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THE SNAP II POWER CONVERSION SYSTEM

TOPICAL REPORT No. 16

2500-HOUR ENDURANCE TEST OF MERCURY RANKINE CYCLE POWER SYSTEM

AEC RESEARCH AND DEVELOPMENT REPORT

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SNAP II POWER CONVERSION SYSTEM
TOPICAL REPORT NO. 16
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RANKINE CYCLE POWER SYSTEM
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ABSTRACT

SNAP I is the designation for a 0.5 kw nuclear auxiliary power supply intended for application in a satellite. SNAP I was designed to convert thermal energy from the decay of a radioisotope into electrical energy using a Rankine engine with mercury as the working fluid.

A successful 2500-hour endurance test of a complete developmental version of the SNAP I power conversion system utilizing a prototype turbomachinery package, an electrically heated boiler, and an air-cooled condenser was accomplished during the months of January to May 1960. This report describes that test, the background leading to the test, and the results obtained.

All indications from the data obtained during the test and from inspection of the system following the test were that many more hours of satisfactory operation could have been obtained on all major system components except the rotating unit pump. The mercury-lubricated bearings, the turbine, and the alternator, all demonstrated excellent endurance capability. Based on previous component tests, it is concluded that the pump performance deterioration was caused by air entrainment in the liquid mercury.

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1.0 INTRODUCTION

SNAP I is the first of the series of Systems for Nuclear Auxiliary Power being developed to provide electrical power in space. Originally developed to provide 500 watts of electrical energy for a 60-day period in a satellite application, a prototype SNAP I system was utilized to investigate the problem areas of long-term operation. This investigation is the subject of this report. In order to adequately describe the SNAP I system tested and the components making up the system, SNAP I development is briefly discussed.

1.1 Description of SNAP I

SNAP I is a mercury Rankine power conversion system. It converts thermal energy to electrical energy by means of a mercury vapor turbine driving a generator. In February, 1957, TRW actively began the development of the SNAP I power conversion system hardware under AEC Prime Contract AT(30-3)-217. This work was performed by TRW under subcontract to the Martin Company. The concepts selected to meet the requirement of providing 500 electrical watts for 60 days in space were as follows:

1. Use thermal energy from the decay of a radioisotope to vaporize the mercury in a boiler.
2. Convert energy in the high pressure, high temperature mercury vapor to electrical energy in the turbomachinery package. Mount all the moving parts of the system on a single rotating shaft and hermetically seal the package.
3. Condense turbine exhaust and reject the waste energy from the system to space in a condenser-radiator.

TRW was responsible for the development of the turbomachinery, condenser-radiator and controls portion of the system. The Martin Company was responsible for the radioisotope boiler and systems integration.

System analysis and component development testing resulted in the selection of the pressures, temperatures, and flow rates identified below.

<u>Location</u>	<u>Pressure, psia</u>	<u>Temperature, °F</u>	<u>Flow Rate, lbm/min</u>
Turbine inlet	210	1300	1.9
Condenser inlet	2.0	500	1.9
Pump inlet	1.9	330	12.0
Pump outlet	290	330	12.0

Component and subsystem development resulted in the turbomachinery package shown pictorially in Figure 1-1 and in cross section in Figure 1-2. This turbomachinery package contains many unique features never before found in a Rankine system. The stringent requirements of high performance, reliability, and unattended long-duration operation in space, dictated each unique feature. All components are mounted on a single shaft supported by mercury-lubricated bearings. The three stage, axial flow, mercury vapor turbine provides the shaft energy to drive the alternator and liquid mercury pump. The rotor speed of this package is 40,000 rpm with the alternator providing electrical power at 2000 cps. Total weight of the package is 15 lb.

Significant features of components making up this package are as follows:

Bearings

The shaft bearings are the hydrosphere type capable of supporting axial as well as radial loads. The developmental program consisted of analytical and experimental evaluation of several bearing configurations and materials combinations. The resulting hydrosphere bearing and socket is shown in Figure 1-3. Figure 1-4 shows the socket configuration utilized. The radial clearance between the sphere and socket is 0.0001 inch with the sphere bottomed. During operation the radial clearance was in the range of 0.0002-0.0003 inch.

Lubricant is supplied to the bearing via a flow restriction. Such a restriction is required to insure that bearing supply pressure will increase if axial thrust increases in order to support the increased load. With mercury lubricant supplied at 350°F, the bearing power consumption is approximately 100 watts at 40,000 rpm. Bearing power losses are a cube function of shaft speed. AMS 5626, a tungsten alloy tool steel (18-4-1), was utilized as the material for both the sphere and socket. This steel was treated to a hardness of 61-65RC.

Turbine

While mercury vapor turbines had been utilized in commercial power plants, the SNAP I application dictated new design requirements. The analytical and experimental turbine program resulted in the selection of a three stage, axial flow, impulse turbine capable of high efficiency at the low output power required. Table 1 shows the essential characteristic of this turbine. Figure 1-5 shows one wheel of the turbine. AMS 5626, a tungsten alloy tool steel (18-4-1), treated to a hardness of 55-59RC was used to fabricate the turbine wheels and stators.

Alternator

As a result of the evaluation for environmental, electrical, stress, and packaging considerations, a radial air gap, permanent magnet, 6 pole, single phase, 2000 cps alternator, rated at 530 watts, 0.8 power factor, and 115 volts, was selected.

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ROTATING UNIT AND SHAFT ASSEMBLY

TURBOMACHINERY PACKAGE DESIGN FEATURES

FIGURE 1-2

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HYDROSPHERE BEARING AND SOCKET

HYDROSPHERE BEARING SOCKET CONFIGURATION

FIGURE 1-4

AXIAL FLOW IMPULSE TURBINE WHEEL

TABLE 1
GEOMETRIC PARAMETERS OF SNAP I TURBINE

<u>Parameter</u>	<u>First Stage</u>	<u>Second Stage</u>	<u>Third Stage</u>
Nozzle			
Number of Passages	1*	7	21
Exit Angle, Deg.	16.0	16.0	18.0
Mean Diameter, In.	1.85	1.80	1.75
Axial Chord, In.	---	0.225	0.225
Exit Blade Height, In.	---	0.1001	0.1145
Throat Width, In. ²	0.0752(dia)	0.0358	0.0558
Exit Width, In. ²	0.1040(dia)	0.0642	0.0709
Trailing Edge Thickness, In.	---	0.010	0.010
Rotor			
Number of Passages	58	44	50
Inlet Angle, Deg.	24.0	27.5	39.6
Exit Angle, Deg.	22.9	28.5	36.1
Mean Diameter, In.	1.85/1.85	1.80/1.75	1.75/1.75
Axial Chord, In.	0.180	0.180	0.180
Blade Height, In.	0.1312/ 0.1312	0.1108/ 0.1608	0.1316/ 0.1316
Tip Clearance	0.004	0.004	0.004
Leading Edge Thickness, In.	0.006	0.010	0.010
Trailing Edge Thickness, In.	0.006	0.006	0.006
Admission, %	5.0	33.0	100.0

* First Stage Incorporates a Conical DeLaval Nozzle

The alternator utilizes an hermetically sealed stator. Special techniques for insulating and sealing the stator from corrosive attack by mercury vapor allow the unit to operate at 500°F without cooling. Figure 1-6 shows the SNAP I permanent magnet alternator. Figure 1-7 shows the electrical performance of this unit. By connecting the windings for two-phase operation, an efficiency of 90% can be obtained. The unit exceeded its overload requirements; it has operated continuously at 1200 watts output with no adverse effects.

Pump

The mercury condensate and lubricant pump developed for SNAP I combines a centrifugal impeller, 0.4 inch in diameter, with a jet boost stage. This pump combination satisfied the severe requirements of cavitation performance with high efficiency. Figure 1-8 shows pump performance as a function of speed, flow rate, and impeller front face clearance. Figure 1-9 shows the pump impeller. The impeller was made of AMS 5643 (17-4PH SS) treated to a hardness of 41-47RC.

To control the speed of the turbomachinery, the SNAP I control senses the alternator frequency and uses any deviation from 2000 cps to modulate a pressure regulator on the boiler inlet which results in increased or decreased flow to the turbine. Turbine inlet temperature was maintained constant by a control integral with the boiler.

The 2500-hour endurance run was obtained with a developmental version of SNAP I known as the Ground Test System or GTS. The primary point of the GTS design philosophy was that it resemble as closely as possible the SNAP I system that would be used in space. It also had to be capable of being a flexible, easily modified unit that could be economically tested in a ground test facility. These two requirements resulted in the use of electrically heated rather than radioisotope-heated boilers and a convective-cooled rather than a radiant-cooled condenser. Figure 1-10 shows the basic system arrangement proposed for the flight version of SNAP I; this arrangement was dictated by vehicle integration considerations. Figure 1-11 shows how the basic arrangement was translated into the hardware arrangement for the Ground Test System. This GTS concept satisfied the three requirements just stated. No major system changes would be needed to evolve into flight versions incorporating radioisotope boilers and a radiant-cooled condenser.

For convenience in assembling and testing the turbomachinery package and associated components, a modular arrangement was utilized for these components together with a compact air-cooled condenser. Figure 1-12 shows this module. Since it was expected that turbomachinery and related auxiliaries would present the greatest need for modification and adjustment during development testing, this modular design permitted maximum utilization of the test facilities by allowing rapid replacement of this portion of the system.

1.2 SNAP I Ground Test System Development

Before completion of Ground Test System fabrication, the flight requirement for SNAP I was cancelled. Because of this and reductions in scope and subsequent termination of the

STATOR

ROTOR

SNAP I ALTERNATOR

SNAP I ALTERNATOR PERFORMANCE

32 Slot Stator - .025 Slot Opening
Efficiency Data - 1.0 PF and 0.8 PF

FIGURE 1-7

FIGURE 1-8

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CENTRIFUGAL PUMP IMPELLER

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FLIGHT TEST SYSTEM COMPONENT ARRANGEMENT

FIGURE 1-10

GROUND TEST SYSTEM COMPONENT ARRANGEMENT

FIGURE 1-11

SYSTEM WITHOUT BOILER

formal SNAP I development program, the requirement to design the GTS leading to integration with a given satellite vehicle was eliminated. This resulted primarily in the substitution of a single electrically heated boiler for the boiler pair originally used when testing determined that the boiler pair did not meet system requirements. Another significant change was the elimination of the use of nuclear radiation resistant materials in several components. While the requirements imposed on the system to meet a given application were considerably eased, the resulting Ground Test System still was kept a prototype of a mercury Rankine space power conversion system but designed to provide the maximum amount of development information.

The formal SNAP I development program ended June 30, 1959. It was recognized, however, that the advanced developmental status of SNAP I put it in a position to make substantial contributions to mercury Rankine space power system technology. Approval was therefore obtained to continue work with the SNAP I Ground Test System oriented toward obtaining the maximum amount of endurance operation. The goal was to provide, at an early date, information on the endurance capability and problem areas of this type of equipment.

The first two months of this effort were funded directly by the AEC under contract AT (30-1)-2559. Beginning in September 1959, the work was performed under AEC contract AT (11-1)-GEN-8, with Atomics International, A Division of North American Aviation, as prime contractor. The conclusion of the endurance run and post-test examinations and analyses were funded by Wright Air Development Division under Contract AF 33(616)-6625.

2.0 COMPONENTS OF THE GROUND TEST SYSTEM USED IN THE 2500-HOUR ENDURANCE RUN

The purpose of this section is to describe the pretest status of the components used in the Ground Test System, primarily, the principal system components: the turbomachinery package, the electrically heated boiler, and the air-cooled condenser. In addition to these, the speed control and several miscellaneous components required for operation of the system such as instrumentation, auxiliary pumps, valving, etc., will be presented.

A schematic representation of the Ground Test System is shown in Figure 2-1. This figure identifies the components and their place in the system.

2.1 Turbomachinery Package

The turbomachinery package used in the endurance run was the first developmental version of the prototype SNAP I turbomachinery unit. This package is shown in Figures 1-1 and 1-2 and incorporated the components described in Section 1.1.

During the SNAP I development program, two of these packages were fabricated. The turbomachinery unit used in the endurance run was the first of these to be built and was designated PTP-1, standing for Prototype Test Package Number 1. PTP-1 had previously accumulated approximately 100 hours of operating time, including 48 hours of continuous design point operation. Just prior to the initiation of the endurance run, PTP-1 was in the following condition:

1. The turbine had slight signs of erosion.
2. The bearings had some slight pit and score marks.
3. The pump appeared to be in good condition.
4. The alternator bore seal had several small cracks such that leakage could occur through the alternator leads and out the cracks in the bore.

2.2 Boiler

Since the SNAP I prime contractor was no longer active in the boiler development program, TRW began the development of a replacement boiler to permit SNAP I system operation. The design of this boiler was based upon heat transfer data obtained from the original SNAP I boiler pair and from SNAP II boiler tests. In the interests of economy, this electrically heated boiler, while of internal configuration similar to a boiler capable of being used in space, externally was designed for ease of fabrication and integration with GTS.

The boiler consisted of a single tube coil, helically wound, and made up of three tubes of different diameters. These tubes were arranged so that flow area increased towards the discharge end of the boiler. The inlet tube was 0.13 inch ID and 4.3 feet long; the intermediate tube was 0.25 inch ID and 14.6 feet long, and the outlet tube was 78 feet long with an ID of 0.38 inch. To increase the heat transfer coefficient, this helical tube had an internal turbulence-promoting device consisting of a helically wound wire in each of the

GROUND TEST SYSTEM SCHEMATIC

FIGURE 2-1

three sections. The boiler tube was immersed in a lead bath which contained electrical immersion heaters.

Testing of this boiler revealed that it had heat transfer capabilities in excess of those required and delivered steady superheated vapor as required. However, after 32 hours of operation, the boiler tube fractured. This fracture was found to be a result of lead stress corrosion. To retain the good heat transfer characteristics of this boiler and to prevent any possibility of a similar failure, an identical coil was fabricated of Type 316 stainless steel and a different mode of heating was utilized. Thermal energy was provided to the boiler coil by radiant electrical heaters which completely surrounded the coil. Testing of this second GTS boiler proved it also had performance characteristics in excess of requirements and it was incorporated into the Ground Test Systems. Figure 2-2 shows the boiler arrangement.

2.3 Condenser

To reject the waste heat from the Ground Test System, a compact air-cooled condenser was used. This condenser, shown in Figure 1-12, consisted of two separate sections—a section devoted to condensing the turbine exhaust vapor and a section for subcooling the turbine flow as well as the bearing lubricant flow. Air supplied independently to these two sections flowing over finned tubes accepted the heat and provided the means to control condenser operation. The condenser was fabricated of Type 347 stainless steel.

2.4 Speed Control

Control of the turbomachinery package rotational speed during the endurance run was accomplished by two related techniques. The SNAP I control as described in Section 1.1 was a part of the system, but for reasons presented in Section 4, the electrical load of the system was used as the primary method of speed control.

2.5 Miscellaneous Components

Ground Test System temperature instrumentation consisted of thermocouples primarily of the contact type with immersion thermocouples used in several key areas. Contact thermocouples were attached by spot welding the junction to the surface whose temperature was being measured.

Pressures were measured by two methods: strain gage pressure transducers provided capability to record pressure data, and Bourdon tube gages permitted visual monitoring of pressures.

Liquid mercury flow rates in the system were recorded by using differential strain gage pressure transducers sensing pressure drops across a calibrated orifice. Mercury differential manometers were also connected across the same orifice to give a continual visual indication of flow rate.

BOILER HEATER ARRANGEMENT

FIGURE 2-2

All instrumentation and electrical connections on the turbomachinery-condenser platform were made on a junction board to permit rapid installation and replacement of this unit. Other instrumentation used in GTS and instrumentation readout and recording equipment will be discussed in Section 3.

The auxiliary portions of the Ground Test System consisted of the bearing drain ejector, filters, and valves. The bearing drain ejector was a jet pump utilizing high pressure mercury from the centrifugal pump discharge to pump the bearing drain lubricant back to the subcooler. Filters were provided at the inlet to the bearing and boiler to trap any contamination that might exist.

3.0 TEST FACILITY

The SNAP I Systems Test Enclosure (STE) was designed and built to perform the following functions:

1. Performance test the complete power conversion system.
2. Endurance test the complete system.
3. Evaluate procedures and techniques for power conversion system startup and shutdown.
4. Perform miscellaneous tests such as boiler heat transfer, component performance, and complete system control dynamics tests.

The STE consists of a metal-walled enclosure approximately 14 feet by 12 feet, 9 feet in height, with consoles of instrumentation and controls. Figure 3-1 shows the control console with some of the associated instrumentation and Figure 3-2 is a view of the enclosure showing instrumentation mounted to it. Through the windows of the enclosure may be seen the Ground Test System.

Included in the design of all SNAP I test facilities built at TRW were special considerations to insure the safety of test personnel. In addition to the usual care taken in the design of high temperature, pressurized components and plumbing, special techniques were required to guard against the hazards created by the toxic characteristics of mercury vapor. This was accomplished by enclosing all apparatus containing mercury within a metal-walled enclosure. Blowers were used to exhaust air from the enclosures to the atmosphere to insure removal of any mercury vapor and to keep the pressure inside the enclosure less than that in the surrounding laboratory area. The concentration of mercury vapor in the laboratory atmosphere as well as that within the enclosure was constantly monitored. Whenever personnel had to enter an enclosure, protective clothing and breathing apparatus were used if needed. Regularly scheduled physical examinations insured that no person could accumulate a dangerous dose of mercury within his body.

Among the features incorporated in the facility was an auxiliary mercury supply system for filling the system with mercury and supplying liquid mercury to the bearings of turbomachinery packages. Provisions were made to be able to start systems by supplying mercury flow to the boilers from this source. Controls and scheduling devices were also included to facilitate system startup by motoring the alternator of the turbomachinery package. The design was made versatile enough to allow either a fully automatic or a manually controlled start.

Electrical controls were provided for all required line and boiler heaters. Rejection of waste heat from the system under test was accomplished by plant air supplied to an air-cooled condenser. Provision was made, however, to incorporate power conversion systems with radiant-cooled condensers.

Instrumentation was originally provided to evaluate system performance rather than complete component performance. Changes in program direction later required that provisions be made to obtain more detailed data and the required items to accomplish this were added. The capabilities of the STE are listed below:

SYSTEM TEST ENCLOSURE

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SYSTEM TEST ENCLOSURE INSTRUMENTATION PANEL

Mercury flow	-	liquid pressure temperature	50 lb/min 250 psia 350°F
Air flow	-	2000 lb/hr	
Instrumentation			
		pressure	static, Bourdon gages dynamic, strain gage transducers
		flow	pump discharge 16 lb/min with manometer and differential pressure transducer with venturi boiler flow 3 lb/min with manometer and differential pressure transducer with venturi
		temperature	24 point logger, 12 station potentiometer
		speed	digital readout and record
		alternator output	volts, amperes, and watts from 25 to 2000 cps

4.0 DESCRIPTION OF ENDURANCE TEST

The purpose of this section is to describe the objectives of the SNAP I endurance test and to discuss events of significance during the test period.

4.1 Endurance Test Objectives

The primary objectives of the endurance test were:

1. To obtain data leading to a realistic evaluation of the endurance capabilities of mercury Rankine space power equipment.
2. To obtain performance data on system components.
3. To obtain information on the performance of endurance test facility to be applicable for similar future facilities.

Originally, there was no quantitative objective for the number of hours of operation of the system. However, after the system was operating satisfactorily, a goal of 3000 hours was set. This objective was later reduced to 2500 hours at the request of the agency supporting the activity at that time, Wright Air Development Division.

4.2 Description of Endurance Test

For convenience in describing the test operation which covered a span of over four months, the overall description will be divided into several portions selected for their unity of subject matter.

4.2.1 System Startup

The components used in the Ground Test System were those described in Section 2.0. The system that resulted was given the designation, GTS-3.

Prior to operation of this system, all attached instrumentation had been calibrated and the system had been checked for leaks. The startup procedures used to bring the system into operation are summarized below:

With a full vacuum applied to the entire system, electrical power is applied to all boiler, line, and turbomachinery package heaters, and the system is brought up to operating temperature. Lubricant flow to the turbomachinery bearings is established from the auxiliary mercury supply and lubricant flow rate and pressure data are taken.

Turbine flow is established by gradually opening the manual boiler throttle valve and allowing mercury from the auxiliary mercury supply to flow to the boiler. Since no valving is between the boiler and turbine, the buildup in

boiler pressure directly establishes turbine flow. The turbomachinery package is brought up to full operating speed and full power operation is established by continuing to increase boiler flow rate until the desired value is reached. Speed is maintained at design value by varying the electrical load on the alternator. As the unit comes up to operating speed, a point is reached where the pump of the turbomachinery package exceeds the pressure supplied by the auxiliary pump system. When this occurs, the check valve arrangement automatically switches the system over to closed loop, self-sustaining operation. At this point the auxiliary supply system can be shut down.

On January 25, 1960, this procedure was used to bring GTS-3 up to full speed operation. Shortly after the start of the test, it was discovered that the set point on the boiler inlet pressure regulator was such that full flow to the boiler could not be obtained. Attempts to change the set point of the regulator while the system was operating were unsuccessful. Therefore, it was not possible to supply the boiler with full flow rate. In order to maintain reasonable alternator output power with the decreased energy input to the system, the turbine speed was reduced to 32,000 rpm. Since the output of the shaft mercury pump at this reduced speed was not capable of supplying system needs, the auxiliary pump was kept running in parallel with the package pump.

For the periods of time that the unit operated at 40,000 rpm, performance of all components was comparable to that obtained during previous turbomachinery and system testing.

4.2.2 Significant Conditions During Endurance Run

Within the first several hours after the Ground Test System was placed in operation, several items were noted that required attention. The first, as was just noted, was that a full flow to the boiler could not be obtained due to the pressure regulator setting. This also did not permit the electronic speed control to take over the speed control duties of the system. Therefore, control of the speed was made primarily by manually adjusting the load on the alternator. After about 30 hours of operation, an auxiliary mercury filter was installed parallel with the original bearing lubricant supply filter of the GTS. This was necessary in order that the bearing supply pressure be maintained when the original filter developed an excessive pressure differential. This modification was accomplished while the system was operating as described.

Because of air leaking into the low pressure portions of the GTS, it was necessary to install two liquid mercury traps in the vacuum line running from the condenser to the test facility vacuum system. This was required in order that the mercury carried along with the air being exhausted from the system be capable of being intermittently removed by this parallel trap arrangement. Because of this air leakage, difficulty was experienced in maintaining condenser conditions at design values. To compensate for this and to increase assurances that test facility vacuum system malfunction would not cause a shutdown, a second vacuum pump was installed while the GTS was operating.

During the first 200 hours of operation, boiler discharge quality was essentially 100%, i.e., all vapor. During the second 100 hours, calculations of boiler discharge quality showed that an average of 8% of the boiler discharge flow rate was liquid rather than vapor. Boiler discharge quality was calculated by comparing the measured flow into the boiler obtained by calibrated differential manometer and the calculated flow out of the boiler as determined from the turbine inlet nozzle geometry and pressure and temperature at the inlet to this nozzle. Since the turbine inlet nozzle cannot detect liquid passing through it, i.e., reveals vapor flow rate only, a ratio of nozzle flow rate to boiler inlet flow rate reveals the amount of the flow that is passing through the nozzle in the vapor form.

In the 192nd hour of continuous operation, a mercury vapor leak developed at the turbine inlet nozzle. A pressure instrumentation line at this point had ruptured resulting in a leak rate sufficiently great to require shutdown at 200 hours by shutting flow to the boiler and allowing the turbomachinery package to spin down to rest. After a bearing static flow check was taken, all power was shut off and mercury was drained from the system. The system was then pressurized with dry nitrogen at about 1 psig to prevent air from contacting the internal portions of the system.

While the turbine nozzle instrument flange leak was being repaired, it was possible to revise the auxiliary system plumbing in order to provide duplicate parallel filters to enable continuous operation in the event of filter clogging. It was also possible to greatly reduce the path for air leakage into the alternator by applying sealant to the alternator leads. The boiler inlet pressure regulator was reset to permit full turbine flow rate.

On February 11 an attempt was made to bring the system into operation, but a malfunction of the boiler inlet preheater prevented this.

On February 13 the system was placed back in operation and the turbomachinery package operated at full design speed. The performance of all components was at the same high levels as at the start of the test. Throughout the remainder of the test, this remained true except for the mercury pump. While the turbomachinery pump performance was at the design point at the start of this test, its performance gradually decreased until the auxiliary mercury supply was supplying the major portion of the flow. Air entrainment in the mercury, due to air continuing to leak into the system, is considered to be the cause for the pump deterioration. Previous testing indicated that small air bubbles collect at the pump inlet and restrict flow, causing cavitation. When these bubbles are removed, pump performance returns to normal.

A procedure was devised for intermittently purging the pump of noncondensable bubbles by increasing the pump flow through a specially installed bypass line. This method was effective in the early portions of the test but was less effective as the test progressed. The reasons for the loss of effectiveness are thought to be:

1. Air entrainment in the liquid mercury became so great that an air bubble continually formed at the impeller eye.

2. Contamination was formed on the impeller during the periods of reduced flow and prevented impeller performance from returning to design value.

It was not possible to control system operation with the boiler inlet pressure regulator because the mercury supply pressure was not high enough to permit it to operate as designed. This was a result of the auxiliary mercury supply pressure being below the design supply pressure of the turbomachinery package pump. Speed control of the system was accomplished, therefore, as done during the first 200 hours of operation, by adjusting flow to the boiler by a hand throttle valve and trimming turbine speed by manually adjusting alternator load.

Operation of the system from 200 to 2509 hours was uneventful except for two incidents. At approximately the 680th hour of operation, a high electrical load of unknown origin was intermittently placed on the alternator, resulting in partial demagnetization of the permanent magnet rotor. While efforts were being made to trace the cause of the load, the turbine flow rate was reduced such that the unit was operating at a very low alternator output power. When circuitry checks showed that no short circuit could be found, the mercury flow rate was increased until full power output was again obtained but at a slightly reduced voltage due to the demagnetization.

At 1100 hours of operation, a test facility power supply circuit breaker malfunction caused a loss of boiler power. The system was shut down while the circuit breaker was repaired, but was back at full operating conditions within one hour after the loss of boiler power.

Filters in the liquid mercury supply lines developed high pressure drops during the run, necessitating replacement. Because of the parallel filter arrangement previously installed, this was accomplished without system shutdown. Another item for maintenance during the course of the test was caused by mercury condensing on electrical contacts within the test enclosure. A small mercury vapor leak from the turbine nozzle developed during the test, providing the source of mercury which condensed on the cooler parts of the enclosure. Mercury condensation on electrical lead wires from heaters resulted in electrical shorts and rendered heaters inoperative until they could be repaired. All heaters were repaired and returned to service without requiring system shutdown.

The test facility vacuum pump system was kept operating throughout the test in order to continuously remove noncondensables from the condenser. Mercury vapor entrained in the air being drawn off and condensing in the vacuum lines caused some difficulty in maintaining condenser pressures at the proper value.

As will be discussed later, instrumentation indicated that moisture existed in the turbine supply during the greater portion of the test. Because of this indication, considerable variations in boiler operating conditions were made in attempts to eliminate this. The subject of delivery of wet vapor from the boiler is more fully discussed in Section 5.1.

4.2.3 Post Test Conditions

On May 19, upon receiving instructions from Wright Air Development Division and also approval from Atomics International, the Ground Test System was shut down in the 2509th

hour of operation. Some time conversions help to make the duration of this endurance test more meaningful:

$$2509 \text{ hours} = 104.5 \text{ days} = 3.5 \text{ months}$$

For more than 90% of this duration, the turbomachinery package operated at design speed—40,000 rpm, or 667 revolutions each second. The total number of shaft revolutions accumulated was 5,900,000,000.

The turbomachinery package was completely disassembled and given a rigorous visual examination. The boiler and condenser were sectioned and selected portions were given a complete visual and metallurgical examination. Mercury drained from the system was labeled as to the point at which it had drained and analysis of it performed. Section 5 describes the results of these examinations.

5.0 DISCUSSION OF TEST RESULTS

It is the purpose of this section to describe the results of the endurance test. Three general areas are covered: (1) the condition of the test hardware at the conclusion of the run as determined by visual and metallurgical examination of component parts, (2) a summary of the system and component performance as determined by performance parameters measured throughout the test, and (3) the performance of the test facility.

5.1 Visual and Metallurgical Examination of Test Hardware

The result of greatest significance from this endurance test was a determination of how well the various pieces of the Rankine system withstood the long-term exposure to operating conditions. All parts removed from the system were inspected visually, with the aid of a stereomicroscope and sections of the boiler and condenser were inspected metallurgically.

5.1.1 Turbomachinery Package

Disassembly of the turbomachinery package was accomplished with no major difficulty. However, in separating the turbine from the alternator housing, several of the retaining bolts fractured. Subsequent investigation revealed that these bolts had received an improper heat treatment prior to use which made them extremely brittle. No factors, such as distortion, were noted in the housing which would tend to limit the turbomachinery life. The components of the turbomachinery package examined are listed below:

Turbine

Turbine wheels and nozzles were in excellent condition. All parts were free from serious erosion deposits or signs of fatigue. The only area of definite erosion pattern that could be noted was in the third stage rotor where small elongated marks were present on the suction side of the leading edges. In all areas but this, any markings on the turbine blading were so slight that they were probably the original surface finish. Figure 5-1 is a photograph of the third stage turbine wheel. The second stage rotor had slight deposits on the leading half on the suction side of its blades. The throat of the first stage nozzle had a slight contamination film approximately 0.001 to 0.002 inch thick.

Alternator

The appearance of the alternator stator was good. The only noticeable change from the original assembly was a discoloration in the surface of the stator bore. An electrical resistance check of the stator windings indicated no change had occurred. Figure 5-2, taken during disassembly, shows the alternator stator within the housing of the turbomachinery package. The non-metallic stator bore seal had adequately protected the stator windings from mercury corrosion. However, as previously discussed, the slight cracks in the bore had resulted in a path for air to leak into the system. Improved stator bore sealing fabricating techniques are required to insure bore seals of proper integrity.

THIRD STAGE TURBINE WHEEL

TAPCO
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933A

ALTERNATOR HOUSING AND STATOR

Bearings

During the test the bearings had experienced rapid speed fluctuations at several times due to varying condenser pressure, wide extremes of boiler operating conditions, and the alternator overload at 680 hours. The unit was also started and stopped two times during the run. Despite these perturbations from design operating conditions, the bearings had adequately supported the radial and thrust loads imposed on them. Visual examination of the bearing spheres and sockets during disassembly revealed no evidence of scoring or galling. All parts had a light gray deposit on them. The amount of this deposit was insufficient for analysis. These films had reduced the total axial clearance from 0.0055 to 0.002 inch. During the test, the effect of this contamination was to change the bearing socket pressures, but these pressures were still within safe operating limits. With the hydrosphere bearing design, a more serious area for contamination deposits to occur is the orifices between the bearing socket and the lubricant supply. The contamination buildup in this area was noted during the test by changing bearing socket pressures. These socket pressures were maintained in the correct operating range by a manual control on the lubricant supply. This indicated that until adequate knowledge of contaminants in mercury systems is obtained, pressure or flow regulators to compensate for the deposition of minor amounts of contaminant should be included as part of the design. Figure 5-3 shows the turbomachinery shaft assembly and gives an indication of the good conditions of the hydrosphere bearings. When the contaminant film had been cleaned from the surfaces, it was possible to note evidence of slight scoring in limited areas. Dimensional checks revealed the scored areas to be less than 0.0001 inch in depth.

Pump

Disassembly of the shaft pump revealed heavy contamination deposits on the impeller and lesser amounts on the volute plate. Microscopic examination of the impeller also revealed serious erosion on the inlet portions of the impeller blades. Contamination formation on the pump impeller is shown in Figure 5-4.

Due to the location of the erosion and the contaminant buildup at the impeller blade inlet, it is concluded that these two effects were caused by air entrainment in the mercury which collected at the pump impeller inlet. The resulting air bubble reduced flow area, causing pressure reduction and pump cavitation. The erosion and contamination noted on the pump coupled with the knowledge that considerable non-condensables were present during the test reveal the cause of the pump performance deterioration during the test. Elimination of non-condensables is therefore expected to greatly improve life capabilities of this component.

SHAFT ASSEMBLY

PUMP IMPELLER

FIGURE 5-4

5.1.2 Boiler

Visual examination of the boiler after the test indicated it to be in good condition. The only noticeable change was that several of the unsupported helical coils had sagged until they were resting on the supported coil, showing a need for a greater number of supports. Metallographic analyses of the boiler tube revealed corrosion depths varying from 0.0015 to 0.006 inch. The greatest amount of attack occurred at the inlet portions of the boiler. Toward the discharge portions of the boiler a contaminant deposition was noted on the walls in a thickness being from 0.001 to 0.003 inch. A photograph of the microstructure of the corrosion attack is shown in Figure 5-5. The deposit was insufficient for analysis.

5.1.3 Condenser-Subcooler

Sections of the condenser and subcooler were generally free from contamination. The surfaces appeared to be nearly as bright and clean at the end of the test as they had at the start. Metallographic analyses of sections revealed a maximum corrosion depth of 0.001 inch. This occurred in the subcooler area which contained liquid mercury only. A photograph of the sectioned condenser is shown in Figure 5-6, while Figure 5-7 shows the microstructure resulting from metallographic examination of section pieces.

5.1.4 Miscellaneous System Components

Bearing Drain Ejector

Performance of the bearing drain ejector was very erratic during the endurance test. At times it would adequately drain the bearings of mercury, and at other times it would not, and the use of an auxiliary test facility ejector was required. Disassembly of the unit indicated no erosion or corrosion or contaminant buildup on its component parts that would cause such erratic performance. Therefore, it is felt that air entrainment in the mercury also affected this pump in the same manner as it did the shaft pump.

Flowmeters

Liquid mercury flowmeters used in the system consisted of a venturi with a differential transducer sensing the pressure differential generated. Dimensional examination of venturi throats at the conclusion of the test indicated the diameters to be within 0.0005 inch of the original, with no apparent contaminant buildup.

Filters

As previously discussed, the several liquid mercury filters in the system exhibited high pressure drops during the test, resulting in the need to by-pass them with a second filter in parallel. This increase in filter pressure drop was attributed to the filter becoming clogged by contamination buildup. However, upon disassembly and examination, little, if any, contaminant could be found in the filters. The

TYPE 316 STAINLESS STEEL
UNETCHED SAMPLE #1 (BOILER INLET LINE)
DEPTH OF PENETRATION 0.0025"

250X

TYPE 316 STAINLESS STEEL
UNETCHED SAMPLE #2 (FIRST COIL OF BOILER)
DEPTH OF PENETRATION 0.006"

250X

MICROSTRUCTURE OF THE STE BOILER

VERTICAL CONDENSER, VERTICAL TUBES - MID AND BOTTOM SECTIONS -
AND SUBCOOLER HEADER DISCHARGE AND SUBCOOLER HORIZONTAL TUBES

**TYPE 347 STAINLESS STEEL
CONDENSER (BOTTOM OF CONDENSER VERTICAL TUBE) 250X**

**TYPE 347 STAINLESS STEEL
SUBCOOLER (HEADER) 250X**

MICROSTRUCTURES OF THE STE CONDENSER AND SUBCOOLER

cause of the high filter pressure drop is not known. It is thought that it is associated with mercury wetting of the filters. It is also thought that colloidal particles might cling to the wetted filter, thus reducing the flow area and increasing the pressure drop. Further investigation in this area is recommended.

Analysis of Mercury Contamination Samples

Difficulty was experienced in obtaining meaningful analysis of contaminant samples collected from the system due to the small amounts that could be gathered. In most cases, samples weighed less than one gram, limiting the examination to spectrographic analysis. For samples greater than one gram, a wet analysis was conducted which provided quantitative results as well as a knowledge of particle sizes. Listed below are the locations of the contaminant samples taken and the results.

<u>Sample</u>	<u>Analysis</u>
1. Liquid mercury from subcooler	Cr, Ni, Si, Fe 1.0% Mn, Sn, Pb, Cu 0.2 - 1.0%
2. Liquid mercury from downstream side of bearing filter	All elements less than 0.005% each
3. Liquid mercury from boiler preheater	Ag-0.01%; K-0.01%; all other elements less than 0.005% each
4. Residue from auxiliary pump impeller cavity	Ni-0.1%; Fe-0.02%; Si, Cu, Ag-0.01%; others less than 0.005% each
5. Residue from rotating unit	Ca, Mg-0.01%; others less than 0.005% each
6. Deposit removed from second stage turbine nozzle	Ag - 0.10%; Ni - 0.01%; others less than 0.001% each
7. GTS bearing supply filter	No residue found. Mercury found in downstream side of the filter contained impurities all less than 0.005% each
8. Boiler inlet filter	No residue found. Mercury in downstream side of filter contained 0.01% Ag; others 0.005% each
9. Auxiliary pump discharge filter #1	No residue found. Mercury in downstream side of filter contained impurities all less than 0.005% each

10. Bearing supply auxiliary filter	No residue found. Mercury in upstream side of filter contained Cr - 0.1%; Fe - 0.005%
11. Auxiliary pump discharge filter #2	Contamination on upstream side filter housing contained Cr - 90%; Ni - 10%; Mn - minor

In interpreting the above analyses, the following factors must be considered:

1. The percentage of element listed is approximate and a function of the operator's experience and ability.
2. All elements present in quantities of 0.005% or less are trace samples and can be neglected.
3. In all samples except #11, mercury was by far the major element in the analysis.

The conclusions drawn from the above analyses are:

1. The major portion of the contaminations settled in the liquid mercury in the subcooler. In previous materials evaluation testing, it has been shown that chromium and nickel are leached from the boiler and condenser and deposited in the cooler portions of the system.
2. Liquid mercury on the upstream side of the filters contained a relatively high degree of impurities whereas mercury on the downstream did not, leading to the conclusion that the filters were effective in preventing passage of the contaminants.
3. The percentage of silver found in many of the samples indicates that it was inadvertently introduced to the system. Since the alternator stator windings contained silver, this could have been the source. However, no change in the electrical characteristics of the alternator was noted, so the stator cannot be positively identified as providing the silver.
4. A method of analysis should be devised that would separate the contamination from the mercury so that it could be examined separately.

The contamination found in the bearing sockets, which reduced axial clearance, appeared in film form with the amount of contamination being so small that it could not be analyzed. The contaminant had the appearance of a mercury oxide. The mean particle size of the samples that could be measured was approximately 2 microns and the range of particle sizes was 0.5 to 75 microns.

5.2 Data Analysis

During the 2509 hours of operation of the endurance test, some 200,000 measurements were collected describing the operation of the Ground Test System. Since these measurements were taken over a large range of system operating conditions, it is advantageous to discuss the results in three different test time intervals. The first interval involves the 200 continuous hours of operation prior to the shutdown caused by the mercury vapor leak in an instrumentation line. Throughout this run the rotor speed had been limited to 32,000 rpm rather than 40,000 rpm due to an off-design setting of the boiler inlet pressure regulator.

The second interval, from 200 to 950 hours, has been termed the "transient operating" period because of variations made to boiler inputs in attempts to understand the boiler discharge moisture problem. The third period, from 950 hours through the end of the test, has been designated the "steady-state" portion of the run.

The key system performance parameters measured during the test have been plotted in Figures 5-8 through 5-11. Figures 5-8 and 5-9 present those parameters primarily associated with the turbomachinery, while Figures 5-10 and 5-11 describe boiler performance.

5.2.1 The Initial 200-Hour Test Period

The first 200 hours accumulated during the endurance test yielded data at some 200 points, at various turbine speeds, inlet pressures, temperatures, and exhaust pressures. From these data and with the use of a digital computer, two important analyses were made:

1. Performance map of GTS 3 System.
2. Moisture effect on turbine performance.

Figures 5-12 and 5-13 show the results of the performance map analysis. In these figures turbine inlet temperature was fixed at the design condition of 1300°F. Figure 5-12 shows the predicted alternator power output versus speed for various values of turbine inlet pressure, and with the turbine exhaust held constant at 2.0 psia. Figure 5-13 presents the same information for a turbine exhaust pressure of 3.0 psia.

Boiler performance during this interval is described by Figure 5-10. Plotted are the boiler weight flow, apparent moisture, tube wall temperatures, nozzle inlet temperature, boiler input powers, and boiler pressure drop. At approximately 100 hours the moisture curve begins to increase, reaching values as high as 20%. During this time total electrical power is decreasing, which at first would appear to be the reason for the increase in moisture. However, a heat balance showed that sufficient power was available to result in qualities of 100%. Nozzle inlet temperature ranged between 1200 and 1300°F during this interval. The inlet and outlet tube wall temperatures were very similar, indicating that boiling was still occurring in the upper portions of the boiler. The low boiler pressure drops of 30 to 38 psi were due to the long boiling and short vapor lengths.

SYSTEM PARAMETERS

FIGURE 5-3

SYSTEM PARAMETERS

FIGURE 5-9

SYSTEM PARAMETERS

FIGURE 5-10

SYSTEM PARAMETERS

FIGURE 5-11

GTS 3-2 PERFORMANCE (EXTRAPOLATED FROM PERFORMANCE DATA)

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FIGURE 5-12

GTS 3-2 PERFORMANCE MAP (EXTRAPOLATED FROM PERFORMANCE DATA)

FIGURE 5-13

Data obtained from liquid flowmeter and vapor nozzle flow measurements during this test indicated that moisture was entrained in the vapor discharging from the boiler. The amount of moisture is determined from the following equation:

$$M = \frac{W_L - W_N}{W_L} \times 100$$

where

M = percent moisture

W_L = liquid mercury flow rate as measured by boiler inlet venturi flowmeter

W_N = mercury vapor flow rate as determined from first stage turbine nozzle calibration curve at the measured inlet pressure and temperature conditions.

The ability of moisture to exist in a superheated vapor is attributed to small liquid droplets carried in the vapor stream. The droplets are formed during boiling and become entrained in the high velocity vapor stream. Since the available means of heat input to the droplets is limited to convection and radiation, and since the droplets are in the boiler a relatively short time due to the high velocity, they do not completely vaporize.

From turbomachinery performance data and from moisture data, an analysis was made to determine the effect of moisture on turbine output power. The results of the moisture analysis indicated no turbine performance reduction for moisture conditions as great as 20%. Since previous GTS turbine data indicated that turbine performance was penalized one-half of one efficiency point for every percent of moisture, the validity of the boiler moisture calculation was challenged. It was felt that instrument calibrations could have changed during the test to cause a false indication of boiler moisture. Further challenging evidence and a more detailed discussion of the boiler moisture question is presented later.

5.2.2 200 to 950 Hours of Operation

After the system was placed back in operation at the 200th hour, it was subjected to significant perturbations from steady-state operating conditions. Figures 5-8 and 5-9 give indications of these, but because of scale, cannot show any but the longer duration transients.

The short circuit in the alternator level occurred during this interval. While checks were being made to determine the cause of the overload, the input energy was decreased to protect the turbomachinery package from overspeed. When full turbine flow rate was re-established, the alternator terminal voltage was 30 volts below its previous level because of the demagnetization of the permanent magnet rotor caused by the overload.

Figure 5-10 shows the boiler performance parameters during this period. Most of the transient operation occurred during the period from 200 to 300 hours of operation. This was primarily caused by a wiring reversal in the upper and lower boiler power heater circuits. When power was intended to be added to the upper boiler, it was really being added to the lower boiler and vice versa. Because of this, very little power was being added to the lower side of the boiler. Consequently, the lower side of the boiler became a preheater and the superheater section became the boiling section, leaving very little length for superheating. The boiler pressure drop during this period ranged between 20 and 30 psi less than previously because decreased tube length was occupied by low density vapor.

5.2.3 950 to 2509 Hours of Operation

During this period, the alternator output power showed a steady decline which would appear to be a performance deterioration with time. However, during this time turbine conditions were changing in a manner which explains this decline. The ideal turbine input power was being reduced as the turbine inlet temperature and pressure were reduced. Throughout the test the turbine exhaust total pressure was held essentially constant at approximately 3.0 psia. The power output during the test can, therefore, be compared with the predicted performance, as shown in the performance map of Figure 5-13.

In order to show the correlation between performance obtained during the endurance test and the predicted performance, predicted alternator power output points have been plotted along the power output curve at 1000, 1400, 1900, and 2500 hours. It will be seen that these predicted power outputs follow the same trend as the observed power output. The difference between these power predictions and the power outputs obtained during the 950 to 2509 hour interval is due to an alternator efficiency change which occurred as the alternator voltage was reduced in the transient short at 680 hours, as previously discussed.

Further analysis of this correlation would indicate that other factors may also be influencing the turbine power output. In particular, it was noted that the amount of non-condensable gas present in the condenser and the turbine exhaust line had an influence. As the amount of non-condensable gas decreased, or as the mercury vapor partial pressure (determined from the turbine exhaust temperature) increased, the alternator power output was observed to decrease. This effect may be seen, for example, by comparing the shape of the partial pressure curve with the alternator output curve. A portion of the alternator power decline which occurred is, therefore, also thought to be associated with this effect.

5.2.4 Boiler Performance

Figures 5-10 and 5-11 show boiler performance during the steady-state operation period from 900 to 2509 hours. Steady-state data from various portions of the test were used to perform a heat transfer analysis in an attempt to determine whether or not moisture existed. Figure 5-14 shows the results of this analysis. The above figure shows boiler flow plotted versus total system input power in kilowatts for qualities from 70% to 100%. A 300°F superheat curve is also shown. The overall heat loss for the system was calculated as 1.65 kw. Adding this heat loss to the heat required to bring the liquid mercury from 375°F

BOILER FLOW RATE VERSUS TOTAL POWER

FIGURE 5-14

to the listed quality or superheat lines enabled direct plotting of boiler power data. Special symbols as shown for ranges of quality between 5% intervals were plotted for various powers and flows. These data are shown falling along a line passing through the estimated heat loss at zero boiler flow. Since this line is past the 300°F superheat line, it appears that adequate heat was available to completely superheat the flow.

This analysis does not completely prove that dry vapor existed at the turbine inlet, since it is dependent upon boiler heat loss which may vary with flow rate and with time. The tight band in which the data points are contained, however, indicates that if moisture did exist, the variation was not so great as indicated by flowmeter data. If moisture existed as great as calculated from the flowmeters, a total band width of 1500 watts would be expected. However, a maximum band width of only 500 watts is observed. This corresponds to a moisture variation band of only $\sim 3.5\%$. From this analysis it may, therefore, be concluded:

1. Heat input to the boiler was adequate to eliminate nearly all the moisture.
2. If moisture did exist, it had a variation, or tolerance band, of only $\sim 3.5\%$.

The boiler heat balance, therefore, supports the conclusion that the turbine inlet vapor flow was relatively dry. This result is in agreement with turbine power output calculations, as discussed before, which indicate turbine efficiencies higher than would be expected with large amounts of moisture. The result does not agree, however, with the turbine nozzle and boiler flow meter data, which indicate that moisture was present.

Since the boiler flowmeter and the turbine nozzle pressure gauge were used to calculate boiler moisture, these instruments were calibrated at the start of the test, during the 200-hour shutdown, and at the completion of the test. Each time the calibrations repeated. It was also considered that the cause for an erroneous moisture calculation could be an increase in turbine nozzle throat area. This area was measured at the completion of the test and found to be slightly smaller due to contamination formation.

Sufficient data is not available to resolve completely the question of what the level of moisture was at the turbine nozzle. The most logical explanation is that the discrepancy is due to a combination of factors, including the following:

1. The liquid flowmeters gave too high a flow indication during the long periods of continuous operation.
2. The boiler heat loss was actually higher than calculated.

A logical conclusion which may be reached is, therefore, that the turbine inlet vapor was not completely dry during the test period, but that the average moisture content was less than approximately 12%. A further important conclusion is that the boiler moisture which did exist had no appreciable effect on turbine performance and did not cause any substantial amount of turbine erosion.

A sizable increase in boiler pressure drop was noted during the 2509 hours of boiler operation. Pressure drops averaged around 30 psi during the first phases of the test and increased to values as high as 60 psi near the end of the test. Definite correlation was established between mercury vapor length and pressure drop. When low pressure drops occurred, the wall temperatures in the discharge portions of the boiler were near saturation temperature, meaning that boiling was occupying most of the available boiler tube length leaving little vapor length for producing pressure drop. When pressure drops were high, the inlet portions of the boiler tube temperatures were as high as 1500°F, indicating long vapor length.

5.2.5 GTS 3 System Performance

The ability to predict system performance is dependent on how well component power estimates are made. Component power, the dependent variable, must be defined by as many independent variables as needed. A power balance is then made summing the equations of the components to the turbine shaft power equation. The following sections describe the effect of endurance operation on component performance and power estimates.

Turbine

Turbine shaft output was affected during the endurance run by nozzle inlet pressure and temperature and by turbine exhaust pressure. The turbine shaft power equation for this test was determined as

$$P_{To} = \frac{0.395 P_o}{(T_o + 460)^{1/2}} \times (\Delta h_i)^{1/2} \times 0.695 \times 10^{-3} N \times \left[0.388 - \frac{0.351 \times 10^{-4} N}{(\Delta h_i)^{1/2}} \right] \quad \text{Eq. 1}$$

where

P_o is nozzle inlet pressure, psia

T_o is nozzle inlet temperature, °F

N is turbine speed, rpm

and Δh_i is the ideal enthalpy drop defined by nozzle inlet pressure and temperature and an isentropic drop to exhaust pressure.

During the test, the turbine exhaust was composed of a mixture of mercury vapor and non-condensables. This was also observed to have a direct effect on turbine shaft power. This effect is readily seen in Figure 5-9 by the parameters of alternator output power and the mercury partial pressure exhaust pressure. The two curves are similar in shape with one being the reciprocal of the other.

Bearing and Pump

Figure 5-9 shows no deterioration in bearing performance during the last 1600 hours of endurance operation. During this same period, however, the pump performance was observed to deteriorate. Inspection after the test showed that deposits and erosion at the impeller center area were responsible.

Alternator

Alternator performance was affected during the endurance test by intermittent shorts which occurred at 680 hours. The result was in the form of a voltage reduction due to demagnetization. The alternator terminal voltage was lowered by approximately 30 volts due to the above condition. This voltage reduction was accompanied with an alternator efficiency reduction.

Overall Performance

Component power equations were found for each of the above components. Combining each of these equations into one and solving for alternator output power (P_{AO}) gives:

$$P_{AO} = \left(\frac{P_{TO} - 10.2 \times 10^{-10} N^{2.47}}{7.23} \right) \quad \text{Eq. 2}$$

Once the turbine shaft power (P_{TO}) is known from Equation 1, the alternator output can be determined. In this manner, off-design performance can be obtained for any turbine condition as seen in Figures 5-12 and 5-13.

5.3 Test Rig Operation

Although this test was primarily to establish the endurance capability of the Ground Test System, it also established the endurance capabilities of the auxiliary system and the instrumentation. The main problems experienced in the auxiliary system were caused by the failure of mechanical mechanisms. The linkage on a temperature logger malfunctioned on several occasions and the gears on an oscillographic recorder jammed on one occasion. This pointed up the need for utilizing proven equipment wherever possible. Depending on its significance to the successful operation of the test, certain test facility items should be provided either in pairs or with switching arrangements to insure uninterrupted operation.

This test also showed the need for a flexible auxiliary system so that main system requirements can be met. An example of this was installing filters in the system without forcing shutdown.

Another problem discovered as a result of this test was thermocouples and thermocouple mountings. Several thermocouples in high temperature regions either stopped reading altogether or changed calibration due to their method of mounting so that their readings could not be trusted. Refined installation techniques can readily remedy this difficulty.

6.0 CONCLUSIONS

A mercury Rankine cycle power conversion system was successfully operated for an accumulated time of over 2500 hours. This test was performed continuously, on a 24 hour per day basis, and the total time was accumulated without a failure of the power conversion system. The test was performed with the power conversion system rotating unit operating for the majority of the time at design conditions of fluid temperature, pressure, and speed.

This test has proved that long-term endurance of a dynamic space power conversion system is possible. Valuable test data has been obtained for the design of future mercury Rankine cycle power conversion systems and the test rigs for evaluating such systems. In general, all components of the power conversion system demonstrated capability of maintaining satisfactory performance for the 2500 hour period, except for the pump. It has been concluded that the decline in pump performance which occurred was caused by air entrained in the mercury. This test has also shown that this type of power system is capable of continuously maintaining a constant electrical power output. Data analysis has shown that, when corrected for changing turbine conditions, no deterioration of power output capability occurred during the test.

All components, with the exception of the pump, were found to be in satisfactory condition. A one-year endurance capability for this type of system is fully indicated, providing that the erosion of the pump impeller can be eliminated.

Further results noted in this test which are of major interest are as follows:

1. System contamination by mercury corrosion and mass transfer products was not severe. The filters were shown to be capable of preventing these products from causing system operating difficulties. The filters were not plugged by these products, but they did exhibit an increasing pressure drop as a result of collection of materials on the upstream side or as a result of wetting phenomenon.
2. The bearings were neither eroded nor substantially contaminated. It was necessary, however, to make bearing flow adjustments to compensate for minor amounts of contamination. Leakage of air into the system may have aggravated this contamination film accumulation.
3. Alternator performance and life were concluded to be very satisfactory. The stator used in this test was not leakproof, however, and development of a completely leakproof seal is essential to prevent loss of working fluid and contamination due to air leakage.
4. Leakage of mercury out of the system and air into the system during the test was a problem. Development of an all welded, hermetically sealed system is essential to achieve unattended, long life capability.
5. Turbine erosion noted during this test was not severe and did not cause appreciable reduction in efficiency or power output.

6. Boiler performance was satisfactory, although the data indicates that the vapor leaving the boiler was not completely dry. Further research concerning the problem of accurate determination of boiler moisture entrainment and means of eliminating it are recommended.

It may be stated in final conclusion that, as a result of this test, the mercury Rankine system has been shown to be fully capable of achievement of one year unattended operation for use in providing space power. To insure this result, the following development is recommended:

1. Perform further testing to verify that pump impeller erosion and contamination may be eliminated by excluding air from the system. Conduct tests in which pump materials and geometry are varied to reduce sensitivity to erosion.
2. Conduct a test program to determine the cause for high filter pressure drop and to determine means of preventing this effect.
3. Continue development of hermetically sealed non-metallic alternator bore seal technique. Conduct life and thermal cycling tests to demonstrate reliability and durability of this component.
4. Conduct tests to determine accurately the moisture entrainment characteristics of single tube boilers. Develop means of eliminating entrainment.
5. Develop hermetically sealed, all welded, power conversion systems to eliminate leakage.

The final requirement for conclusive demonstration of one year endurance capability is, of course, to actually conduct such a test. In order to provide information of positive validity, this type of demonstration should be done with more than one power system. It is concluded that such a test would make a major contribution to space power technology and could be economically accomplished by use of unattended operation techniques based upon use of fully automated and hermetically sealed power systems.

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