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# EXPERIMENTAL INVESTIGATION OF THE SNAP-8 MERCURY RANKINE-CYCLE POWER CONVERSION SYSTEM

By

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AEROJET-GENERAL CORPORATION
Azusa, California

CASE FILE
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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center

Contract NAS-5-417

Martin J. Saari, Program Manager

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TOPICAL REPORT

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December 1969

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NASA Lewis Research Center
Cleveland, Ohio
Martin J. Saari, Program Manager
SNAP-8 Program Office

# FOREWORD

The work described in this report was performed by Aerojet-General Corporation, Azusa, California, as part of the SNAP-8 electrical generating system contract being conducted within the Power Systems Department. The work was directed under NASA Contract NAS 5-417, with Mr. Martin J. Saari as NASA Program Manager, and Dr. W. F. Banks as Aerojet-General Corporation Program Manager.

# ABSTRACT

A breadboard of the SNAP-8 nuclear-electric space power system was tested to determine the operating characteristics of the SNAP-8 power conversion system. Component-system interactions, component performance, transient behavior, and system problem areas have been identified and evaluated. The feasibility of SNAP-8 as a Rankine cycle, space power system has been demonstrated.

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## SUMMARY

SNAP-8 is a nuclear space power system currently being developed to produce more than 35 kw of useful electrical power. The system operates on a mercury Rankine cycle using NaK (sodium-potassium mixture) as the heat-input and heat-rejection fluid. This report covers the system testing of Power Conversion System-1 (PCS-1) from November 1965 to January 1968. A transition was made in January 1968 from 9M steel to a refractory metal (tantalum) as the boiler mercury-containment material. All subsequent testing in PCS-1 has made use of the refractory metal boiler. It is planned to report this subsequent testing at a later date.

The primary objective of PCS-1 has been to evaluate the performance and endurance potential of the SNAP-8 components and system. Components have been previously operated in an individual test facility simulating system conditions, but not until PCS-1 has it been possible to investigate the systems-aspects of SNAP-8. Specific objectives have been to observe interactions between the components and within the system, to detect any life-related degradation or other reliability phenomena. Another objective was to obtain basic off-design system performance data, and investigate transients, including the demonstration of start and stop modes. These objectives have been successfully met. The testing identified numerous areas of significant component and system interactions such as cause and effect relative to boiling instability, system contamination, mercury inventory control, and transient operation. Endurance testing has provided a measure of system reliability and has strengthened confidence in the integrity of the SNAP-8 power conversion system to operate continuously for at least 10,000 hours. Performance mapping of the system has been accomplished to identify basic off-design performance of the components and system. The mapping has defined the reactions of the system to disturbances that would be imposed by the reactor control system, sun-to-shade operation, radiator temperature variations, and inventory variations.

The testing in PCS-1 has provided a physical demonstration of the feasibility of large liquid metal power conversion systems for space use. PCS-1 has also contributed to the knowledge of material properties, large liquid metal loop cleaning techniques, and liquid metal test facility design.

In addition to establishing a basis for SNAP-8 evaluation, PCS-1 testing has directed attention toward areas requiring further research and testing. These areas include improving low gravity simulation, additional evaluation of transient response, extended endurance testing, mission adaptation tests, mass transfer evaluation and noncondensable gas control.

## I. INTRODUCTION

SNAP-8 is a nuclear space power system utilizing a mercury Rankine cycle to produce 35 killowatts of useful electrical power. The system consists of three major subsystems: a nuclear system consisting of a reactor, reactor controls and shielding; a flight radiator assembly consisting of radiators for rejecting heat into space; and the power conversion system consisting of a turbine-alternator assembly, a boiler, condenser, mercury and NaK pump-motor assemblies and necessary controls.

The power conversion system is a four-loop system consisting of three liquid-metal loops and an organic fluid lubricant-coolant loop (see Figure 1). The primary loop uses liquid sodium-potassium eutectic (NaK) to transport heat from the reactor to the boiler. The Rankine-cycle secondary loop, using mercury as the working fluid, converts thermal energy into mechanical and electrical energy as the mercury expands through a turbine-alternator assembly. The mercury is then condensed and returned to the boiler. The third loop (the heat rejection loop), containing NaK, transports the heat from the mercury condenser to the radiator where it is radiated to space. The fourth loop contains an organic fluid (polyphenyl ether) which lubricates the bearings of the mercury loop rotating components and provides necessary cooling for the electronics, alternator and electric motors. There is an auxiliary loop which functions during the startup sequence, and provides heat transfer directly from the primary loop to the heat rejection loop to minimize reactor transients and to warm the radiator.

SNAP-8, in its present configuration (see Figure 1), has been under development since 1963. During this period, emphasis was placed upon effective test programs to obtain data for design improvement and to demonstrate reliability of the components and system to continuously operate for a minimum of 10,000 hours.

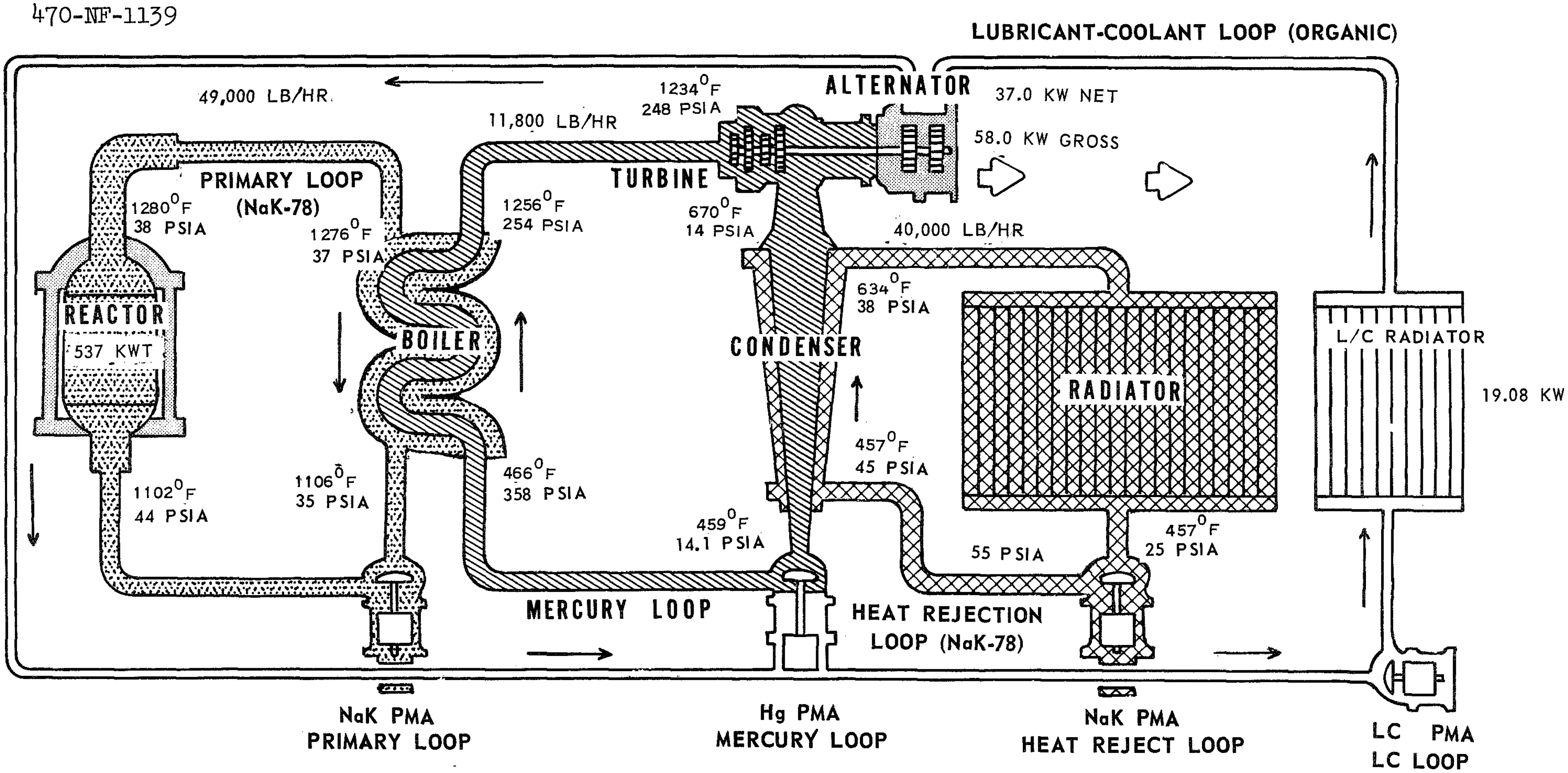

Figure 1. SNAP-8 System Schematic

Test programs have been conducted at both NASA (Lewis Research Center) and Aerojet-General Corporation (Azusa Facility). The NASA testing was performed during the period 1965 through 1969 using a test facility known as W-1. The program comprised three phases. The first phase (Reference 1) was a study of reactor transients. The facility contained a boiler and condenser; other components were simulated with test support equipment. The second phase (References 2 and 3) was a period of testing using a complete power conversion system. The principal objective was endurance testing using a double containment, tantalum and stainless steel boiler. The third phase (References 4 and 5) studied startup and shutdown characteristics of the system.

At Aerojet, testing began in 1964 with a facility known as Rated Power Loop No. 2 (RPL-2) (Reference 6). The facility had a complete mercury loop with test support equipment used in the NaK loops. The testing primarily studied boiler, turbine, and condenser performance.

During 1965, testing began on a complete breadboard system known as Power Conversion System 1 (PCS-1) (Reference 7). This system incorporated all of the SNAP-8 components with the exception of the reactor, radiator, and fluid reservoirs. System testing was conducted with gas heaters replacing the reactor, an air-cooled heat exchanger replacing the radiator and gas-covered reservoirs replacing flight-type bellows reservoirs.

The primary objective of the test program was to evaluate the performance and endurance potential of the SNAP-8 components and system. The interactions between components and the system were studied. Endurance testing was conducted to identify long-term system failure modes, and system performance mapping tests were made to determine off-design system performance as it related to conditions imposed by possible SNAP-8 missions. In addition, information was obtained on several system problem areas. These areas included boiler conditioning, system transients, materials selection and mass transfer. This report covers the results of the testing up to January 1968.

During the PCS-1 testing, improvements in components and test support equipment have resulted in increased testing efficiency and a significant increase in total hours of system testing. The accumulated operating times for the various loops of the SNAP-8 system are presented in Table I.

TABLE I - SYSTEM OPERATING TIMES

| Year | Primary Loop (Hrs) | Mercury Loop (Hrs) | Heat Rejection Loop (Hrs) | Lubricant/Coolant Loop (Hrs) |
|---|---|---|---|---|
| 1965 | 233.5 | 120.0 | 139.5 | 164.0 |
| 1966 | 1053.7 | 468.6 | 648.4 | 1030.8 |
| 1967 | 2799.2 | 2508.6 | 2692.6 | 2866.4 |

## II. DESCRIPTION OF POWER CONVERSION SYSTEM-1 (PCS-1)

### A. GENERAL

Power Conversion System-1 evolved from the earlier RPL-2 test facility. Other components were added until RPL-2 was defined as a breadboard SNAP-8 power conversion system which resulted in renaming the test facility to Power Conversion System-1 (PCS-1).

An overall view of PCS-1 is not possible in one illustration due to the interference of test-cell walls and structure. Photographs of a scale model are used to give the best perspective of the test facility and system size and geometry. Figures 2a and 2b show front and rear views, respectively, of a 1/4-scale model of the facility and system. The overall floor area occupied by the facility, exclusive of the gas heaters, heat-rejection air cooler, and cell venting system, is approximately 650 square feet. By contrast, the equivalent SNAP-8 flight system could be packaged in a conical shape approximately 12 feet in diameter and 27 feet high (or smaller) as shown by the model in Figure 3.

PCS-1 testing was divided into three distinct phases identified as Steps 1, 2, and 3. Each succeeding phase of operation involved more system components and testing which became more system-oriented. Schematics of the system existing in each of Steps 1, 2, and 3 are presented in Figures 4, 5, and 6, respectively. The components used for each operating phase are listed in Table II. Currently, PCS-1 contains all the SNAP-8 power conversion system components with the exception of the working fluid inventory expansion tanks, which have no bearing on system performance.

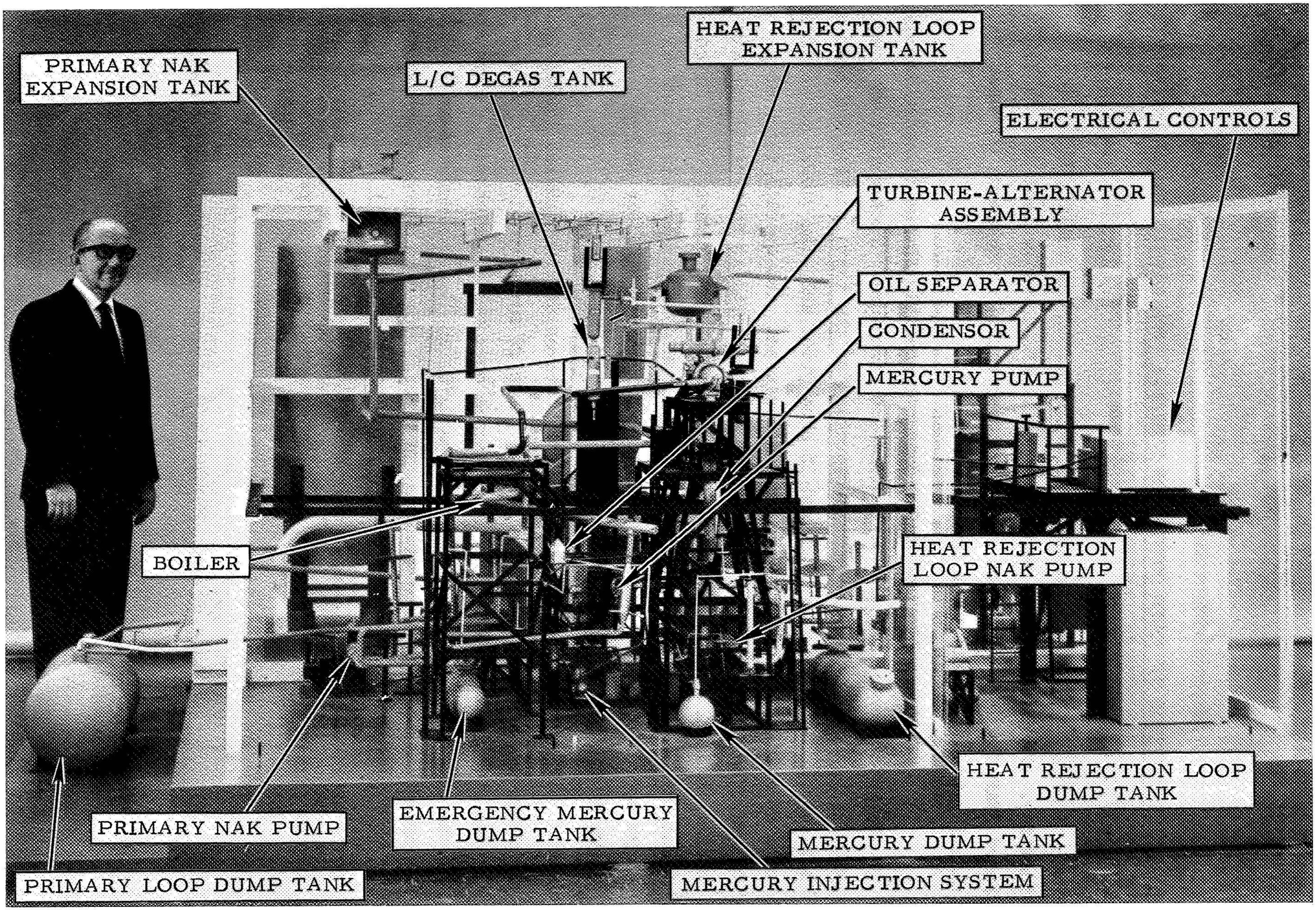

Figure 2a. Power Conversion System-1 Test Configuration 1/4 Scale Model (Front)

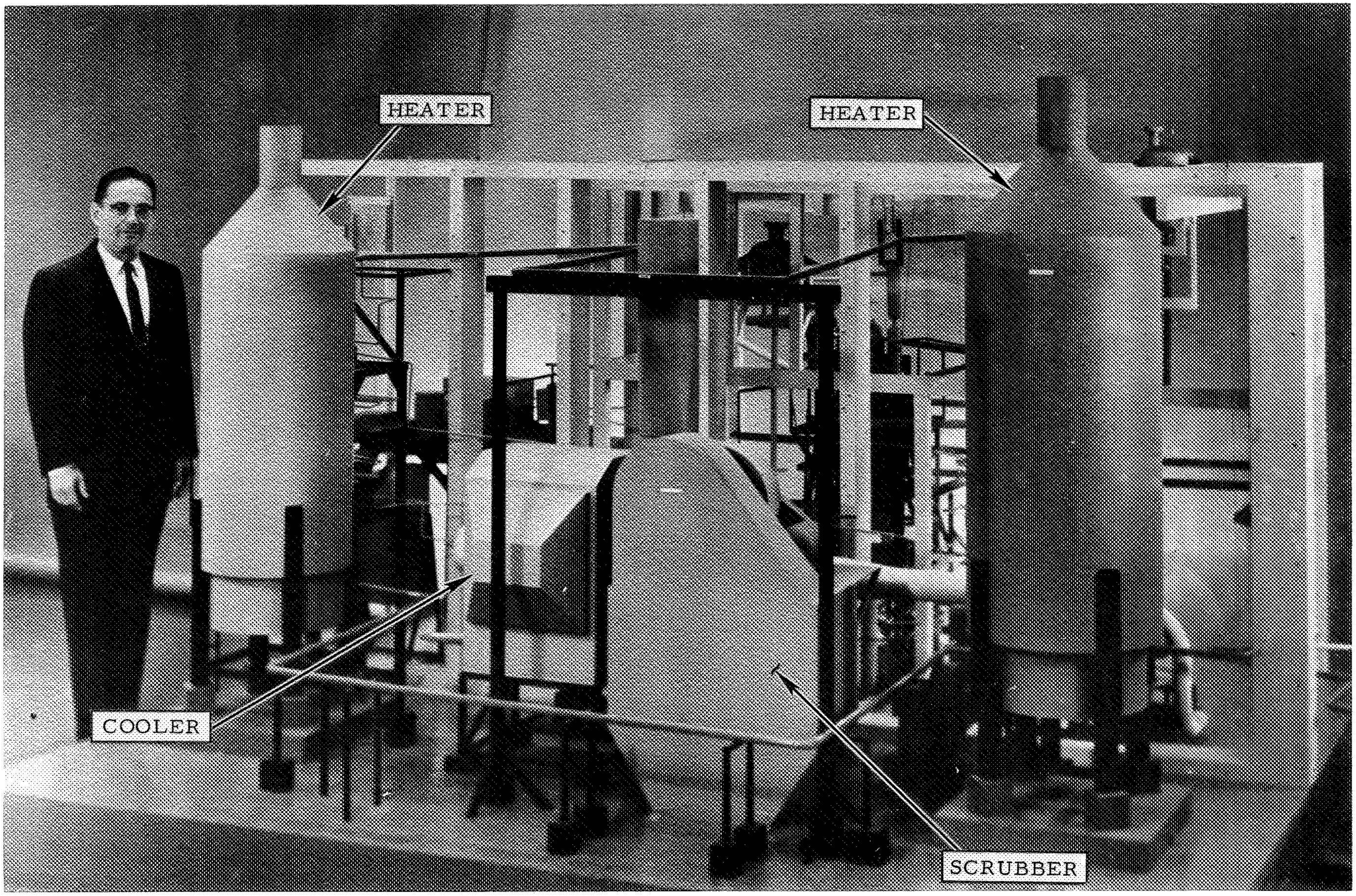

Figure 2b. Power Conversion System-1 Test Configuration 1/4 Scale Model (Rear)

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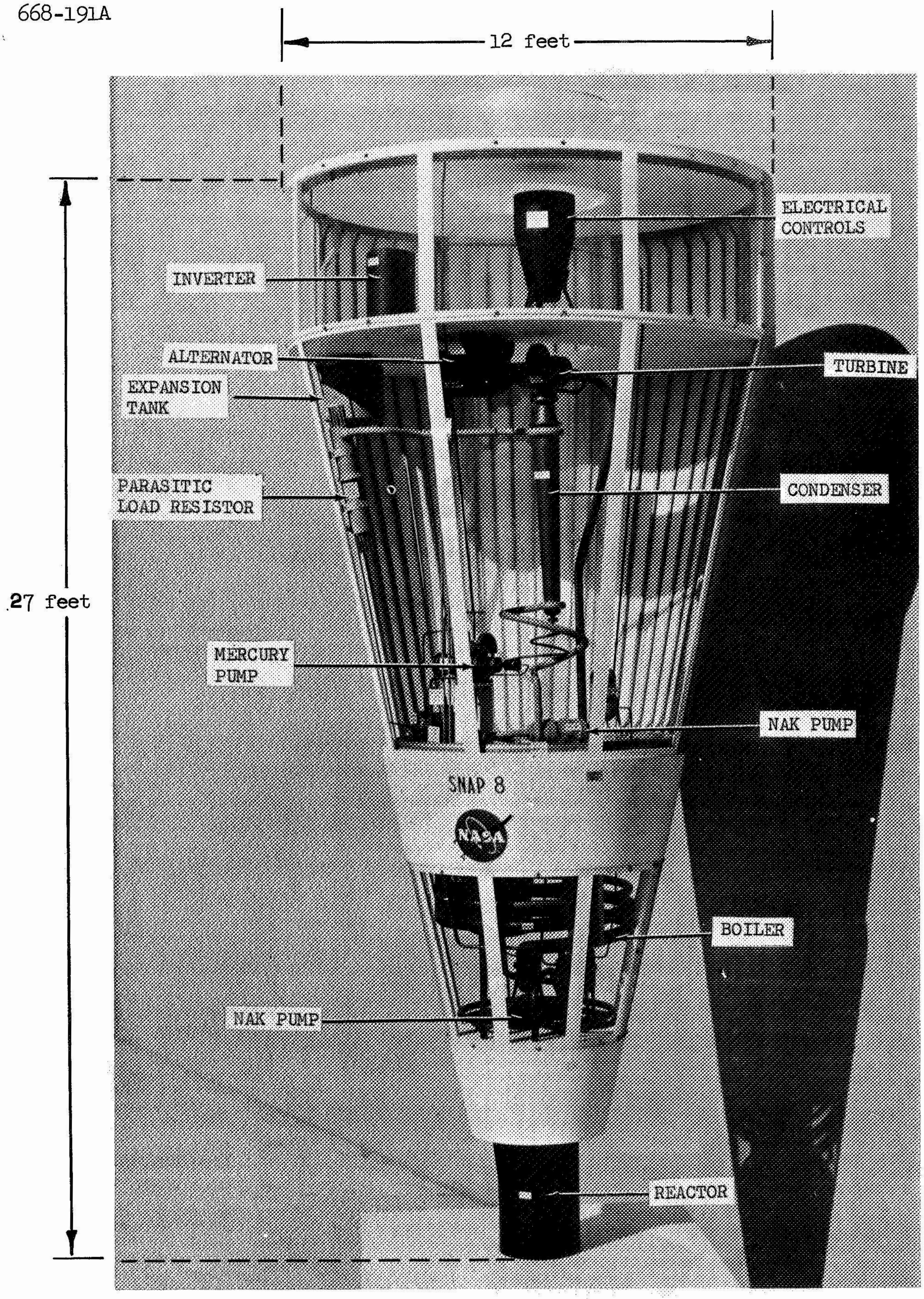

Figure 3. A Conceptual SNAP-8 Flight Configuration

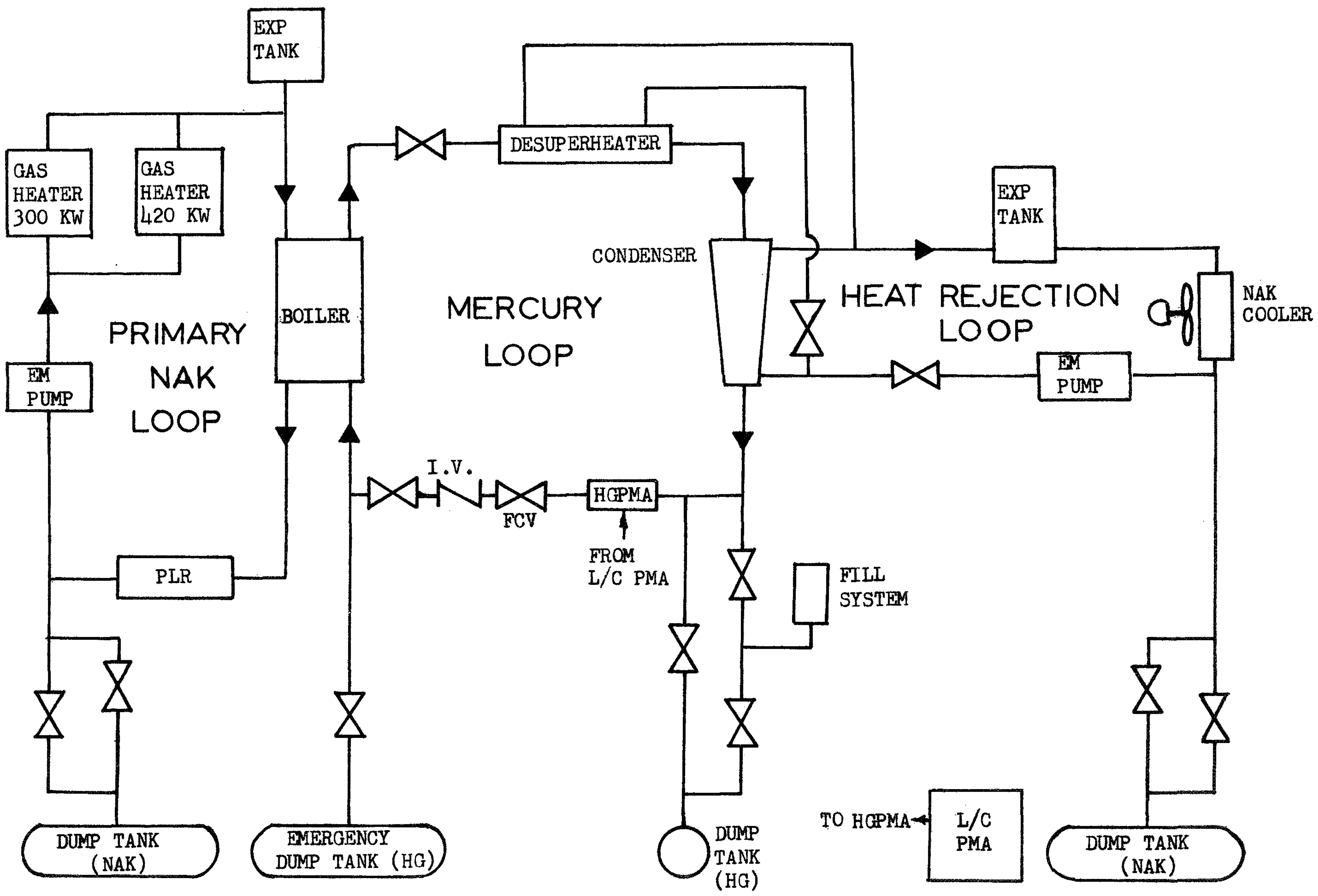

Figure 4. PCS-1 Step 1 Schematic Diagram

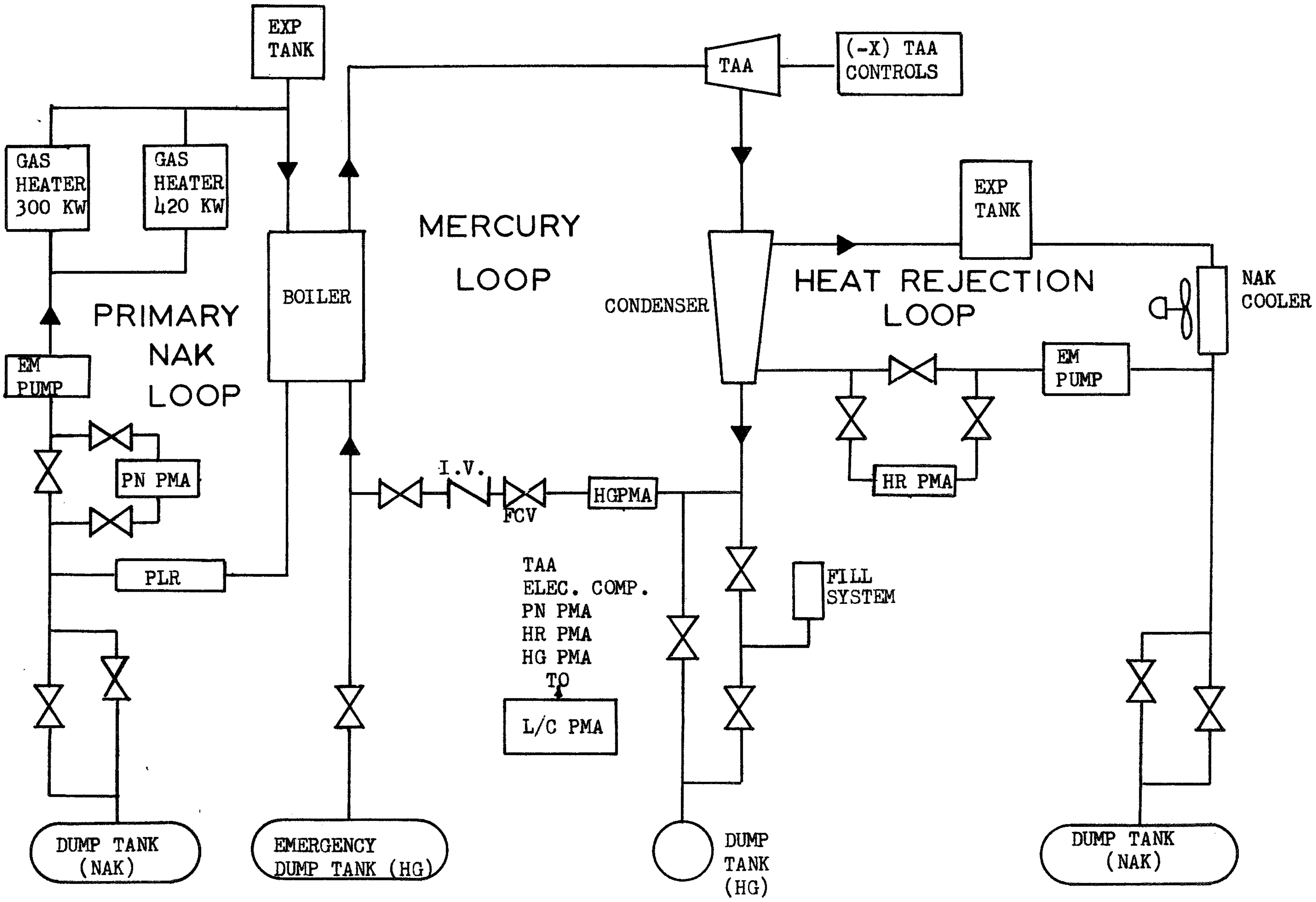

Figure 5. PCS-1 Step 2 Schematic Diagram

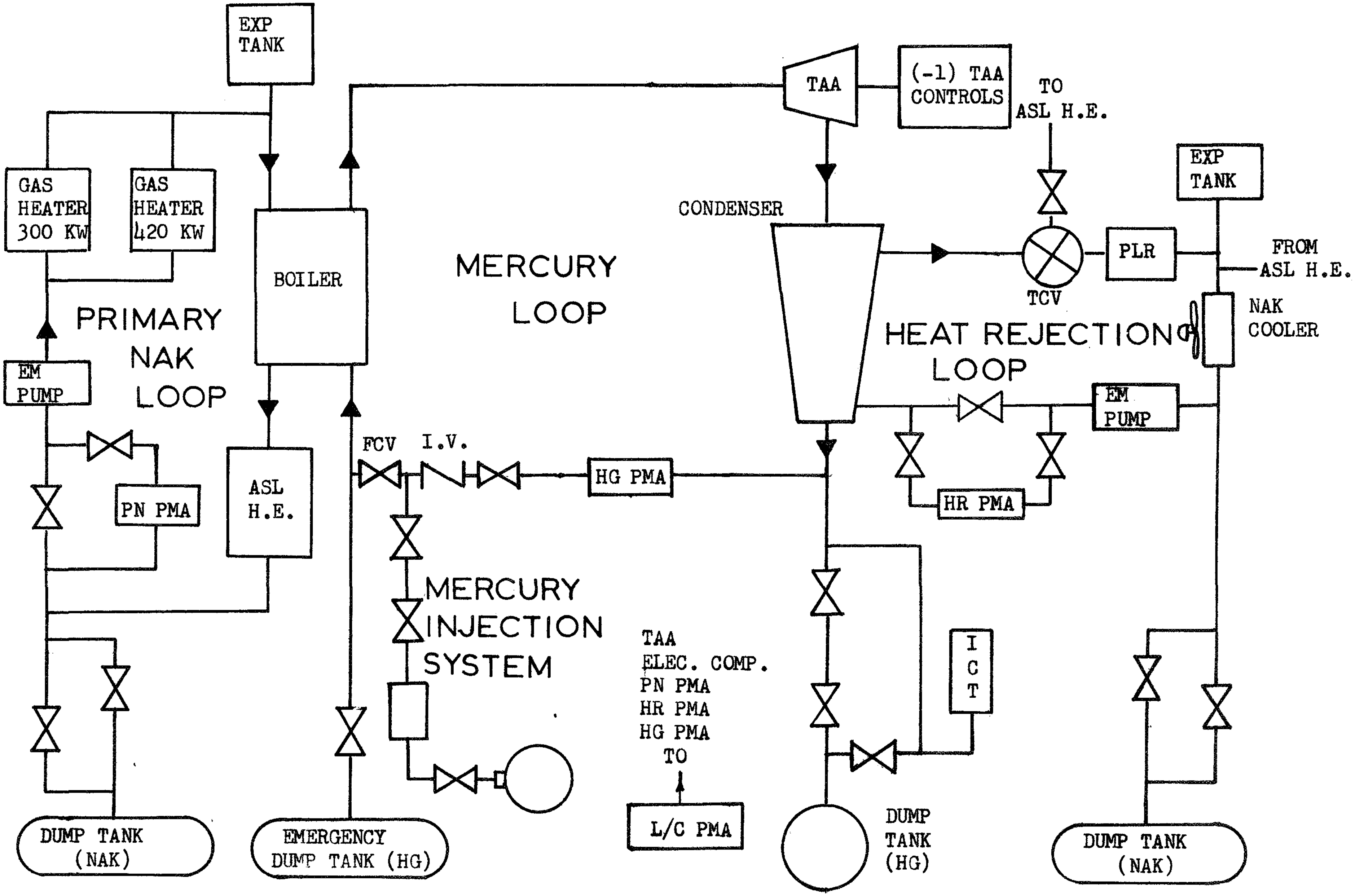

Figure 6. PCS-1 Step 3 Schematic Diagram

## TABLE II

## PCS-1 COMPONENT USAGE

| Step 1 | Step 2 | Step 3 |
|---|---|---|
| Mercury Pump | Mercury Pump | Mercury Pump |
| Lubricant-Coolant Pump | Lubricant-Coolant Pump | Lubricant-Coolant Pump |
| Boiler | Boiler | Boiler |
| Condenser | Condenser | Condenser |
| Parasitic Load Resistor | Parasitic Load Resistor | Parasitic Load Resistor |
| Hg Flow Control Valve | Hg Flow Control Valve | Hg Flow Control Valve |
| Lubricant-Coolant Valves | Lubricant-Coolant Valves | Lubricant-Coolant Valves |
| Mercury Isolation Valve | Mercury Isolation Valve | Mercury Isolation Valve |
| | Turbine Alternator | Turbine-Alternator |
| | Speed Control Amplifier | -Speed Control Module |
| | Saturable Reactor | -Saturable Reactor |
| | Voltage Regulator | -Voltage Regulator |
| | Static Exciter | -Static Exciter |
| | Primary NaK Pump | Primary NaK Pump |
| | Heat Rejection NaK Pump | Heat Rejection NaK Pump |
| | | Auxiliary Start Loop Heat Exchanger |
| | | Temperature Control Valve |
| | | Mercury Injection System |
| | | Start Programmer |
| | | Inverter |
| | | -Motor Transfer Contactor |
| | | -Speed Control Transformer |
| | | -Stabilization Assembly |
| | | -Protective System |

## B. COMPONENT DESCRIPTIONS

### 1. Turbine-Alternator Assembly

The turbine-alternator assembly consists of a turbine assembly and an alternator assembly. The unit is shown in Figure 7. The turbine is a four-stage, axial impulse machine. The first and second stages are partial admission, the third and fourth are full admission. The alternator is a hermetically sealed, radial-air-gap, homopolar inductor with a brushless, solid rotor with a 3-phase, 120/208 volt electrical output at 400 Hz (See Reference 8). The turbine is cantilever-mounted and the alternator is straddle-mounted with separate bearing assemblies. The turbine operates at 12,000 rpm with a mercury vapor flow of 11,800 pounds per hour (12,300 pounds per hour mercury liquid flow) at 1250°F and 250 psia with an exhaust pressure of 14.0 psia. At these conditions the gross electrical output is about 58 kw for a net useful system output of 35 kw.

### 2. Boiler

The SNAP-8 boiler is a counter-flow heat exchanger which couples the reactor-coolant NaK loop to the power conversion system mercury loop. The boiler shown in Figure 8 is representative of those tested during the period of this report. The heat input consists of 1300°F NaK from the reactor. On the mercury side of the boiler, the mercury makes a single pass through seven parallel tubes. The mercury enters at 450°F in a subcooled state and leaves the boiler at 1250°F (200°F superheat).

### 3. Condenser

The SNAP-8 condenser consists of 73 parallel tapered tubes enclosed in a shell. (Reference 9). The mercury condensation occurs in the tubes and the heat-rejection-loop NaK flows in the outer shell. The taper of the tubes provides a decreasing vapor-flow area so that vapor velocity is maintained even though the mass flow of vapor is decreasing. This feature provides a stable liquid-vapor-interface location under conditions of zero gravity operation. The condenser is shown in Figure 9.

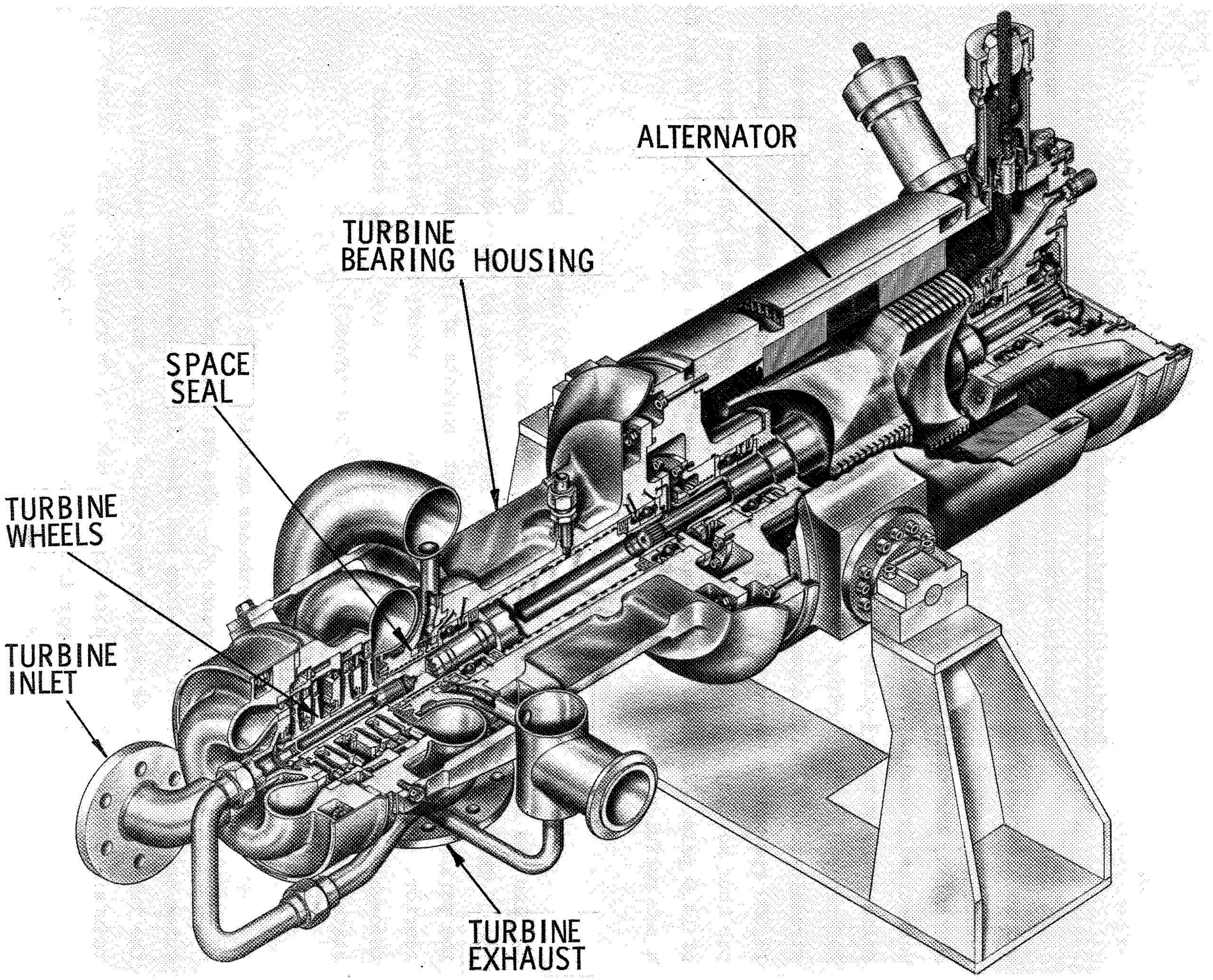

Figure 7. SNAP-8 Turbine-Alternator Assembly

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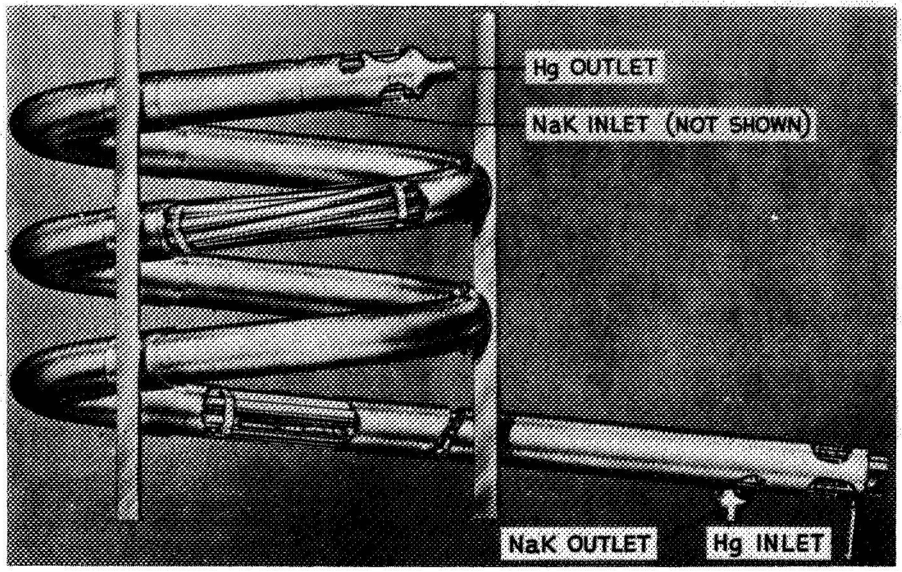


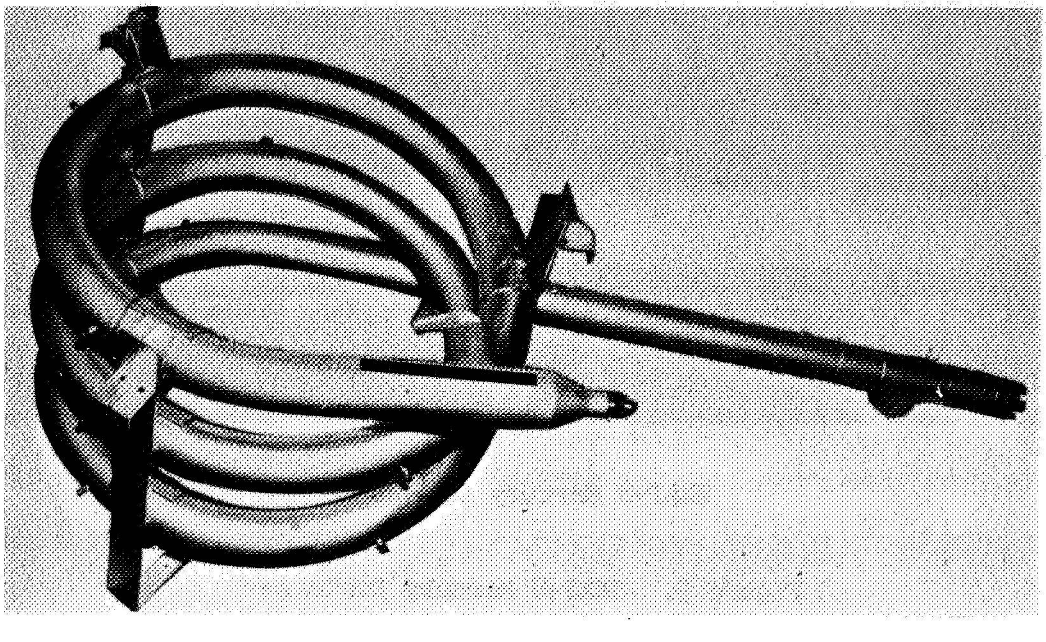
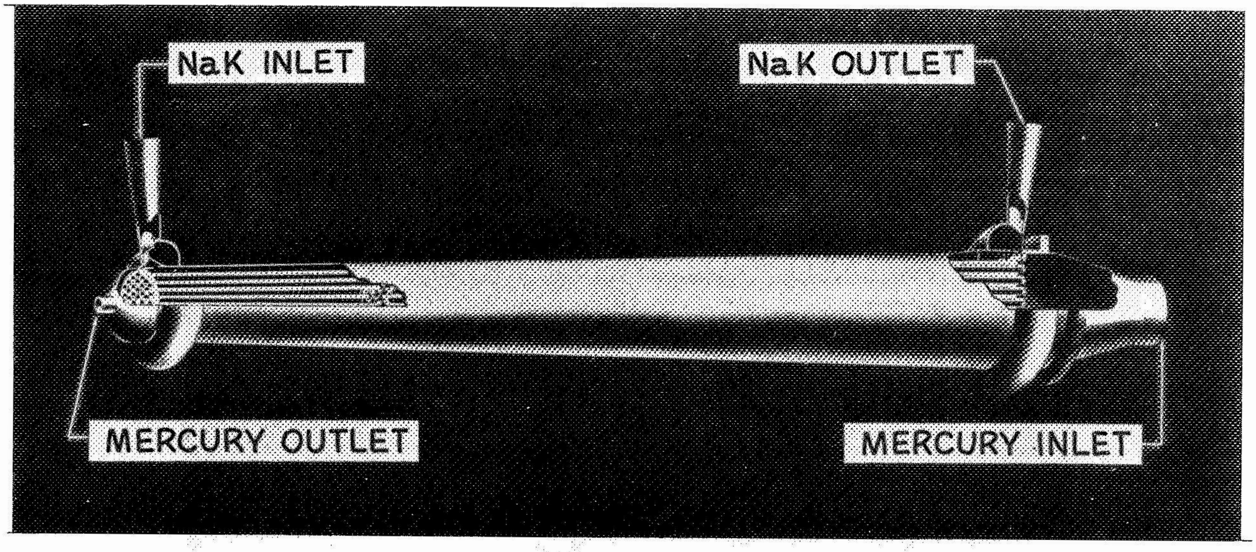
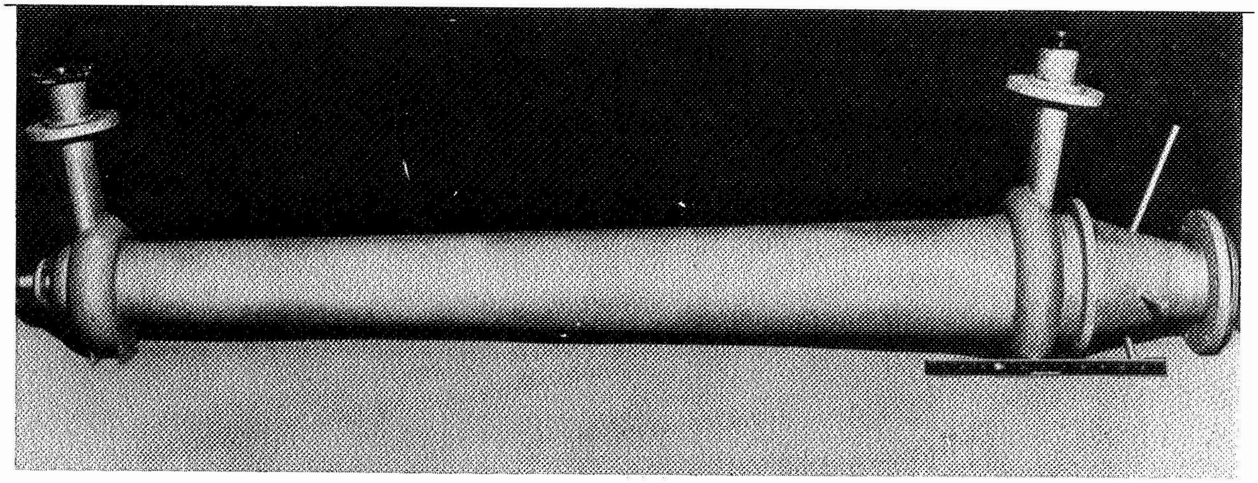


Figure 8. SNAP-8 Tube-in-Tube Boiler



SNAP-8 Mercury Condenser Cutaway



SNAP-8 Mercury Condenser

Figure 9. SNAP-8 Mercury Condenser

The functions of the condenser are to condense the mercury vapor, subcool the liquid to provide adequate NPSH for the liquid mercury pump, and provide the proper backpressure for the turbine. At the nominal operating condition, the condenser operates at a mercury vapor inlet temperature of 670° F (14.0 psia). The mercury condenses at 670° F and then is subcooled to about 462° F. The NaK-side of the condenser operates with an inlet temperature of 460° F. A typical liquid mercury inventory in the condenser is 35 lbs which occupies about 22 inches of the total tube length of 50 inches.

### 4. Electrical Controls

The function of the electrical control system is to maintain the turbine-alternator assembly speed constant at 12,000 rpm within ± 2% while delivering any required vehicle load (system net output) between 0 and 35 kw, and to control the vehicle load voltage to 120/208 volts within ± 5%.

The electrical controls consist of a voltage regulating unit and a speed control unit. The voltage regulating unit is of the solid-state magnetic (saturable reactor) type. The unit senses voltage and frequency and regulates the voltage to maintain a constant ratio of volts to frequency (see Reference 10). The speed control unit operates by sensing frequency and changing alternator load to correct any change in frequency (see Reference 11). A parasitic load is used by the speed control unit to change the alternator load. The parasitic load consists of a set of resistors for power dissipation and is located in the heat rejection loop.

### 5. Mercury Pump

The mercury pump is hermetically sealed and is made up of a centrifugal pump, dynamic seals, induction motor, and angular-contact ball bearings (see Figure 10). A jet booster pump is integral with the unit to suppress cavitation during the startup phase when the system-developed net positive suction head is low. Bearing lubrication, space seal, and motor cooling are provided by the polyphenyl ether lubricant-coolant fluid. The unit operates with $460^{\circ}F$ mercury and $210^{\circ}F$ lubricant-coolant fluid (see Reference 12).

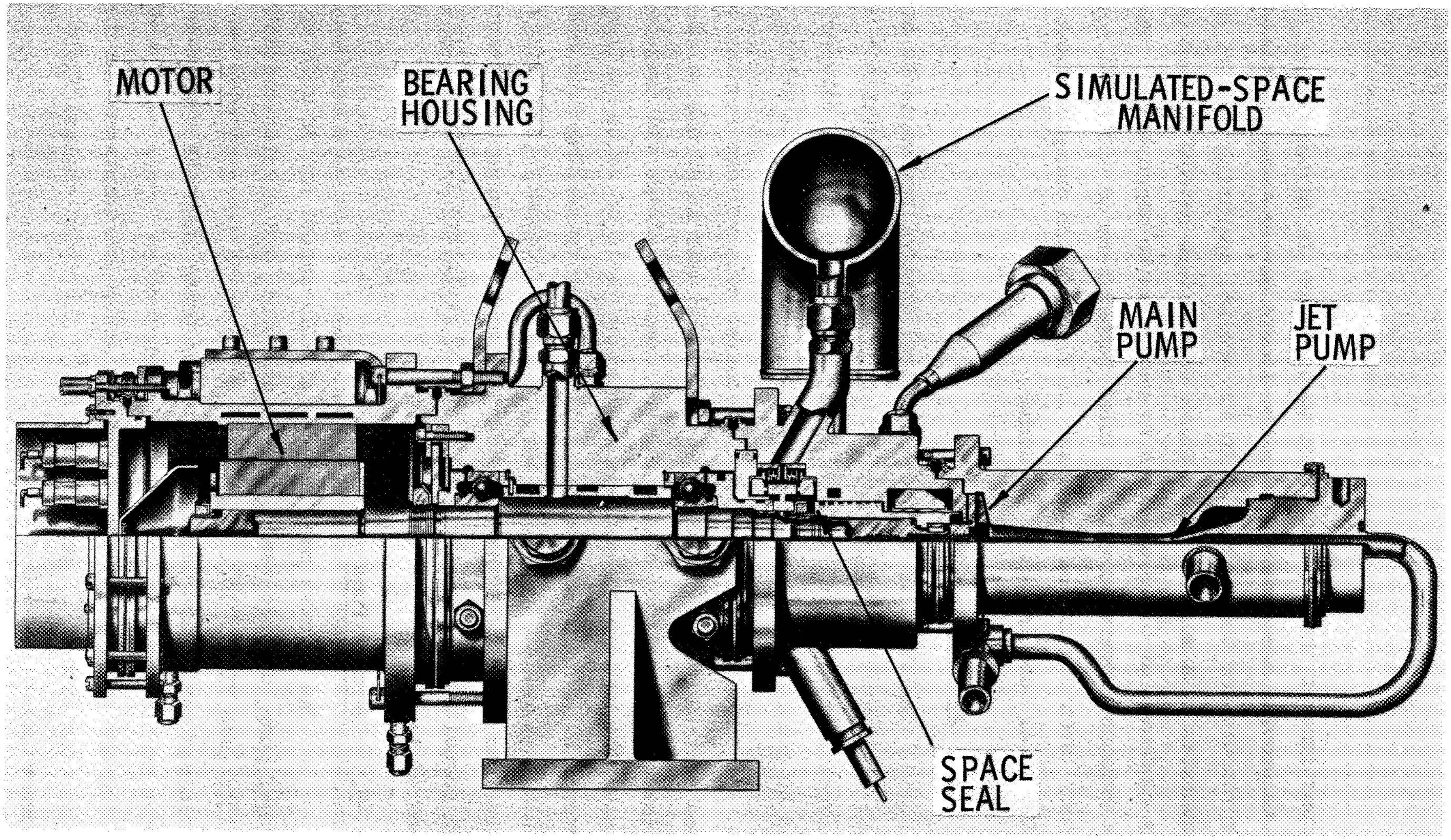


Figure 10. SNAP-8 Mercury Pump

### 6. NaK Pump

The NaK pump (see Reference 13) is shown in Figure 11. Identical units are used in both the primary and the heat rejection loops. The pump is hermetically sealed, incorporating a centrifugal pump, hermetically sealed motor, an internal NaK lubricant-coolant recirculation pump, and NaK-lubricated bearings. Integral with the assembly is an external recirculation loop containing a cold trap system, heat exchangers, and a filter. No static or dynamic seals are used in the assembly. Isolation of the main loop NaK and the recirculation loop NaK is accomplished by a close-clearance annulus around the shaft between the pump and the motor. The recirculation loop NaK cools the motor and supplies the bearings with clean NaK. Any oxide migrating through the annulus from the main loop, where the oxide level may be unacceptable for the bearings, is trapped by the recirculation loop cold trap. The normal operating temperatures of the pumps are 1135° F for the primary loop pump and 460° F for the heat rejection loop pump. The motor temperatures are approximately 350° F.

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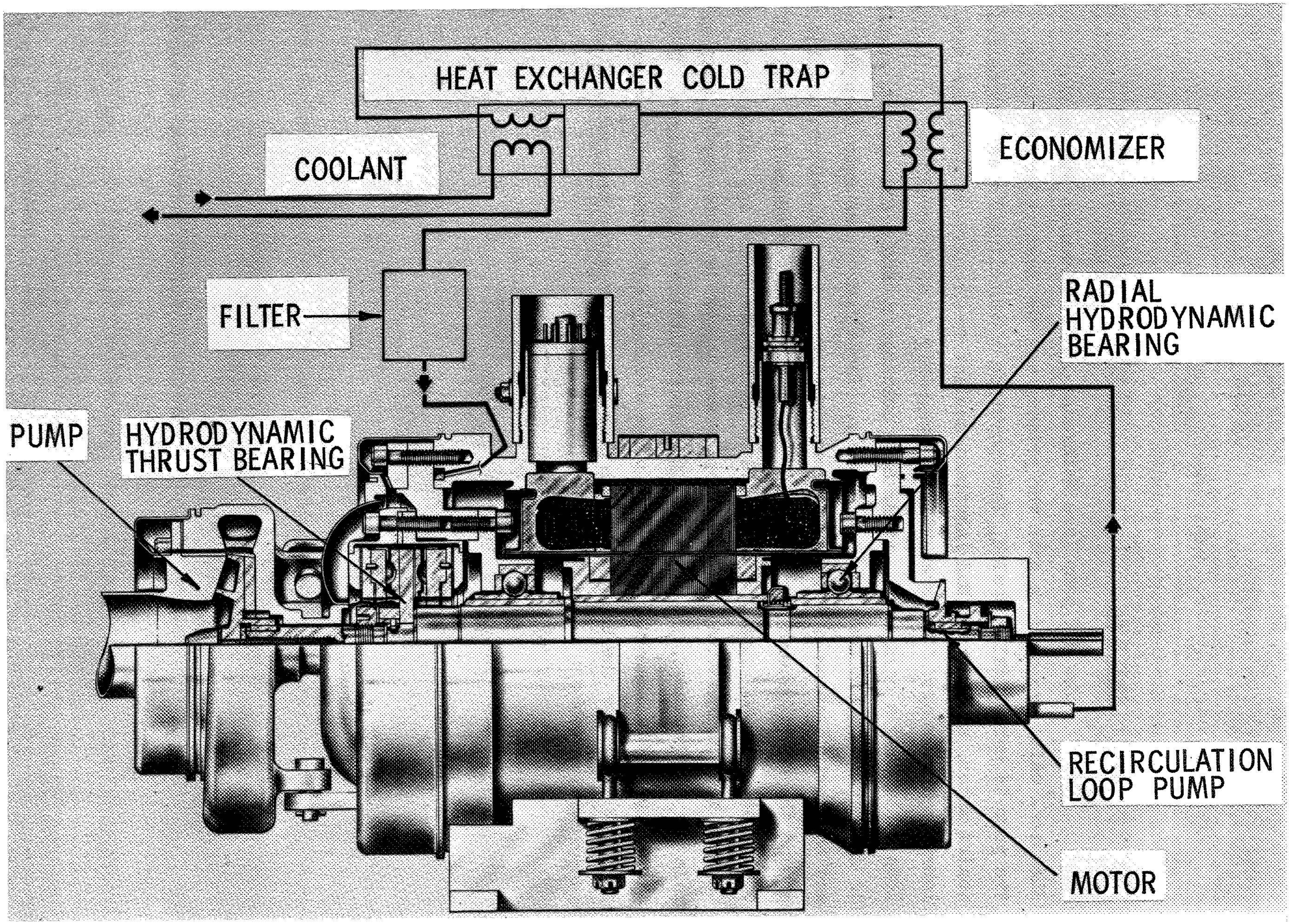


Figure 11. SNAP-8 NaK Pump

# III. INSTRUMENTATION, CALIBRATION, AND DATA PROCESSING

## A. INSTRUMENTATION

### 1. Flow

NaK flowrates in PCS-1 were measured with venturi-tubes and magnetic flowmeters. These magnetic flowmeters were installed during the period that RPL-2 was upgraded to PCS-1. The venturi-tubes have been recalibrated several times in the Hydraulics Laboratory with water and no changes in their calibration curves have been detected. Magnetic flowmeters were used as backup instruments to the venturi-tubes, and installed in series with them. The magnetic flowmeters were not calibrated. Their calibration curves are based upon theoretical equations and a calibration of the field strength of the magnets. Periodically, the flux of these magnets has been measured, and no deterioration of field strength has occurred. The magnetic flowmeters have given results that agree within ± 5% of the venturi data. Magnetic flowmeters have also been successfully employed where flow measurement with a venturi is impractical; for example, when flowrates are very low and a differential pressure measurement is difficult.

Mercury liquid and vapor flowrates were measured with venturi-tubes. For PCS-1 a new liquid venturi was designed and built to give a higher pressure drop, thus making the differential pressure measurement an easier task. A new vapor service venturi was also designed and built. This venturi not only develops a higher pressure drop, but it also has incorporated into its design, annular sections which permit a circumferential averaging of the upstream and throat pressure measurements. This venturi was calibrated both at AGC and the Colorado Engineering Experiment Station in Boulder, Colorado and both calibrations agreed.

The liquid service venturi has been calibrated three times during the period July 1965 to December 1967. In that time period, the discharge coefficient of the venturi increased by about 1%, indicating either a streamlining (smoothing) of its throat or an increase of throat area by about 1/2 of 1%. Approximately 3100 hours of actual mercury flow through the venturi occurred during this time period.

Lubricant-coolant flowrates were measured in PCS-1 with four turbine-type flow tranducers. Three of these flowmeters use conventional magnetic pickups to sense the rotational speed of their rotors. These transducers have been recalibrated on several occasions and no deterioration in their calibration factors has been detected. The fourth transducer was used to measure a very low flowrate (200 lb per hour or 0.36 gal per minute). The rotational speed of its rotor was sensed by an oscillator preamplifier system, eliminating the drag incurred by the normally used magnetic pickup. The bearings of this transducer have a tendency to wear out because they are extremely small. Experience in PCS-1 and other test loops indicated that they should be repaired after approximately 2500 hours running time.

### 2. Pressure

Pressure measurements in PCS-1 were made with pressure transducers and pressure gages. Three types of pressure transducers were used during RPL-2 testing: strain gage, potentiometer, and variable reluctance. During the preparations for PCS-1 testing, it was decided to standardize on strain gage type pressure transducers for the following reasons:

- The variable reluctance transducer system was not reliable. It was difficult to determine whether this unreliability was due to poor transducer operation and/or signal conditioner drifting. Also, the variable reluctance circuit does not provide the capability of checking out the system such as the shunt-calibration method used with strain gage and potentiometer instruments. This reduced the confidence in the variable reluctance pressure transducers.

- The potentiometer pressure transducers were very easily damaged by overpressure surges and their wiper arms occasionally wore out because the pressure media was fluctuating slightly over one point.

- Strain gage pressure transducers were developed and obtained which can take up to 15 times overpressures without damage and are compensated for use up to 400°F.

Visual absolute and gage pressure measurements in PCS-1 were made with conventional bourdon type pressure gages. Visual differential pressure measurements were made with bellows type gages.

The greatest problem to overcome when making NaK pressure measurements is to prevent oxide precipitation and the resultant plugging of the pressure instrument's port. During the conversion from RPL-2 to PCS-1, a separate NaK purification system was added for each NaK loop reducing the plugging problem considerably. Also, two new successful methods of installing pressure transducers were introduced in PCS-1. In the first method, the transducer was mounted above the pressure tap to keep the NaK at the transducer's pressure port above the oxide precipitation temperature (by thermal convection) and also allow any solids to drain back into the process piping.

The second method, illustrated in Figure 12, is especially recommended for a loop with a high NaK oxide content. This installation minimizes temperature gradients between the process fluid and the pressure transducer and provides a plugging time delay. The stilling section operates at a temperature closer to that of the transducer than the temperature of the NaK in the process pipe. Therefore, the convection currents between the intermediate stilling section and the process fluid are much larger than the convection between the stilling section and the transducer. This tends to minimize the precipitation of oxides near the transducer.

During RPL-2 and early PCS-1 testing, many pressure transducers failed due to pressure surges frequently occurring in the mercury system. A bonded strain gage pressure transducer was developed which, by use of an overload stop, can survive 15 to 1 overpressure surges without suffering calibration shifts. A schematic of the internal construction of this transducer is shown in Figure 13.

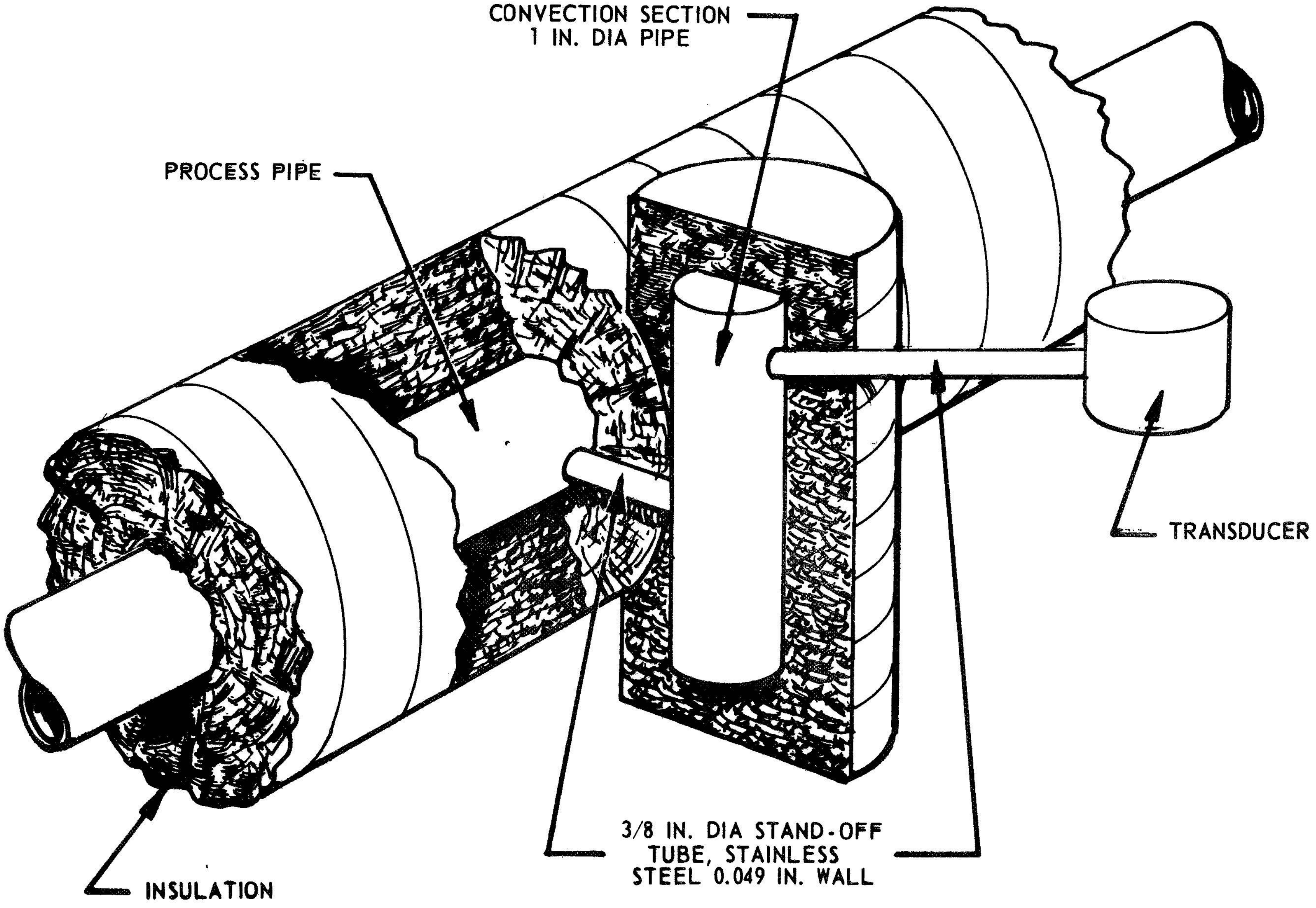


Figure 12. Pressure Transducer Installation with Convection Section for NaK Service

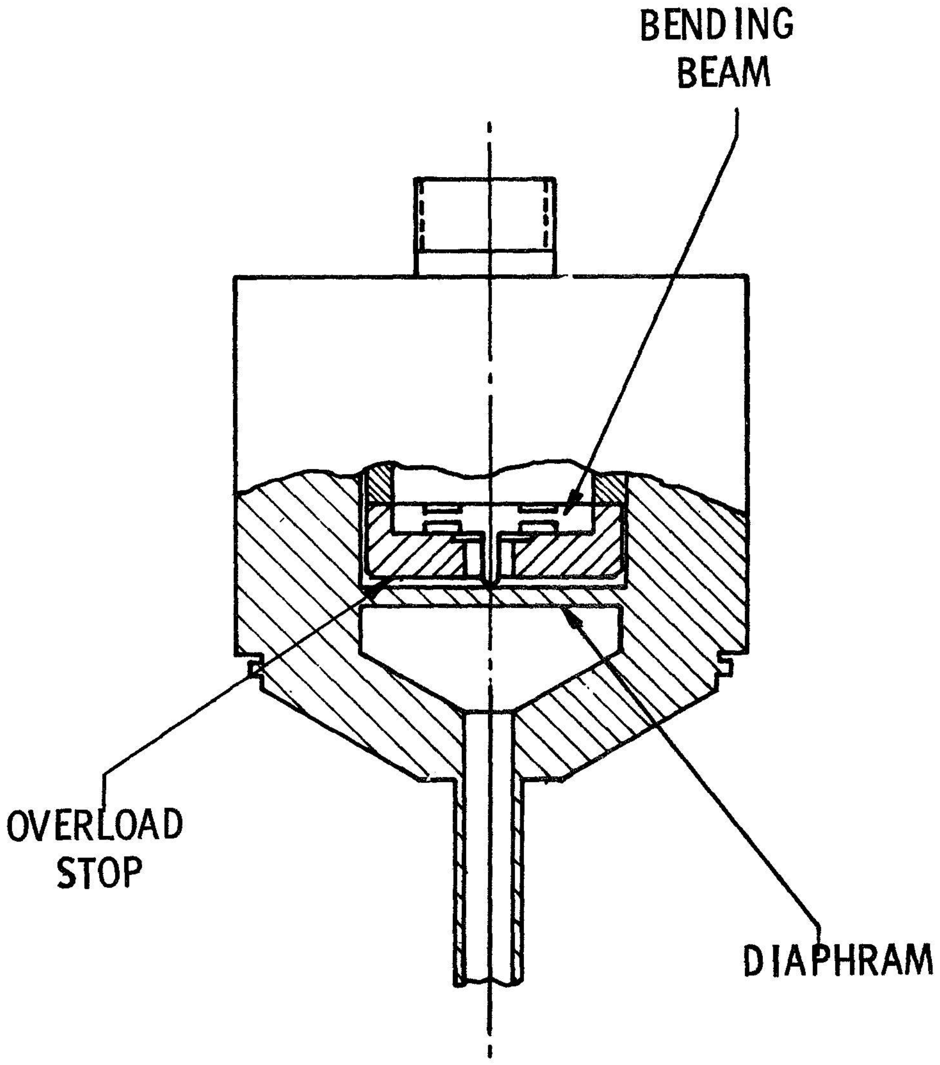


Figure 13. Pressure Transducer - 15:1 Overload

A potential major problem in making mercury vapor pressure measurements is the corrosion of the pressure stub connecting the transducer to the process pipe. High corrosion rates (due to refluxing, caused by the condensation-vaporization cycle) of 0.01 inch per 1000 hours at 1275°F and 275 psia were experienced. This hazard has been overcome in PCS-1 by the use of 9M pressure taps. A typical installation is shown in Figure 14 which shows how the pressure transducer is mounted with the liquid vapor interface occurring in the 9M stub portion.

### 3. Temperature

Thermocouple channels recorded on the Digital Data Acquisition System (DDAS) pass through "heated" reference junctions which incorporate a "bucking voltage" system to achieve an effective 32°F reference. Seven reference junctions of this type are used for PCS-1, each having a 50 channel capacity. Temperatures recorded in the control room also pass through these reference junctions. A "quick look" temperature indicator located on the operator's control console and multipoint temperature recorders associated with the NaK purification systems use "built-in" reference junctions. The temperature measurements are made with Chromel-Alumel extension wire thermocouples.

A special surface thermocouple was designed for use in many PCS-1 temperature measurement locations. A photo of a typical installation of this thermocouple is presented in Figure 15 and shows the ceramic insulators and welding strap that make this instrument so rugged and reliable. Since it requires no penetration into the process fluid, the danger of a potential leak has been completely eliminated. Also, inaccuracies are minimal in liquid metal service because of the very high film coefficients. In PCS-1, these thermocouples are covered with a thick layer of insulation. These surface thermocouples were economical to build and easily installed.

### 4. Vibration

Vibration measurments were made with piezoelectric accelerometers mounted on various rotating components in PCS-1. These sensors were connected to charge amplifiers located in the signal conditioning room.

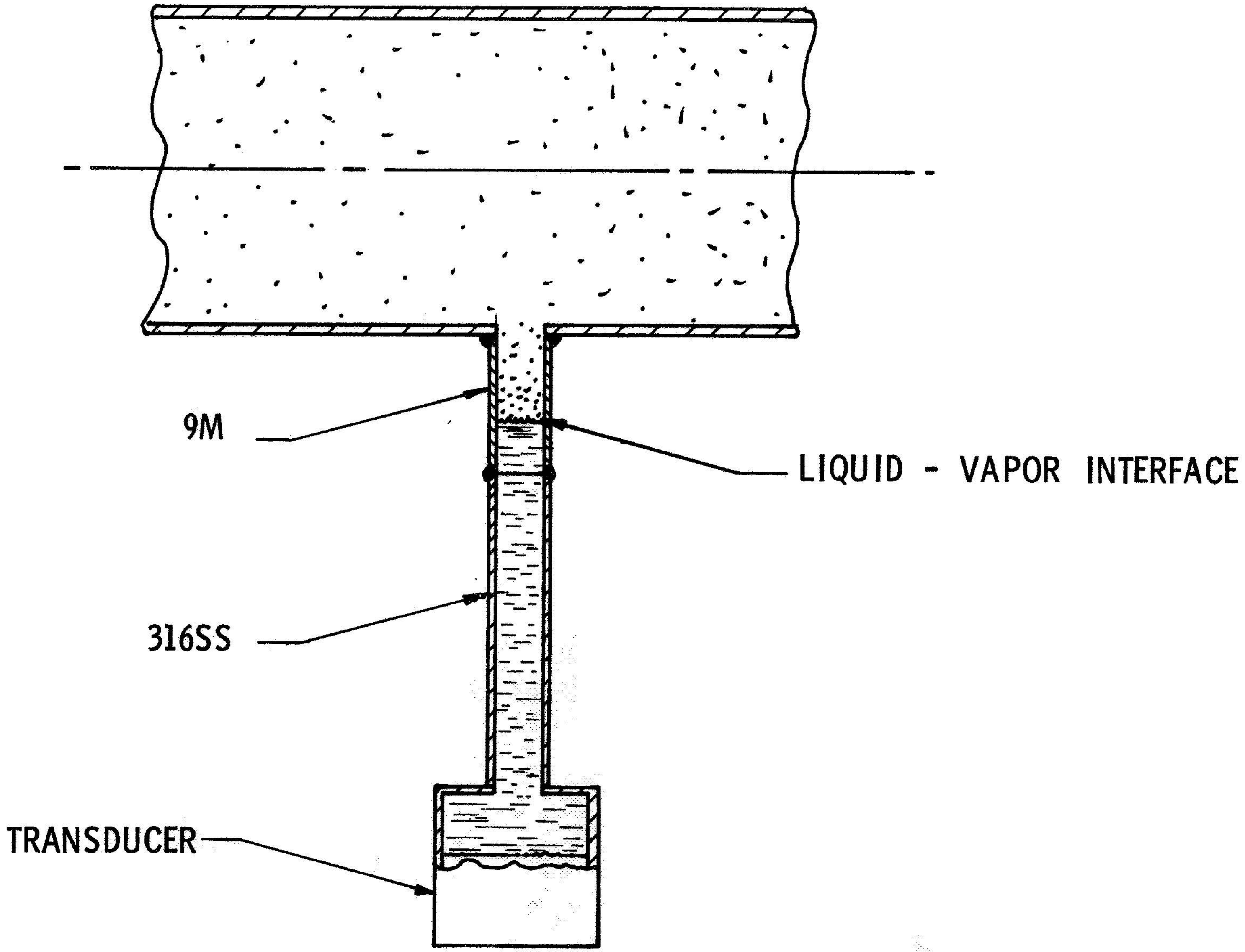


Figure 14. Pressure Transducer Installation - Hg Vapor Service

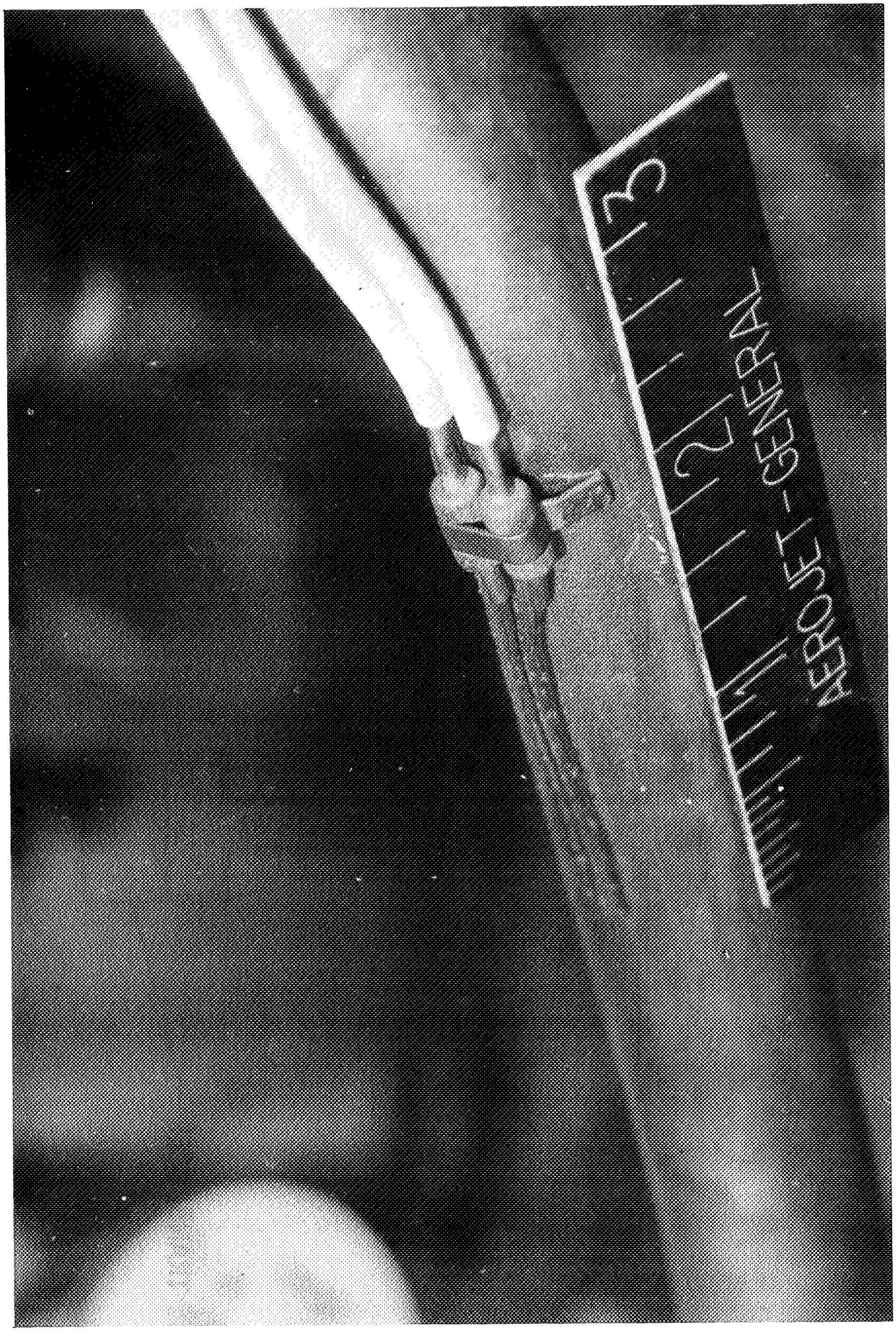


Figure 15. Surface Thermocouple Installation

The signals were read out and/or recorded in the control room. Figure 16 shows a block diagram of the PCS-1 vibration monitoring system. The system is briefly described below:

- All twelve channels are wired to a high speed tape recorder. This recorder is turned on manually for short periods of time at "data points" and during startup and planned shutdown periods. The recorder will also turn on automatically when an unscheduled emergency shutdown occurs.
- Four critical channels are also recorded on two tape recorders which operate continuously. These recorders always have one hour of previous data stored on tapes, thus providing a record of any malfunction.
- A sonic analyzer graphically displays frequency versus acceleration information.
- An audio system provides sounds proportional to acceleration.
- A series of selector switches permit the display of any accelerometer output on the sonic analyzer or its audible representation through the audio system. These switches also allow playback of any channel from any recorder on the sonic analyzer or the audio system.

### 5. Liquid Level

Although PCS-1 level measurements were used for operational information only and not recorded, they played a vital part in the startup, shutdown, and operation of the system. Numberous improvements and innovations in liquid metal level instrumentation technology have been made as follows:

#### a. Digital Level Measurement

Prior to the existence of PCS-1, all level measurements in RPL-2 were made with contact probes employing an electrical insulator between the probe and the tank as shown in Figure 17.

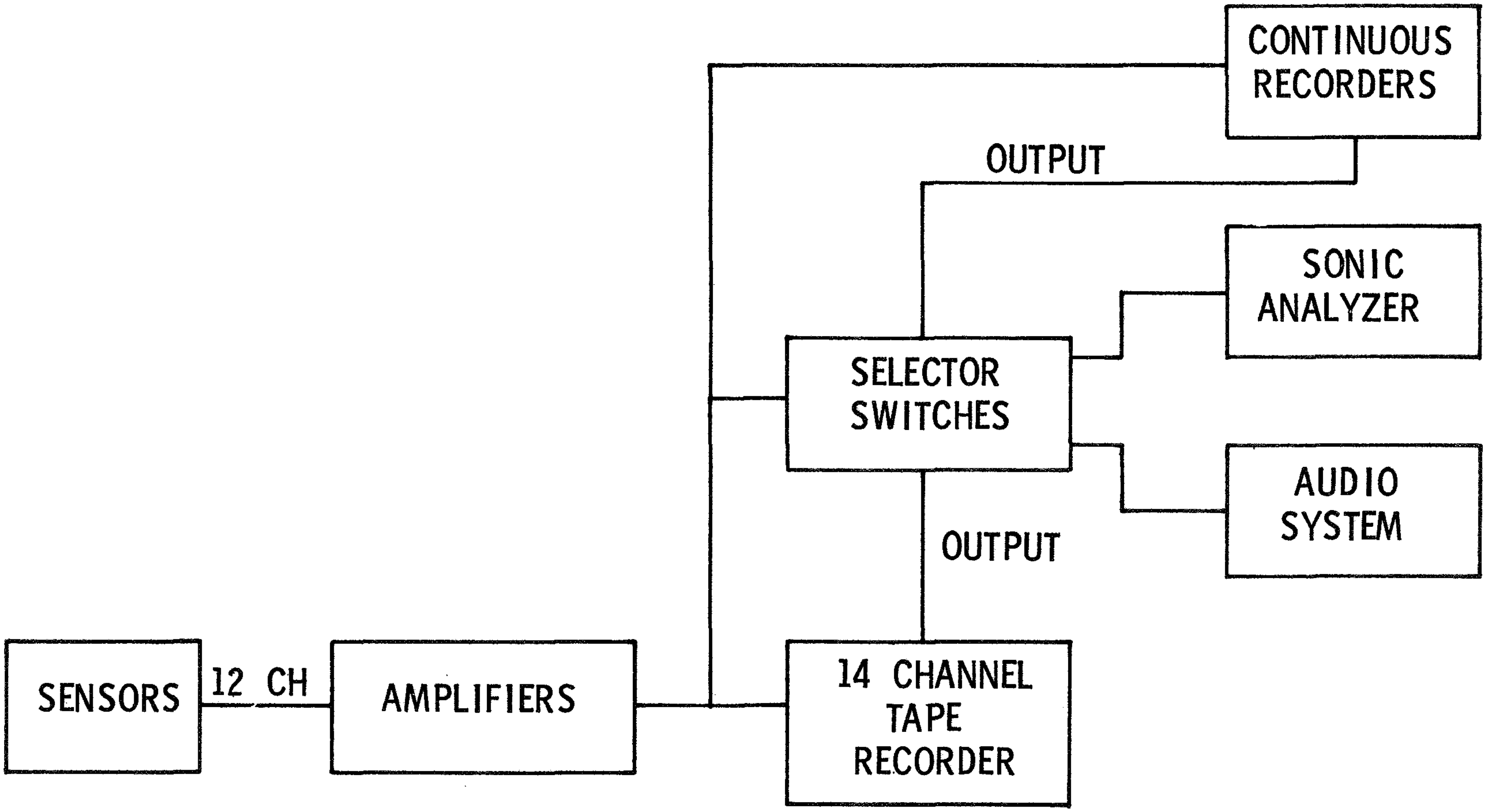


Figure 16. PCS-1 Vibration System Basic Block Diagram

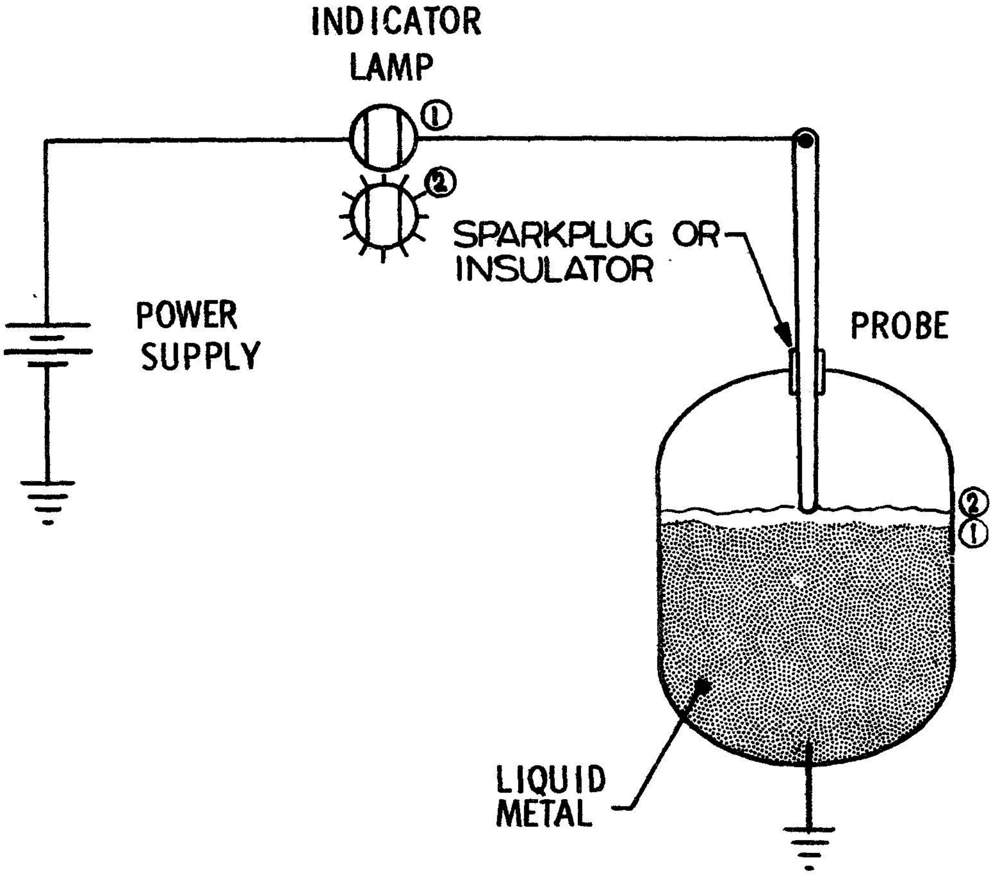


Figure 17. Contact Probe Electrical Circuit

In this type of installation, as the NaK contacts the probe, a circuit is completed allowing current to flow and a lamp lights. This type of measurement proved unreliable because the probe tended to short out to the tank due to wetting and/or oxide buildup.

The spark plug probe types have been replaced with digital level type probes which are welded into the tank as shown in Figure 18. This design has proven to be very reliable. It operates on the following principle. When NaK is below the probe, current flows up through the sheath and the voltage drop across the sheath is relatively high. When NaK contacts the probe, current flows through the NaK to ground, resulting in a decreased voltage drop across the sheath. This step change in voltage drop is detected and used as a digital level measurement.

### b. Analog Level Measurement

Originally, NaK analog level measurements were primarily made utilizing "J" probes. Problems with these probes had been experienced resulting from failures at the bent section due to thinning, difficulty in installing and removing a "J" configuration probe, and a lack of confidence in the readings from these systems by test engineers.

Improved probes and related circuitry were designed to overcome these difficulties. A combined analog-digital probe was developed and is shown in Figure 19. This probe utilizes a multiconductor material in which two conductors are used for the analog system and other conductors are utilized with digital circuitry to provide digital check points on the analog measurements. This combination of digital-analog methods has eliminated the lack of operator confidence previously mentioned.

A top entry analog probe system and associated circuitry has also been developed and is shown in Figure 20. This system utilizes an extension piece to obtain an analog top entry straight probe. When NaK touches the extension, a second parallel current path is provided. Voltage drop across the parallel paths is measured to obtain a signal which is

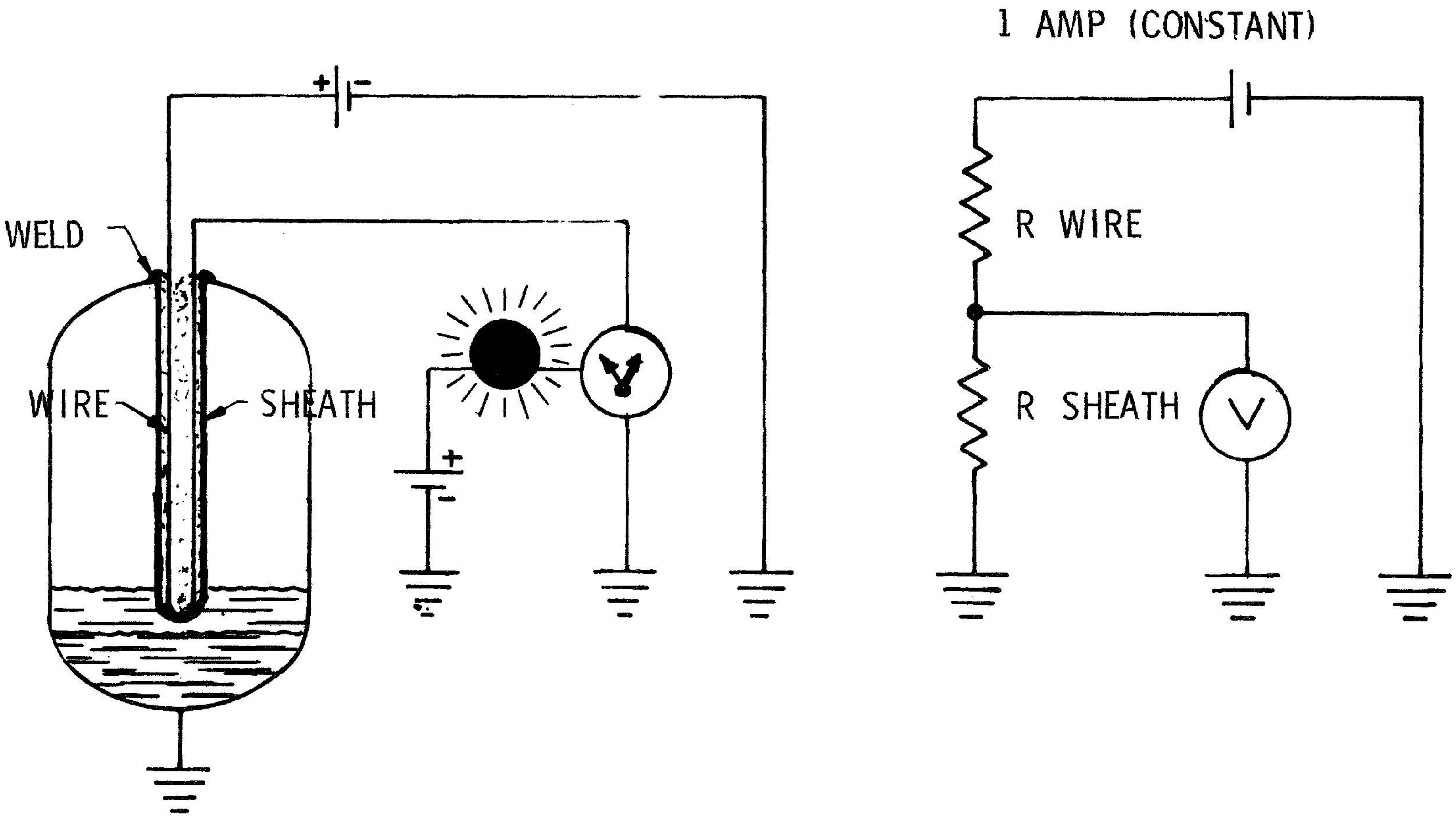


Figure 18. Digital Level System - Welded Installation

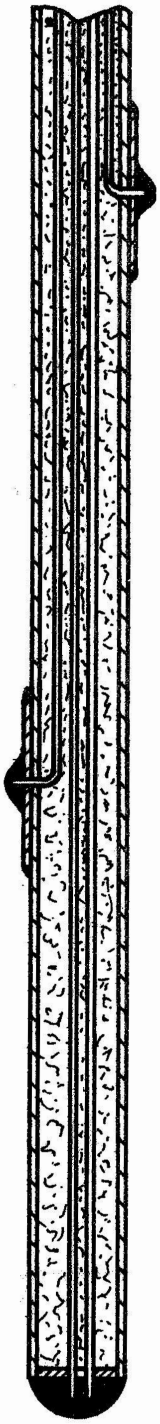


Figure 19. Combined Analog - Digital Level Probe

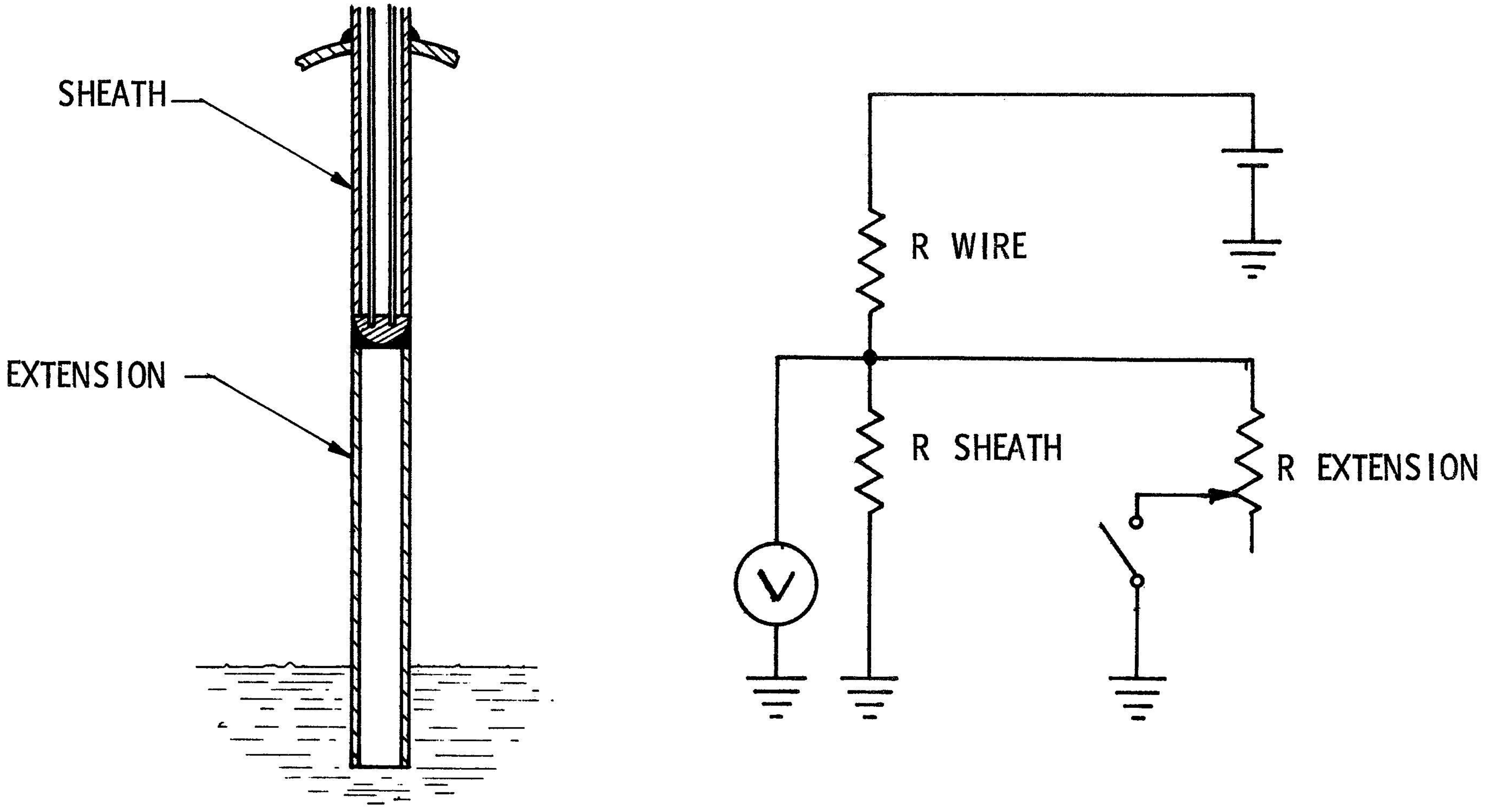


Figure 20. Analog Level System - Top Entry, Straight Probe

proportional to level. It also provides a digital check point when NaK first touches the extension since there is an abrupt change in voltage drop at this time.

## B. CALIBRATION TECHNIQUES

### 1. Flowmeters

Venturi tubes are calibrated with water for liquid metal service and with $N_2$ for the mercury vapor flow measurement. The water or $N_2$ calibration data is converted to give a curve of Reynold's Number versus discharge coefficient for each venturi. Data from this curve are then used to calculate the values required to plot a curve of flowrate versus differential pressure. ASME approved equations are used in the above described method. During lengthy shutdowns of PCS-1, the venturi tubes are removed from the system piping and recalibrated.

Turbine-type flow transducers (used on lubricant-coolant service) are calibrated by the transducer manufacturer with water and oil having the same kinematic viscosity as that of the lubricant-coolant in PCS-1. Before installation in PCS-1, the transducers are calibration-checked in Aerojet's Hydraulic Laboratory with water to verify the vendor's calibration. The transducers are periodically removed from PCS-1 and recalibrated with water.

Calibration curves for magnetic flowmeters used on NaK service were calculated using theoretical equations. A digital computer program has been prepared to perform the calculations required to develop the calibration curve. Gauss measurements of the magnets are periodically taken utilizing a Hall effect gauss meter and/or a sweep coil.

### 2. Pressure Transducers

Before a pressure transducer is qualified for use in PCS-1 it must pass a rigorous qualification for test program. These qualification tests check each transducer for linearity, hysteresis, zero shift due to temperature and line pressure changes, sensitivity shift due to temperature changes, and overpressure damage resistance. The tests are performed in careful laboratory controlled conditions. After a transducer is qualified for use in PCS-1, it is subjected to an end-to-end system calibration. In this end-to-end calibration, the transducer is pressurized with $N_2$ to precise known values by means of a calibration cart. The transducer is connected to the same signal conditioner it uses during PCS-1 testing, utilizing a cable having the same resistance as the one connecting the two components. Data from this end-to-end calibration are recorded and used in subsequent data reduction calculations.

During the end-to-end calibration, two different electrical resistances are shunted into the wiring system. Output signals from this shunt-calibration are recorded. Subsequent shunt-calibrations are performed during and after PCS-1 test runs to determine if any electrical changes had taken place between the transducer and its signal conditioner. The operational stability of the signal conditioner is also checked periodically by disconnecting it from its transducer and connecting it to a reference Wheatstone bridge.

Pretest and post-test in-loop pressure calibrations are performed on all pressure transducers and gages. This is accomplished by pressurizing the loops with argon, utilizing a secondary standards gage as a reference gage, and conducting a five-step in-loop calibration in both increasing and decreasing pressure directions.

Several pressure measurements in the PCS-1 mercury loop are considered so important that an on-line calibration system has been built for these channels. The on-line calibration system consists of valving and piping which allows the pressure transducer to be disconnected from the mercury loop while the loop is operating. The pressure transducer can then be calibrated end-to-end by means of the previously mentioned calibration cart.

### 3. Thermocouples

All PCS-1 temperature measurements are made with Chromel-Alumel thermocouples. Surface thermocouples built in-house use wire having a reading accuracy of ± 2°F between 0 to 530°F and a ± 3/8% reading accuracy from 530° to 2300°F. The extension wiring has an accuracy of ± 2°F. Critical measurement thermocouple probes used in PCS-1 are calibrated prior to use in Aerojet's Primary Standard Laboratory with freezing point standards equipment. Before initiation of a PCS-1 test run, all thermocouple channels are checked to see whether they record a reasonable ambient temperature. Many channels are further checked by inserting a known voltage between the thermocouple and its readout device. The sum of the inserted voltage and the thermocouple generated electro motive force (emf) due to the known ambient temperature will give a readout that is checked on an emf versus temperature table for Chromel-Alumel thermocouples.

## C. DATA PROCESSING

### 1. Data Sources

The Data Reduction Group receives raw recorded test data from the sensors in two basic forms. Digital data are recorded by the Digital Data Acquisition System (DDAS) on magnetic tape. Analog data are recorded on strip chart and oscillograph recorders and are indicated on visual gages. Vibration data are also recorded on magnetic tape. Digital and visual gage data are recorded in engineering units, while the strip chart and oscillograph record data are in millivolts or trace deflection.

The raw recorded data are processed within the Data Reduction Group and presented to the data users in the most convenient and usable form. Visual gage data are presented in tabular form. Vibration data are presented on a polaroid picture of the sonic analyzer's CRT output. The largest portion of the data is processed by utilizing computer programs and methods which are discussed in the following sections of this report.

## 2. Computer Data Processing

During the period of July 1965 to December 1967, the data processing programs were compiled into a standard data package. The package first included only the Automatic Data Processing No. 2 (ADP-2) computer routine which presented digital data recorded by the Digital Data Acquisition System averaged for selected time intervals.

The initial addition to the standard data package was the SNAP-8 Data Analysis (SEDAN) routine. This routine calculates system and component performance data from the averaged data values of ADP-2. Subsequent changes to the standard data package included the addition of computerized data plotting of the recorded test data, revising of the ADP-2 printout format from one summary value per page to eight summaries per page and adding of a loop schematic and temperature profile section. This revised presentation became ADP-3.

ADP-4 came into being with the changeover from the IBM 7094 computer to the new generation IBM 360 computer. ADP-4 incorporated changes in programming and control card setup which resulted in improved efficiency. Data presentation remained basically the same as ADP-3; however, computer processing time was significantly reduced and routine control card revision was simplified.

The standard data package is processed on a daily basis during PCS-1 system operation. The package fulfills the bulk of the data users' needs and thus is the heart of the data presentation. The standard data package consists of three major data forms:

(a) Recorded data processed by Automatic Data Processing No. 4 (ADP-4) computer code.

(b) Plots of parameters vs time generated on the Cal-Comp plotter.

(c) SNAP-8 Data Analysis (SEDAN) performance data.

The sequence of events for the standard data package starts at 2400 hours with the availability of the final daily data tape from the DDAS. The recorded data tapes plus the necessary ADP-4 control cards are submitted for computer processing. The output of the ADP-4 computer code consists of a listing of averaged recorded data values, a history tape (Dlymerg) of all recorded data and a summarized recorded data tape (SUMDAT) which contains only the averaged values for each requested data point. The SUMDAT tape is the input data tape for both the Cal-Comp plotter and the SEDAN computer program. Figure 21 describes the overall processing of the complete standard data package.

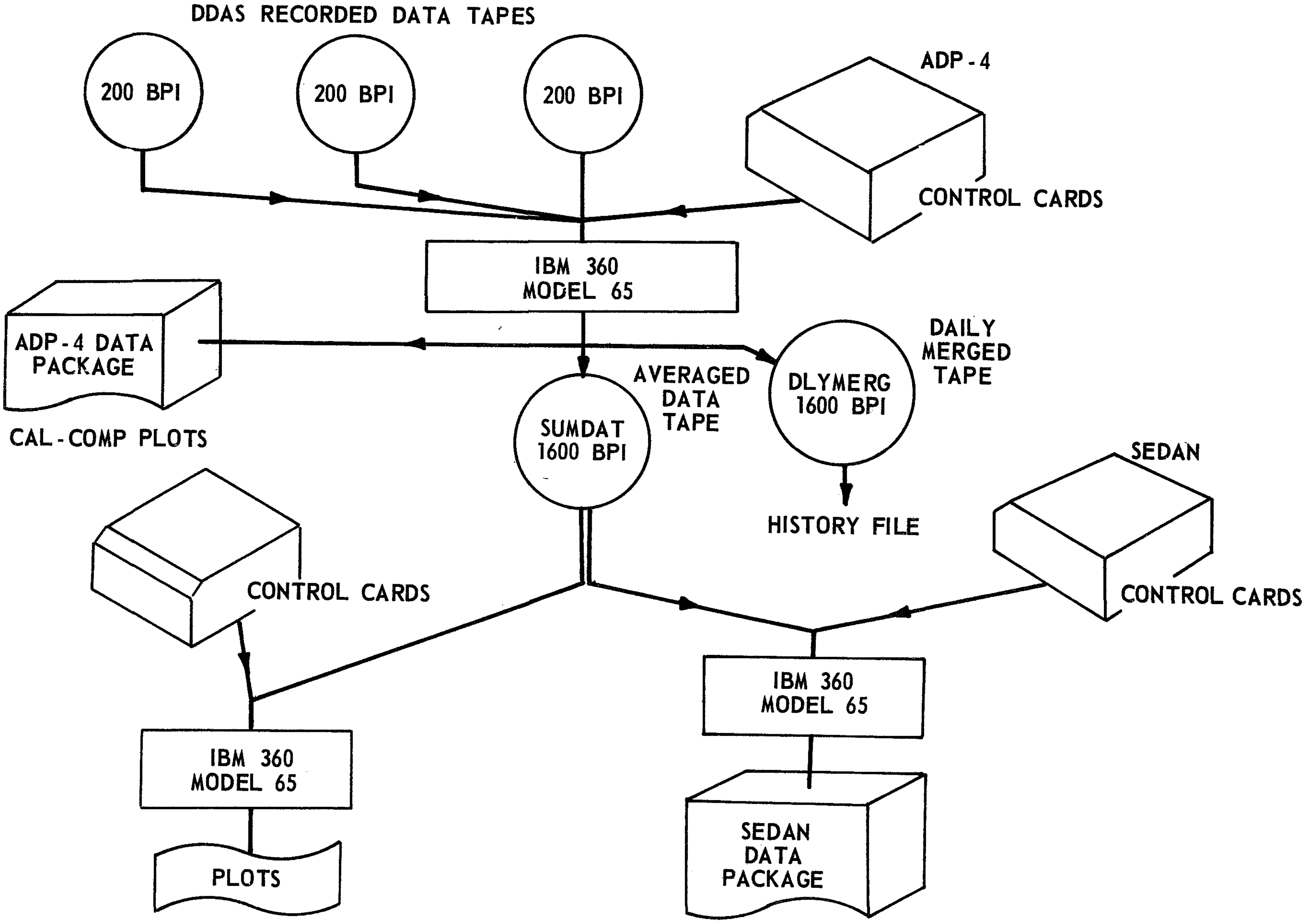


Figure 21. Standard Data Package Processing Flow Chart

## IV. TEST RESULTS AND DISCUSSION OF RESULTS

The results of testing in PCS-1 have been grouped into five basic categories: overall system performance, component performance, system-component interactions, system off-design performance, and general contributions of PCS-1. Each of these categories is discussed below.

### A. OVERALL SYSTEM PERFORMANCE

The most direct measure of the performance of PCS-1 is the amount of time it is operational and the power levels at which it operates. A utilization factor has been established as an indication of the time PCS-1 has been operational and is defined as the ratio of the mercury loop flow time divided by calendar time. The overall utilization factor is 18% for operation of PCS-1 from December 1965 through December 1967. It is evident that the effectiveness of the operation increased greatly with time, since the utilization factor during the last five months of the report period was approximately 65%. It is interesting to note that the best utilization factor achieved in the RPL-2 facility for a similar time period was about 20%. Since the PCS-1 facility and system is more complex than the RPL-2 facility, the utilization factor comparison is indicative of the marked improvement in testing methods, equipment, and workmanship experienced in PCS-1.

The mercury flow at which the system operated can be considered a measure of system performance since the power level is proportional to the mercury flow. In general, the objective was to operate at full power. The principal deterent to the accomplishment of this objective has been deconditioned boiler performance. Figure 22 presents a graphical summary of PCS-1 operating power levels. Approximately 75% of the operating time was at mercury liquid flows greater than 10,000 pounds per hour (nominal = 12,300 lb/hr for a net output of 37 kw). By contrast, the mercury flow in RPL-2 was above 10,000 pounds per hour only about 38% of the time. The maximum length run in RPL-2 was 333 hours, whereas the maximum length run in PCS-1 was 757 hours.

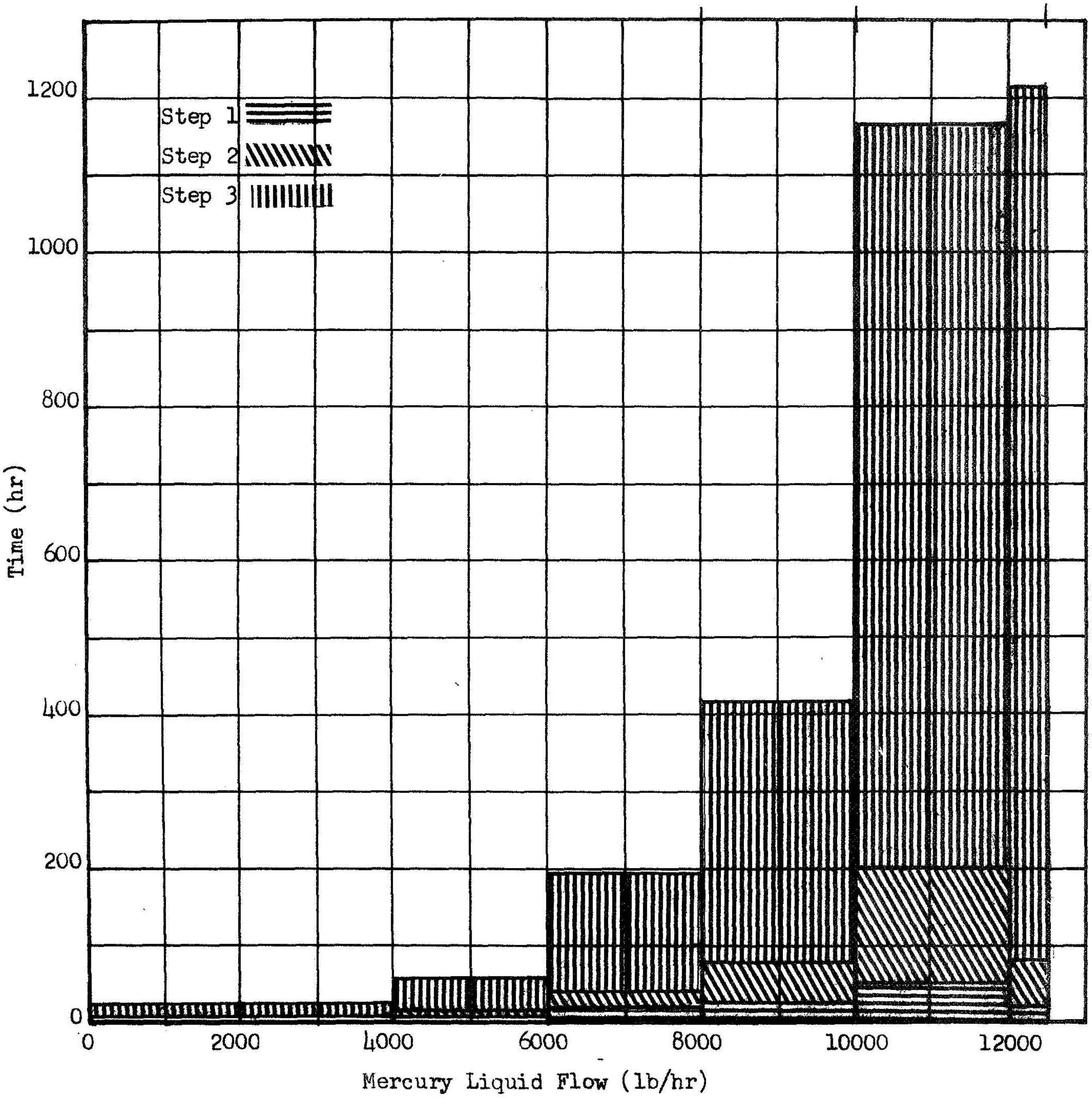


Figure 22. System Operating Power Levels

## B. COMPONENT PERFORMANCE

The performance of the turbine and boiler is so system-related that their performance is included here on an individual basis to provide a more extensive understanding of the SNAP-8 system as viewed from the component level. The turbine (and alternator) directly produce the electrical output of the system, while the boiler provides the energy input for the turbine.

### 1. Turbine Performance

Six turbines have been tested to December 1968 in PCS-1. All of these units have been analyzed to determine their performance and are discussed here on a comparative basis. The performance of all the units is presented in Figure 23 which shows turbine aerodynamic efficiency as a function of velocity ratio (wheel tip speed/spouting velocity).

The first turbine tested in Step 2 (designated Buildup 2/3), was characterized by having a distinct and fairly rapid change in performance after about 88 hours of operation. The performance change amounted to a drop of about 6 kw of output power.

The next two turbines tested, Buildups 5/2 and 6/1, had essentially the same performance as turbine 2/3 after its degradation. In all tests, their performance was distinctly lower than that of the Buildup 2/3 unit before degradation. The question is unanswered whether Buildups 5/2 and 6/1 were degraded. There was no two-level performance indicated in the data. If degradation did occur, it would have had to occur at the beginning of the test. There was some evidence of degradation from the post-test examinations (nozzle diaphragm and nozzle movement, shroud distortion, seal eccentricity, thrust seal/turbine wheel rubbing). These degradation modes represent possible explanations for the lower performance of the latter units.

An alternative explanation to turbine degradation is differences in buildup tolerances and variations in nozzle areas of the various units. The units were not selectively assembled and it is known that the first-stage nozzle area was different for each unit. It is possible that Buildup 5/2 and Buildup 6/1 actually experienced no significant degradation, but simply had poorer performance as a result of their particular buildups.

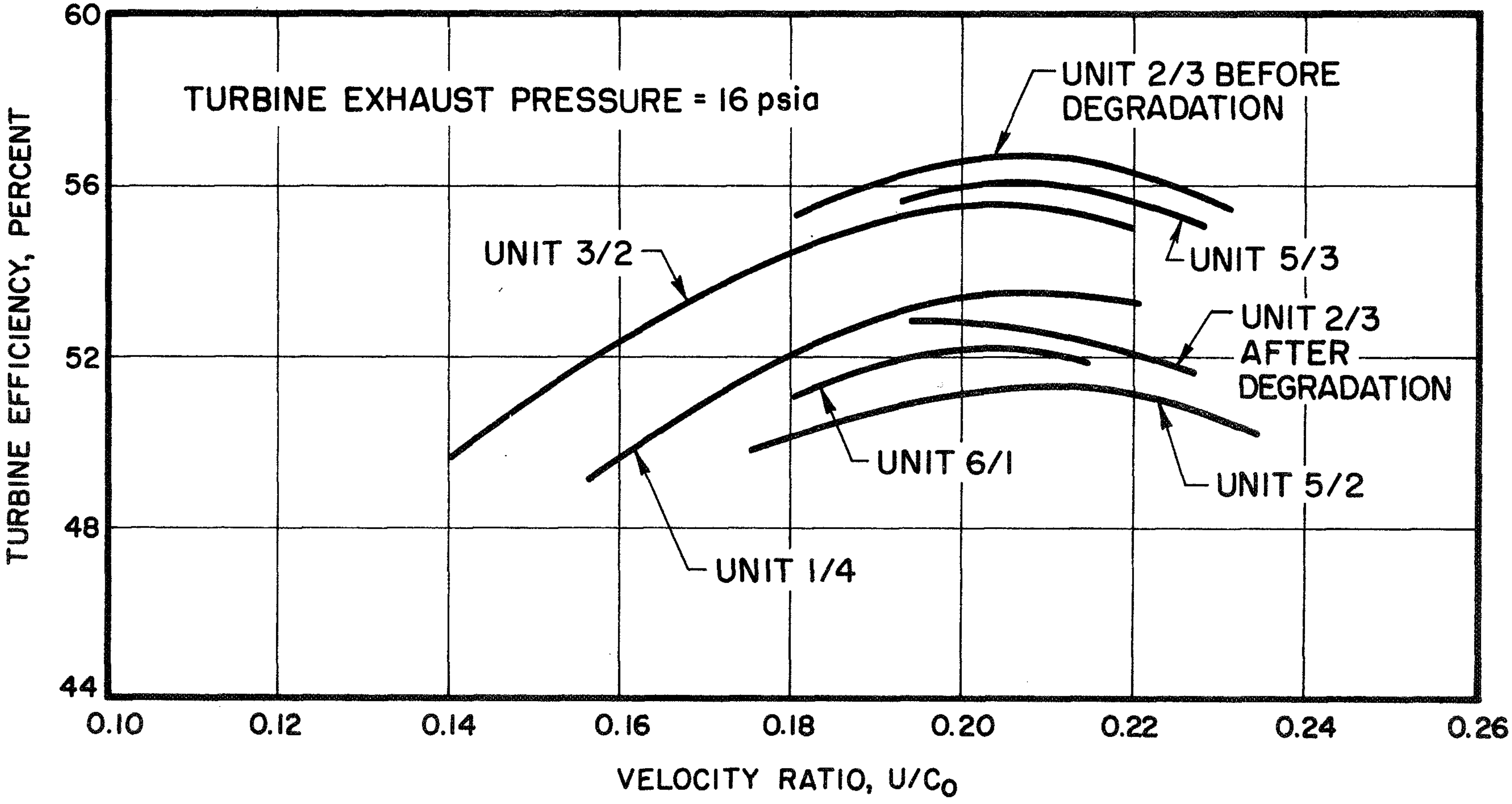


Figure 23. Comparative Turbine Performance

The performance of the Buildup 2/4 turbine was satisfactory and was comparable to that of Buildup 2/3 prior to degradation. The material in the new unit was S-816 for both the shroud and diaphragm instead of a 17-7 Ph shroud and Stellite 6B diaphragm as in the previous turbine.

The fifth turbine tested was Buildup 1/4. This turbine was aerodynamically the same as past units tested with two exceptions. First, Buildup 1/4 had the smallest first stage nozzle area of any of the units tested. The nozzle area of the other four units was toward the high side of the allowable tolerance. Second, the Buildup 1/4 second stage nozzle assembly had a 0.005 inch radial clearance between the shroud and diaphragm around its entire periphery at operating temperatures. The other turbines had this clearance only in the region of the nozzle vanes. This additional leakage space was expected to diminish the turbine efficience by about 1.2 percentage points. Testing determined the Buildup 1/4 turbine efficiency to be about 53 to 54%. This efficiency was basically equivalent to an average of past turbine efficiencies. The testing on this unit ended with an automatic shutdown caused by a turbine overspeed. This turbine was again operated (as Buildup 1/5) following replacement of the alternator which seized during the overspeed. The turbine later failed due to an extreme thermal shock.

The sixth, and last, turbine unit tested in PCS-1 was Buildup 5/3 which incorporated improved aerodynamic design features as verified by an improved efficiency of 56%. Upon shutdown and disassembly, extensive mass transfer buildups were found in the turbine nozzles. It was determined that the original performance mapping had been done after significant mass transfer products had already accumulated. Corrections to the performance data were made to account for that amount of the mass transfer considered to have been present at the time of the performance mapping. The estimated Buildup 5/3 turbine efficiency with the corrections was about 57%. The estimated efficiency was confirmed by test and found to be about 57 to 58%, definitely the best performance obtained with any of the turbines.

## 2. Boiler Performance

A boiler is very susceptible to internal contamination by oxidation or oil on the surface of the boiler tubes which results in poor heat transfer. This degradation of boiler performance is called "deconditioning." The symptoms of a deconditioned boiler are incomplete heat transfer, unusually low pressure drop, low vapor quality, pressure instability, and a large inventory of working fluid retained in the boiler. Deconditioning occurs in degrees varying from slight impairment of performance to the extreme case in which the boiler outlet conditions are unacceptable for turbine operation.

PCS-1 experience has included boilers which conditioned immediately upon startup to boilers which did not condition even after hundreds of hours. The time required to condition a boiler is not predictable, but in general, the cleaner the boiler and associated loop, the sooner conditioning is achieved. Experience has shown that once conditioned, a boiler remains conditioned, provided no contamination of the boiler occurs.

Two methods have been used to achieve conditioned boiler operation. The foremost, and obvious, method has been to thoroughly clean the boiler. Cleaning methods using repeated flushes of solvents and subsequent drying have been developed and have proven effective. A second method that has been used to achieve conditioning has been the use of additives in the mercury. About 1000 ppm of rubidium added to the mercury has resulted in instantaneous conditioning of the boiler. The conditioned state achieved using rubidium has persisted as long as no oxygen, or other material which could react with the rubidium, entered the loop. Figure 24 shows the instantaneous change in vapor quality resulting from a rubidium injection. Full superheat is achieved in about seven minutes following rubidium injection.

There are, however, potential problems involved with the use of rubidium. Rubidium could accumulate in the space seal area since the mercury would have a more rapid rate of evaporation through the seal and out to space than would the rubidium. The rubidium concentration might eventually become high enough to form a solid amalgam in the space seal. Because of these potential problems, the use of additives has not been pursued as a conditioning method for SNAP-8. The emphasis has been placed upon material selection and surface preparation.

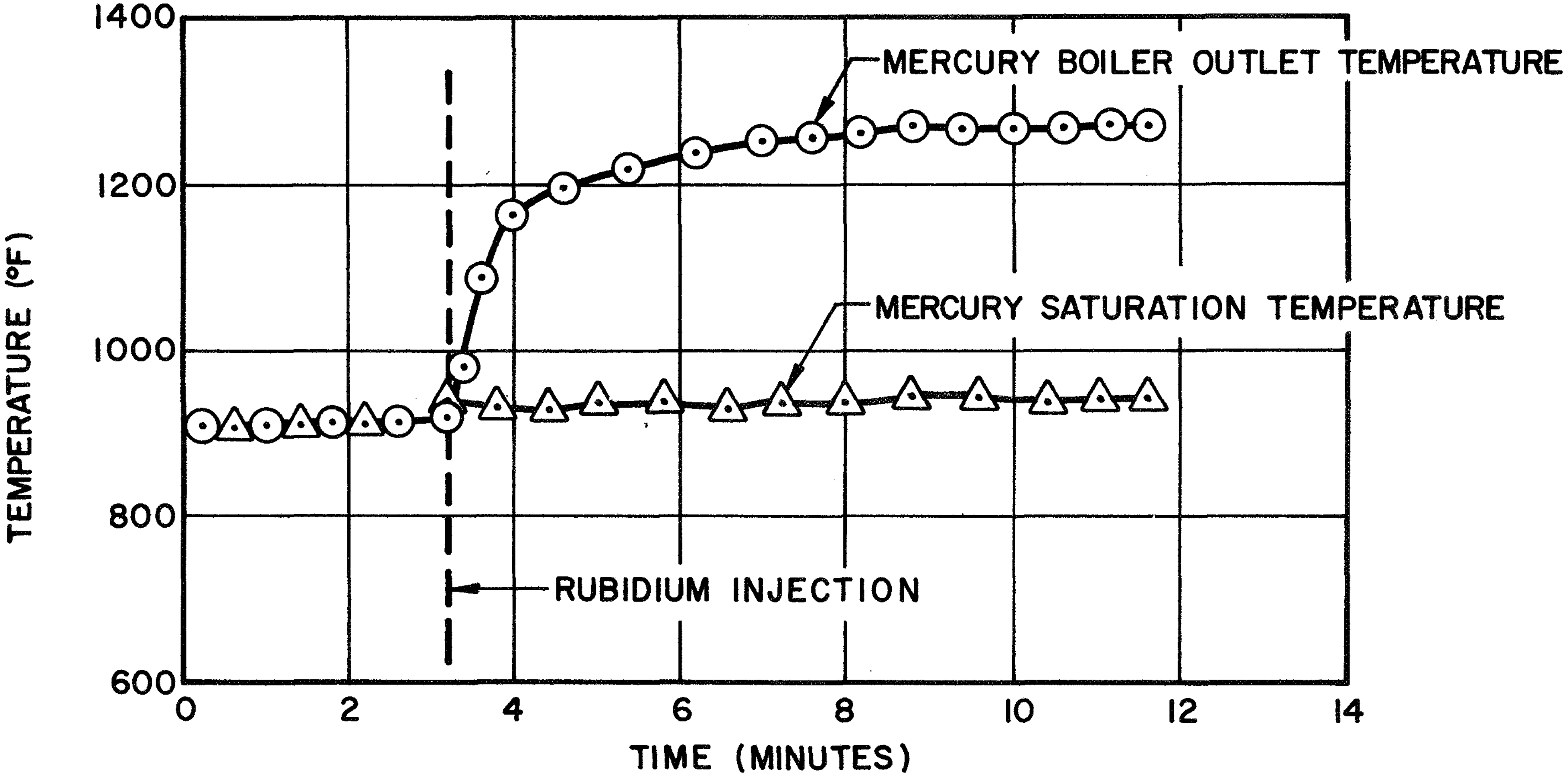


Figure 24. Effect of Rubidium Injection on Boiler Conditioning

Three boilers were involved in PCS-1 testing during this report period and in each case, the boiler failed by developing a leak between the mercury and NaK loops. The first boiler (designated Unit 2) was used during Step 1 and Step 2 testing and its performance was excellent. The performance of this same boiler at the beginning of Step 3, however, was the least satisfactory of any boiler tested to date. The boiler was so deconditioned that much of the time insufficient vapor was developed to maintain turbine speed even without an alternator load. The operating time of this boiler in Step 3 was short and testing ended after 162 hours (Step 3 time) when the boiler developed a mercury-NaK leak. The total operating time on the boiler (Steps 1, 2, and 3) was 583 hours.

The second boiler (Unit 3) also had a considerable period of deconditioned performance, but not the severely deconditioned performance experienced with the previous boiler. The boiler operated for a 1365-hour test period with the Buildup 5/3 turbine and eventually failed with a mercury-NaK leak. The total operating time on this boiler was 1752 hours.

The Unit 3 boiler provided a good example of the wide degree of conditioning that can be experienced by a boiler. At the beginning of the testing, the boiler was in a deconditioned state. Operation brought about improvement in performance, but not until after 860 hours of operation did the boiler achieve conditioned performance. At this time, the boiler was in a conditioned state upon startup of a run. However, after about one day, the performance began to degrade and the boiler returned to approximately a 50% conditioned state. Subsequently during the run, the conditioned status was regained.

Generally, shutdowns were not harmful to boiler performance and time improved performance. One or two exceptions to this have been found where the boiler was less conditioned upon startup or where the performance was declining with time. This phenomenon is considered to be the result of oil or other contaminants in the mercury loop; on one occasion of degrading performance, oil was found in a sample taken from the mercury loop. The oil apparently entered the loop due to the previous shutdown. The exact mechanism of entry was never resolved, but subsequent similar shutdowns (commercial power failures) did not cause a repeat occurrence with the oil.

Figure 25 pictorially demonstrates the wide variations experienced with the Unit 3 boiler. The figure presents several boiler NaK-side temperature profiles for comparison. These profiles have been selected at times during boiler testing which were representative of the main conditioning states the boiler experienced. The following times were selected:

(a) The beginning of a run when the boiler was completely deconditioned.

(b) The beginning of a run when the boiler was well conditioned even though the boiler had only been about 50% conditioned at the end of the previous run.

(c) A poor performance period after degradation from an initial good performance condition.

(d) The end of a run during which oil had apparently been in the mercury loop.

(e) The final performance of the boiler just prior to its failure.

The curves of Figure 25 show the range of conditioning status the boiler experienced. The profile for the start of testing, Condition 'a', is very flat, indicative of the deconditioned state of the boiler upon startup.

The temperature profile for Condition 'b' has the maximum slope, and the steep-slope area is the furthest into the plug region (first five feet of boiler length) of any of the profiles. This is indicative of excellent performance.

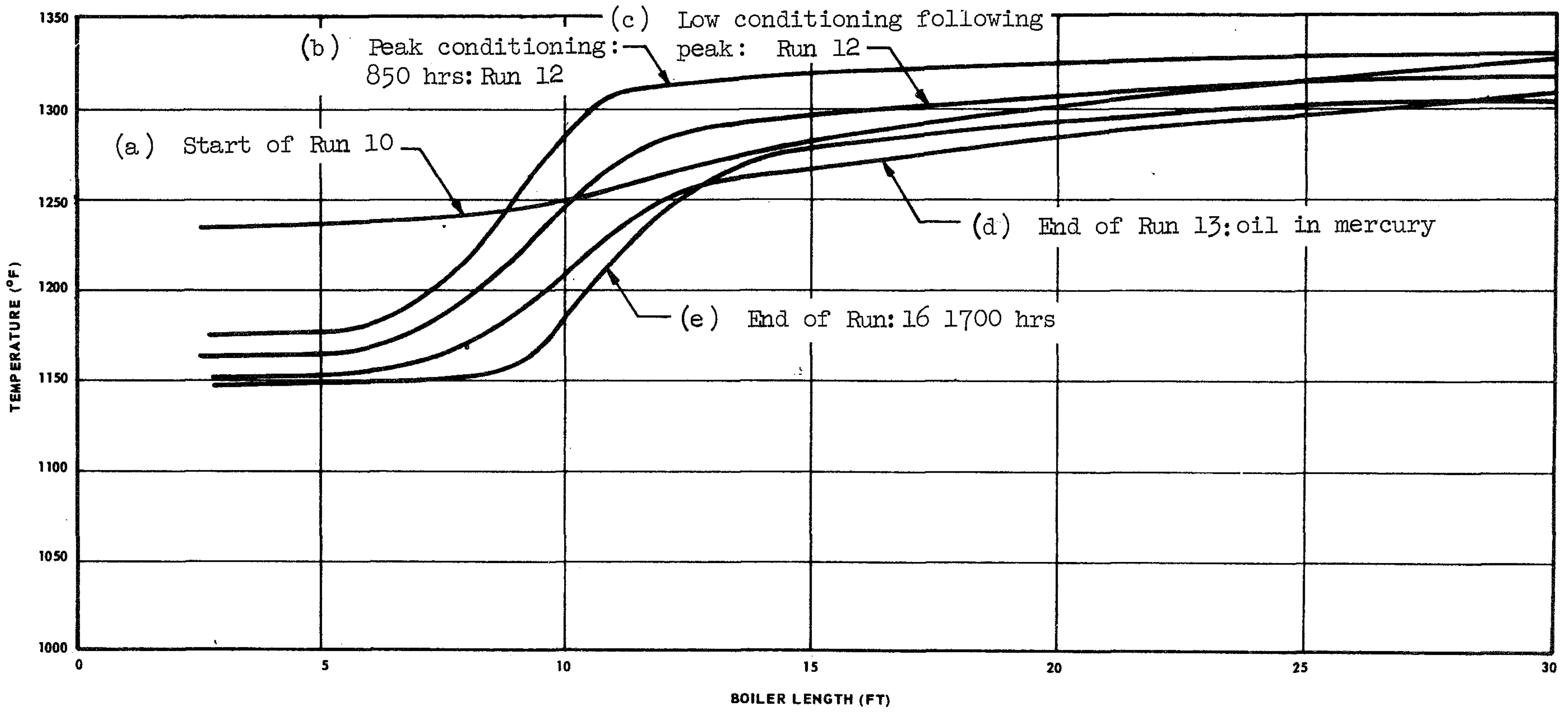


Figure 25. Comparative Boiler Temperature Profiles - Unit 3

Condition 'c' occurred about 24 hours after Condition 'b'. The steep slope of the profile moved to the right as a result of a partial deconditioning that occurred (probably due to oil or other contaminants in the loop from the previous shutdown). An occasion when oil was in the mercury loop, Condition 'd', indicated the least desirable profile shown (with the exception of the initial completely deconditioned profile).

It is interesting to note that the profile which has its steep-slope region most-removed to the right is for the last day of the test series (Condition 'e'). Even though the profile had shifted to the right, the boiler was in one of its most nearly conditioned points of the test series. This phenomenon was characteristic of the Unit 3 boiler; that is, the plug-region boiling tended to decrease with time even though the overall performance might be significantly improving. The plug region of the boiler was rather ineffective during the testing and became less effective with time. Thermally, however, the boiler was reasonably conditioned over much of the testing period.

A phenomenon observed with the Unit 3 boiler was a continued decline in mercury-side pressure drop. The pressure drop declined with time even though the thermal performance was improving. That is, the pressure drop early in the test series with a deconditioned boiler was higher (but normal) than later in the test series when the boiler was conditioned. Apparently, the percentage of boiling in the plug region of the boiler gradually decreased through the test series even though the overall thermal performance reached a period of complete or nearly complete conditioning. This is illustrated by the shifting of the boiling region in Figure 25.

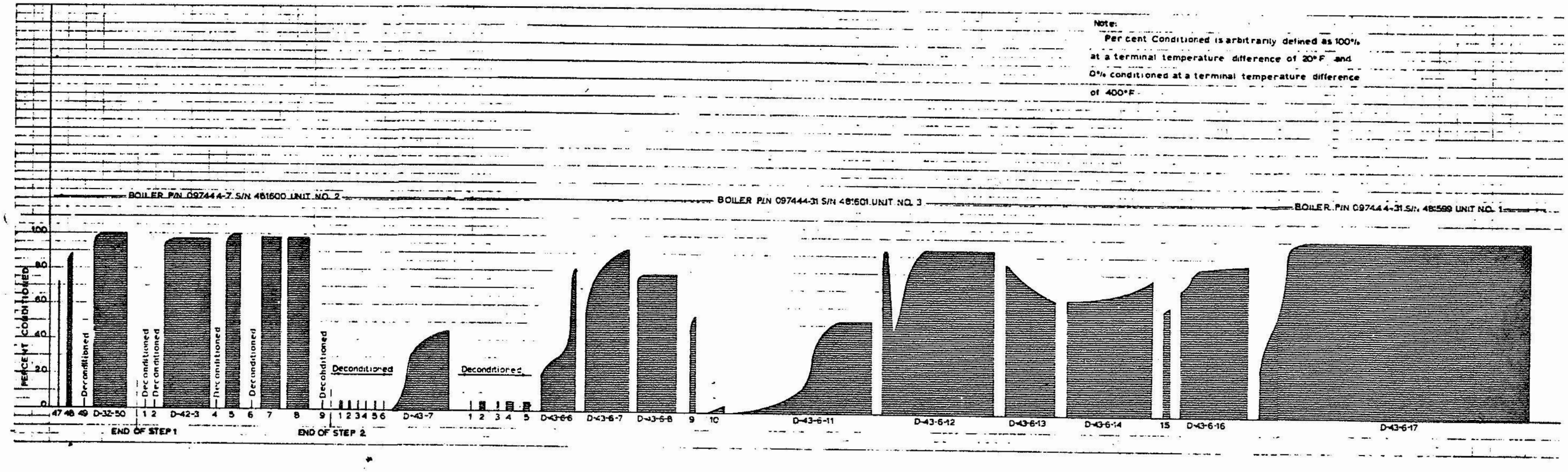
The third boiler (Unit 1) used in Step 3 had the most satisfactory performance of the three boilers tested. The boiler achieved conditioned performance within three days and continued to perform excellently for the remainder of the run. This was the longest run achieved during the period of this report (757 hours). Operation with this boiler ended when the boiler developed a mercury-NaK leak.

The performance of the Unit 1 boiler was only equalled by the Unit 2 boiler in Step 1 testing. Using terminal temperature difference as a criterion, these two boilers were equally conditioned in that they both had terminal temperature differences of about 20°F. The average terminal temperature difference during other operating times of Step 3 was more like 50° to 100°F.

To provide an overall picture of the performance of the boilers as a function of time, an illustration has been prepared which quantitatively defines how well conditioned each boiler was during its entire operating history. Terminal temperature difference has been selected as a measure of the conditioned state of a boiler. An arbitrary scale has been devised. The scale uses a terminal temperature difference of 20°F for a fully-conditioned state (100%) and a terminal temperature difference of 400°F for a fully-deconditioned state (0%). By this definition, the 0% conditioned state typically reflects a boiler with an exit quality of perhaps 60% at a mercury liquid flow of 10,000 pounds per hour. Although the above quantitative definition of boiler conditioning is arbitrary, it serves well for comparing one boiler with another and for observing time-related conditioning.

Figure 26 shows the history, with respect to conditioning, for the three boilers used in PCS-1. The ordinate of the figure defines the percent conditioned as defined above and the abscissa represents time. The length of each run on the time scale represents the relative length of the run. Run lengths range from minutes to 757 hours for the last run. Figure 26 allows an immediate overall picture of the increase and decrease in boiler conditioning resulting from shutdown, operating time, etc.

As stated previously the three boilers used in PCS-1 eventually failed due to mercury-NaK leaks. The failure of the first boiler (Unit 2) on 8 August 1966 was by far the most serious. On this first failure, more time was spent in diagnosis before shutdown, and consequently, the leak had become more extensive. As a result, major loop disassembly and cleaning were required to return the system to service. The subsequent failures were diagnosed more readily and only loop cleaning was required.



Note:
Per cent Conditioned is arbitrarily defined as 100% at a terminal temperature difference of 20°F and 0% conditioned at a terminal temperature difference of 400°F.

Figure 26. Boiler Conditioning Status PCS-1
29 Nov. 1965 through 16 Nov. 1967

The condenser is the mercury storage vessel for the loop and, therefore, a boiler mercury leak is reflected by a decrease in condenser mercury inventory. Figure 27 presents the condenser mercury inventory history for the first boiler failure. It is estimated that greater than 90 pounds of mercury leaked into the primary NaK loop before the system was shut down. More than 20 additions of mercury were made to the system to replenish the decreasing inventory. Figure 27 also shows a flow parameter which is obtained by dividing the indicated flowrate given by the primary loop venturi meter by the indicated flowrate given by the primary loop EM flowmeter. This flow parameter was found to be sensitive to primary loop fluid density. A distinct increase in its value occurred as the mercury content in the NaK increased. Subsequently, the primary pump current was also adopted as a measure of changing primary loop density.

The failure of the second boiler (Unit 3) occurred on 10 September 1967. Plotted data on condenser inventory, pump performance, and flowrate ratio are shown in Figure 28 for the time period during leak development. The plot of condenser inventory shows a very slight decline (about 3-4 lb of mercury) for the period from two days before shutdown to the day before shutdown. This decline in condenser inventory was only cause for observation, not alarm, since boiler inventory requirements could easily change by this amount. Also, there were no indications of mercury in the NaK as measured by the pump current and the primary loop flow ratio.

Mercury was first added at 1525 hours on 9 September 1967. From that time on, the pump current began to increase and the rate of condenser inventory loss became very significant (about 1 lb/hour). The primary loop flow ratio also began to increase steadily (the flow ratio normally wanders about ± 1% which makes it difficult to identify the beginning of a real upward trend).

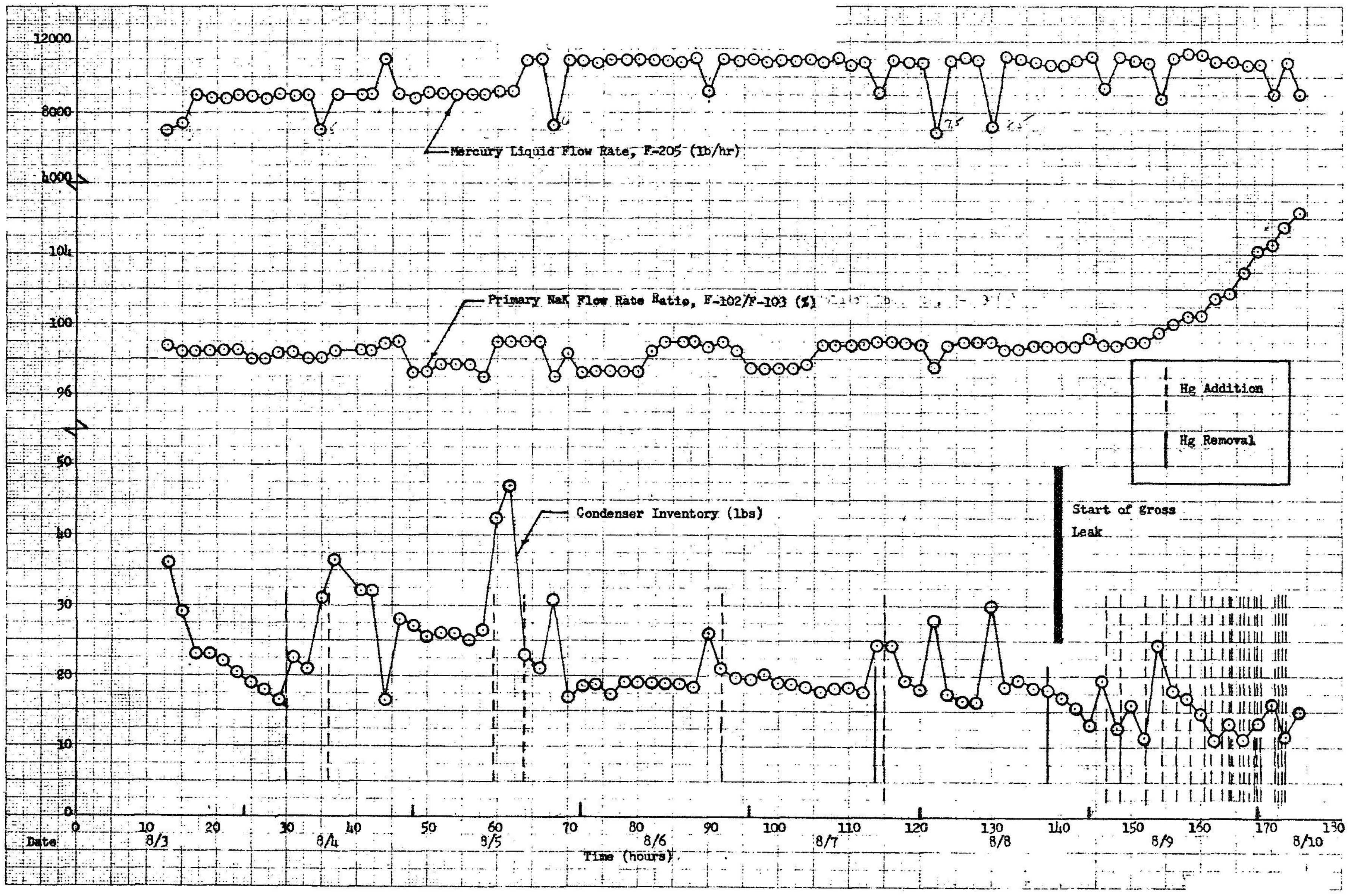


Figure 27. Evidence of Mercury to NaK Leak PCS-1 Step 3 Boiler Unit #2

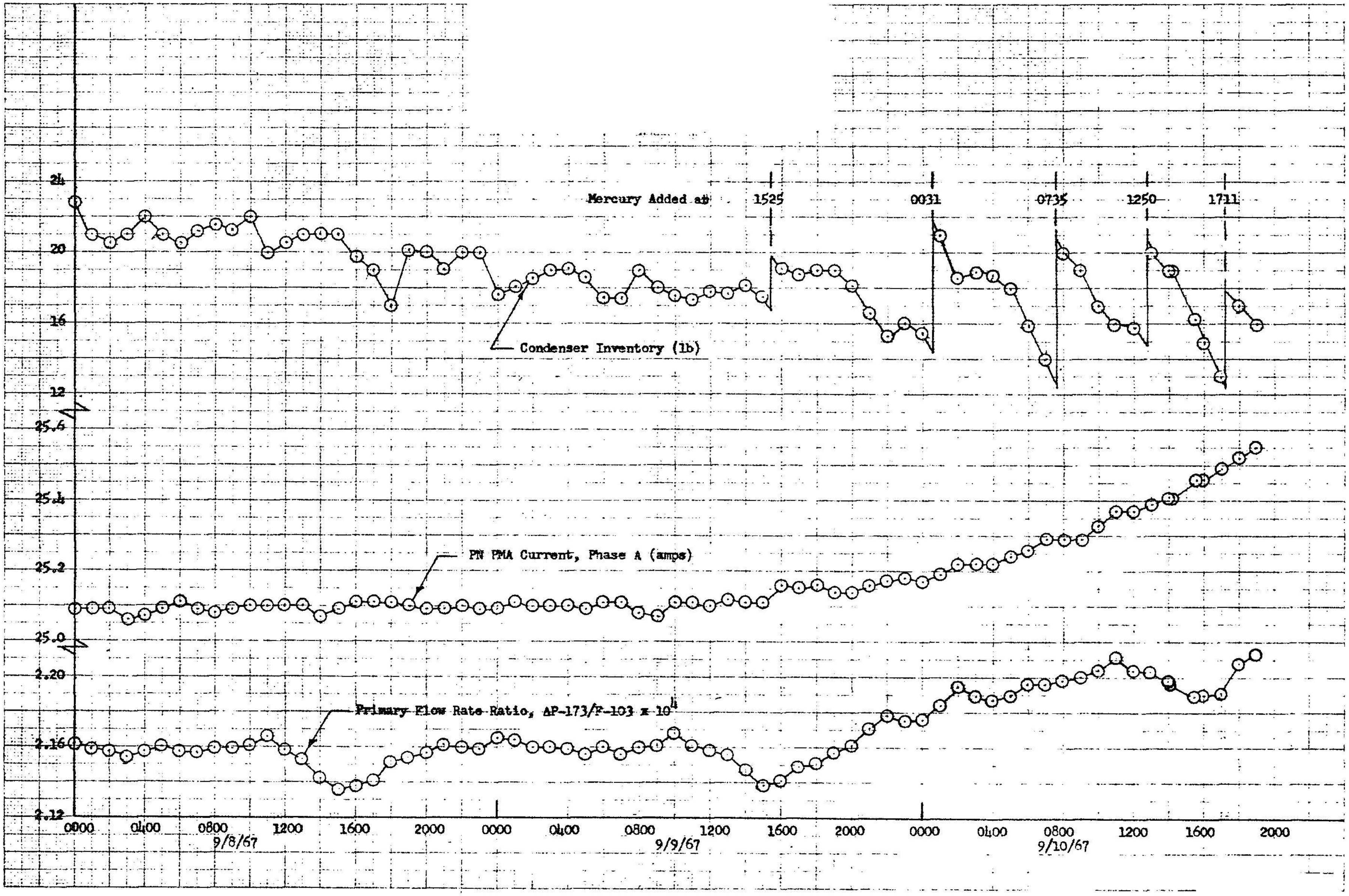


Figure 28. Evidence of Mercury to NaK Leak PCS-1 Step 3 Boiler Unit #3

The leak detection and shutdown decision were made much more rapidly in this situation than in the first (August 1966) boiler leak. By comparison, the pump current rose 2% this time compared to 6.5% in 1966. The primary loop flow ratio rose 3% as compared to 8% in 1966. The mercury inventory lost was 38 pounds (five additions) as compared to more than 90 pounds (20 additions) in 1966. The relatively quick decision to shut down resulted in reducing the seriousness of the failure.

The third boiler (Unit 1) failed on 15 November 1967. A plot of condenser inventory during the period of the leak is shown in Figure 29. The only indication of the leak was the loss of condenser inventory. The plotted parameter of primary loop flow ratio did not give an identifiable indication. The more accurate measure of pump current was not available since a backup electromagnetic pump, rather than the SNAP-8 pump, was in use. Confirmation of the leak was obtained from a primary loop NaK sample which indicated mercury in the amount of 9600 ppm in the dump tank. Because of dilution in the dump tank, the 9600 ppm measured was equivalent to about 18,000 to 20,000 ppm in the loop. This is the same amount of mercury found in the primary loop during the previous boiler failure on 10 September 1967. Consequently, the system shutdown was soon enough to require only loop cleaning and not extensive system disassembly.

Because of the repeated boiler failures, a new boiler design was initiated. The mercury containment material was changed from 9M (see Reference 14) to tantalum (see Reference 15). Although design and fabrication problems were introduced by switching to tantalum, the problem of corrosion and erosion of the mercury containment tubes was eliminated. Testing of a newly designed tantalum boiler (not covered in this report) is in progress and every indication is that a successful boiler design has been accomplished.

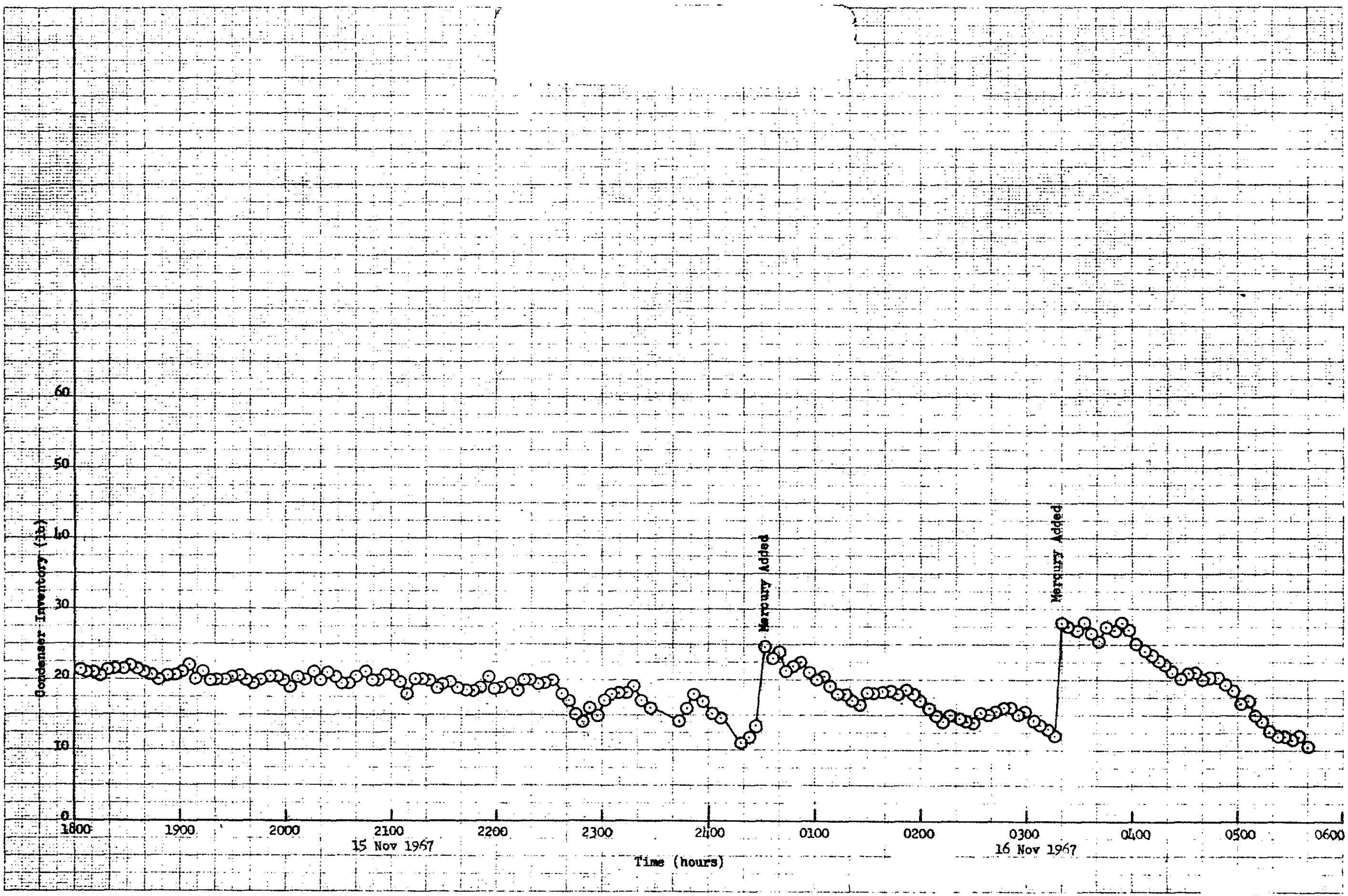


Figure 29. Evidence of Mercury to NaK Leak PCS-1 Step 3 Boiler Unit #1

## C. SYSTEM-COMPONENT INTERACTIONS

PCS-1 testing has resulted in acquisition of data regarding the performance of all the components in a system. Identification of interactions of the components and their effects on system output has been a major accomplishment of the program. The system and component interactions observed in PCS-1 are discussed below.

### 1. Boiler

#### a. Liquid Carryover

The many accumulated hours of system testing in PCS-1 have provided much data pertinent to boiler-induced system phenomena. One of the primary effects the boiler has on the system is a phenomenon called "liquid carryover." Liquid carryover consists of minute drops of liquid mercury being carried along in the vapor stream even though the vapor is superheated. Surface tension and infrequent contact of the drops with the heated boiler tube walls prevent vaporization of these liquid droplets.

Figure 30 shows test data reflecting the quantity of liquid carryover that has been experienced. At design operation, conditioned boilers show about 2 to 5% liquid carryover. A less-conditioned boiler has less effective heat transfer and a shorter length of boiler available for superheating and consequently, has somewhat more carryover. Figure 31 shows the relationship found between liquid carryover and boiler conditioning. A 50% conditioned boiler appears to have 4 to 7% liquid carryover compared to 2 to 5% for a 100% conditioned boiler.

The effect of liquid carryover on the system is a change in turbine performance. The lower velocity of the liquid droplets results in a drag effect on the turbine wheels. No data have been generated in PCS-1 testing to define the precise magnitude of the effect of carryover. However, extrapolation from steam data in the literature indicates that the system might experience approximately 0.75 kw loss of output power for each

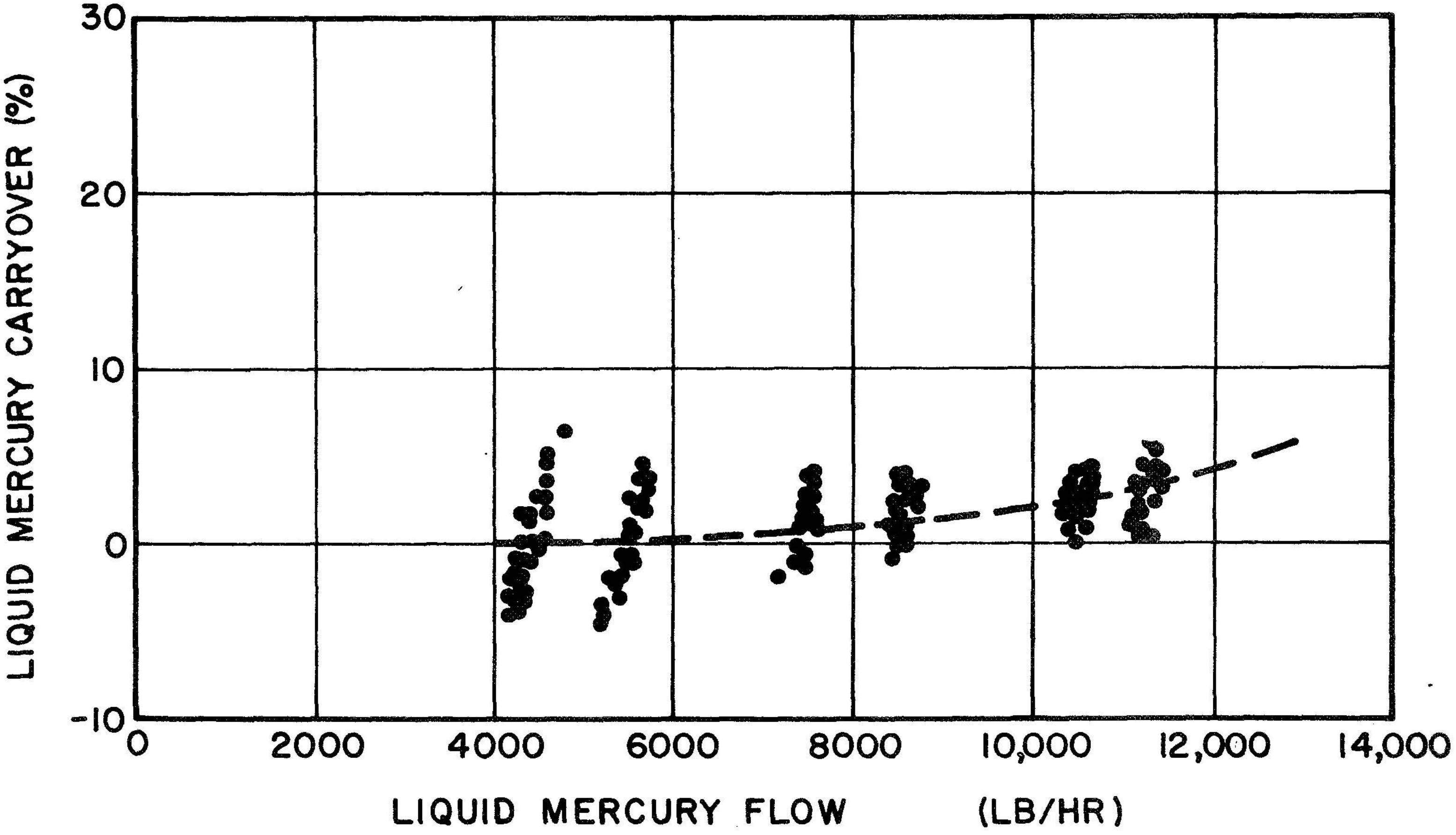
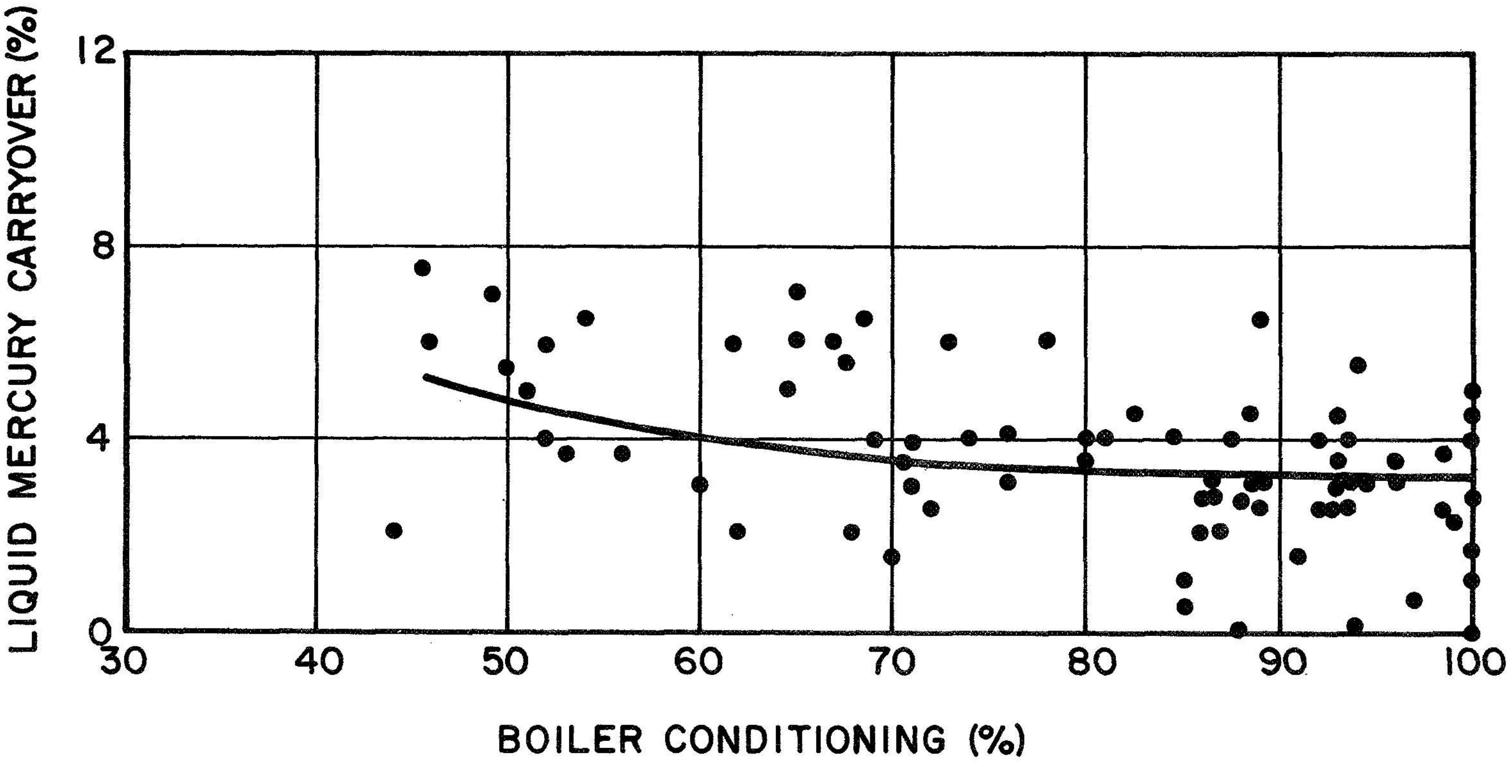


Figure 30. Liquid Mercury Carryover in Vapor Stream



NOTE: PERCENT CONDITIONED IS ARBITRARILY DEFINED AS ZERO AT A TERMINAL TEMPERATURE DIFFERENCE OF 400°F AND 100% AT A TERMINAL TEMPERATURE DIFFERENCE OF 20°F.

Figure 31. Effect of Boiler Conditioning on Liquid Mercury Carryover

1.0% of liquid carryover. For design purposes, it is assumed that a 4% liquid carryover will always prevail. Future boiler designs will be directed to the reduction of the carryover content. Turbine erosion damage due to the liquid carryover has not been a problem. Over 2000 hours of testing on a single turbine, with estimated carryover quantities of 4%, have shown only minor erosion damage to the bucket leading edges which is acceptable and would not effect performance within 10,000 hours of operation.

b. Stability

Pressure fluctuations in the mercury loop are generated within the boiler and transmitted throughout the loop. The system effect from the fluctuations is a cyclic turbine inlet pressure, cyclic condensing pressure, variable mercury vapor density, and sometimes, variable mercury liquid flowrate. The phenomenon can be caused by variable heat-transfer conditions within the boiler. Suspected factors within the boiler which tend to vary the heat transfer conditions are slug-flow boiling, nonuniform heat transfer of one tube with respect to another, and NaK flow stratification.

The boiler design objective was to restrict the pressure fluctuation to less than ± 3%. The fulfillment of this objective has been demonstrated in PCS-1 as illustrated by a typical pressure trace shown in Figure 32. The pressure oscillations have a maximum magnitude of ± 1.5% at a frequency of 0.5 Hz. Oscillations could be greater for a less-conditioned boiler; however, over a considerable range of conditioning, the test data have indicated that the fluctuations do not increase appreciably. A boiler sufficiently deconditioned to have excessive (greater than ± 5%) fluctuations would already be unacceptable to the system because of low vapor quality and potentially excessive turbine erosion rates. The minor pressure fluctuations (2 to 3%) do not represent a hazard to system operation.

The pressure fluctuations are reflected in the system as alternator output power variations which occur at the same frequency as the pressure and flow variations. Figure 33 shows a typical trace of alternator

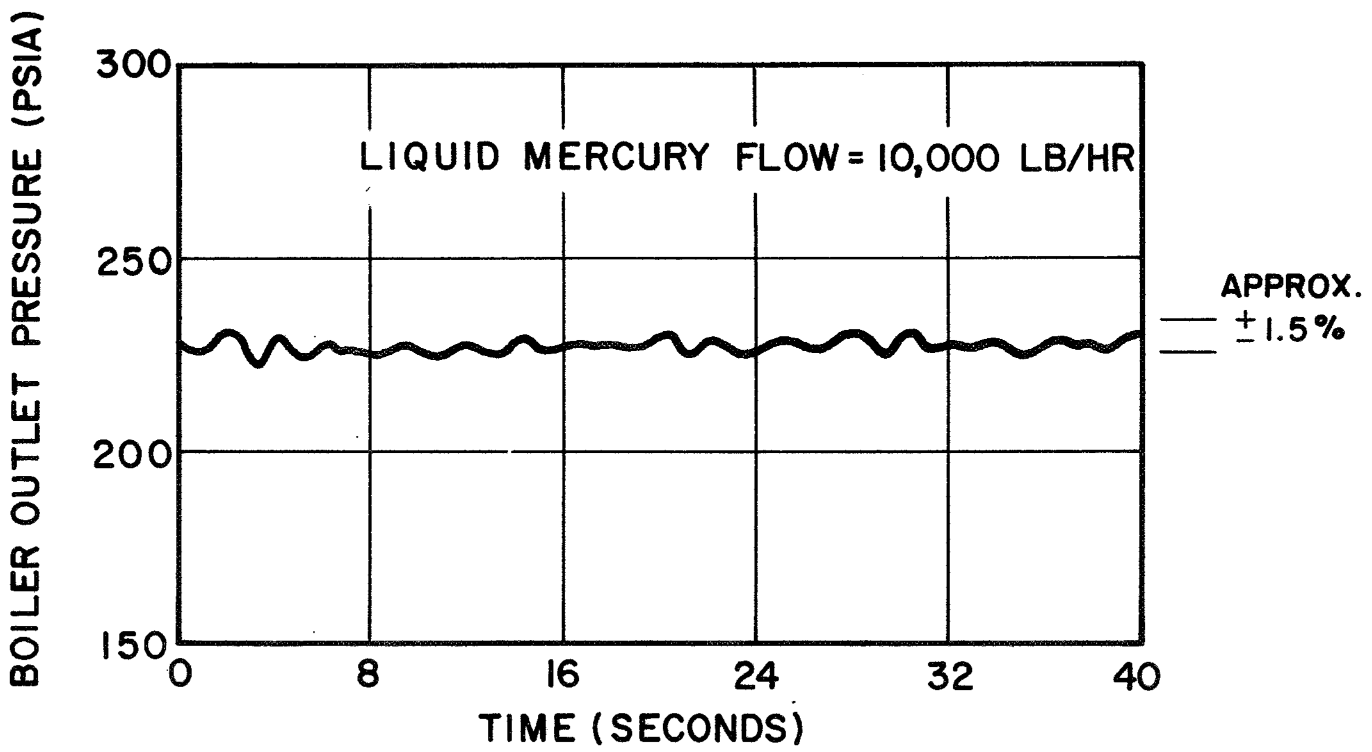


Figure 32. Boiler Outlet Pressure Fluctuations

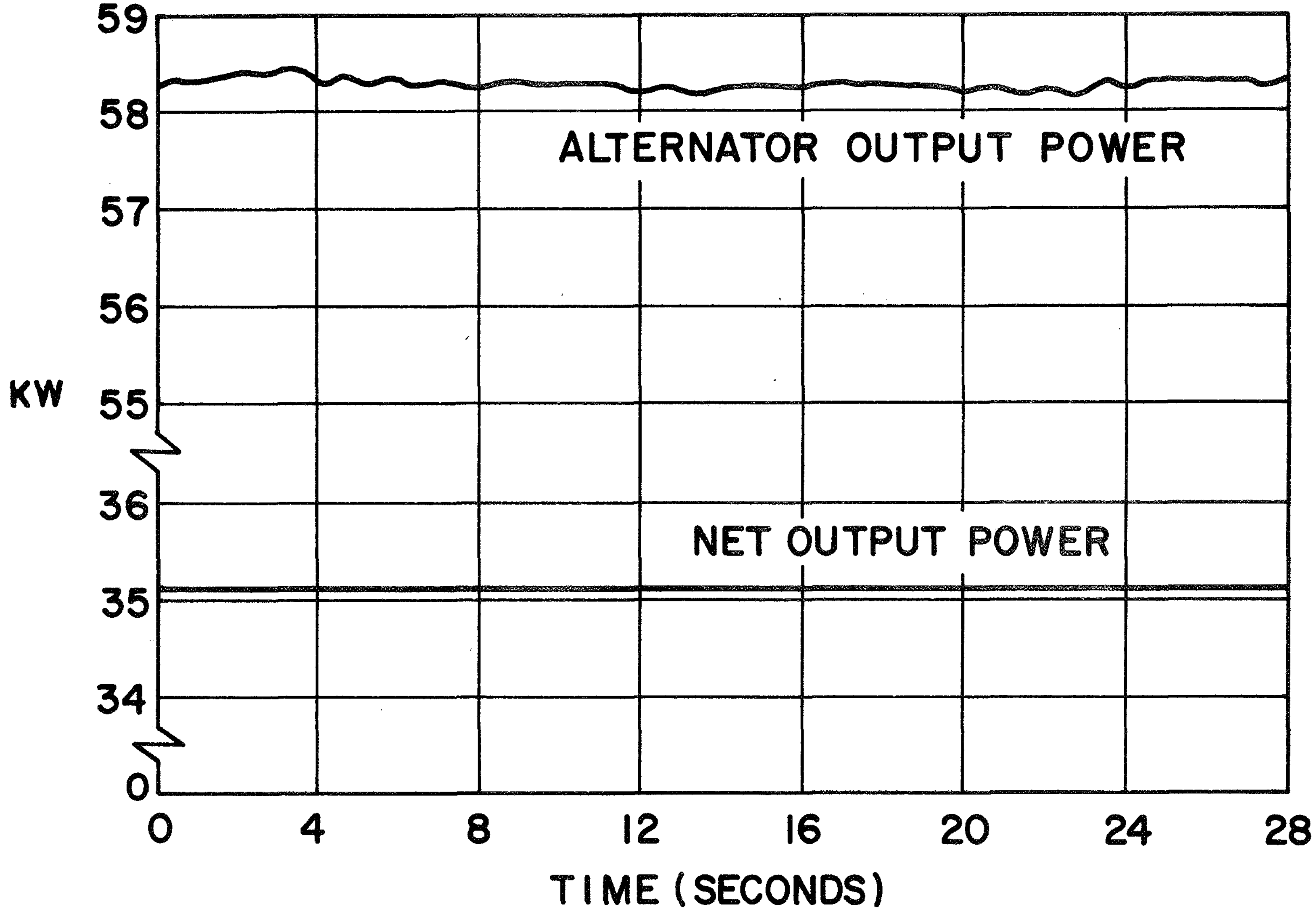


Figure 33. Effect of Boiler Conditioning on System Output Stability

output power, with variations that amount to ± 0.2% of the total power. The net electrical output of the system does not reflect the power variations seen at the alternator, since the SNAP-8 speed-control system absorbs excess power not required as useful electrical output. Therefore, the useful electrical output remains at a constant level with power fluctuations being absorbed by the parasitic load resistor of the speed-control system (see Reference 11). The penalty imposed by the boiler pressure fluctuations is a reduction in the net output power since the speed control set point must allow for the largest possible oscillations.

### c. Mercury Inventory

Variation of mercury inventory is another characteristic of the boiler. The amount of mercury contained within the boiler is a function of heat-transfer conditions and boiler conditioning status. The normal mercury inventory is 20 to 30 lb for a conditioned boiler. PCS-1 experience has shown inventories as high as 75 lb for deconditioned boilers. Large variations of boiler inventory can be a system problem during both startup and steady state operation. During startup, a large boiler inventory requirement means a greater amount of mercury must be injected to insure that the condenser liquid level reaches a minimum value of at least several inches. An inadequate condenser inventory can result in loss of mercury pump NPSH. During steady state operation large boiler inventory variations can alter the system operating point by affecting condenser operation. For instance, if the boiler inventory decreases due to boiler conditioning, the mercury, when returned to the condenser causes an increase in turbine back pressure.

### d. Transient Operation

The above descriptions of boiler-system interactions are based upon steady-state operation. The SNAP-8 startup scheme calls for mercury injection into the boiler with the NaK-side of the boiler at maximum operating temperature (1300°F). This gives a potential for higher initial heat-transfer rates than would be experienced during steady-state operation. Therefore, there is the possibility of boiling, and high pressure drops, near the mercury inlet end of the boiler during startup. This phenomenon has been observed during some, but not all, startups. A typical plot of boiler pressure drop for a startup involving a pressure-drop surge is presented in Figure 34. The boiler pressure drop temporarily reached a peak of about 130 psi and then settled back to a normal value near 35 psi. Other startups have had a smooth pressure-drop ramp with no peak. Presumably, the conditioning status of the boiler and the initial mercury flow affect the extent of a pressure-drop surge but a quantitative correlation has not been possible.

The effect on the system of a pressure-drop surge is a surge in boiler mercury inlet pressure. The change in boiler inlet pressure changes the pressure drop across the liquid-mercury flow control valve, resulting in a dip in liquid-mercury flow. No effects occur at the boiler outlet and, consequently, the mercury-vapor flow and alternator power do not show any response to the pressure surges. The net effect is that the mercury liquid and vapor flows are temporarily unequal, but the effect is absorbed by a temporary variation in boiler mercury inventory.

### 2. Turbine-Alternator Assembly

The turbine-alternator assembly is the heart of the SNAP-8 power conversion system. Every perturbation imposed upon the assembly directly affects the useful electrical output of the overall system. Consequently, the design, operational mode, and system interactions involving the turbine-alternator assembly performance are of paramount importance. Testing experience with the turbine-alternator assembly has demonstrated areas of significant component-system interactions.

#### a. Turbine Efficiency

The turbine has an aerothermodynamic efficiency of about 58% when operated at design conditions. Any deviation from design conditions causes an efficiency decrease and resultant decline in useful system output. During PCS-1 operation, internal turbine changes occurred that affected the system output. A shifting of the first-stage nozzle block

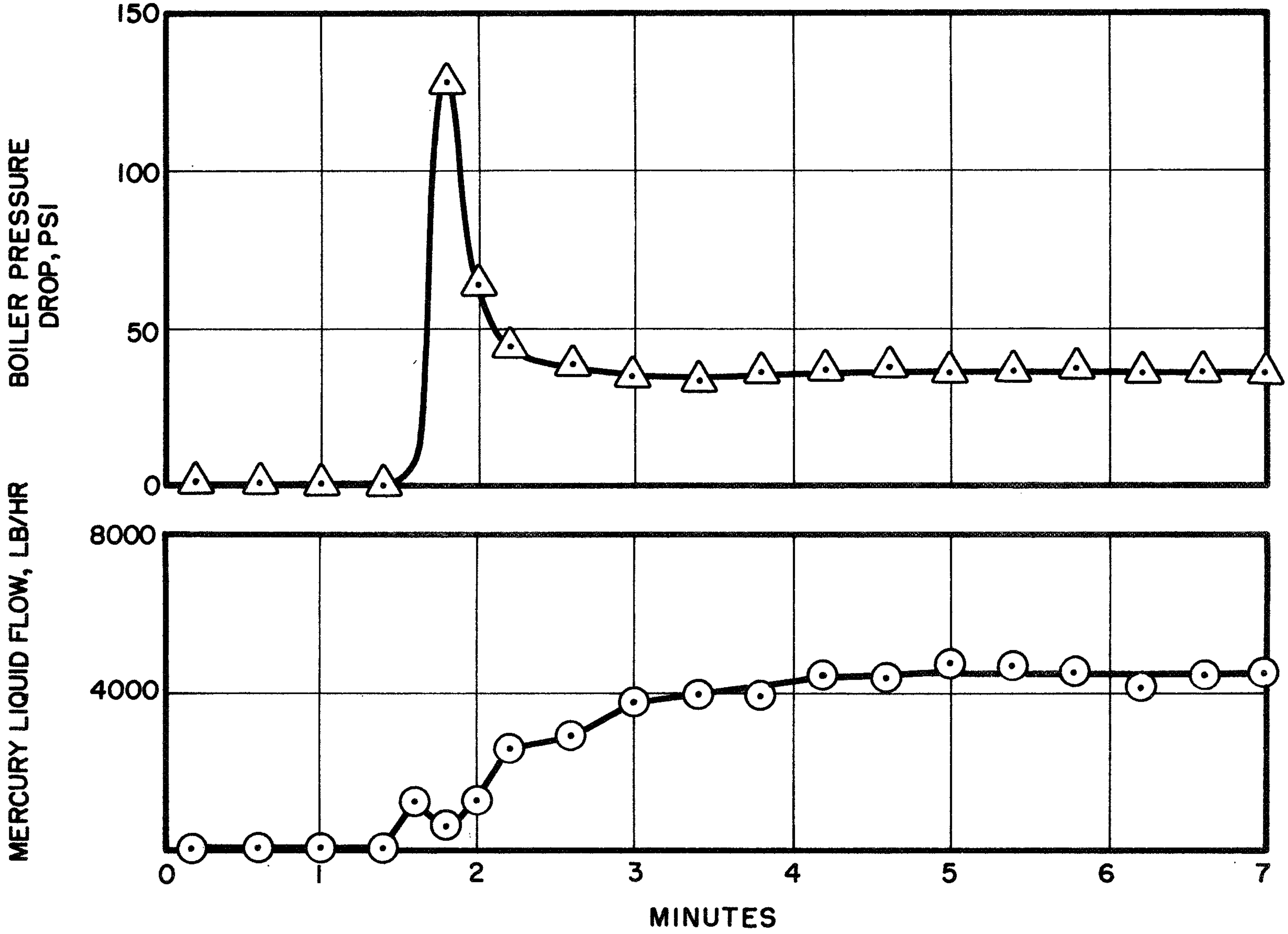


Figure 34. Boiler Pressure Surge During Startup

occurred which increased the effective nozzle area by about 13%. A cracked second-stage diaphragm, with associated increased leakage paths, was also found. The overall system effect was a decrease in efficiency and power output. The majority of the internal change appeared to have occurred over a period of one hour. Figure 35 shows the changes, during a time span of several hours, in turbine inlet pressure (which is inversely proportional to nozzle area), alternator electrical output, and turbine efficiency. For a few minutes there was an actual improvement in performance due to the initial nozzle-block shifting. The output power and turbine efficiency rose about 10%. Apparently, a more optimum nozzle effective area was temporarily achieved by reducing clearance and built-in leakage paths. However, the net effect after the nozzle block had settled into its final position was a decrease of about 10% in alternator output and turbine efficiency. The first stage nozzle block retention mechanism was redesigned and the second-stage diaphragm material was changed to correct this condition.

A second experience with internal turbine changes was the result of mass-transfer buildups within the turbine. This was apparently a function of system materials and boiler operation at low vapor quality. During an extended period of boiler operation at low qualities, a reduction of about 25% in first-stage nozzle area occurred. Reduction of nozzle areas in the other three stages also occurred, but to a lesser degree. These areas gradually increased as the boiler performance improved. The second, third, and fourth stages regained most of the area they had lost, but the first stage returned to only 85 to 90% of its original value.

The change with time of the first-stage nozzle effective area and mercury vapor quality are shown in Figure 36. At nominal operating conditions, the area change shown would result in a turbine-efficiency dip of 4 to 5 percentage points and a system output power dip of 4 to 5 kw. The remedial action was to maintain the boiler at higher outlet vapor qualities during periods of conditioning.

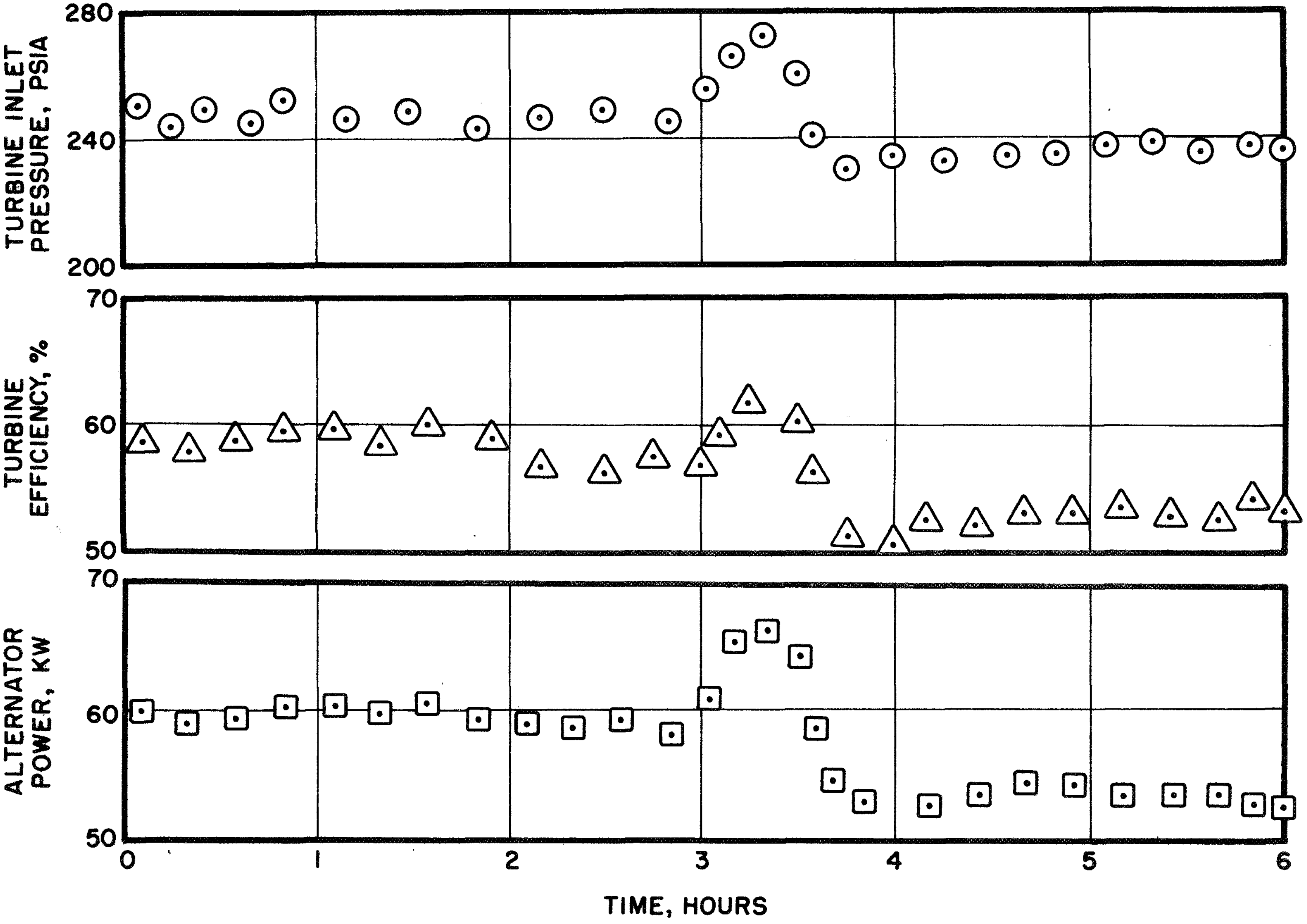


Figure 35. Effect of Turbine Nozzle Block Shift

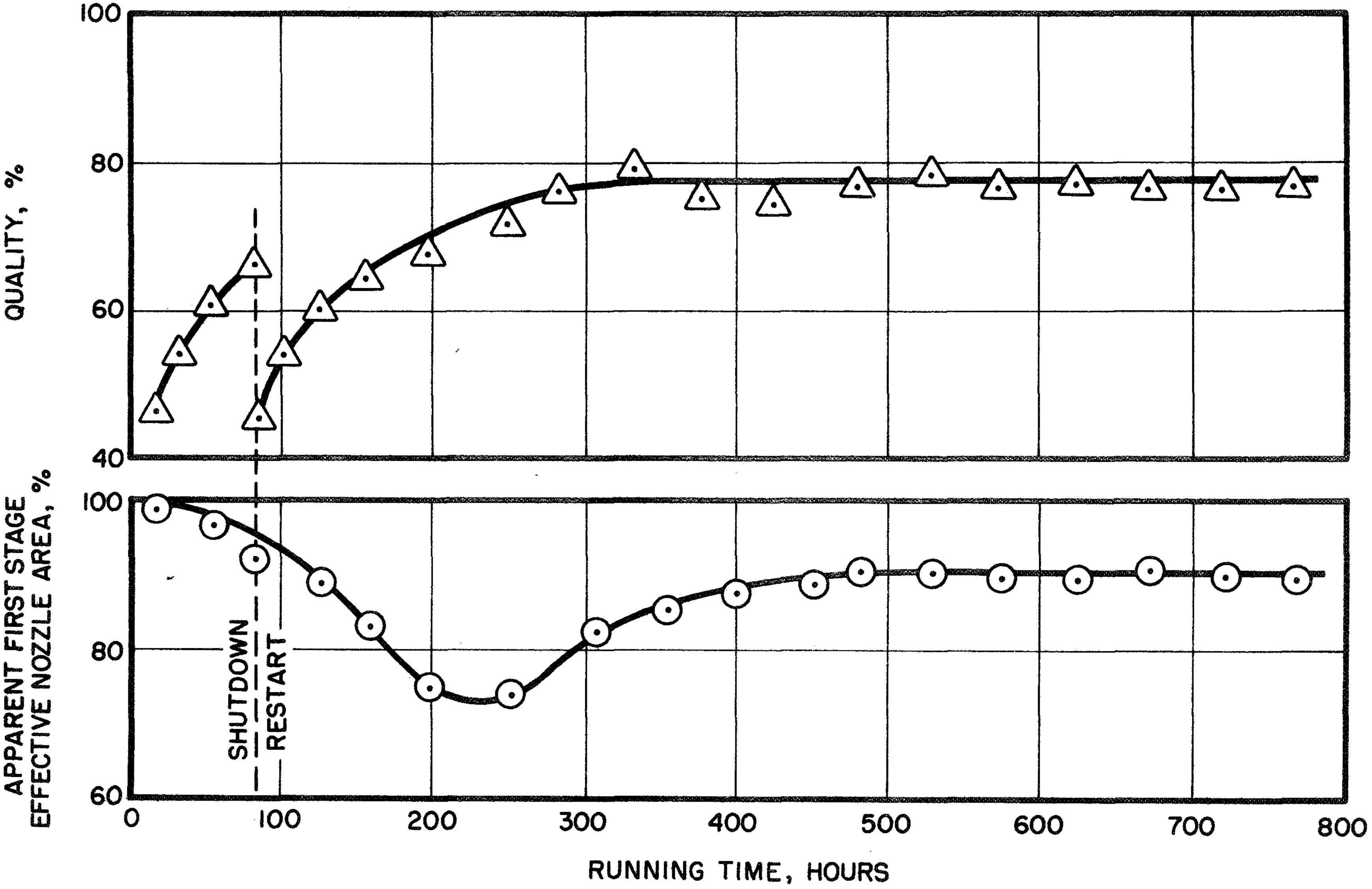


Figure 36. Effect of Mass-Transfer on Turbine First Stage Effective Nozzle Area

### b. Space Seals

The turbine-alternator assembly contains two different fluids. Mercury is used as the turbine working fluid, and a polyphenyl ether is used as a bearing lubricant. The prevention of the intermixing of these two fluids is critical to system performance. The assembly contains a space seal as a barrier to prevent intermixing (References 16 and 17). The space seal operates on the principle of dynamically holding the two fluids apart, and then venting to space those portions of the fluids which evaporate and thereby succeed in crossing the dynamic barrier. Space simulation was accomplished in PCS-1 testing by creating a vacuum.

The effect on the system of space-seal leakage is actually one of improved performance as shown in Figure 37. A loss of mercury decreases the condenser inventory, which increases the condensing area and decreases the turbine backpressure. Therefore, the system electrical output increases as a result of the inventory loss. This would only be true up to the point where the condenser inventory approaches zero, for beyond this point, there is the danger of mercury-pump cavitation. It is more desirable to minimize inventory loss to prevent reaching the critical point of condenser inventory depletion. Lubricant-coolant loss has no effect on system performance unless the inventory is depleted to the point of causing lubricant-coolant pump cavitation.

System testing to date has not been designed to accurately measure the long-term space-seal leakage and interdiffusion. Other tests have, however, demonstrated that space-seal leakage and interdiffusion rates are within the design objectives. The contribution of PCS-1 testing to space-seal evaluation has been in the area of system startup and shutdown leakage evaluation. Since the space seal depends on dynamic action to cause sealing, the startup and shutdown conditions require special static seals to restrict leakage. During a startup, rubbing-contact face seals are kept in

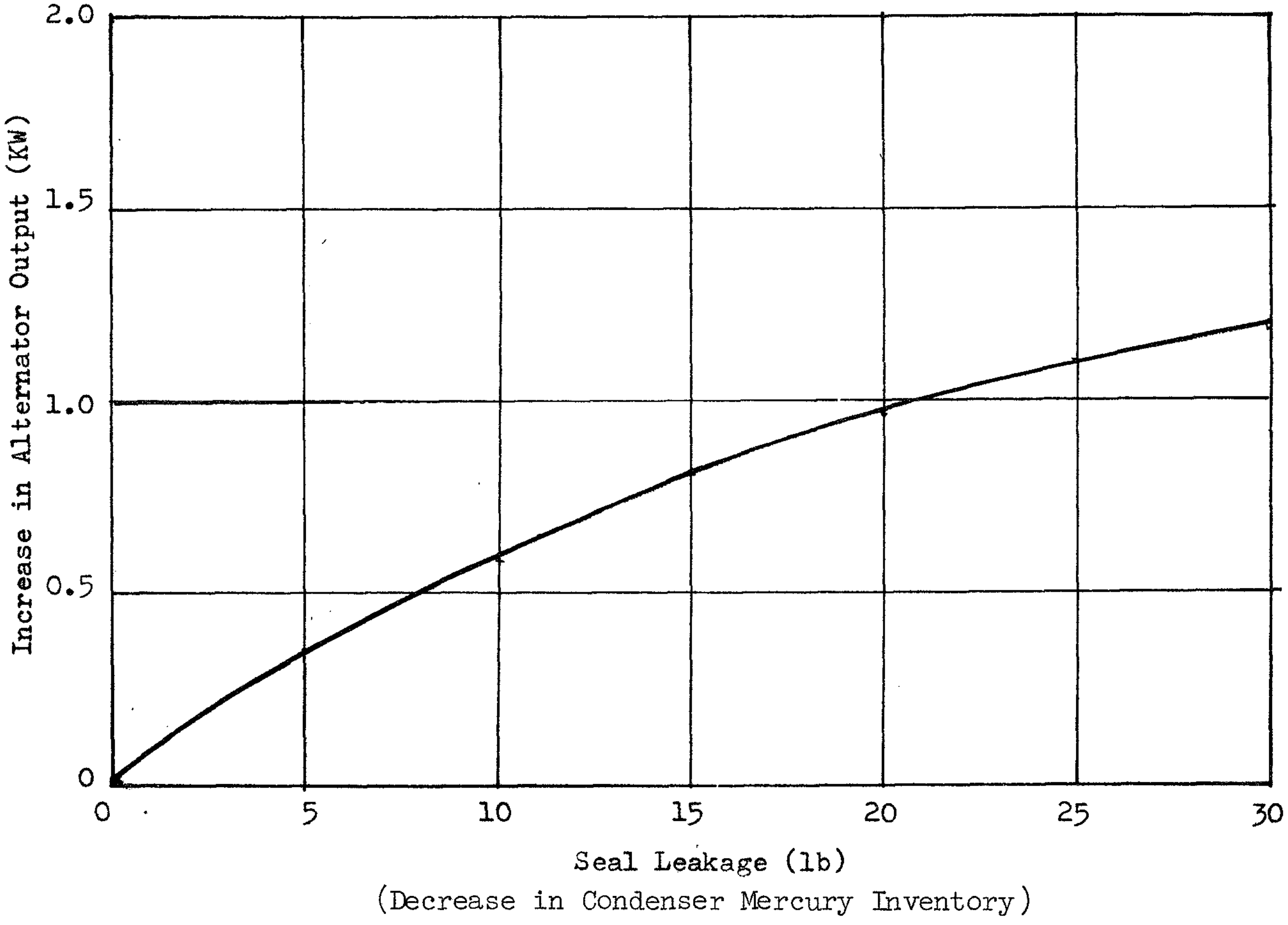


Figure 37. Effect of Space Seal Leakage on Alternator Output

contact until a minimum speed has been reached. When the minimum speed has been reached, the seals are pneumatically lifted. System testing has demonstrated that the startup and shutdown leakages can be effectively restricted. On isolated occasions, when the face seals were not properly engaged, startup and shutdown leakages were observed. But with properly functioning face seals, no visible leakage of mercury or lubricant-coolant has been detected. Design work is continuing on the face seals to improve their actuation method.

Provisions were made in PCS-1 testing to handle any gross contamination of the mercury by oil. The liquid mercury passes through a gravity oil separator. On some shutdowns, oil has been found in the separator, apparently the result of improper face-seal actuation or sealing. In zero-g operation, the system must depend on proper functioning face seals to protect the boiler from oil.

### c. Failures

Three turbine-alternator assemblies have failed during breadboard system testing. One failure involved the disintegration of the first-stage wheel and the other two were visco-seal seizures in the alternator resulting from severe overspeeds. The disintegration of the first-stage wheel was a good example of the possible severity of component-system interactions. The failure was the indirect result of a NaK-loop pump failure. The system was operating normally when an open circuit on the primary NaK-loop pump motor caused a loss of NaK flow to the boiler. The loss of NaK flow rapidly resulted in a loss of mercury superheat followed by a decreasing mercury vapor flow and quality. The decrease in mercury vapor flow reduced the boiler outlet mercury pressure which, in turn, allowed the mercury temperature to decrease because the mercury vapor was saturated. The overall effect on the turbine was a very rapid change in inlet mercury temperature with a maximum gradient of about 800°F per minute. The temperature gradient and liquid slugs in the saturated vapor precipitated the failure. The material for the turbine nozzles and wheels was changed from Stellite 6B to S816 which should provide the ability to withstand a thermal shock equivalent to that which caused the failure. A system safety feature was added to avoid a recurrence of the events which led to the turbine failure. An automatic transfer mechanism now starts an auxiliary electromagnetic pump (test support equipment) in the event of a loss of primary NaK flow.

### 3. Condenser

By establishing the turbine pressure, the condenser can have a considerable effect on system overall performance. PCS-1 testing has demonstrated two main areas of important component-system interactions.

#### a. Noncondensables

The condenser provides a natural barrier to the passage of any gas that cannot be condensed at the temperature and pressure of the condenser. The velocity of the condensed liquid leaving the condenser is not sufficient to move a gas bubble against the floating action of 1 g operation; during zero-g operation, the gas could move through the condenser. During ground testing, any noncondensable gas in the system is trapped in the condenser. The mercury-vapor velocity entering the condenser is sufficiently high that it is assumed that the noncondensables occupy a volume adjacent to the liquid-vapor interface. The effect is that the condenser has a decreased area available for heat transfer which results in an increase in turbine backpressure and a decrease in system electrical output.

The effect of noncondensables on the existing PCS-1 system performance is shown in Figure 38 where system electrical output is shown as a function of the magnitude of noncondensables. Because of the adverse effect of noncondensables on system performance, it is important to restrict their entrance into the system.

Two basic sources of noncondensables exist. The first source is incomplete outgassing and loop evacuation prior to startup which has been handled in PCS-1 testing by establishing minimum acceptable vacuum-retention requirements prior to startup. Prior to a startup, the vacuum system is valved-off and the pressure buildup rate is monitored. The acceptable buildup rate is established at a minimum that assures no potential noncondensable problems. Loop outgassing is assisted by pumping on the system with the boiler heated to full operating temperature by the primary NaK loop.

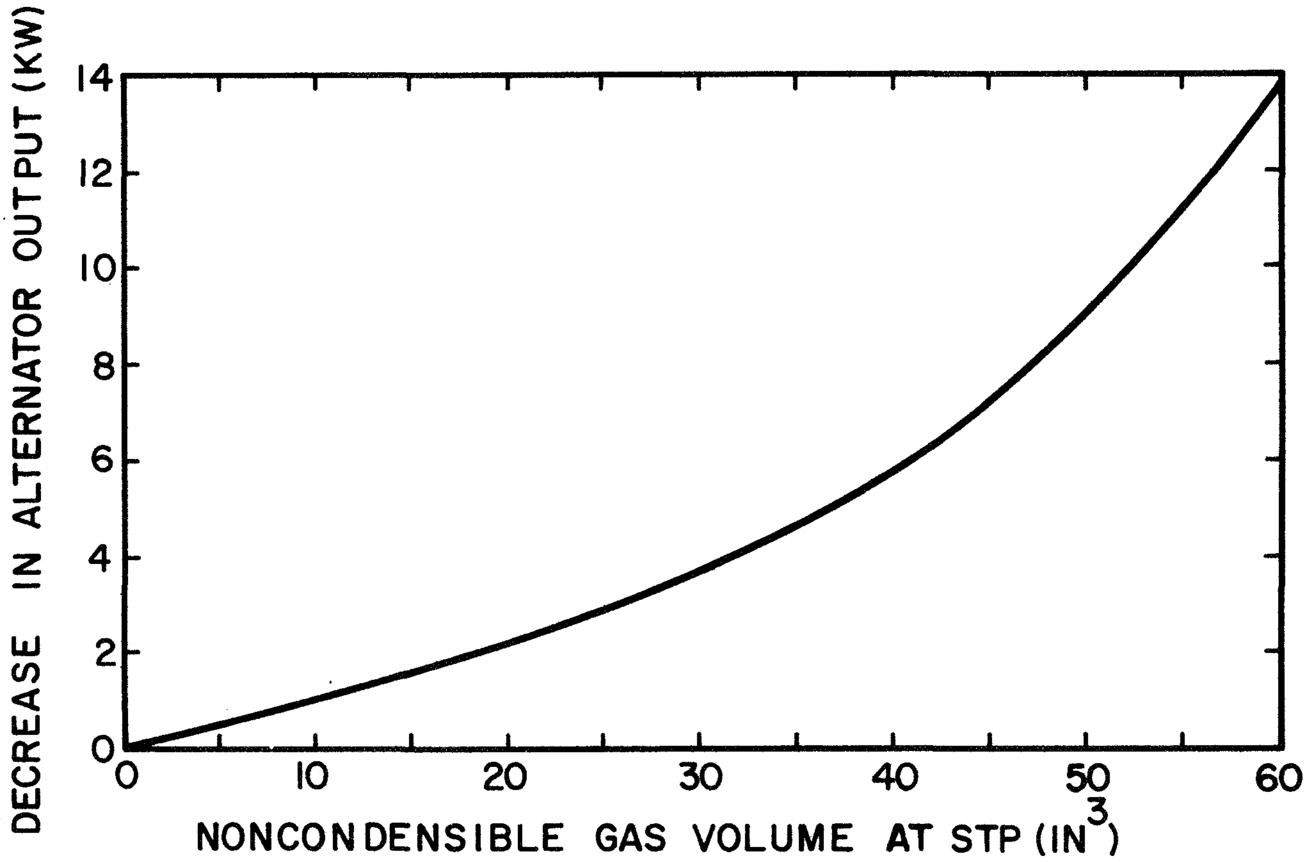


Figure 38. Effect of Noncondensibles on Alternator Output

The second source of noncondensables is in-leakage during operation and applies only to ground testing. With the exception of the area from the turbine exhaust to the condenser, the mercury loop always operates above atmospheric pressure. Therefore, there is ordinarily only a limited portion of the loop where a leak could permit gas entry. However, turbine interstage pressure instrumentation has provided an additional region where a leak could result in gas in-leakage. The interstage pressure instrumentation lines pass through an internal turbine cavity which is vented to the turbine exhaust. On several occasions in the test program, leakage has occurred at the location where these instrumentation lines pass through the internal turbine cavity. The result was a significant ingestion of noncondensables (air). This source of noncondensables has now been eliminated by changing from brazed to welded instrumentation connections.

The question arises concerning removal of noncondensables during testing. This has not been attempted to date in the test program. One problem is how to accomplish the removal. If the theory is valid that the noncondensable gas is located inside the tubes, then venting of the condenser inlet would probably be ineffective and only remove mercury vapor. Removal of the noncondensables from the top of the condenser would require raising the liquid-vapor interface to push the noncondensables out the top. To remove the noncondensables by this procedure would be impractical because the turbine back-pressure would rise simultaneously, probably to unacceptable levels. The opposite approach, of removing the noncondensables from the bottom of the condenser, could be used but would require lowering the liquid-vapor interface out of the condenser. Provided that the mercury pump NPSH was maintained, this approach might prove acceptable. However, no plans are presently in effect to attempt to vent the condenser. Except for the problem of turbine instrumentation tap leaks, which has been corrected, there appears to be no problem of noncondensable buildup.

### b. Stability

The condensing pressure (turbine backpressure) fluctuates in a manner similar to the boiler outlet pressure. These pressure fluctuations at the condenser affect alternator output power the same as the boiler outlet (turbine inlet) fluctuations. Therefore, an important consideration is whether the condenser pressure fluctuations are self-generated due to the condensing process or are simply reflections of the boiler inlet pressure fluctuations. If the pressure rise at the turbine inlet and at the outlet coincide, the torque developed by the turbine would not vary as much as it would if the pressure fluctuations were 180 degrees out of phase (a peak at the turbine inlet matching a dip at the turbine outlet). The ultimate power delivered by the system is a function of the source and phase relationship of the condensing pressure fluctuations.

PCS-1 test data have provided the answer to the question on the relationship between the condenser and the boiler pressure variations. Figure 39 shows traces of boiler outlet pressure and condensing pressure with variations essentially in-phase and of the same frequency. Therefore, it is concluded that system output power variations are minimum for the turbine inlet and outlet pressure variations that are experienced. There are no significant out-of-phase relationships.

## 4. Electrical Controls

The interactions between the electrical controls and the system fall into two main categories: The control required because of normal system perturbations and the control required because of sudden changes in vehicle load. Each of these phenomena has been evaluated during PCS-1 testing.

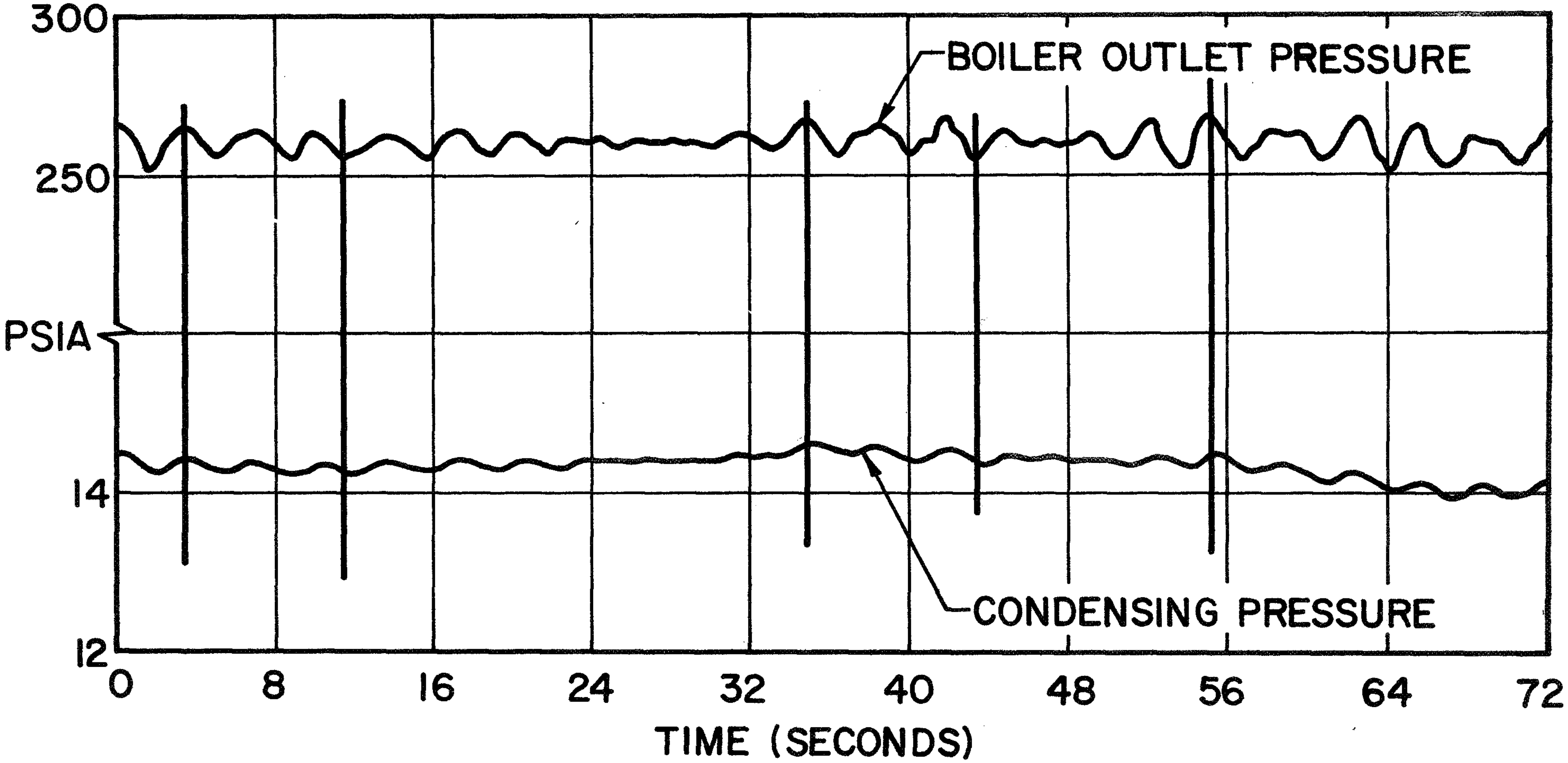


Figure 39. In-Phase Relationship of Boiler Outlet Pressure and Condensing Pressure

### a. Normal System Perturbations

Normal system perturbations comprise the fluctuations in flow and pressure caused by the boiler. These fluctuations result in variable torque development in the turbine. The requirement of the electrical controls is to vary the parasitic load so as to compensate for the variable alternator output and provide a constant vehicle voltage. Test experience has included boiler operation with performance varying from a relatively stable, conditioned state to operation at a deconditioned stage giving rise to alternator output power variations of ± 8%. The PCS-1 testing has demonstrated that the electrical controls maintain speed and voltage within the design requirements under all conditions.

### b. Sudden Change of Vehicle Load

The most extreme operating condition of the electrical controls is during a sudden application or removal of full vehicle load. This operating condition requires a sudden transfer of 35 kw either from, or to, the parasitic load resistor. A load transfer of this magnitude inevitably causes a perturbation in alternator speed and voltage. The objective, which was successfully met in PCS-1 testing, was to make the transfer with a frequency transient of no more than ± 20 Hz and with a damping time of not more than five oscillations. Figure 40 shows a trace of frequency and voltage during a typical application and removal of a 35 kw vehicle load. The perturbation magnitude and damping time are approximately equal to the design objective.

## 5. Pumps

A pump is used in each of the four loops of the power conversion system. Since the pump working fluids are liquid, the magnitudes of component-system interactions are small by comparison with the interactions of the components discussed thus far. Experience concerning the pumps has been

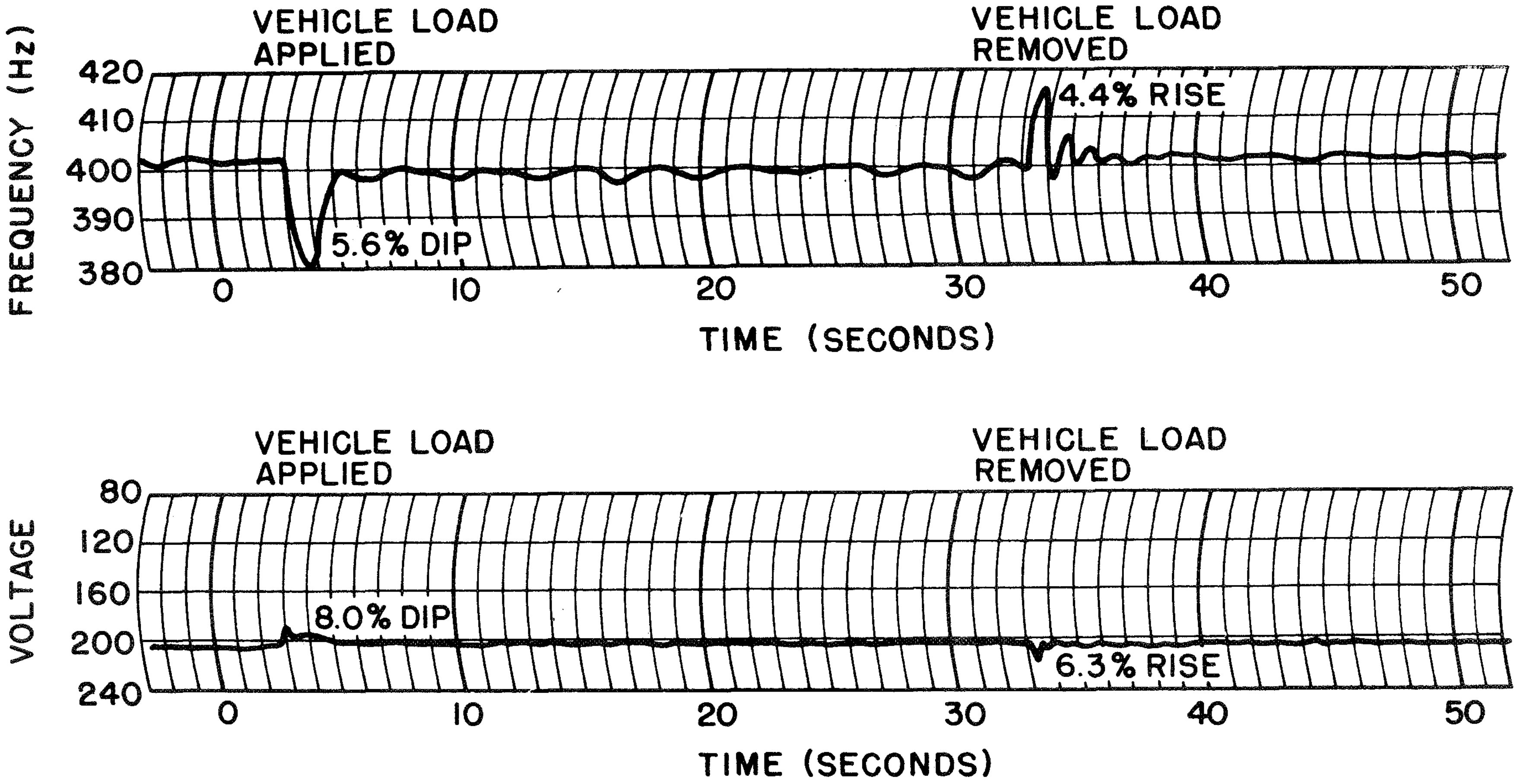


Figure 40. Suddenly Applied and Removed Load of 35 kw

primarily the observation of the effects on the components of system cleanliness and operational methods. The pumps for the mercury and NaK loops are discussed individually below. The lubricant-coolant pump has been virtually trouble-free and is not discussed.

### a. Mercury Pump

A very significant system-component interaction has been observed during PCS-1 testing. In most cases, the head developed by the mercury pump has been 3 to 8 feet (4 to 10%) lower than measured in earlier component test facilities. The probable explanation is mass transfer deposits in the eye of the pump impeller. Due to the mercury density, the centrifugal action of the pump "floats" contaminants to the eye of the impeller. The mercury velocity into the impeller is low enough that the deposits remain at the eye. It is estimated that only about 0.1 cubic inch of deposits would cause the decrease in head typically found with mercury pumps in PCS-1. Disassembly of pumps has confirmed the presence of mass transfer deposits. Further confirmation is given by the fact that the initial performance of pumps in PCS-1 has been at the higher, expected, performance level. The drop in head occurs within perhaps a day and then no further decrease occurs. Presumably, the maximum quantity of deposits is reached and beyond that point the contaminants pass through the pump. The need of a contaminant-free loop has been well-demonstrated by this phenomenon discovered in PCS-1 testing.

The second component-system interaction observed was associated with the mercury pump space seal which is functionally the same as in the turbine-alternator assembly. With respect to leakage and interdiffusion, the discussion of the turbine-alternator assembly space seal applies here also. In addition, two specific space-seal phenomena unique to the mercury pump have been observed during testing. On one occasion, the lubricant-coolant pressure at the discharge of the pump was set too high. As a result, the dynamic slingers were unable to scavenge the bearings and lubricant-coolant overran into the motor cavity. The effect of flooding the motor cavity is an increase in motor power of as much as 1 kw, depending on the degree of flooding. The increase in motor power must be supplied by a decrease in vehicle load unless the parasitic load has excess power available. The problem was corrected by operating with normal lubricant-coolant discharge pressures so that bearing scavenging is effective.

Another incident involving the space seal was a burned-out motor caused by mercury in the motor. Disassembly disclosed mercury droplets coating the windings and other interior surfaces and also revealed considerable corrosion damage. The start seals had worn considerably during a previous period of testing when they were engaged during operation. With worn start seals, mercury could cross into the oil-side of the pump-motor assembly during system startup or shutdown. The problem was corrected by adding a pump motor cavity drain.

### b. NaK Pump

Two primary component-system interactions have been experienced with the NaK pumps. The first type of interaction is the result of incomplete "bleeding" of the assembly. Before a pump is filled with NaK, its motor cavity is evacuated to remove all the gas. Any residual gas is bled during the NaK-fill operation. Incomplete bleeding results in erratic recirculation loop flow rates and high motor temperatures. On one occasion, gas entrapment in the recirculation loop caused flow variations of ± 2% in the main NaK loop. The gas in the recirculation loop had caused variations in recirculation loop flow which resulted in a heating and cooling cycle of the main pump-motor shaft. The temperature variation of the shaft caused a variation of the shaft caused a variation of impeller-to-housing clearance which changed the pumping characteristics of the pump. A subsequent modification was made which permitted direct bleeding of the motor cavity, thereby reducing the possibility of gas entrapment.

A second basic component-system interaction has been the result of mass transfer and NaK oxide deposits within the pump. Under normal operating conditions, the loop oxide level is maintained below 30 ppm by a NaK purification system which cold traps NaK oxides and mass transfer products. However, on many occasions, such as during pre-start loop purification, it was necessary to operate for periods without the NaK pump-motor assemblies. During these periods, electromagnetic pumps were used and the pump-motor assemblies were bypassed. When bypassed and sitting idle, the pumps were cold relative to the loop. Consequently, the pumps tended to collect oxides and mass transfer products. These deposits were the cause, at least once, of a pump completely freezing so that it could not be started normally. The pump was finally started by rotating it alternately forwards and backwards.

## D. SYSTEM OFF-DESIGN PERFORMANCE

Considerable system off-design testing was performed in PCS-1 to observe the reactions of the system and to compare the performance with a computer program which had been prepared for the study of off-design operation. One area of the off-design testing was to evaluate the effects of variations in system mercury inventory. The test objective was to observe the system response to changes in the amount of mercury inventory. Inventory variations (such as space seal leakage) can make significant changes in the system performance. Additional test conditions were selected to simultaneously evaluate the effects of varying the heat rejection loop temperature, a phenomenon to be expected on a mission involving sun and shade conditions.

The testing involved 12 sets of three data points. Each set of data points represented a condition where no parameters were altered with the exception of condenser inventory. Thus, the responses of all parameters in the system could be observed as functions of inventory change only. All variables were allowed to change during a given set of data points as dictated by the changes in inventory.

Data results from system mapping were too extensive for inclusion in this report but are reported in Reference 18. However, the results of a representative case are presented in Table III. The case selected is a mercury flowrate of 11,500 pounds per hour, a heat rejection flowrate of 42,000 pounds per hour, and a condenser NaK inlet temperature of 450°F. At these conditions, all the parameters were analyzed to determine the system response to an inventory variation from 50 to 10 pounds in the condenser.

Table III includes a comparison between the test data and the results of a SNAP-8 steady-state computer program, SCAN (SNAP-8 Cycle Analysis). The parameter trends compared favorably which was the significant feature to be ascertained. A column is also included in the table which gives an explanation of why the observed changes took place.

The testing was very successful and proceeded smoothly with the data being normal and consistent. The mapping was conducted over a wide range of parameters and considerable off-design data were obtained along with the basic mapping of the effects of mercury inventory loss.

A second area of off-design testing was to evaluate the effects of variations in boiler NaK inlet temperature with constant system mercury inventory. The primary objective was to observe the response to NaK temperature variations which simulate the variations to be imposed by the reactor. The testing was outlined to cover a range of NaK temperatures greater than the normal range of the reactor. The intent of this wider range was to gather basic off-design data for the system and components.

The testing was in progress when a shutdown occurred which resulted in a deconditioning of the boiler which made it impossible to complete the planned testing. Only six of the outlined 44 test conditions were completed and those were all at a mercury flowrate of 10,000 pounds per hour. Flowrates of 11,000, 12,000, and 13,000 pounds per hour were not accomplished. The complete test is planned for a later date when conditioned boiler performance is available.

Table III. System Response to Variable Mercury Inventory

Mercury Flowrate = 11,500 lbs/hr
HRL Flowrate = 42,000 lbs/hr
Condenser NaK Inlet Temperature = 450°F

| | Effect of Varying Condenser Inventory From 50 lbs to 10 lbs | | |
|---|---|---|---|
| Function | Test Data | SCAN Data | Explanation of Effect |
| Condensing Pressure | 1 psi decrease | 3 psi decrease | Increased condensing area in condenser |
| Condenser Mercury Outlet Pressure | 14 psi decrease | 15 psi decrease | Decreased liquid head in condenser and decreased condensing pressure. |
| Hg PMA Suction Pressure | 13 psi decrease | 15 psi decrease | Decreased liquid head in condenser and decreased condensing pressure. |
| Mercury Liquid Flowrate | 200 lbs/hr decrease | 100 lbs/hr decrease | Decreased Hg PMA suction pressure resulting in decreased Hg PMA discharge pressure. |
| Alternator Output Power | 3 kw increase | 3 kw increase | Lower turbine exhause pressure more than compensates for decrease in mercury flowrate. |
| Boiler NaK Outlet Temperature | No noticeable change | No noticeable change | --- |
| Boiler Pinchpoint Temperature Difference | No noticeable change | No noticeable change | --- |
| Boiler Mercury Pressure Drop | No noticeable change | --- | SCAN data not included since SCAN boiler performance is based on Step 1 data and Step 2 boiler performance was different than Step 1 performance. |
| Turbine Inlet Pressure | 4 psi decrease | 1 psi decrease | Decreased mercury flowrate. |
| Turbine Inlet Temperature | No noticeable change | No noticeable change | --- |
| Condenser NaK Inlet Temperature | No noticeable change | No noticeable change | Controlled parameter. |
| Condenser NaK Outlet Temperature | 3°F decrease | 3°F decrease | Less heat rejection due to higher cycle efficiency and decreased mercury flow. |

A summary of the system response for the data which were acquired is presented in Table IV. This table lists all the system parameters evaluated and gives the magnitude and cause of the particular responses observed. The responses to two different NaK temperature ranges are listed. The first range is for a boiler NaK inlet temperature variation from 1330°F to 1280°F. This range represents the temperature range of the reactor control system. However, the particular test conditions of PCS-1 were at a high boiler pinch-point temperature difference (difference between NaK temperature and mercury temperature at the location within the boiler where boiling begins; the difference is a minimum at this location). Since the variations in NaK inlet temperature from 1330° to 1280°F were not at the normal range of pinch-point temperature differences, the response to a second range of NaK inlet temperatures is also listed in Table IV. This latter range is from 1260° to 1210°F which represents a normal pinch-point temperature difference range of 60° to 30°F. The response of the system to the second temperature range was more pronounced. If the test program had been completed, it would have been possible to analyze the system response relative to the effects of simultaneously having the proper NaK inlet temperatures and the proper pinch-point temperature differences.

A comparison has been made between the test data and the data obtained from the SCAN computer program with independent variables of the test data points used as computer input. The system response as predicted by the computer program is also tabulated in Table IV to present the computer data over each of the two NaK inlet temperature ranges investigated. The observed trends appear normal and the agreement between the test data and SCAN is considered to be satisfactory.

## E. GENERAL CONTRIBUTIONS OF PCS-1

There have been many contributions by PCS-1 to the SNAP-8 Program and to liquid metal technology in general. The main body of this report has discussed these contributions, but from the viewpoint of test results. There are, however, various areas of general technology, not specifically related to test results, which are among the contributions of PCS-1. These latter contributions are discussed below.

### Table IV. System Response to Variable Boiler NaK Inlet Temperature

| Function | Effect of Varying Temperature From 1330 to 1280°F | | Effect of Varying Temperature From 1260 to 1210°F | | Explanation of Effect |
|---|---|---|---|---|---|
| | Test Data | SCAN Data | Test Data | SCAN Data | |
| Heat Input to Boiler | 1% increase | 1% increase | 0.2% decrease | 0.2% increase | Net effect of decreased heat transfer potential and increased mercury flowrate. |
| Condensing Pressure | No noticeable change | 0.1 psi increase | No noticeable change | 0.1 psi increase | Net effect of increase in mercury flowrate and decrease in turbine exhaust enthalpy. |
| Turbine Inlet Temperature | 30°F decrease | 50°F decrease | 50°F decrease | 50°F decrease | Boiler terminal temperature difference remains essentially constant. Difference between test and SCAN data possibly due to vapor line heaters |
| Turbine Inlet Pressure | 0.8 psi decrease | 0.6 psi decrease | 1.2 psi decrease | 0.8 psi decrease | Flow passes through turbine at lower pressure due to higher density caused by lower temperature and/or higher carryover. |
| Boiler Mercury Outlet Pressure | 0.8 psi decrease | 0.5 psi decrease | 2.4 psi decrease | 1.1 psi decrease | Lower turbine inlet pressure. |
| Boiler Mercury Outlet Temperature | 45°F decrease | 45°F decrease | 45°F decrease | 45°F decrease | Boiler terminal temperature difference remains essentially constant |
| Heat Rejection | No noticeable change | 1 kw increase | No noticeable change | 1 kw increase | Increased system heat input |
| Boiler Pinchpoint Temperature Difference | 45°F decrease | 45°F decrease | 35°F decrease | 45°F decrease | Pinchpoint follows NaK inlet temperature. |
| Boiler Mercury Pressure Drop | 3 psi decrease | 6 psi decrease | 8 psi decrease | 10 psi decrease | Lower pinchpoint temperature difference. |
| Boiler Mercury Inlet Pressure | 4 psi decrease | 7 psi decrease | 9 psi decrease | 10 psi decrease | Greater mercury liquid flowrate. |
| Condenser NaK Outlet Temperature | No noticeable change | No noticeable change | No noticeable change | No noticeable change | -- |
| Condenser Inventory | 4 lb decrease | 5 lb decrease | 8 lb decrease | 10 lb decrease | Decrease in boiler pinchpoint temperature difference causes increase in boiler inventory |
| Alternator Output | 0.5 kw decrease | 0.3 kw decrease | 0.8 kw decrease | 0.3 kw decrease | Lower turbine inlet temperature and more liquid carryover. |
| Mercury Liquid Flow | 100 lbs/hr increase | 100 lbs/hr increase | 100 lbs/hr increase | 100 lbs/hr increase | Lower boiler mercury pressure drop and higher mercury vapor density |
| Boiler Outlet Pressure Instability | ±1.0% increase | -- | ±1.3% increase | -- | Lower boiler pinchpoint temperature difference. |

## 1. Feasibility of SNAP-8

The PCS-1 operation has demonstrated the feasibility of a mercury Rankine space power system. PCS-1 is a complete power conversion system that has accumulated thousands of hours of operation as a system. It represents the successful merger of numerous components, each of which is theoretically system-worthy, to demonstrate a reliable, full-scale system.

PCS-1 has also demonstrated the ability of the SNAP-8 system to start up automatically, as will be required in the ultimate flight version. Simulations of completely automatic startups have been made which have not only demonstrated that the startup sequence can be programmed automatically, but that the power conversion system will be compatible with the reactor heat source during the stringent transients of a startup.

## 2. General Liquid Metal System Technology

Aside from the contributions of PCS-1 to the SNAP-8 program, there have been several points concerning liquid metal technology which have become evident from the development of, and testing in, PCS-1. The reliability of off-the-shelf commercial products was generally lower than had been anticipated. In general, these commercial products were not designed for a typical lifetime of 10,000 hours in liquid metal service. This experience indicates that the problem of test support equipment selection and implementation should not be underestimated. The proper selection of test support equipment, its environment, and lifetime-expectancy should be a well-thought-out part of system design.

System complexity, or the need to avoid it, was also demonstrated by PCS-1. A certain amount of backup or redundancy is necessary. However, on several occasions in PCS-1 testing, problems were encountered as a direct result of system complexity which led to inadvertent test-operation oversights. Obviously, a degree of backup is valuable, even essential. To find the optimum degree of backup is a challenge of proper system design. Probably PCS-1 went beyond the optimum in its degree of complexity. Fewer loop penetrations and fewer backup valves would probably have increased the overall reliability of PCS-1.

PCS-1 has also made a contribution in the selection and preparation of materials. The proper handling and cleaning of materials has greatly improved with operating experience. Boiler conditioning and noncondensable gas buildup in the condenser are examples where PCS-1 material cleanliness has had a measurable effect on system performance. Special cleaning procedures for materials preparation have been developed (see Reference 18) during PCS-1 testing. Materials preparation and handling techniques have reached a level conducive to reliable system performance.

Knowledge of materials properties has also been acquired. Testing of the turbine in PCS-1 has disclosed that Stellite 6B undergoes a phase transformation and hardening at the SNAP-8 operating temperatures, and becomes brittle. The understanding of 9M as a mercury-containment material was also enhanced from PCS-1 testing. The 9M was selected for its mercury corrosion resistance. However, test experience has shown this material to be less corrosion-resistant than expected. Excessive corrosion and erosion was found in the boiler. Consequently, 9M has been eliminated in favor of refractory metals for use in the boiler.

A valuable lesson was learned in PCS-1 with respect to electrical connections. Originally, for the sake of versatility, a soft-wired system (patch panels and relays) was used on electrical connections. There were approximately 20,000 soft-wired connections. The reliability of the connections was only about 6% (10,000-hour basis). The soft-wired system was eventually removed and replaced with a hard-wired system (soldered or mechanical connections). To date, after 2 and 1/2 years, there has not been a single case of a hard-wired connection failure. The test program with PCS-1 required many changes in electrical connections. To effect these changes without error, in a soft-wired system, was not possible. Thus, the use of a hard-wired system was a necessary condition and one which should be considered in any complex, changing test facility.

## V. CONCLUSIONS

Development of the SNAP-8 system has included many test programs. Several test facilities have been developed for the study and testing of components of the system. The most important accomplishment of the test program, however, has been the testing of all the components as a complete SNAP-8 breadboard power conversion system (PCS-1). PCS-1 has been instrumental in the identification and solution of numerous system and component problems. It has also added knowledge in the general field of liquid metal power conversion systems.

The PCS-1 test results that specifically relate to SNAP-8 are summarized as follows:

> Characteristics of boiler performance and system interactions have been identified.
>
> Turbine performance and design have been evaluated, leading to materials and design changes for improved integrity.
>
> Effects on the system of condenser performance and noncondensible gas buildup have been determined.
>
> The capability of electrical controls to maintain speed and voltage under conditions of both steady-state and sudden load transfers has been verified.
>
> Effects on the pumps of system gases and mass-transfer materials have been identified.

In the general field of Liquid Metal System Technology, PCS-1 has demonstrated:

- Feasibility of large Rankine cycle power conversion system.
- Feasibility of automatic, remote startup of large dynamic power conversion system.
- Importance of proper selection of test support equipment.
- Need for less complexity in system design.
- Importance of materials selection and cleaning methods.

Many areas of further study and testing remain. Some of these areas were identified in the PCS-1 test program; others are natural consequences of the SNAP-8 program and await evaluation in either PCS-1 or an equivalent system. These additional test areas are briefly discussed below.

Better low-gravity simulation would be a valuable contribution to the program. PCS-1 presently has the condenser mounted vertically with about a 2 to 3 foot liquid head between it and the mercury pump. A worthwhile modification would be to mount the condenser nearly horizontal and relocate the mercury pump, resulting in no liquid head between the condenser outlet and the pump inlet.

Transient system behavior has been studied to a degree in PCS-1. However, the whole realm of transient response, particularly as related to the rapid transients of system startup and to reactor capability, requires more evaluation.

Further analysis is required to determine long-time system and component degradation. The complete evaluation of component and system degradation can only be found through lengthy endurance testing. Continued endurance testing would further enhance the comprehension of possible degradation modes.

Mission adaptation tests are required to further analyze varying requirements that could be imposed upon the system. The proximity of the sun, sun and shade cycles, the requirement to shutdown and restart, and other mission-imposed conditions require further analysis.

Corrosion, erosion, and mass transfer create a problem which needs further investigation. Testing experience has identified definite incidents of corrosion and erosion damage. A worthwhile future test program would be to investigate the effects of temperature and flow as they relate to the possible deposition and removal of mass transfer products.

Further testing is recommended to gain experience with noncondensables and to determine their effect on system performance. A very valuable test program could be conducted to evaluate the relative merit of methods to remove the noncondensables while the system is in operation.

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