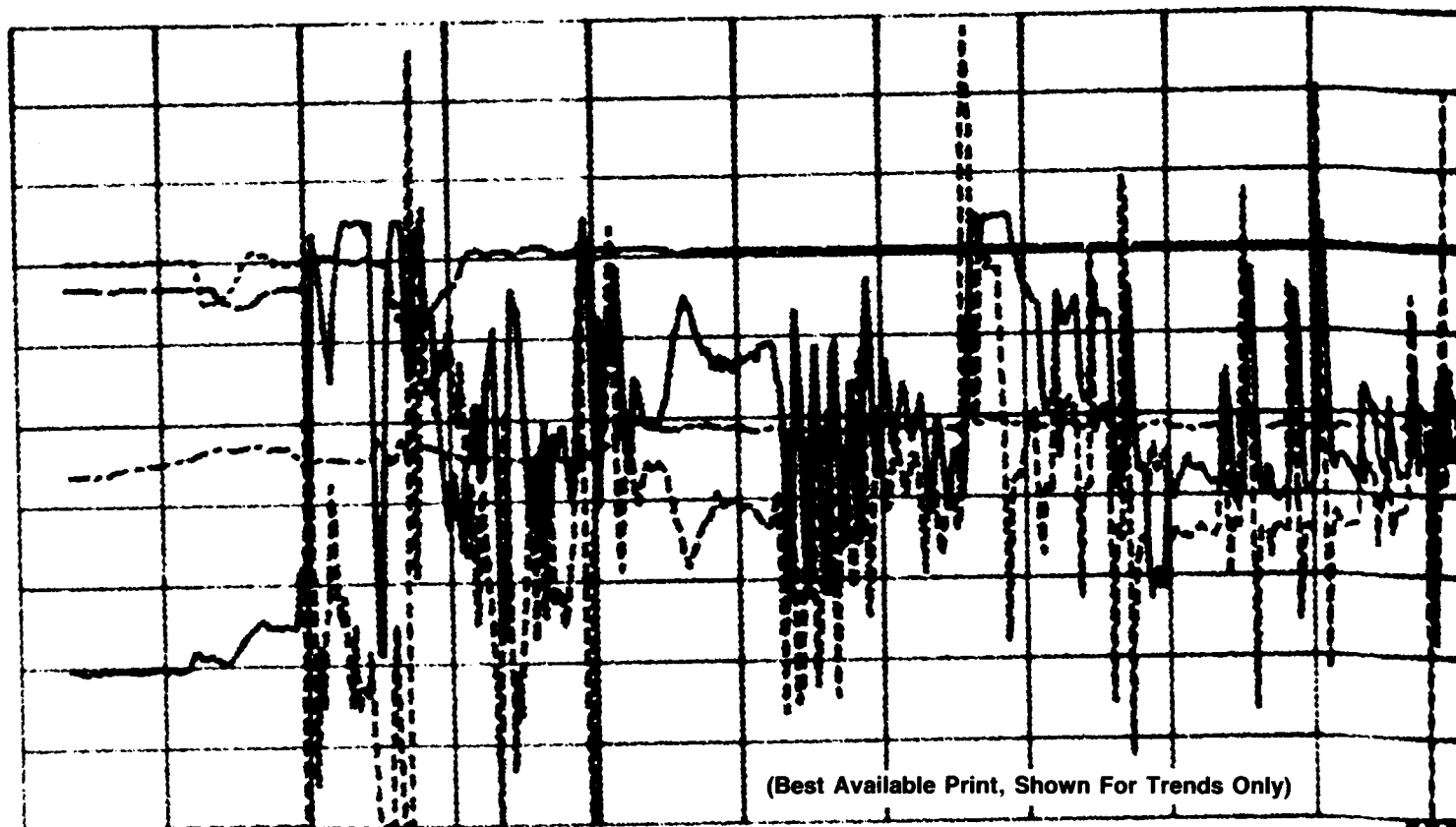
Figure 3.21(b). Maximum Single Train Mode 6 Operation – Turbine Parameters

SOLAR DATA PLOT

PLOT # R12

REFERENCE TIME: 124 13 00 00.000

FOR

NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)

0.00  
FI3712P  
TI3711P  
FI3706P  
TI3704P  
TEX3551

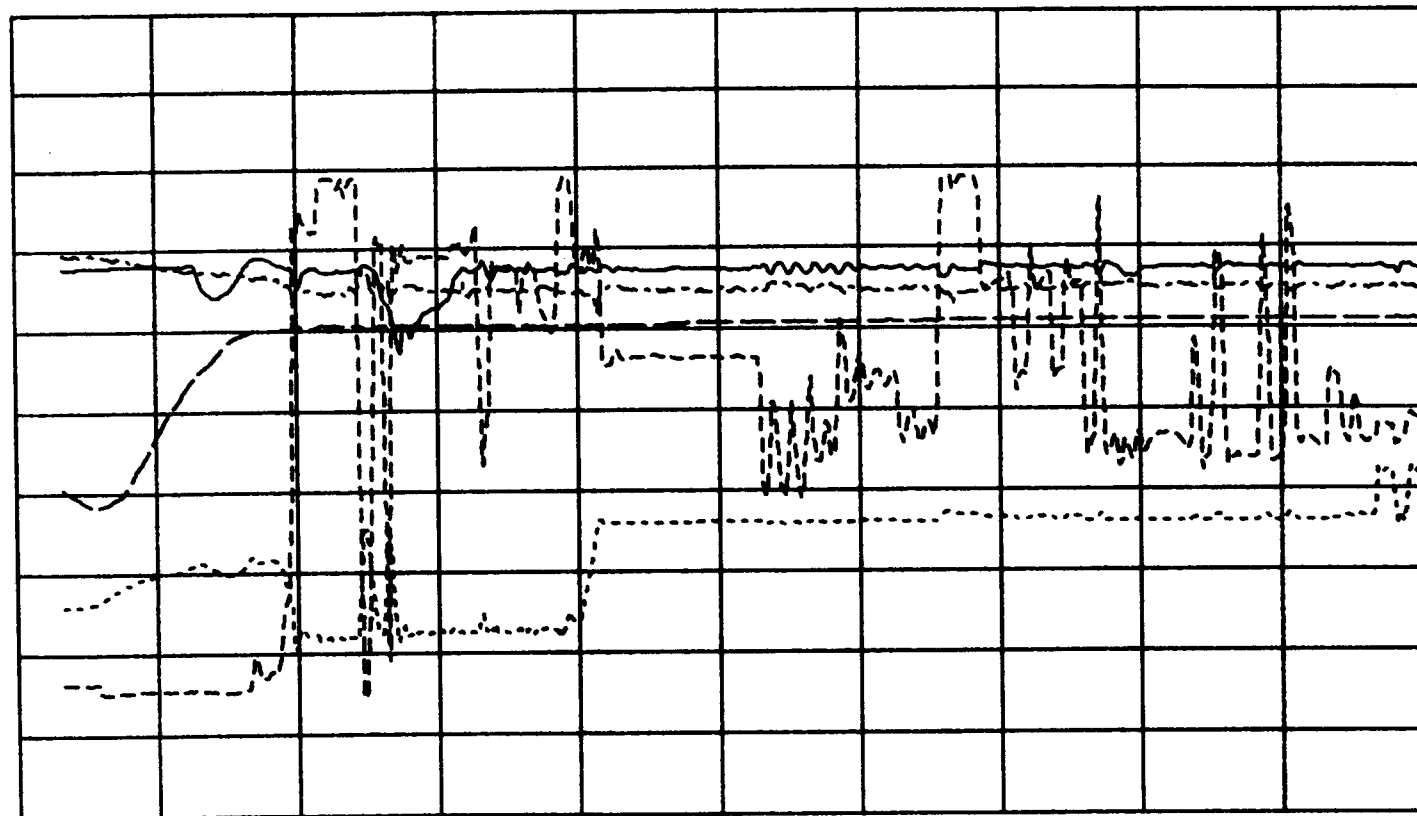
TS EXTRACT SUPHTR OIL FLOW (TRAIN 1)  
TS EXTRACT SUPHTR INLET OIL TEMP (TRAIN 1)  
TS EXTRACT BOILER OIL FLOW (TRAIN 1)  
TS EXTRACT BOILER INLET OIL TEMP (TRAIN 1)  
TS EXTRACT OUTLET OIL TEMP (TRAIN 1)

0.00 - 400.00 KLBM  
0.00 - 800.00 DEGE  
0.00 - 500.00 KLBM  
0.00 - 800.00 DEGE  
0.00 - 800.00 DEGE

Figure 3.21(c). Maximum Single Train Mode 6 Operation – Train 1 Oil Parameters

SOLAR DATA PLOT PLOT # R10  
REFERENCE TIME: 124 13 00 00.000

FOR NTH SAMPLE AVERAGE = 10  
600.0000 MINUTE(S)



0.00					600.00
TI3710P	TS EXTRACTION STEAM TEMP (TRAIN 1)	0.00 -	800.00	DEGF	_____
PI3714P	TS EXTRACTION STEAM PRESS (TRAIN 1)	0.00 -	800.00	PSIG	-----
FI3715P	TS EXTRACTION STEAM FLOW (TRAIN 1)	0.00 -	80.00	KLBH	-----
TI3503P	TS BOILER FEEDWATER TEMP (TRAIN 1)	0.00 -	400.00	DEGF	_____
PI3502P	TS BOILER FEEDWATER PRESS (TRAIN 1)	0.00 -	800.00	PSIG	-----
x					

Figure 3.21(d). Maximum Single Train Mode 6 Operation – Train 1 Water/Steam Parameters



SOLAR DATA PLOT PLOT # BLANK  
REFERENCE TIME: 056 10 00 00.000

FOR NTH SAMPLE AVERAGE = 1  
300.0000 MINUTE(S)

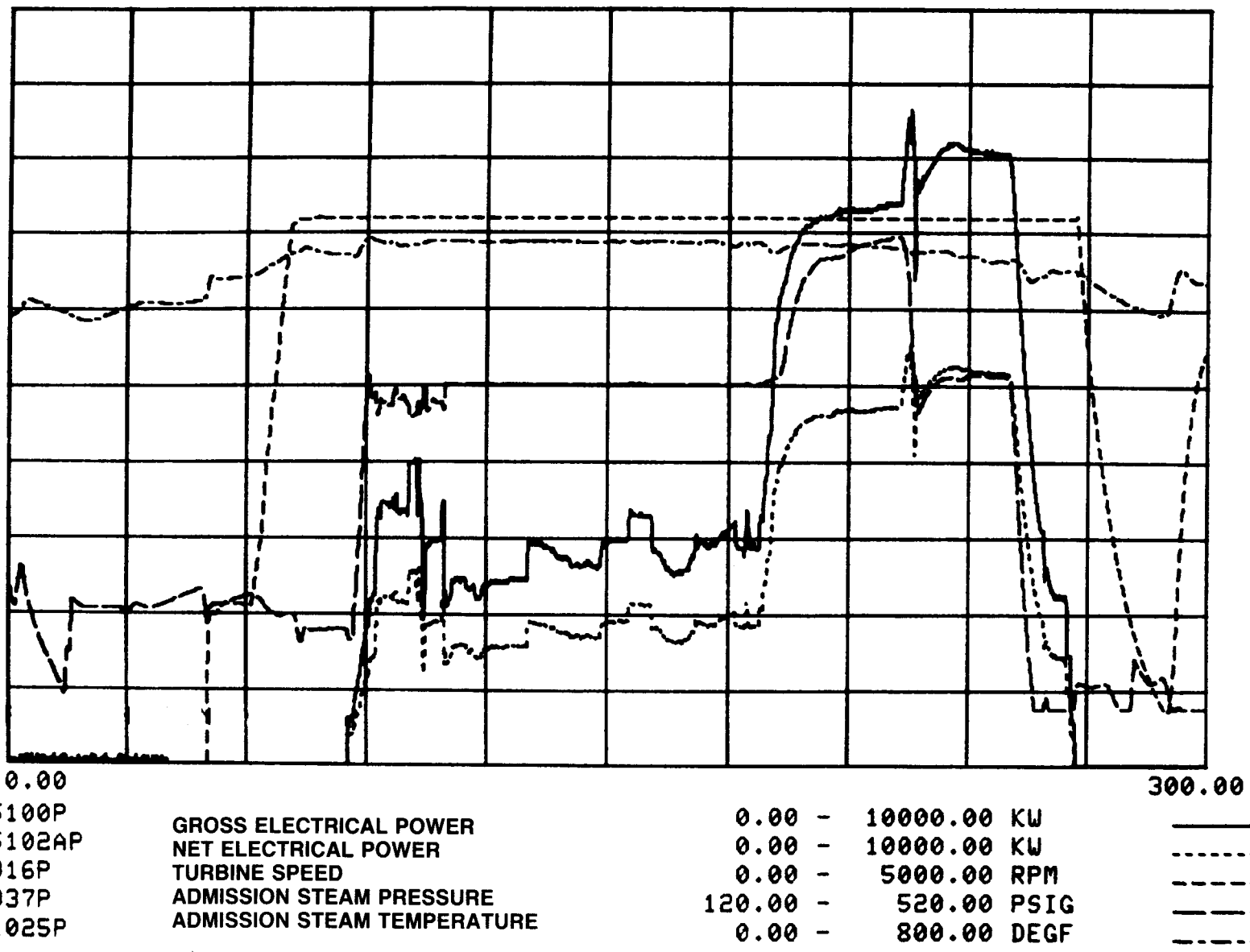


Figure 3-22(a). Maximum Dual Train Mode 6 Operation - Turbine Parameters

the turbine load reached 8.2 MWe (gross) and 7.3 MWe (net), thus verifying the design point. The measurement used to establish the net output was JI5102P, not NE5102AP (Figure 3.22a), due to calibration problems with NE5102AP. At the peak stabilized power the turbine admission steam control valves were wide open (ZI943P, Figure 3.22b) and peak Mode 6 power was attained. The steam and oil parameters for Train 1 and Train 2 are shown in Figures 3.22c and 3.22d, respectively.

Another design point verification test was conducted on 5/18/83 (day 138) when the plant was operated in Mode 6 to verify continuous operation for four hours above 7 MWe (net). The thermal storage tank had been fully charged (see Section 3.5.2.3) prior to the extraction test. Following a trip due to high TSU pressure, both extraction trains were started (Figure 3.14e) and the turbine/generator was brought on-line (2:12 PM). With Train 1 in FLOW control and Train 2 in pressure control, the pressure was ramped and the net power (JI5102AP) was above 7 MWe by 2:20 PM (Figure 3.23a). Net power remained above 7 MWe until 6:14 PM (a total of 3 hours 54 minutes above 7 MWe net), with the 28 MWHe design value achieved by 5:54 PM. Turbine admission conditions for the verification run are shown in Figure 3.23b. Turbine operation continued at reduced power and admission pressure until 9:14 PM (extraction Train 1 taken out of service at 7:50 PM) with a total generation of 43.4 MWHe (net).

#### 3.5.2.3 TSU Thermocline

Motion of the thermocline (Section 2.5.2.3) through the TSU during the maximum extraction Mode 6 test described above (day 138) is shown in Figure 3.24. The TSU had been essentially fully charged the day before, with final charging operations continuing until 11:35 AM on day 138. Tank temperature profiles

SOLAR DATA PLOT PLOT # BLANK NTH SAMPLE AVERAGE = 1  
 REFERENCE TIME: 056 10 00 00.000 FOR 300.0000 MINUTE(S)

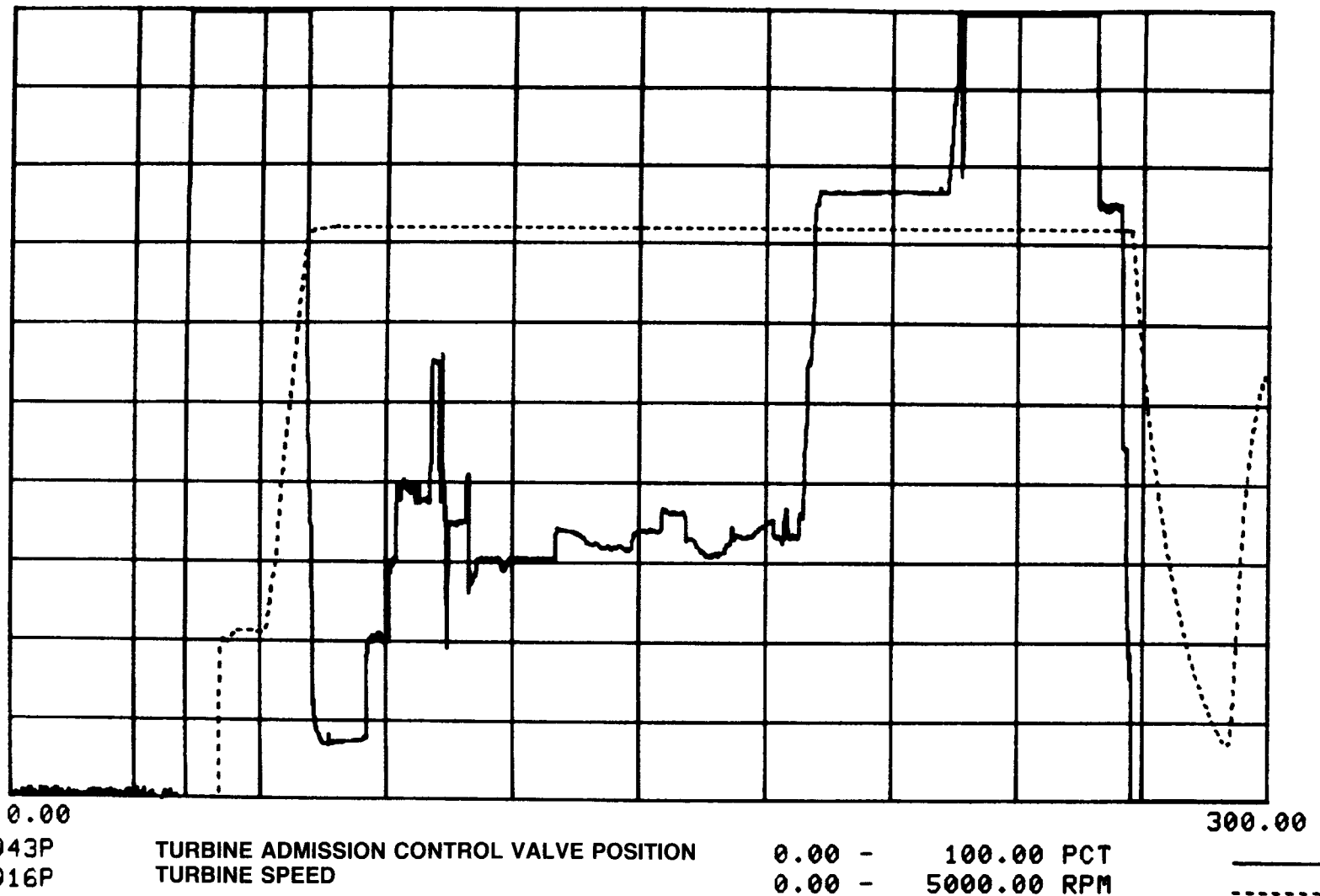
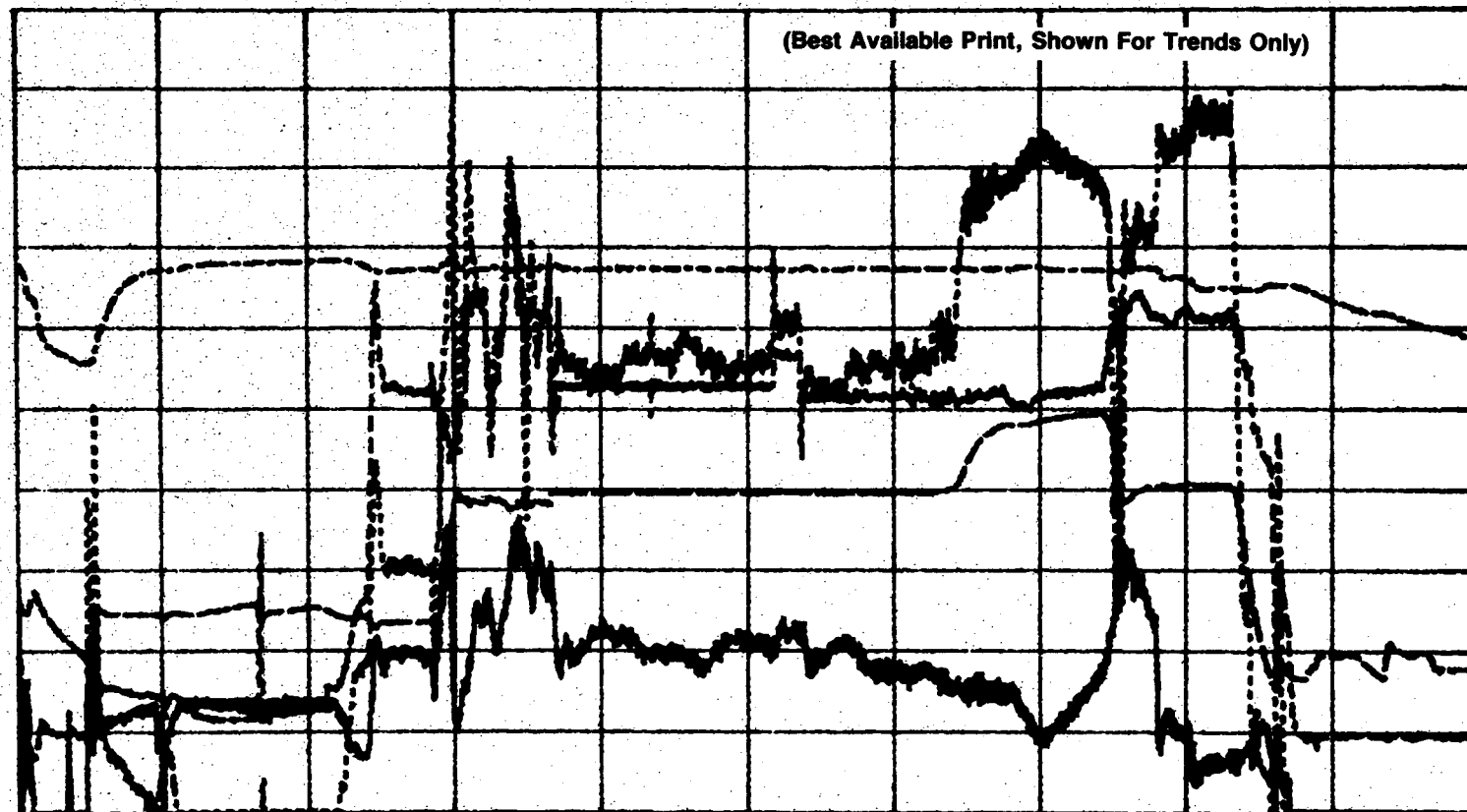


Figure 3-22(b). Maximum Dual Train Mode 6 Operation – Turbine Parameters

\*

1 SOLAR DATA PLOT PLOT # BLANK HTH SAMPLE AVERAGE =  
 REFERENCE TIME: 056 10 00 00.000 FOR 300.0000 MINUTE(S)



0.00										300.00
F13712P	TS EXTRACT SUPHTR OIL FLOW (TRAIN 1)	0.00	-	400.00	KLBH	_____				
F13706P	TS EXTRACT BOILER OIL FLOW (TRAIN 1)	0.00	-	500.00	KLBH	.....				
F13715P	TS EXTRACTION STEAM FLOW (TRAIN 1)	0.00	-	80.00	KLBH	_____				
P13714P	TS EXTRACTION STEAM PRESS (TRAIN 1)	0.00	-	800.00	PSIG	_____				
T13710P	TS EXTRACTION STEAM TEMP (TRAIN 1)	0.00	-	800.00	DEGE	.....				

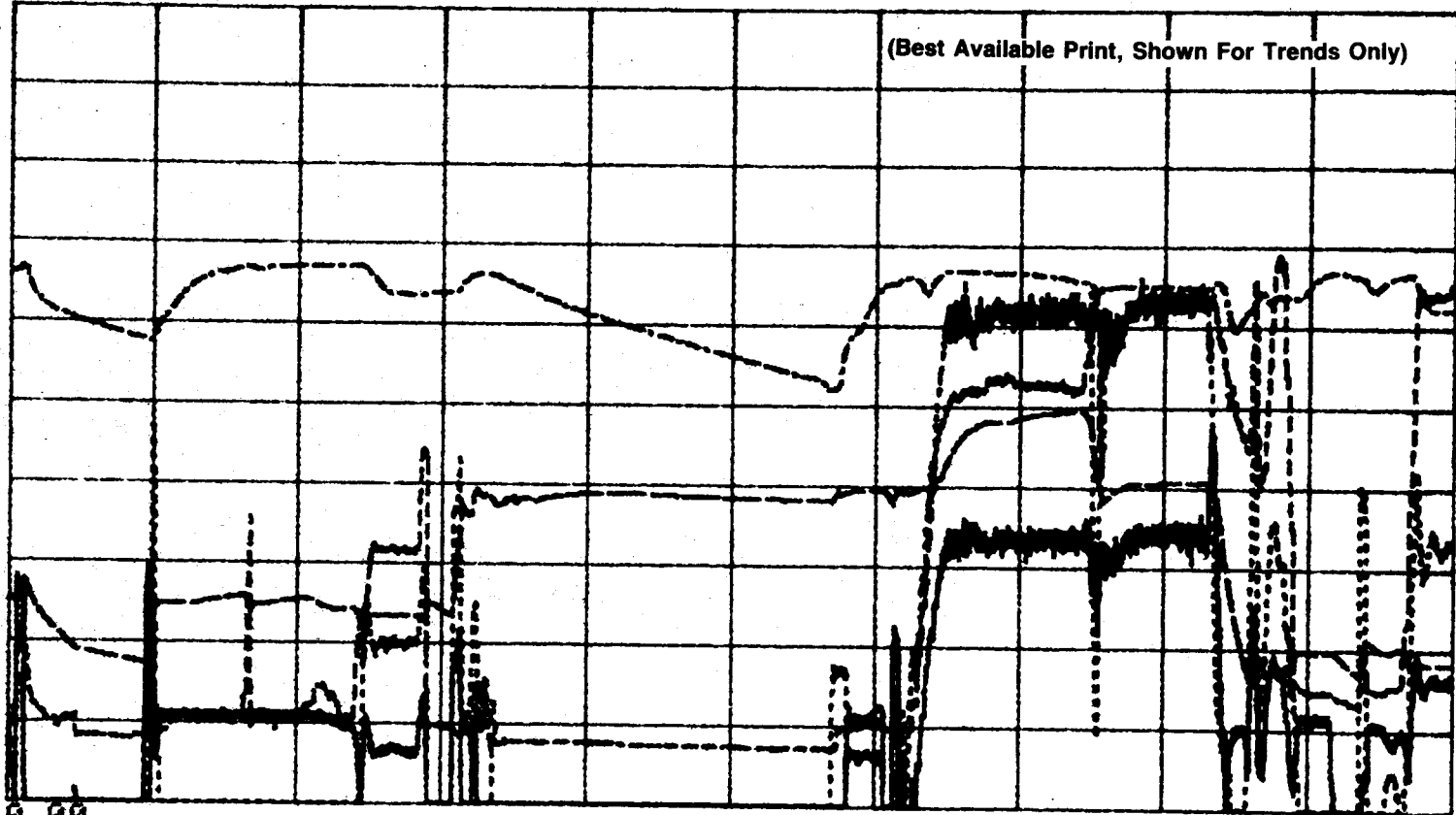
Figure 3.22(c). Maximum Dual Train Mode 6 Operation – Train 1 Oil Parameters

1

SOLAR DATA PLOT PLOT # BLANK  
REFERENCE TIME: 056 10 00 00.000

FOR NTH SAMPLE AVERAGE =  
300.0000 MINUTE(S)

(Best Available Print, Shown For Trends Only)



0.00  
FI3812P  
FI3806P  
FI3815P  
PI3814P  
TI3810P  
\*

TS EXTRACT SUPHTR OIL FLOW (TRAIN 2)  
TS EXTRACT BOILER OIL FLOW (TRAIN 2)  
TS EXTRACTION STEAM FLOW (TRAIN 2)  
TS EXTRACTION STEAM PRESS (TRAIN 2)  
TS EXTRACTION STEAM TEMP (TRAIN 2)

0.00 - 400.00 KLBH  
0.00 - 500.00 KLBH  
0.00 - 80.00 KLBH  
0.00 - 800.00 PSIG  
0.00 - 800.00 DEGE

201

Figure 3.22(d). Maximum Dual Train Mode 6 Operation – Train 2 Oil Parameters

SOLAR DATA PLOT PLOT # BLANK  
REFERENCE TIME: 138 14 00 00.000

FOR NTH SAMPLE AVERAGE = 1  
300.0000 MINUTE(S)

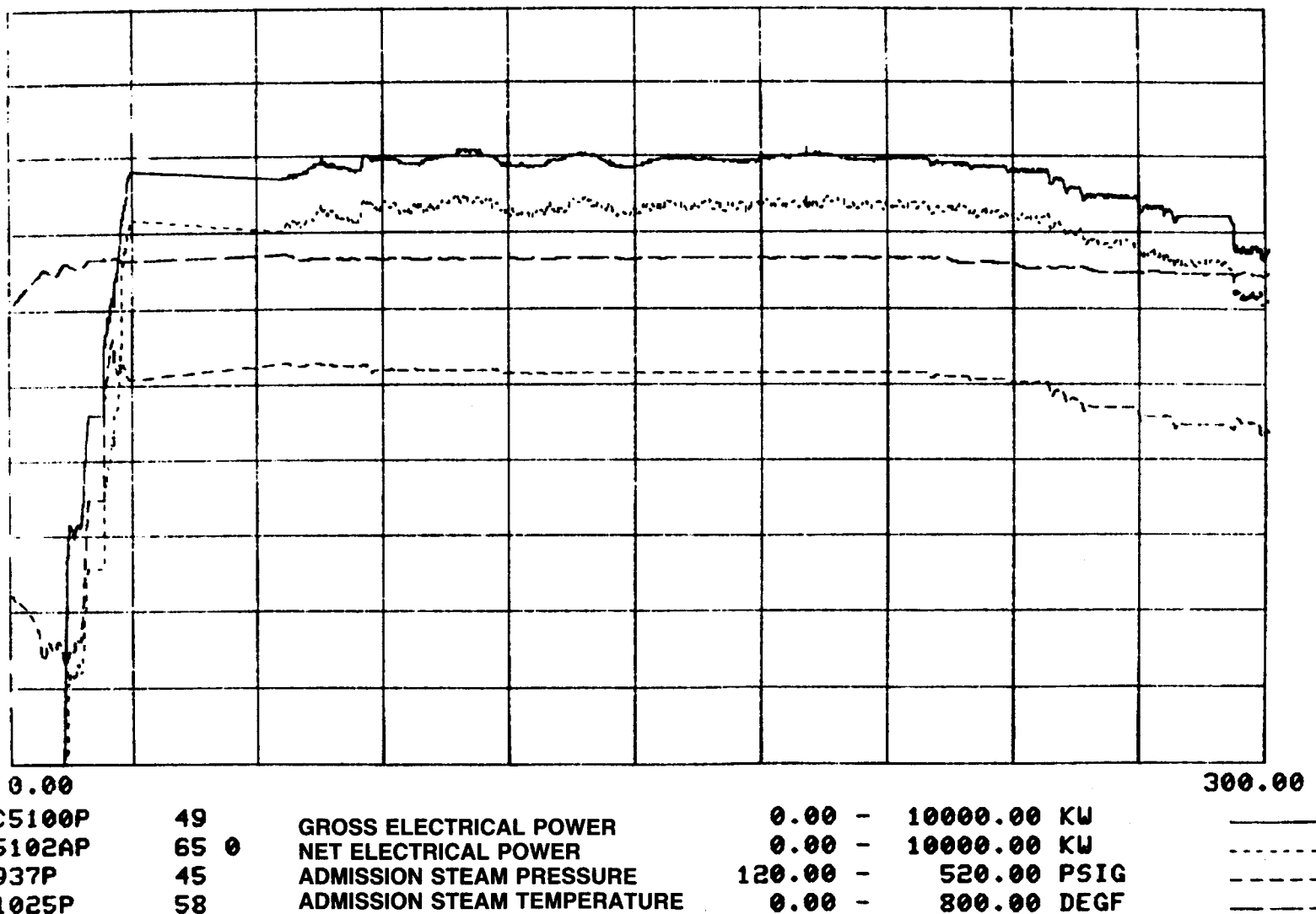
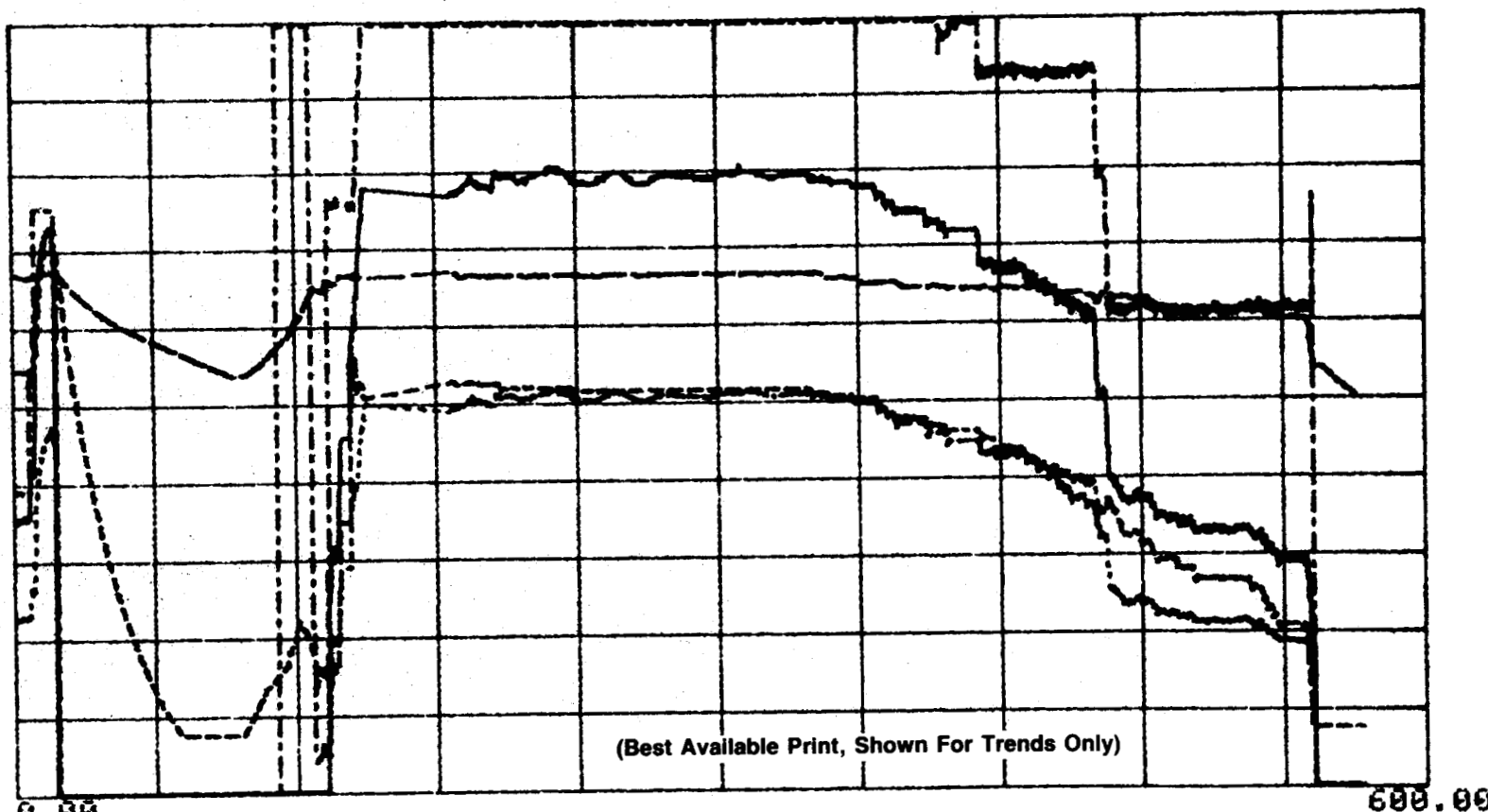


Figure 3-23(a). Mode 6 Design Point Verification Run – Turbine Parameters

1 SOLAR DATA PLOT PLOT # BLANK NTH SAMPLE AVERAGE =  
 REFERENCE TIME: 138 12 00 00.000 FOR 600.0000 MINUTE(S)



GE5100P  
 NE5102AP  
 PI937P  
 TI1025P  
 ZI943P

GROSS ELECTRICAL POWER  
 NET ELECTRICAL POWER  
 ADMISSION STEAM PRESSURE  
 ADMISSION STEAM TEMPERATURE  
 TURBINE ADMISSION CONTROL VALVE POSITION

0.00 - 10000.00 KW \_\_\_\_\_  
 0.00 - 10000.00 KW - - - - -  
 120.00 - 520.00 PSIG - - - - -  
 0.00 - 800.00 DEGE - - - - -  
 0.00 - 100.00 PCT - - - - -

Figure 3-23(b). Mode 6 Design Point Verification Run – Turbine Parameters

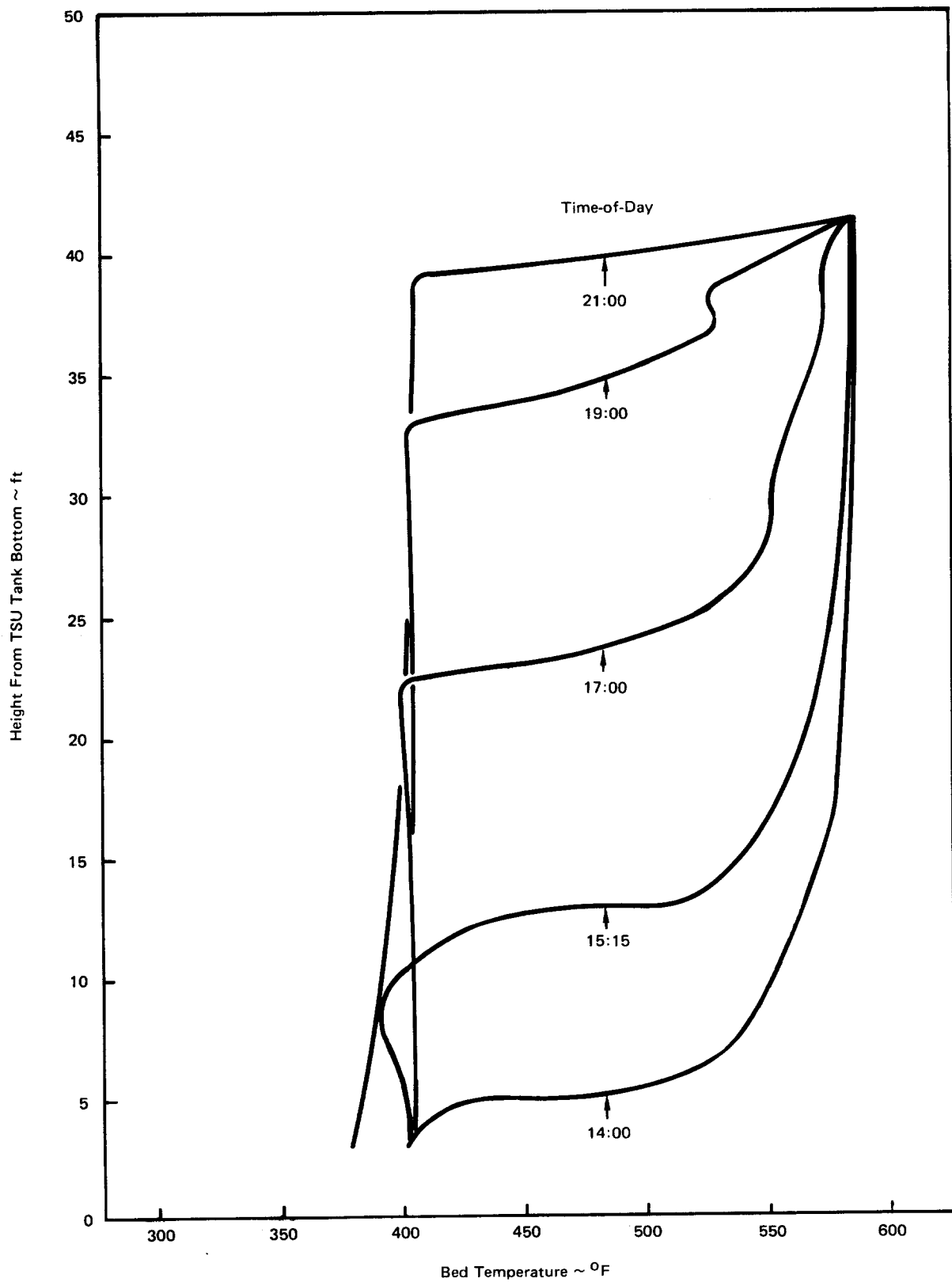


Figure 3.24. Mode 6 Design Point Verification Run – TSU Thermoclines



are shown at 2:00, 3:15, 5:00, 7:00 and 9:00 PM. Heating of the extraction steam generators by oil flow from the TSU was initiated at 1:27 PM and the turbine was rolled on extraction steam at 1:55 PM. Mode 6 operation continued until 9:14 PM. The total amount of thermal energy removed from the TSU during this test was evaluated by integration of the tank enthalpies based on bed temperature distributions at 1:00 PM and 9:00 PM. The thermal energy removed from the tank was 221 MWh<sub>t</sub>, including energy for extraction train warm-up and turbine roll, which resulted in the generation of 43.4 MWh<sub>e</sub> (net). As can be seen from Figure 3.24, the TSU was fully depleted at the termination of Mode 6 operation, and that complete energy utilization was accomplished by reduction in admission steam pressure and temperature during the latter period of operation (see Figure 3.14c).

The motion of the thermocline through the TSU during the all-night extraction Mode 6 test (day 179) is shown in Figure 3.25. As previously mentioned, continuous low-load power generation is not practical due to the high cycle heat rate associated with off-nominal operation.

### 3.5.3 Mode 6 Trips

The plant trip system is designed to protect plant equipment by sensing key parameters and automatically shutting down plant equipment when the key parameters are significantly out of limits. The parameters which monitor the TSS and which would "trip" the TSS extraction system are:

1. High boiler water level.
2. High extraction oil pressure.
3. High extraction steam pressure
4. High TSU oil level.
5. High flash tank condensate level.

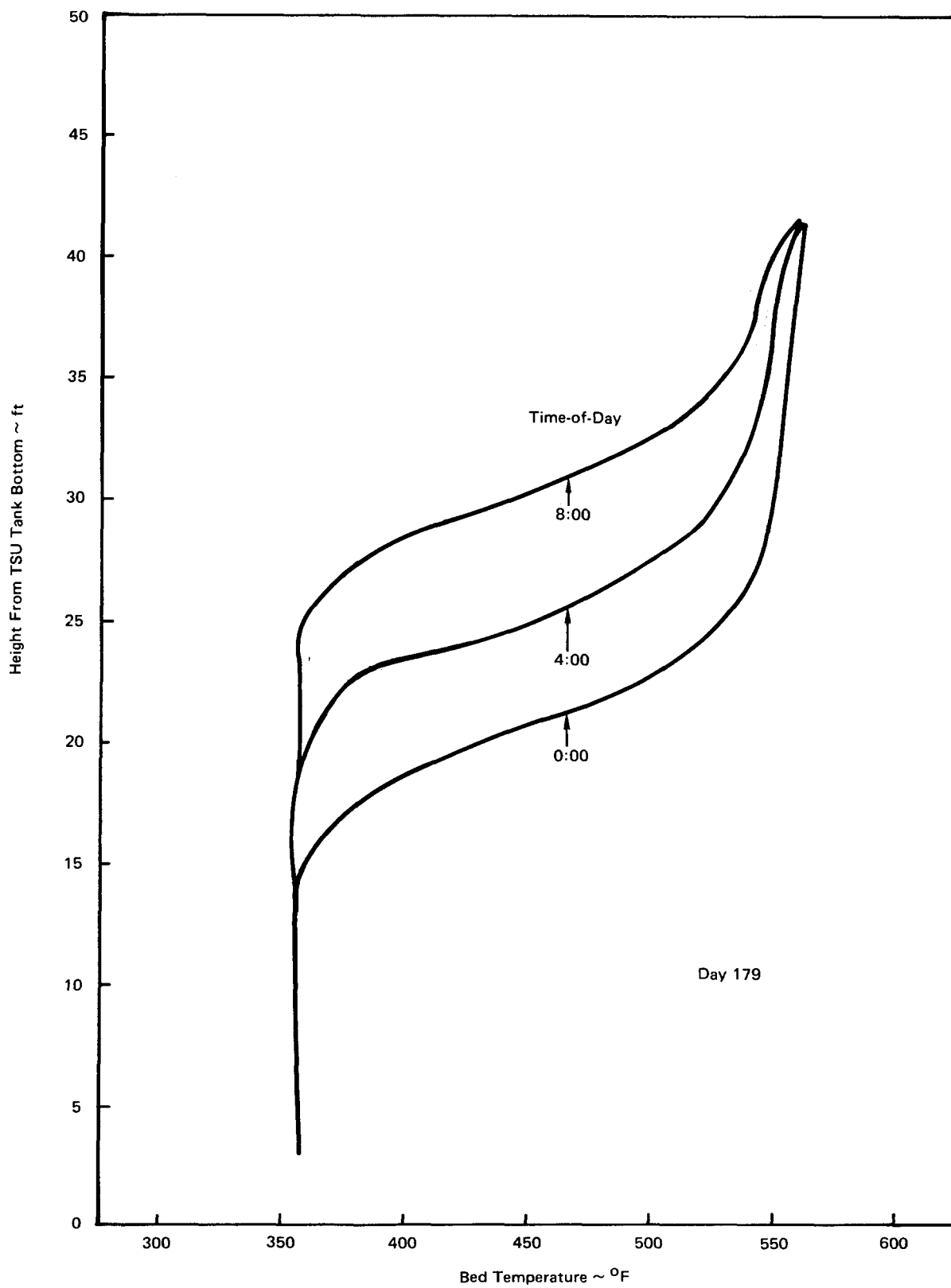


Figure 3.25. Low Load Mode 6 Operation -- TSU Thermoclines

6. High flash tank pressure.

7. High or low TSU ullage pressure.

Also, the plant operator can initiate an extraction system trip (pushbutton). A trip of the extraction system will close the turbine steam valves, shutoff the extraction oil pumps and open the steam generator bleed valves to the TSS flash tank (AOV3117/3118).

During normal plant operation, extraction system trips occurred which demonstrated each of the above conditions and the plant was automatically transitioned from Mode 6 to a lower level of plant operation (Mode 8). One specific trip test was planned as a part of Mode 6 testing; a trip of the turbine-generator while under relatively high load. The following examples of trips occurred during Mode 6 demonstrate satisfactory transition from Mode 6 to Mode 8 (inactive).

A trip of the plant during Mode 6 operation due to high TSU pressure occurred on day 138 prior to the maximum extraction run. Data for this event are shown in Figure 3.14 (a-e). Both extraction trains were in service and the turbine load was being increased to initiate the extraction (Mode 6) run. Oil system data are shown in Figures 3.14a and 3.14b, and steam system data are shown in Figures 3.14c and 3.14d. The trip, which occurred at approximately 12:15 PM, resulted in a shutdown of the extraction oil pumps and the turbine automatically tripped due to low load (Figure 3.14e). After the TSU pressure was reduced, the steam generators were restarted and the turbine was brought back on line at 2:10 PM.

On 9/7/83 (day 250), a trip of the thermal storage extraction system was initiated by depressing the extraction trip pushbutton during Mode 6. The purpose of the test was to verify TSS/turbine response to an extraction trip occurring at relatively high load during Mode 6. The trip was initiated at

approximately 5:20 PM at a generator output of 3.33 MWe (gross). Conditions prior to the trip are shown on Figure 3.12 (a-c) and subsequent to the trip on Figure 3.26 (a-b). Figure 3.26a shows the turbine response as the admission control valve (ZI943P) and admission stop valve (ZI901P) both closed (subsequent movement of the admission control valve was the result of an attempt by the pressure control system to control admission pressure with the steam supply shutoff - stop valve closed). The initial increase in admission steam pressure (PI937P) was the result of sudden closure of the admission stop valve (with continued steam generation due to steam generator thermal transients) and subsequent decay as the steam was rerouted to the TSS flash tank. Flash tank pressure (PI3114P) is shown on Figure 3.26b with increasing pressure due to the admission of steam when the bleed valve (AOV3117) was opened (ZI3117P). The flash tank pressure increased to 124 psig (maximum) as steam was continued to be generated due to residual heat from the boiler. Satisfactory transition from Mode 6 to Mode 8 as a result of the trip was demonstrated. The main concern was the transition of steam flow from the turbine to the flash tank without significant pressure upsets. The gradual flash tank pressure increase exhibited a controlled transition, with the peak pressure well below the 165 psig relief level.

### 3.6 Conclusions

As with Mode 5, the conclusions with regard to Mode 6 operations are both qualitative and quantitative in nature; qualitative with regard to overall plant operation, equipment characteristics and operating philosophy and quantitative with regard to performance evaluation and equipment limitations.

Plant operation with electric power generation by TSU extraction only, and pressure control provided by the turbine steam system, was demonstrated over a wide range of operating conditions during the Mode 6 test program. Plant

SOLAR DATA PLOT PLOT # BLANK  
 REFERENCE TIME: 250 17 15 00.000

NTH SAMPLE AVERAGE = 1  
 FOR 30.0000 MINUTE(S)

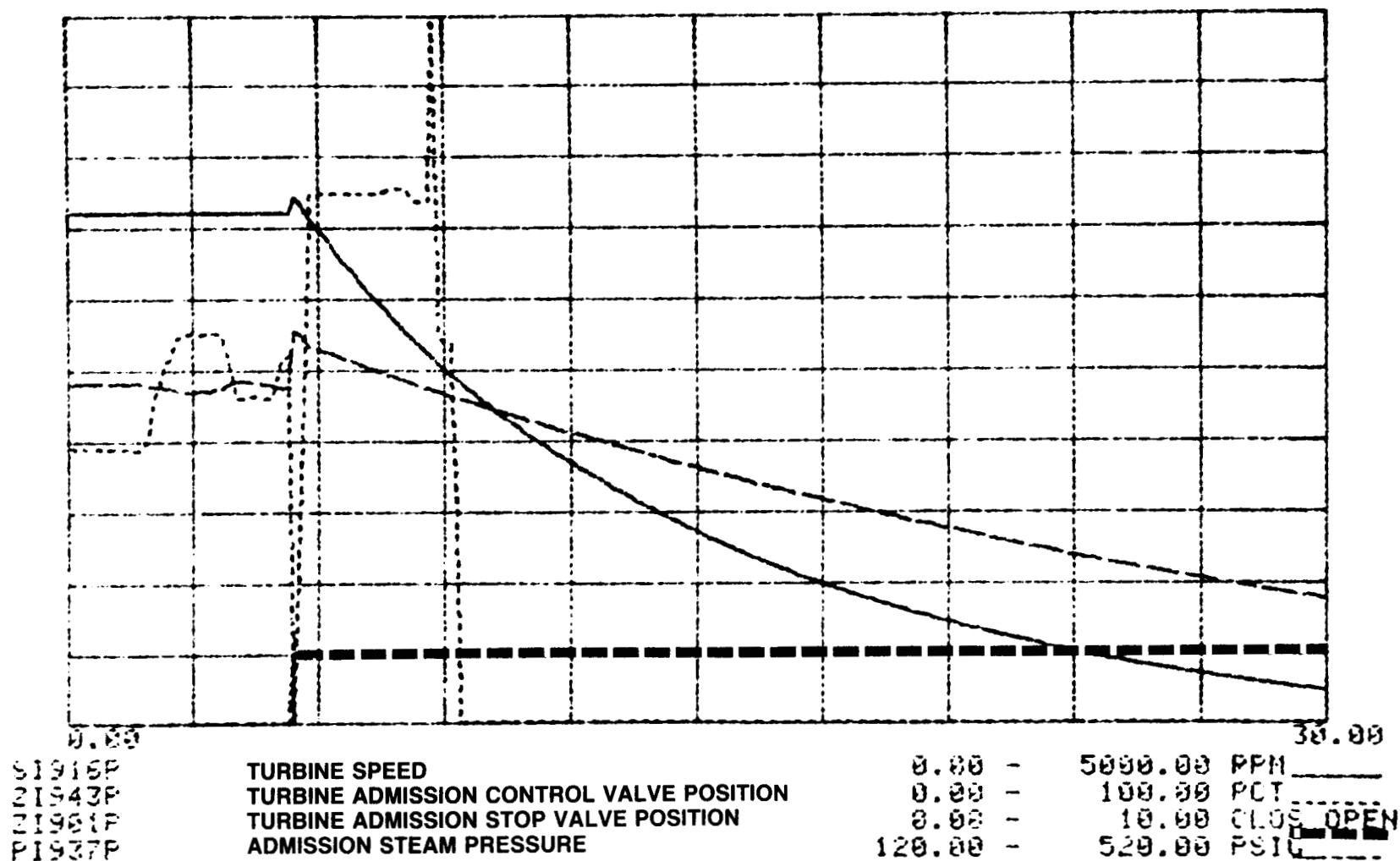


Figure 3-26(a). Mode 6 Extraction Trip – Turbine Parameters

SOLAR DATA PLOT

PLOT # BLANK

NTH SAMPLE AVERAGE = 1  
FOR 60.0000 MINUTE(S)

REFERENCE TIME: 250 17 15 00.000

FOR

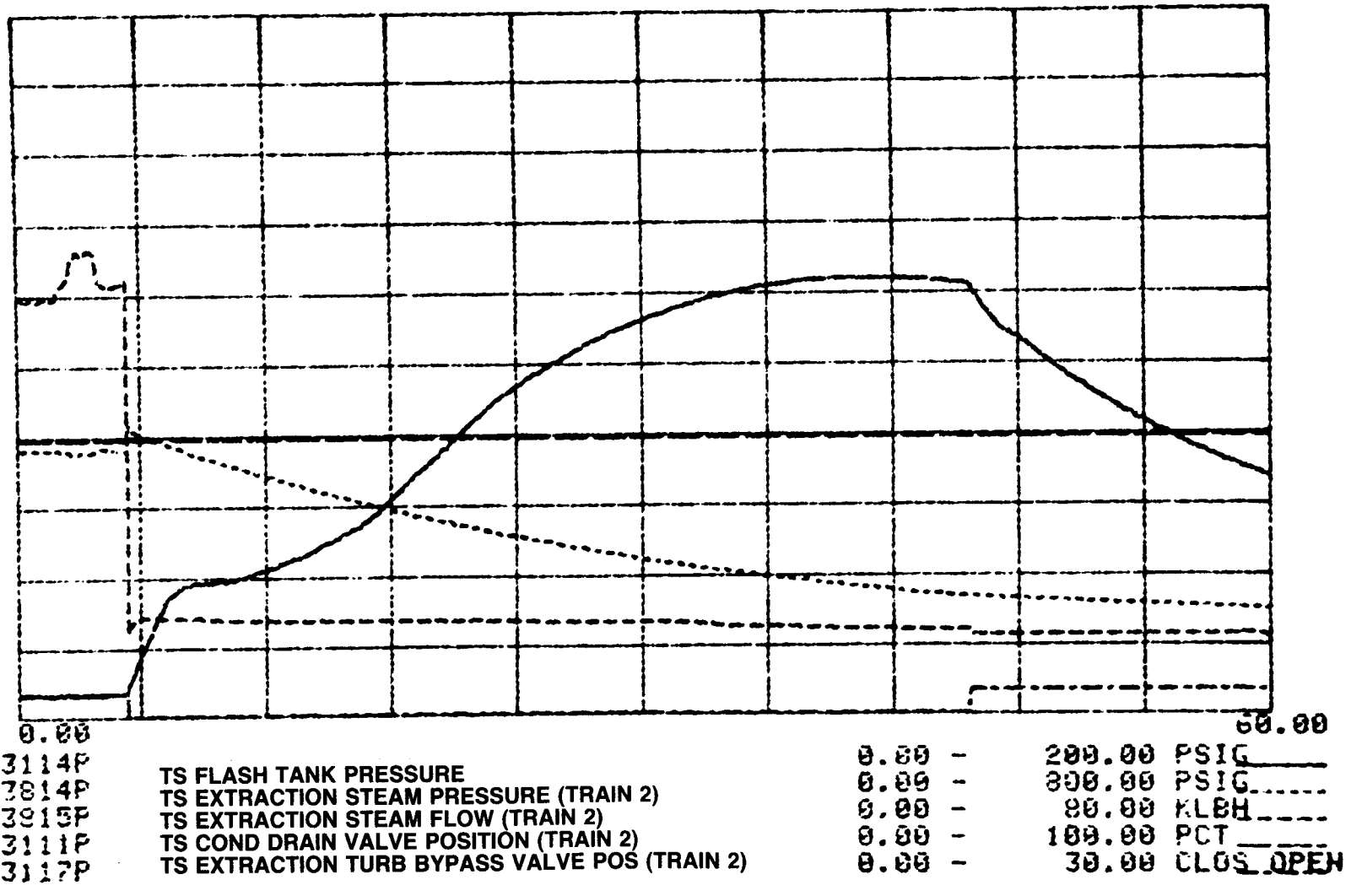


Figure 3.26(b). Mode 6 Extration Trip - TSS Parameters

operation during cloudy periods demonstrated the effectiveness of using Mode 6 when receiver operation for turbine-direct steam would not be practical. The sequence for start-up and transition of the plant to Mode 6 was developed during the test program (See Section 3.5.1). Turbine roll by manually controlling the admission steam stop valve was implemented and the startup sequence was automated as much as possible to minimize required operator actions.

Based on the results of Mode 1 (turbine-direct Ref. 4), Mode 2 (turbine-direct and charging, Ref. 3) and Mode 5/6 test programs, it was determined that Mode 1 was best for electrical power generation and Mode 5 was best for TSU charging. Since Mode 1 was determined to be the best mode for power generation, it is better to accomplish TSU charging as fast as possible in order to be able to return to Mode 1 for power production at or near the design point. Frequent and extended periods of Mode 6 thermal storage extraction operation were determined to be impractical. This was due to the continual need for the limited quantity of stored thermal energy for seal steam generation and the need to devote extended periods of receiver operating time to recharge the TSU once it was depleted. Low load plant operation in Mode 6 was determined to be the least desirable from a plant performance standpoint. This operating approach suffers the double penalty of poor performance attributable to turbine operation on admission steam and that associated with off design turbine steam flows. Prolonged operation in this manner could deplete the entire charge from the Thermal Storage Unit while contributing no net electrical energy to the grid.

Dual extraction train operation was demonstrated during Mode 6 testing. The advantage of this equipment configuration was that the turbine could be

operated at the minimum Mode 6 cycle heat rate. Due to equipment problems, only limited operating time was logged with both extraction trains operating. It was determined that turbine operation in Mode 6 could be extended, as the TSU became depleted of charge, by reducing the admission steam temperature and pressure and/or switching from dual-train to single-train operation. The disadvantage of this operating procedure was that only limited net power could be produced at the expense of TSU depletion (due to high off-design cycle heat rate). No control problems existed with dual-train operation; one train was operated in FLOW while the other train was operated in LOAD control. Stable single train operation at 0.7 to 1.0 MWe (gross) was demonstrated but, at this generator output, the net power was near zero.

Due to the lack of reliable extraction steam flow instrumentation, steam flow to the admission port of the turbine was based on corrected boiler make-up water flowmeter data. Under steady-state conditions, the boiler water levels were constant and make-up water flow was equal to steam generation. Using these steam flows, Mode 6 gross cycle heat rate was determined at various turbine loads. The calculated values were slightly lower (better) than predicted and also, as expected, were higher (for a given load) than those for Mode 1. The scatter of data was such that no clear advantage could be ascertained for the use of heat recovery paths (in reducing cycle heat rate). Also, data scatter (and insufficient data) prevented the determination of an optimum admission pressure level different from design.

Utilization of dual media energy storage on a large scale was verified during the Mode 6 test program and deliverable total energy (thermal and electrical) in excess of design was verified. The shape and motion of the TSU thermocline were as predicted from analytical studies and scale test data.



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2. 10 MWe Solar Thermal Central Receiver Pilot Plant Mode 1 (Test 1110) Test Report. Contractor Report SAND 84-8181, October 1984.
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