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ENGINEERING REPORT 4050

SNAP I POWER CONVERSION
SYSTEM DEVELOPMENT

PREPARED BY

NEW DEVICES LABORATORIES, TAPCO GROUP
THOMPSON RAMO WOOLDRIDGE INC.

AS AUTHORIZED BY

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FOREWORD

SNAP I is the first of a family of devices to convert nuclear energy to electrical for use in space. The SNAP Systems for Nuclear Auxiliary Power – programs are sponsored by the Atomic Energy Commission; the SNAP I prime contractor is The Martin Company. SNAP I was designed to utilize a radio isotope as the energy source.

The SNAP I Power Conversion System utilizes mercury as the working fluid for a Rankine cycle. A radioisotope is used as the energy source to vaporize mercury in a boiler; turbo-machinery extracts the useful energy from the vapor and converts it into electrical energy; the exhaust vapor is condensed by rejecting the waste thermal energy to space in a condenser-radiator.

During the SNAP I Power Conversion System development, Thompson Ramo Wooldridge has been responsible for the development of the following items:

    Turbo-machinery

        Mercury vapor turbine
        Alternator
        Lubricant and condensate pump
        Mercury lubricated bearings

    Speed Control

    Condenser-Radiator

A series of eight Engineering Reports have been prepared describing Thompson Ramo Wooldridge's SNAP I Power Conversion System development program. These are as follows:

ER-4050	Systems
ER-4051	Turbine
ER-4052	Alternator
ER-4053	Pump
ER-4054	Bearings
ER-4055	Control
ER-4056	Condenser-Radiator
ER-4057	Materials

The material in this report deals specifically with the developmental history of the SNAP I Power Conversion System. This report is submitted as part of the requirements of Purchase Order OE-0101 from The Martin Company, issued under the Atomic Energy Commission prime contract AT(30-3)-217.

TABLE OF CONTENTS

1.0 SUMMARY

This report describes the development of the SNAP I Power Conversion System. SNAP I is the first of the series of Systems for Nuclear Auxiliary Power being developed to provide electrical power in space. It was designed to convert the thermal energy produced by the decay of a radioisotope into 500 watts of electrical energy by means of a mercury Rankine cycle method of power conversion.

Thompson Ramo Wooldridge was responsible for the development of the turbomachinery, condenser-radiator and control portions of this AEC sponsored program. The Martin Company, as prime contractor, was responsible for the development of the radioisotope boiler and systems integration. TRW's SNAP I developmental effort began in February 1957, and continuing to the present, has resulted in significant advances in the analysis, design, fabrication and experimental evaluation of this type of space powerplant.

The efforts expended during the SNAP I developmental program resulted in the successful operation of the Power Conversion System. Both component and system performance requirements were met and the system endurance capability was demonstrated by operating for nearly twice the 60 day required lifetime.

SNAP I, by virtue of its component and systems testing and supporting analytical efforts, has demonstrated the feasibility and desirability of the Rankine system for obtaining power in space. The major achievements with respect to performance and life capabilities of the SNAP I power conversion system components have provided a firm technological base upon which future Rankine space power systems can and are being developed.

2.0 INTRODUCTION

2.1 Description of SNAP I

SNAP I is a mercury Rankine power conversion system. It develops electrical power by means of a turbine driven generator.

The many advantages of the Rankine turboelectric method of converting thermal energy into electrical energy has made it the world's largest producer of electric energy. The Rankine cycle utilizes thermal energy from a wide variety of fuels to convert liquid to high pressure, high temperature vapor in a boiler. When this vapor is expanded through a turbine, a portion of its thermal energy is converted into shaft energy which is used to drive an electrical generator, resulting in the production of the electrical energy. The unusable thermal energy in the vapor exhausting from the turbine at low pressure and temperature is removed in the condenser, which converts the fluid back to liquid. The condensed fluid then passes to a condensate pump, which returns it to the boiler.

Figure 2-1 shows a block diagram of a space Rankine power system. While the principle of operation of a space Rankine power system and its corresponding central station power-plant on earth are essentially the same, very significant differences in environment require numerous component design refinements for a space Rankine system. Major environmental factors dictating a need for component design changes are the absence of an atmosphere, which requires that the space system must reject all waste energy by radiation rather than by convection, and the complete absence of gravitational forces, which causes a considerably modified approach to fluid mechanics considerations. Further component and system design innovations are dictated as a result of the stringent requirements of the space power mission. Great premiums are placed upon minimizing weight and bulk. Reliable unattended operation is mandatory. High performance, for extremely long durations is essential.

The Rankine method for obtaining electrical power can be further designated by the type of fluid used in the cycle. Water is the most common fluid used in central station power-plants, although mercury has been used in several large, high efficiency, powerplants. As will be later described, optimization of SNAP I to meet space power requirements, resulted in the selection of mercury, not only as its working fluid, but as the lubricant for the turbomachinery bearings.

SNAP I was originally designed to provide 500 watts of electrical power, for an earth-orbiting satellite, and to have a useful life of 60 days. For the requirements of this mission the power conversion system components were selected and the overall cycle conditions chosen as will be described.
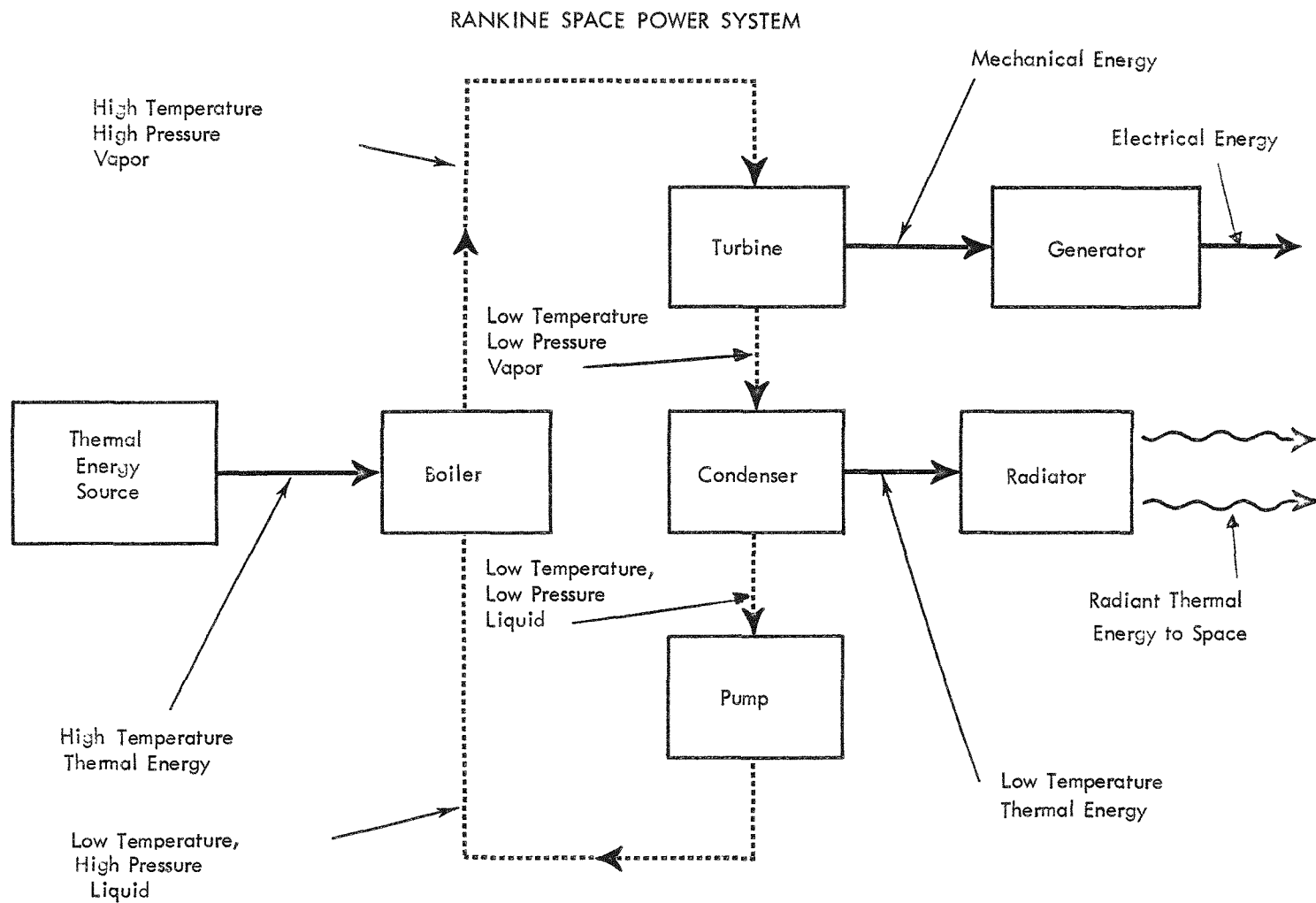
RANKINE SPACE POWER SYSTEM

FIGURE 2-1

TAPCO GROUP

Thompson Ramo Wooldridge Inc.

Cycle conditions – Figure 2–2 is a flow schematic of the SNAP I system on which are indicated the various temperatures, pressures and flow rates associated with the design point operation of the system.

Energy source and boiler – SNAP I was designed to use the radioisotope, Cerium 144, as its energy source. The mercury boiler was designed as an integral part of the fuel container assembly. This component of the system was developed by the Martin Company, and therefore will not be discussed extensively in this report. However, since certain features of the boiler design affect the remainder of the power conversion equipment, a brief discussion of the boiler and energy source is included here.

Cerium 144 was chosen as the radioisotope to best meet the system requirements, on the basis of specific power, cost, and availability. A disadvantage to the use of Cerium 144, the significant gamma radiation associated with its decay, was overcome in the SNAP I design by means of special shielding and handling procedures. To be compatible with satellite vehicle requirements, the boiler was built in two identical units, so that half the cycle mercury flow would pass through each boiler. Each half-power boiler consisted of a central cylindrical refractory metal block within which the radioisotope was encased. The boiler tubing was helically wrapped around this block and was thermally bonded to it by liquid lead. Heat losses from the boiler were reduced by multiple stainless steel shells which served as thermal radiation insulation. Control of thermal input to the mercury associated with the excess heat of radioisotope decay was provided by means of controlling an opening in these insulating shells.
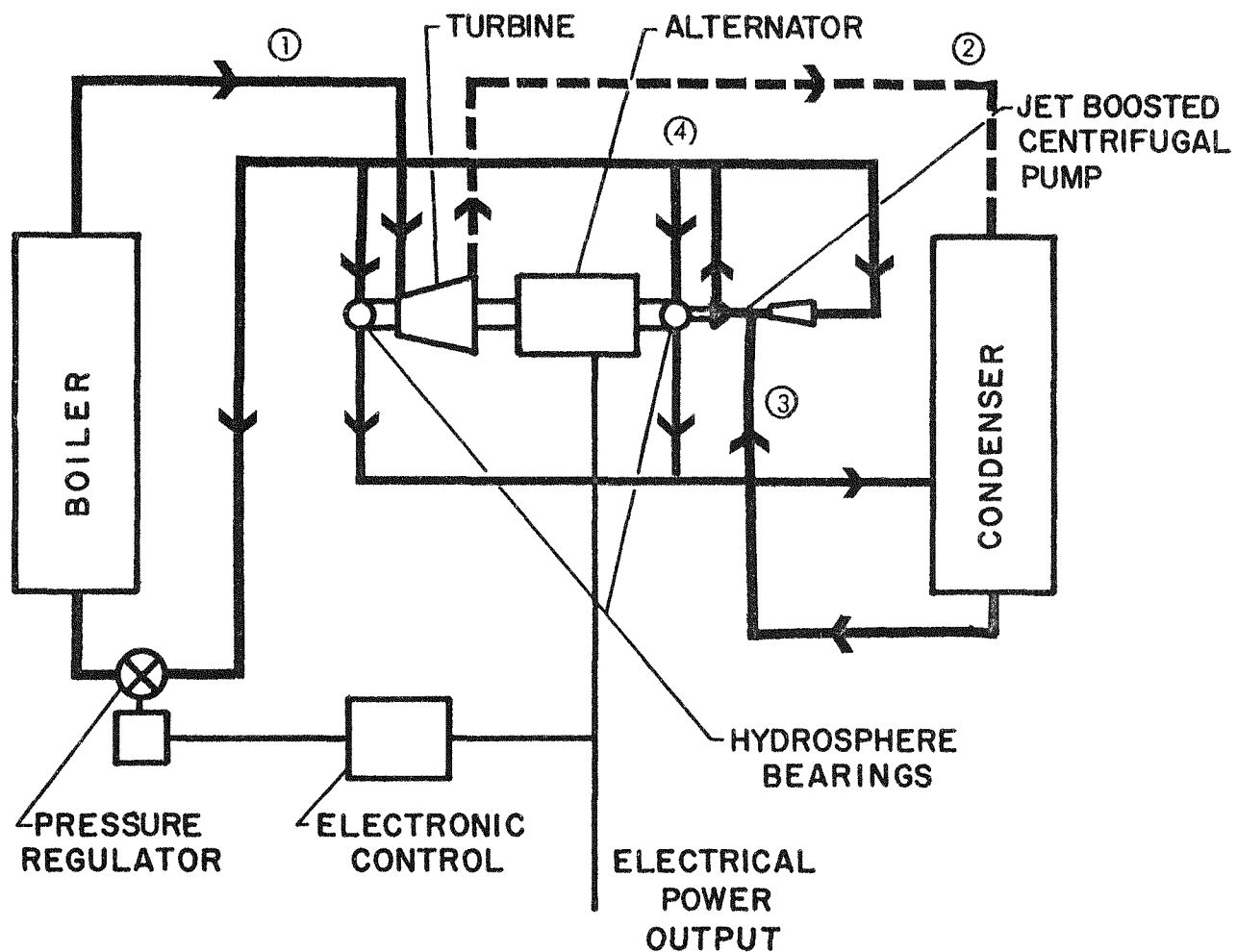
Turbomachinery – The turbomachinery developed for SNAP I contains many unique features, never before incorporated into a Rankine system. The stringent requirements for performance, reliability in the launching and space environments, and the long duration, unattended operation, dictated each unique feature. Figure 2–3 shows the turbomachinery package resulting from the SNAP I development. Its key features are a three-stage mercury vapor turbine, permanent magnet alternator, and liquid mercury pump mounted on a single shaft supported on liquid mercury lubricated bearings. The design and development of this package are treated in detail in Section 6 of this report.

Other Components – In addition to the boiler and the turbomachinery package, the SNAP I system requires a condenser-radiator to reject waste heat, and a control system. These are further described in the following section.

2.2 The SNAP I Development Report Series

The accomplishments of TRW's SNAP I power Conversion System development program are presented in a series of eight Engineering Reports. A separate report describes the analysis, development, and performance of each of the system components—turbine, alternator, pump, bearings, control, and condenser-radiator. In another report, a summary of the materials development is presented. This report describes the design, the development, and performance of the complete SNAP I Power Conversion System. A brief description of the material

4

SNAP I POWER CONVERSION SYSTEM SCHEMATIC

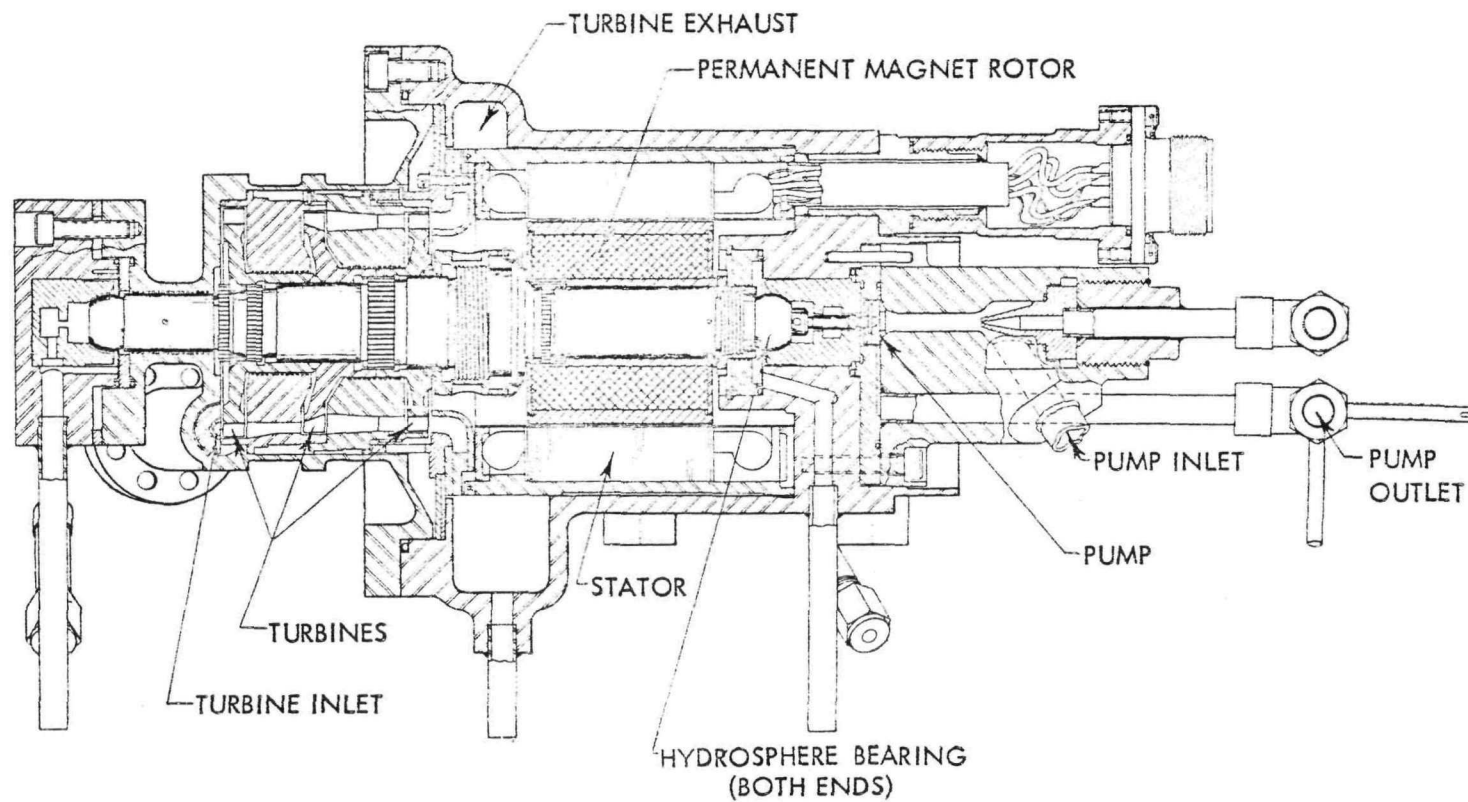| STATION	LOCATION	PRESSURE PSIA	TEMP. °F	FLOW RATE LB/MIN
①	Turbine Inlet	210	1300	1.9
②	Condenser Inlet	2.0	500	1.9
③	Pump Inlet	1.9	330	12.0
④	Pump Inlet	290	330	12.0

FIGURE 2-2

SNAP I TURBOMACHINERY PACKAGE

TURBINE EXHAUST
PERMANENT MAGNET ROTOR
PUMP INLET
PUMP OUTLET
PUMP
STATOR
TURBINES
TURBINE INLET
HYDROSPHERE BEARING
(BOTH ENDS)

contained in the component reports is presented here in order to summarize these results and to provide background for the complete system discussions.

Turbine (TRW Engineering Report ER 4051) – Mercury vapor turbines have been operated in the past in commercial power plants, but the SNAP I system required a new set of standards concerning miniaturization, high speed, and unattended operation. The turbine development program included analysis, design, fabrication, and testing of several types with the final configuration consisting of a three stage, axial flow, impulse turbine. Analytical and empirical design procedures were evolved and verified for low power output, high pressure ratio, high speed, mercury vapor turbines. Figure 2.4 is a photograph of one wheel of the three stage turbine.
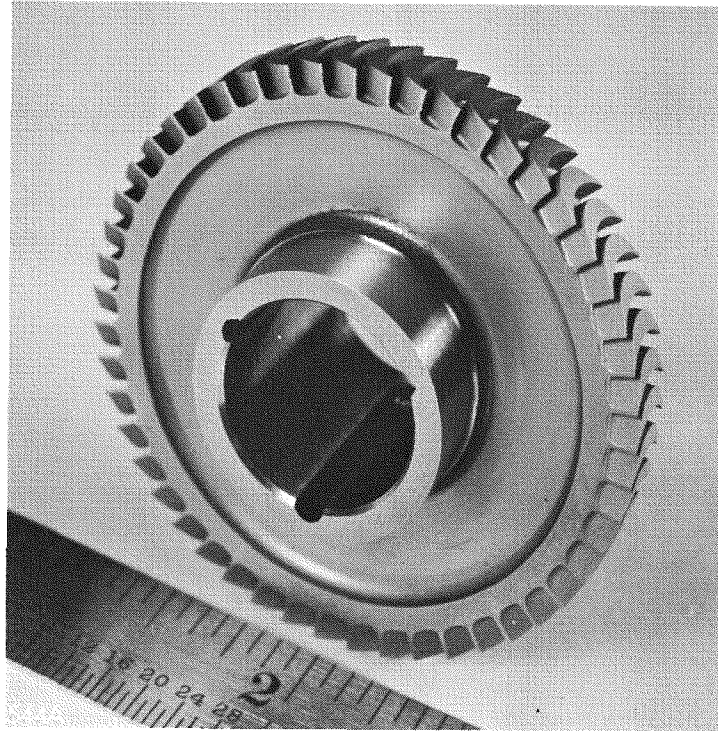
Alternator (TRW Engineering Report ER 4052) – Stringent requirements are placed on the alternator by the environment to which it is exposed. The reliability of a brushless alternator is substantially better than that of a machine utilizing brushes. A permanent magnet alternator is simpler and more reliable than a conventional wound field design. A major advance in the state-of-the-art of high temperature materials, achieved during a TRW-sponsored materials development program, allows the alternator to operate at high temperatures namely 550°F without cooling. Techniques were also evolved for sealing the stator bore to isolate the stator windings from the mercury vapor. These considerations allowed the design of an alternator able to meet performance and life requirements. Figure 2-5 is a photograph of the SNAP I permanent magnet alternator.

Pump (TRW Engineering Report ER 4053) – Since, in a gravitationless field, no static head is available, the design of the condensate pump presents problems of cavitation. Several pump types were investigated, both analytically and experimentally, with the final selection of a centrifugal pump with a jet boost stage at the inlet to maintain the impeller inlet pressure above the cavitation limit. Performance of this type of pump was very satisfactory for the low flow, high head, and high speed conditions of the SNAP I system. A photograph of the pump impeller is shown in Figure 2-6.
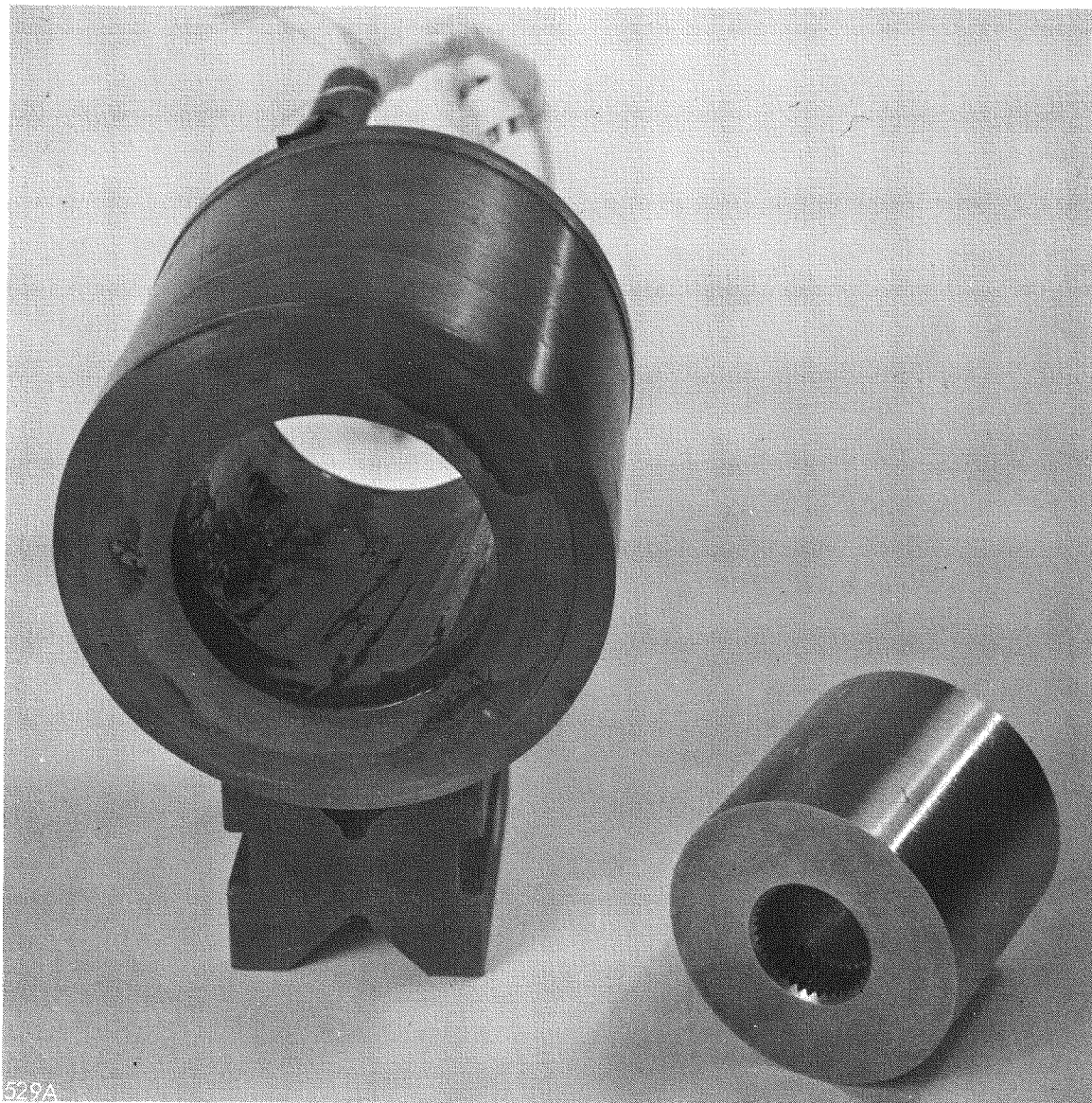
Bearings (TRW Engineering Report ER 4054) – In the turbomachinery package the pump, turbine, and alternator, are mounted on a common shaft by mercury lubricated hydrosphere bearings. These bearings are the result of a development program consisting of the evaluation of several bearing types and the search for materials which have suitable bearing properties and are compatible with mercury. Figure 2-7 is a photograph of a hydrosphere bearing and socket.

Control (TRW Engineering Report ER 4055) – The SNAP I control system was required to maintain stable system operation and to provide constant electrical output frequency while delivering constant power to a satellite vehicle's electrical power system. As a result of analysis and analog simulation, a control was developed which sensed speed with a frequency discriminator providing the signal to a pressure regulator on the boiler inlet which modulated the flow to the turbine. This control system performed satisfactorily in component and system tests.

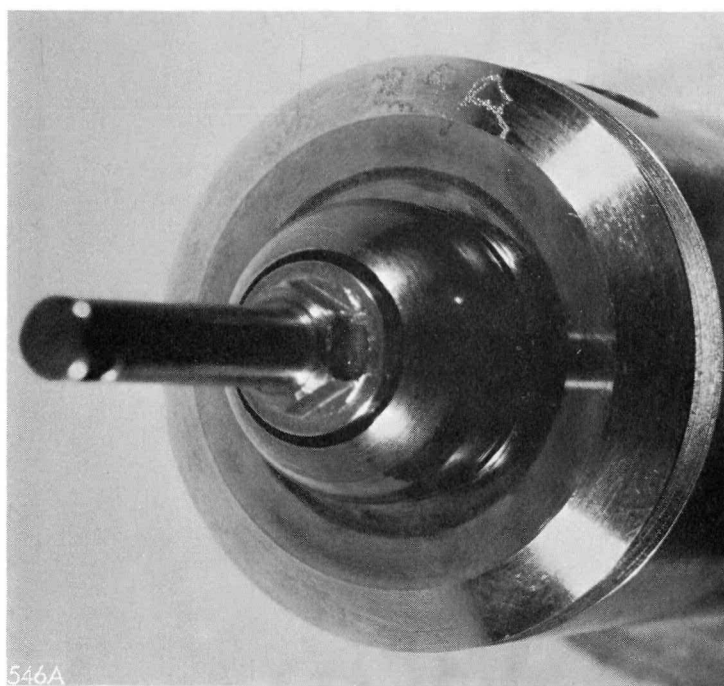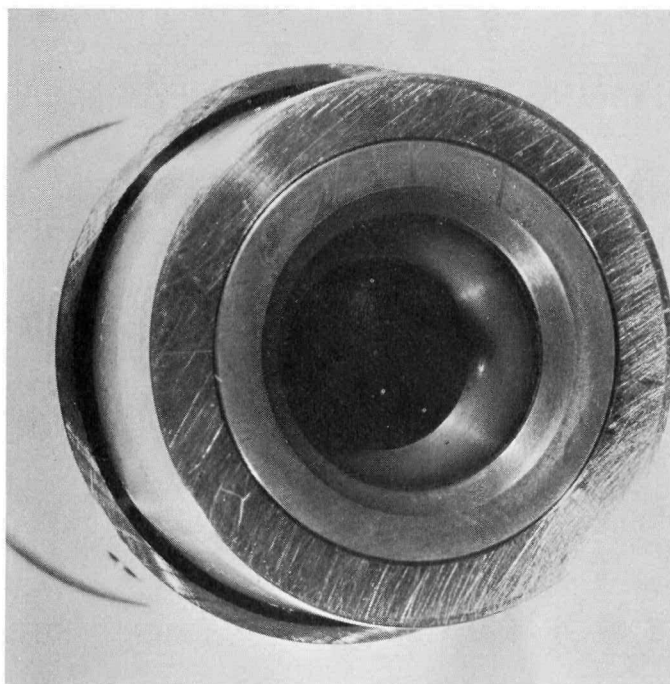SNAP-I AXIAL FLOW IMPULSE TURBINE WHEEL

FIGURE 2-4

Stator   Rotor

SNAP I ALTERNATOR

FIGURE 2-5

SNAP-1 CENTRIFUGAL PUMP IMPELLER

FIGURE 2-6

TAPCO GROUP ⧩™ Thompson Ramo Wooldridge Inc.

HYDROSPHERE BEARING SET

FIGURE 2-7

Condenser-Radiator ITRW Engineering Report 4056)

The only means of eliminating waste heat from a body in space is by radiation. Thus the design of a condenser-radiator to condense the turbine exhaust and radiate the waste heat was completed. Analysis and experimentation was carried out on the phenomena of heat transfer and fluid dynamics of a condensing fluid in a gravitationless field. The ability to condense against the force of gravity was demonstrated. These and subsequent zero gravity tests, established the feasibility of condensation in the space environment.

Materials (TRW Engineering Report 4057)

To assist in the development of the above components a materials development program was established. Both metallic and non-metallic materials were included in order to arrive at materials which are compatible with mercury and are capable of performing the desired functions.

A wide variety of metallic materials were shown to have satisfactory compatability with mercury to permit use as required in the power conversion system. Non-metallic materials having excellent properties for use as insulation and alternator bore seals, were also found.

3.0 REQUIREMENTS

SNAP I was designed to provide the electrical power for an earth orbiting satellite. The following general requirements were therefore imposed on SNAP I.

Reject all the waste heat by thermal radiation

Unattended operation

Zero gravity

Absolute vacuum

Compatible with satellite's payload

Capable of withstanding the launching environment

Protected from hazards of meteorites

The specific requirements of the SNAP I power conversion system (as defined here, "power conversion system" does not include boilers or structure) that were used as a guide during the development program were as follows:

Power output	500 watts
Life	60 days
Weight	minimum (110 lbs objective)
Overall system efficiency	10%

Detailed requirements based upon these specifications and characteristics of the satellite vehicle are listed in Table 3-1.

Throughout the SNAP I development program these requirements were used as the objectives to be met. They were broken down into specific requirements for the several components of the power conversion system to guide their respective developmental efforts. The first detailed specification of system and component parameters, issued early in 1957, is shown in Table 3-2.

The numerical value of these performance goals assigned was the result of considerations of existing status, and the probability of achieving the goals at a minimum cost to the total program. As development progressed, and new insight into component characteristics was obtained, these specific goals were modified in order that the achievements in one area could ease the requirements in others. However, near the end of the formal SNAP I

TABLE 3-1

Electrical output	Power – 500 watts – constant Voltage – 115 $\pm$ 10% Frequency – 2000 cps $\pm$ 10% Power factor – 0.8 lagging Total distortion – less than 10% Radio interference per MIL-I-6181B

Nuclear Radiation
The SNAP I system would be exposed to gamma radiation originating at the radioisotope heat sources. The intensity of this radiation would not exceed 1.5×10^5 roentgens per hour at the surface of any power conversion system component.

Radiator
Was not to be a structural part of the vehicle, total area less than 25 square feet, maximum radius of curvature 2 ft. 3 in., OD; minimum radius of curvature 2 ft. 0 inches ID.

Weight Distribution

Radiator	68 lb
Turbomachinery	25 lb
Controls	7 lb
Mounting	10 lb
Total	110 lb

Environment
The SNAP I unit had to be operable through the launch as well as the orbital environment, therefore, it had to withstand the following accelerations and vibrations.

Longitudinal accelerations	8 g
Lateral accelerations	1.5 g

Shock* – 10 g with rise time of .003 sec and dwell time of .012 sec along any axis

Vibration* – 2 g from 5 cps to 2000 cps with double amplitude limit of .125 inches for frequencies below 17.7 cps, along any axis.

*These would be attenuated by a shock mount for all SNAP I components.

TABLE 3-2

EARLY SNAP I PERFORMANCE PARAMETERS AND OBJECTIVES

1. Thermodynamic Conditions

Max. superheat temp.	1300°F
Boiler pressure	210 psia
Condenser temp.	500°F
Subcooler	330°F
Pump outlet pressure	250 psia
Low temp. cooler outlet temp.	200°F

2. Rotational Speed = 40,000 rpm

3. Component Performances

Turbine efficiency	40%
Bearing power consumption	40 watts
Pump efficiency	20%
Alternator efficiency	90%
Control power consumption	25 watts

4. Cycle Efficiency   10% = 500 watt output

5. Flows

Turbine inlet	1.87 lbs/min
Subcooler inlet	12.0
Control and Alternator cooling	1.13
Bearings	10.0

development program, funding reductions resulted in further component development efforts being curtailed, and necessitated a re-evaluation of the performances then achievable. Table 3-3 presents the detailed specification for SNAP I components resulting from this.

TABLE 3-3

FINAL SNAP I PERFORMANCE PARAMETER AND OBJECTIVES

1. Thermodynamic Conditions

    Nozzle Inlet Temperature   1300°F

    Nozzle Inlet Pressure   210 psia

    Condenser temp.   500°F

    Boiler inlet temp.   330°F

    Pump outlet pressure   287 psia

2. Rotational Speed = 40,000 rpm

3. Component Performances

    Turbine efficiency   40%

    Bearing power consumption   100 watts

    Pump efficiency   20%

    Alternator efficiency   80%

    Control power consumption   25 watts

4. Cycle efficiency   7% = 350 watts output

5. Flows

    Turbine   1.87 lbs/min

    Subcooler   11.87

    Bearings   10.0

4.0 DEVELOPMENT

SNAP I has pioneered the application of dynamic power conversion in space. This has meant that much original work has been accomplished in the anlaysis, design, fabrication, and test of the power conversion system components and of the complete system. This section summarizes these developmental efforts that resulted in the SNAP I power conversion system, and provides a suitable introduction to a description of the several power conversion packages which were developed during the program.

4.1 Pre SNAP I Development

The SNAP I Power conversion system is the result of TRW efforts beginning in 1955. It was in the fall of that year that TRW, then Thompson Products, in conjunction with Lockheed Aircraft Corp., submitted a proposal to the Air Force and the AEC for a study program to select the electrical power supply for an earth-orbiting satellite. This proposal resulted in the award of USAF contract AF(33-616)-3441 to TRW, under subcontract to Lockheed. This effort began in February, 1956, and called for analysis of methods to obtain power in space, and feasibility testing of potential problem areas of the machinery selected to perform the task.

Analysis performed during this study showed that the Rankine thermodynamic cycle using mercury as the working fluid, was superior to any other cycle or working fluid for the application. Analysis of the Brayton gas cycle showed that between two given temperature limits, its efficiency is much lower than that of a Rankine cycle. This is because the Rankine cycle more closely approximates the Carnot cycle, and also because losses due to component inefficiencies are much more severe in the Brayton cycle.

Mercury was selected as the working fluid for SNAP I because of the several advantages it displays over competing fluids. In order to keep total power conversion system weight low, the vapor pressure of the working fluid must not be excessive at the working temperatures of the system. At the working fluid boiling temperature, for example, the mercury vapor pressure is about 200 psia whereas, if water would be used at this temperature a pressure of over 3000 psia would result. The use of high temperatures in Rankine space power plants is required in order that size of the radiator to reject the waste heat not become excessive.

Use of higher temperatures was not undertaken, since the problems associated with using other fluids possessing favorable vapor pressure characteristics were considered to be beyond the scope of the SNAP I development criteria. Materials, such as phosphorus, rubidium, sulphur, and potassium, were recognized to be attractive for space power systems at higher power levels and higher operating temperatures. Mercury was selected as the working fluid for SNAP I however, because of its favorable vapor pressure characteristics in the temperature range of interest, and because prior experience had shown no formidable materials problems had to be solved. It could also be used as the lubricant

for the bearings of the turbomachinery.

The turbomachinery package selected as most promising for this application is shown in Figure 4-1. The key features of this unit were the use of a single stage, re-entry turbine to convert the thermal energy in the mercury vapor to mechanical energy, and an axial gap permanent magnet alternator to convert the shaft energy into electrical energy. The shaft was supported on mercury lubricated hydrosphere bearings and the liquid mercury pump was also a part of the shaft. The re-entry turbine was of interest for this application for several reasons:

- Analyses indicated that the required turbine efficiency could be obtained and that it would be superior to those of conventional small turbines.

- Possibility of turbine erosion was considered to be less severe.

- Fabrication problems are not difficult.

- Its physical design was compatible with the application.

The axial gap, permanent magnet alternator, was selected based upon the following considerations:

- Brushes or commutators could not be used due to the mercury vapor environment existing within the turbomachinery cavity; therefore, a brushless unit was required.

- Higher reliability would result from no electrical conductors within the rotor.

- The conductors in the stator could be protected against the corrosive mercury vapor.

- The axial gap construction combined with the re-entry turbine configuration provided a highly compact turbomachinery unit.

The pressurized hydrostatic bearing in the specialized form of the hydrosphere was selected to support the turbomachinery shaft. The reasons for the selection were:

- It combines both radial and axial load carrying capacity.

- It is insensitive to considerable misalignment.

- Lubricant flow rates are not large.

EARLY RANKINE TURBOMACHINERY CONCEPT

PART NUMBER	DESCRIPTION	PART NUMBER	
1	TURBINE INLET	12	ALTERNATOR COOLING
2	TURBINE OUTLET		JACKET
3	DRAG TURBINE	13	HYDROSPHERE BEARING
4	TURBINE SCROLL	14	BEARING LUBRICANT
5	CENTRIFUGAL PUMP		INLET
6	PUMP SCROLL	15	BEARING AND LEAKAGE
7	PUMP INLET		DRAIN
8	PUMP OUTLET	16	LABYRINTH SEALS
9	ALTERNATOR PERMANENT	17	CAPILLARY TUBES
	MAGNET	18	MOUNTING PILOT
10	MAGNETIC BACKING RING	19	POLE FACE
11	ALTERNATOR STATOR	20	ELECTRICAL LEADS

SECTION C-C

SECTION A-A

FIGURE 4-1

The mercury condensate and lubricant pump selected for this application was a centrifugal pump mounted directly on the turbine shaft. Reasons for its selection were based primarily upon considerations of no leakage, low power consumption, high reliability, and low weight.

The pre-SNAP I work also provided for the first detailed investigation of the means of condensing the turbine discharge vapor and rejecting the waste heat to space by radiation. Due to the many unknowns concerning mercury condensation in a zero gravity environment, a wide range of possible conditions were analyzed. The results revealed that with proper experimentation and further analyses, the design of a space condenser radiator should present no unsurmountable problems.

This study also investigated the various practical means of controlling the Rankine space power system. Such considerations as the effect of turbomachinery speed variations and fluid flow upon the stability of the satellite were considered, as well as the transients due to electrical load variations, the satellite passing from the sunlit side of the earth to the night side.

The effort under this AF contract also provided for feasibility testing of turbines and bearings since these two components were suspected of requiring the most effort to obtain a practical Rankine space power system. Re-entry turbines were dynamometer tested using steam and air as working fluids. Steam was originally used in order that testing with a vaporous fluid could be accomplished. However, the steam supply limited the pressure ratios available and the availability of a high pressure air supply resulted in subsequent tests being run with air. All turbines were tested in a specially designed high speed dynamometer capable of measuring the small torques involved with high precision.

The bearing testing resulted in proof of the feasibility of mercury lubricated hydrosphere bearing concepts as well as providing additional emperical design methods for these bearings. This program also resulted in techniques for manufacturing, superfinishing, and inspecting the highly precise bearing parts required.

In the fall of 1956, concurrently with the AF effort, TRW performed a conceptual design of a radioisotope fueled mercury vapor power conversion system under AEC Contract AT(30-3)-217. The resulting design, submitted to The Martin Company, was the basis from which SNAP I directly evolved. This unit was very similar to the one just described except that its design was specifically tailored to the radioisotope energy source. This unit was designed to produce 133 watts of electrical output for 60 days with an over-all efficiency of 10%. The work performed during this study resulted in the cycle conditions that have been used throughout on the SNAP I program.

An understanding of the developmental facilities that would be required to translate design concepts into reliable, high performance hardware was also an important result of

this effort.

4.2 SNAP I Development

In February, 1957, TRW actively began the development of SNAP I Power Conversion System hardware. This development was sponsored by the AEC under Prime Contract AT(30-3)-217. The work performed by TRW was under subcontract from The Martin Company. The work to be performed under this effort called for further optimization of the Rankine thermodynamic cycle to convert energy into electrical energy, design and development of components to accomplish this, and integration of these components into a workable power conversion system. The requirements for the system to be developed were those presented in Section 3 of this report, and the methods for accomplishing them made up the SNAP I program at TRW. A summary of the SNAP I component developments are presented in Section 2 of this report. This section traces the highlights of SNAP I development leading to the integration of the several components into the system.

As stated in Section 4.1, a Rankine space power system had been conceptually designed using radioisotope energy to produce 133 electrical watts. Concurrently with the beginning of SNAP I effort, this power requirement was raised to 500 watts resulting in a need to re-evaluate the conceptual design. Also contributing required modifications in this design were the results of component feasibility testing carried out at TRW.

The most significant departure from the original design was in the turbine area. Feasibility testing of re-entry turbines had shown that a significant state-of-the-art development would be required in order to achieve the desired efficiencies. Preliminary evaluation of conventional axial flow impulse turbines showed them to have better immediate potential for the higher efficiencies required. Further investigation also showed that axial impulse turbine erosion was not a serious problem in turbine design if a multi stage unit, with superheat would be employed.

The axial gap alternator in conjunction with a re-entry turbine had resulted in a compact turbomachinery package. With the turbine concept changed to a multi-stage axial flow machine, a radial gap permanent magnet alternator was preferred. This type also displayed a performance advantage over its axial gap counterpart.

The original choice of the hydrosphere bearing proved to be a sound one. Early in the SNAP development, performance and preliminary endurance testing of this concept showed it to be a desirable method of reliably supporting a high speed shaft for long periods.

Testing of several simple configurations of mercury pumps resulted in the knowledge that simple, single stage pump designs were not capable of meeting the system requirements. Primarily to meet the low pump inlet head requirement, the development of the jet boosted centrifugal mercury pump evolved.

The concept of utilizing but one moving part, the common turbomachinery shaft, for the power conversion system remained. Further analysis of system operating characteristics and control requirements showed this arrangement to be very satisfactory. Selection of the control mode for the SNAP I power conversion system was based on previous analyses and a better understanding of the system requirements. Using a boiler inlet pressure regulator to control flow to the turbine by sensing the alternator speed was chosen as optimum. This provides a simple system, having a large tolerance to load disturbances, without consuming any appreciable amount of electrical power.

The following three sections describe the several power conversion packages designed and tested during the program that utilize the component concepts just outlined.

5.0 TURBINE-ALTERNATOR TEST PACKAGE - TATP

The Turbine-Alternator Test Package was the first complete turbomachinery package designed and tested on the SNAP I program. This section will discuss its purpose, design and test history.

5.1 Purpose

Since the TATP was the first SNAP I turbomachinery package, it was required to provide data on several aspects important to the successful attainment of a Rankin space power plant. Most important of these were the following:

1. Provide a means for evaluating the performance of small high speed mercury vapor turbines.

2. Provide a means of demonstrating operating capabilities and performance of mercury lubricated hydrosphere bearings in the environment imposed by the system.

3. Provide a means for determining the suitability of materials used in the high temperature mercury environment.

4. Provide a means for determining the effectiveness of turbomachinery seals in the actual environment.

A later version of the TATP included the centrifugal pump on one end of the shaft thereby making it a complete turbomachinery package. This permitted the evaluation of the complete package with respect to component performance and interrelationships at an early date.

5.2 Design and Fabrication

The design philosophy employed in TATP was to obtain a unit capable of providing the desired data in economical, flexible manner. This was accomplished by designing all parts for ease of fabrication assembly, and modification. A high degree of precision in selection of tolerances and machining was required, however, in order to insure that TATP results would be meaningful to future turbomachinery designs.

Figure 5-1 is a cross-sectional drawing of the TATP. The first TATP units consisted of a three stage, impulse turbine mounted coaxially with the alternator on a shaft supported by a spherical bearing at each end. The turbine, alternator rotor, and bearings were separated from each other by labyrinth seals. The sockets of the spherical bearings were contained in end plates attached to the housing at opposite ends. A solid block-type of insulation (Mycalex) surrounded the turbine stators to prevent heat loss from the turbine to the housing and also served as the structural member between the turbine and the housing. In order to provide the desired wide range load for the turbine, a flux switching alternator was employed. Instrumentation taps were provided in order to measure several important
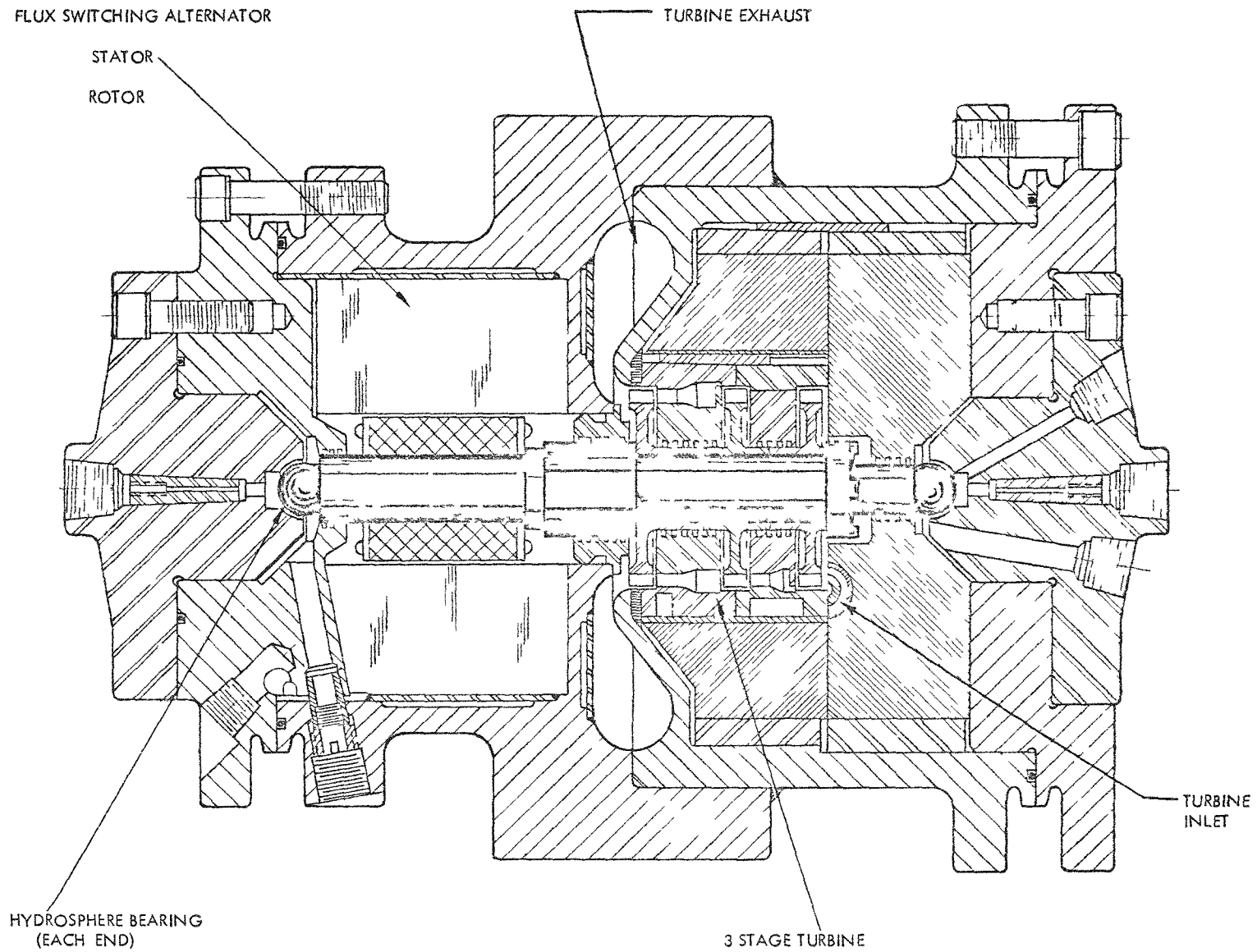
SNAP I

TURBINE - ALTERNATOR TEST PACKAGE

FLUX SWITCHING ALTERNATOR

STATOR

ROTOR

TURBINE EXHAUST

TURBINE INLET

HYDROSPHERE BEARING (EACH END)

3 STAGE TURBINE

FIGURE 5-1

parameters within the package as well as measuring parameters supplied to the package. Key among the internal measurements were turbine interstage temperatures, and bearing socket pressures.

In order to obtain component and system data that TATP would furnish early in the program, this unit was designed and placed in service concurrently with the development being carried-out on several of its components. Single stages of the axial flow impulse turbines were being tested in the SNAP I air dynamometer, but the TATP provided the first mercury vapor test of multistage turbine. Component test activity on the hydrosphere bearings provided bearings sufficient for early TATP tests, but complete turbomachinery tests, along with continued component development, further refined the design.

The bearings were supplied with liquid mercury which entered through the bearing end plates and flowed through a replacable pressure dropping capillary type flow restriction. High temperature mercury vapor entered the turbine thru a removable conical first stage nozzle. Labyrinth shaft seals were used to insure that a minimum of working fluid was lost from the desired flow path thru the turbine. A labyrinth seal was also employed to control leakage between the alternator cavity and the alternator end bearing. An important parameter in the operation of the hydrosphere bearing pair is the total axial clearance between the bearing sockets and the shaft. Considerations of materials, and temperature gradients in the TATP resulted in satisfactory axial clearances being maintained over the operating range. The initial axial clearance could be accurately set by removing material from the faces of the bearing end plates during assembly.

The experience gained in fabricating and assembling the TATP contributed to the development of several fabrication techniques required for highly precise turbomachinery of this type. In order that the performance and reliability of the unit be high, the many clearances within the unit must be maintained at their desired values. This meant that machining techniques for maintaining the very close tolerances had to be developed. Further methods had to be devised to assure dimensional stability in order that these clearances would remain fixed over the range of operating temperatures. All close fitting parts were stress relieved after rough machining to minimize subsequent warpage, and final dimensions ground to size.

One of the most important fabrication developments of TATP was the machining of the turbine parts. The three axial flow turbine wheels were rough machined from solid blanks of tool steel and heat treated to a high hardness. Final turbine blade contours were formed in the rim of each wheel by Eloxing – electric arc machining. This enabled the complex contours of each blade to be reproduced with great precision.

The shaft of this unit was made hollow to reduce heat losses from the turbine and improve critical speed characteristics. It was created of two separate pieces of tool steel welded in the center. Dynamic balancing of the entire shaft assembly was performed with all rotating components in place. After balancing to the desired precision (less than 0.001 inch-ounces of unbalance) the shaft was disassembled in order to integrate with the

remainder of the package, and reassembled, making sure that the rotating parts were returned to their original positions on the shaft.

Close attention to the cleaning and inspection procedures during assembly was required in order to insure a properly functioning unit. Thorough visual inspection of all close fitting parts was required to insure the surfaces were free of burrs or raised spots that could cause galling during assembly, or damage during running. Experience with TATP assembly resulted in the construction of an air conditioned, dust free room that was used for such activities.

5.3 Test Results

Testing of the turbine alternator test package was carried out in the SNAP I breadboard test facility described in Section 8 of this report. TATP test experience indicated that all of the goals used in the design of this unit were satisfactorily met. A summary of the accomplishments of TATP testing is listed below:

1. Quantitative data on the performance characteristics of the three stage mercury vapor turbine was obtained.

2. Performance characteristics of the hydrosphere bearing pair was obtained.

3. The successful integration of the shaft driven pump was demonstrated.

4. Valuable information concerning the testing of high speed mercury vapor turbo-machinery packages was obtained.

The most important object of the TATP effort was to obtain turbine performance information that would be useful in the design of prototype systems. In accomplishing this end, the other achievements were also obtained.

In order to obtain valid turbine data, it was mandatory to determine the performance characteristics of the other components of the package. This was required in order that the turbine shaft power output could be obtained by measurements of the units electrical output. The experimental tool used in accomplishing this was the spin-down technique. This type of testing is accomplished by permitting the shaft to decelerate through the desired speed point with no driving force applied to it. By recording the deceleration rate and knowing the inertia of the shaft, the torque acting on the shaft to cause the deceleration may be readily calculated.

Applied to TATP testing, this method was used to calibrate the flux switching alternator, to determine bearing frictional power, and to obtain labyrinth seal and windage losses of the shaft assembly. By knowing alternator efficiency and parasitic losses, it was possible to obtain accurate turbine output power from a knowledge of alternator output.

While simple in principle, spin-down testing procedures with turbomachinery such as the TATP were difficult to perform. The principle difficulty encountered during TATP testing was to insure that no input energy was supplied to the turbine during the spin-down process The test facility instrumentation requirements were stringent since highly accurate turbine speed deceleration recordings were required.

Test experience showed it difficult to insure that the working fluid supplied to the turbine was completely shut off during the spin-down, especially when operating on mercury vapor. It was difficult to obtain a low mercury containing volume between the turbine inlet shut-off valve and the turbine. For example, liquid mercury in the cooler portions of the turbine inlet pressure line would begin to vaporize as the pressure decayed, thus providing flow to the turbine after the turbine inlet valve had closed. It was also difficult to obtain reliable fast acting operation of the valving in the turbine inlet line which was required to operate at 1300°F.

For this reason, most of the successful spin-down tests were obtained using nitrogen as the working fluid. With the TATP preheated to operating temperature, the error introduced by using a different working fluid was negligible and experimental results of much greater consistency and accuracy were obtained.

Figure 5-2 shows the parasitic power of the TATP as a function of a shaft speed as obtained from these tests. Once this curve had been obtained, along with an accurate alternator calibration, it was possible to analyze the performance of the turbine. Operation of the TATP at constant speed with variable mercury inlet and exit conditions, resulted in the obtaining of many valid data points that could be used for turbine performance analsysis. One of the key results of these analyses was that the TATP turbine had a peak efficiency of 46% but the speed at which peak efficiency was obtained was below the design speed of 40,000 rpm. Engineering Report 4051, the SNAP I Power Conversion System Turbine Report of this report series, presents a detailed discussion of these analyses.

The TATP tests were also responsible for showing the sensitivity of low power output turbines to shaft seal leakage. Since losses due to working fluid leakage through labyrinth seals is chargable against turbine efficiency, reduction of interstage and high pressure seal leakage results in an improvement in turbine efficiency. Because of SNAP I's low turbine flow rate, these efficiency gains from reducing labyrinth seal clearances were significant.

The hydrosphere bearings first used in TATP were the result of early component testing. TATP experience combined with concurrent testing on the component level, established that this configuration could be improved. TATP test experience, therefore, was responsible for an improvement in the hydrosphere bearing performance, primarily with respect to radial load capacity. TATP tests showed that the capillary flow restrictions used were sensitive to con-taminantion of the lubricant supply. TATP experience provided the beginning of an under-standing of these problems leading to their solution. More detailed discussions of bearing results are found in ER-4054, the SNAP I Power Conversion System Bearing Development Report.

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TURBINE-ALTERNATOR TEST PACKAGE PARASITIC POWER
POWER

FIGURE 5-2

A modified version of the TATP incorporated the shaft driven, liquid mercury pump. This unit, sometimes referred to as the Turbine Alternator Pump Package (TAPP) was used to demonstrate that the SNAP I single shaft concept was feasible and presented no unforeseen developmental problems. System test rig difficulties prevented the acquisition of steady-state pump data, but pump performance was found to be satisfactory. More notable, however, the pump flow was coupled to supply the bearings, with complete success; performance was stable and no adverse intereactions were present.

6.0 PROTOTYPE TEST PACKAGE - PTP

The Prototype Test Package was the first turbomachinery unit designed with the objective of fulfilling the requirements of the SNAP I Power Conversion System to be used in space. This package included many of the features of the Turbine Alternator Test Package but was extensively modified because of the change in purpose as well as the availability of test information gathered during TATP tests.

6.1 Purpose

The purpose of the Prototype Test Package was to provide a turbomachinery unit identical in concept to that which would be utilized in the final power conversion system. It was also meant to be a "workhorse" unit in that it would undergo performance, endurance, environmental, and finally, nuclear hot cell tests. Unlike the end product however, the PTP was to be capable of being easily disassembled, in order that effects of operation could be easily determined and component changes incorporated without scrapping an entire package.

The PTP design philosophy, therefore, was based upon converting a maximum amount of thermal energy from the boiler to electrical energy, in the most compact, lightest package consistent with the above considerations. Because of this, emphasis was placed upon reducing heat loss, viscous drag and combining the components in an optimum manner.

6.2 Design and Fabrication

The design of the Prototype Test Package was based on the integration of the following components; three stage axial flow impulse turbine, radial gap permanent magnet alternator, mercury lubricated hydrosphere bearings with flow controlling orifices, and a jet primed mercury centrifugal pump. Figure 2-3 shows a cross section of the PTP identifying these components.

A major factor in the design of the package was to obtain a shaft assembly which would meet the requirements of satisfactory operation at high speed in a high temperature environment with minimum weight and angular momentum. The PTP shaft was designed such that its critical speed was significantly greater than the maximum expected operating speed. A conservative analysis of the shaft used in PTP, assuming no stiffening obtained from components and a reduced modulus of elasticity to account for the operating temperature, yielded a critical speed of 52,000 rpm, or 30% greater than design speed.

Another major design consideration was to maximize the PTP performance by reducing heat losses and loss of turbine working fluid. Considerations of mercury compatibility, low weight and dimensional stability, required that no internal insulation be used. Therefore heat losses were controlled primarily by reducing the area available for heat flow.

The turbine interstages were constructed with small fingers or tabs on surfaces which contacted the turbine housing. The turbine housing also utilized thin wall construction between the turbine inlet nozzle and the exhaust scroll areas. The first stage conical nozzle was designed to have minimum heat loss by using a double wall construction with low thermal conductivity insulating material between. To reduce heat transfer from the turbine working fluid to the cooler bearing lubricant flow, use was made of thin wall construction in the area from turbine inlet to turbine end bearing housing. Contact area of the turbine wheels on the shaft was minimized and the hollow shaft also resulted in small areas for heat flow. The sphere portions of the hydrosphere bearings were positioned on the shaft in a conical seat and the resulting line contact minimized heat flow.
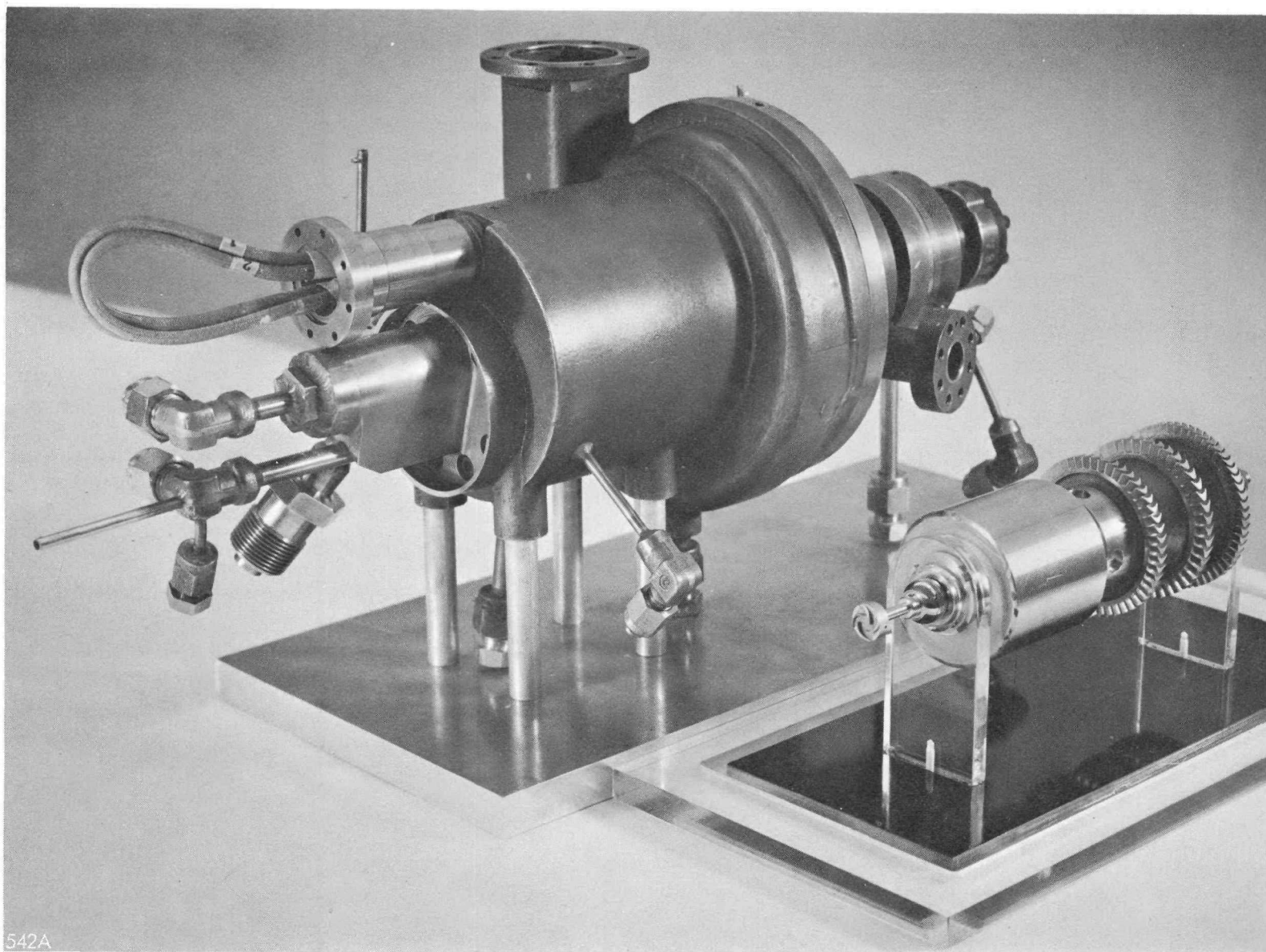
Due to the small turbine flow rate, losses normally unavoidable due to labyrinth seal leakage away from the turbine could easily become a significant portion of the total flow. This would result in inefficient utilization of the thermal energy contained in the mercury vapors. Therefore, great care was taken in the design of the shaft labyrinth seals to restrict such leakage to a minimum consistent with required running clearances. Seal leakage is especially important from the first stage turbine wheel cavity to the turbine end bearing cavity due to the high pressure ratio. For this reason, this seal is the longest in the package, as can be seen from Figure 2-3.

Heat losses from the PTP to the immediate surroundings were minimized by enclosing it in a low conductivity insulation and providing low conductivity, minimum area points for mounting the package to supporting structure.

The mounting of the rotating components on the shaft had to be compatible with considerations of critical speed, heat transfer, and working fluid leakage. This required that labyrinth seal lengths be as long as possible yet over-all shaft length as short as possible. Carefully planned location of components on the shaft resulted in an optimum configuration. For example, the lock nut securing the turbine wheels was placed in the center of the shaft so that the high pressure labyrinth seal length would be maximum - significantly longer than TATP. Turbine wheel hubs were dished to permit increased interstage labyrinth seal lengths.

Precise balancing of the rotating components is especially vital in SNAP I due to the high rotating speed. Minimizing unbalance results in lower bearing loads and negligible vibration generated by the turbomachinery. Since it was only feasible to build the turbine stators as solid cylindrical units, it was required that the turbine wheels be removed to install these stators after the rotating assembly had been dynamically balanced. Special positioning devices were required to insure that the turbine wheels could be reassembled onto the shaft in the exact positions previously occupied during balancing. A unique wedge ring positioning device was used to accomplish this and to lock the turbine wheels and alternator rotor in place. The PTP shaft assembly is shown in Figure 6-1.

The design of the turbine used in PTP was based heavily on the TATP test results. Partial admission was employed in the first two stages with the last stage full admission and

PROTOTYPE TEST PACKAGE AND SHAFT ASSEMBLY

FIGURE 6-1

TAPCO GROUP ◣™ Thompson Ramo Wooldridge Inc.

incorporating slight reaction in order to reduce the chances of erosion due to wet vapor. Design details of this turbine can be found in ER-4051 of this report series. Fabrication of the turbine parts was similar to that employed with TATP: the machined and hardened wheel blanks had blade profiles machined in their rims by eloxing.

A significant advance in the state-of-the-art of electrical insulation resistant to high temperature, nuclear radiation and mercury vapor made the SNAP I alternator possible. The stator of the package runs uncooled in a 550°F environment. Details of this component are described in ER-4052 of this report series.

The hydrosphere bearings employed in PTP were the same as those used in the later versions of TATP. They used one half inch nominal diameter, ungrooved sockets as had been proved optimum, but their flow restrictions were modified to eliminate sensitivity to lubricant contamination. The flow restriction consisted of a short stub shaft extending outboard of the bearing through a controlled housing diameter. The annular space created between the stub shaft and the housing was the flow restriction area. The centrifugal pump, mounted on one of these extensions on the alternator end of the shaft, was of the configuration previously developed in component and TATP testing. Design details of the bearing and pump are found in engineering reports ER-4054, and 4053, respectively, of this report series.

A steel casting was used for the alternator housing in order to most easily satisfy the complex flow passage required for the turbine exhaust volute. This volute was designed to collect the turbine exhaust vapor and maintain a constant velocity sufficiently high to carry with it any condensed mercury particles issuing from the turbine. Since PTP was to have been tested in the nuclear radiation environment that would be present when the system was evaluated with the radioisotope boiler, no radiation sensitive parts could be used. The package was also designed to be capable of modification for a complete hermetic seal by welding, but had to be capable of being disassembled. These two factors meant that metallic o-rings had to be employed to provide seals at the several joints.

A view of the Prototype Test Package is shown in Figure 6-1. External electric heaters are provided for preheating before startup. No insulation that could be considered to be prototype was fabricated for PTP, since this was to have been a later program development. In operation, commercial insulation in block and mat form is applied to the package to control heat losses. Total weight of the prototype test package, although several compromises were made to make it the "workhorse" unit as described, is only 13 lbs.

6.3 Prototype Test Package Testing

All evaluation of PTP was carried out in either the Breadboard Test Facility or the Systems Test Enclosure described in Section 8 of this report. Testing in the Breadboard was primarily to determine the unit's performance capabilities while that which took place in the STE determined the performance and endurance capabilities of the unit when integrated into the complete

Rankine system – the Ground Test System. This section deals primarily with the evaluation of the PTP with respect to performance as it was obtained in either test facility.

The Breadboard Test Facility with its calibrated source of high temperature mercury vapor provided an excellent facility for evaluating the performance characteristics of PTP. Prior to actual running the complete turbomachinery package, the removable first stage turbine nozzle was flow calibrated in this facility. Since this nozzle operates with a pressure ratio greater than critical, sonic conditions are reached at its throat allowing the vapor flow rate to be readily calculated by knowledge of inlet temperature and pressure. Calibration runs were performed to obtain the required discharge coefficient of the nozzle, in order that very accurate flow measurements could be calculated. Figure 6-2 is a typical calibration curve and shows that the calculated flow is in very good agreement with that measured during calibration. Determining flow by this method is applicable to saturated or superheated vapor only, since moisture droplets will pass through the nozzle undetected. Therefore, if the vapor supplied to the nozzle is wet, the nozzle's actual flow rate will be higher than that calculated, by the amount of moisture passing through the nozzle. This fact is put to good advantage if an accurate flow rate of the fluid supplied to the boiler and hence to the turbine is known. By measuring these two weight flows the fact that the turbine is receiving wet or dry vapor of calculatable quality, is readily determined. This fact is mentioned here primarily because it assumed significant importance during the later GTS testing.

One of the first results of PTP testing in the Breadboard was the determination that the alternator motoring startup technique was not satisfactory, utilizing the startup system available. It was found that the capabilities of the variable frequency power supply that was to supply the PTP's alternator did not contain sufficient capacity at the very low frequencies to yield the required breakaway torque. Since the component activity in this area had been suspended, and PTP could be adequately started on vapor to the turbine, development to obtain a motor startup was not continued.

Of the PTP hot mercury vapor runs in the Breadboard Test Facility, one is outstanding. On May 14 and 15, 1959, PTP-1 operated continuously at full speed and power for 48 hours. This scheduled demonstration coming only two weeks after the beginning of testing of this new package provided much valuable performance data and gave excellent indications of the endurance capability of this unit. During this test, speeds up to 45,000 rpm were obtained and the shaft pump was used to supply the entire bearing lubricant flow. Figure 6-3 is a plot of key parameters from this test.

As a result of the highly successful Ground Test System endurance run of 2510 hours, much data on PTP performance has also been obtained in complete system tests. When being run with boilers that produced wet vapor, the performance of the PTP was degraded. It was found that turbine output suffered not only from the decreased energy content of the vapor but that wet vapor resulted in lower turbine efficiencies also. For example, when running on 80% quality vapor, it was found that turbine efficiency was decreased by approximately 10 points.

PTP NOZZLE CALIBRATION

TOTAL INLET PRESSURE VS WEIGHT FLOW
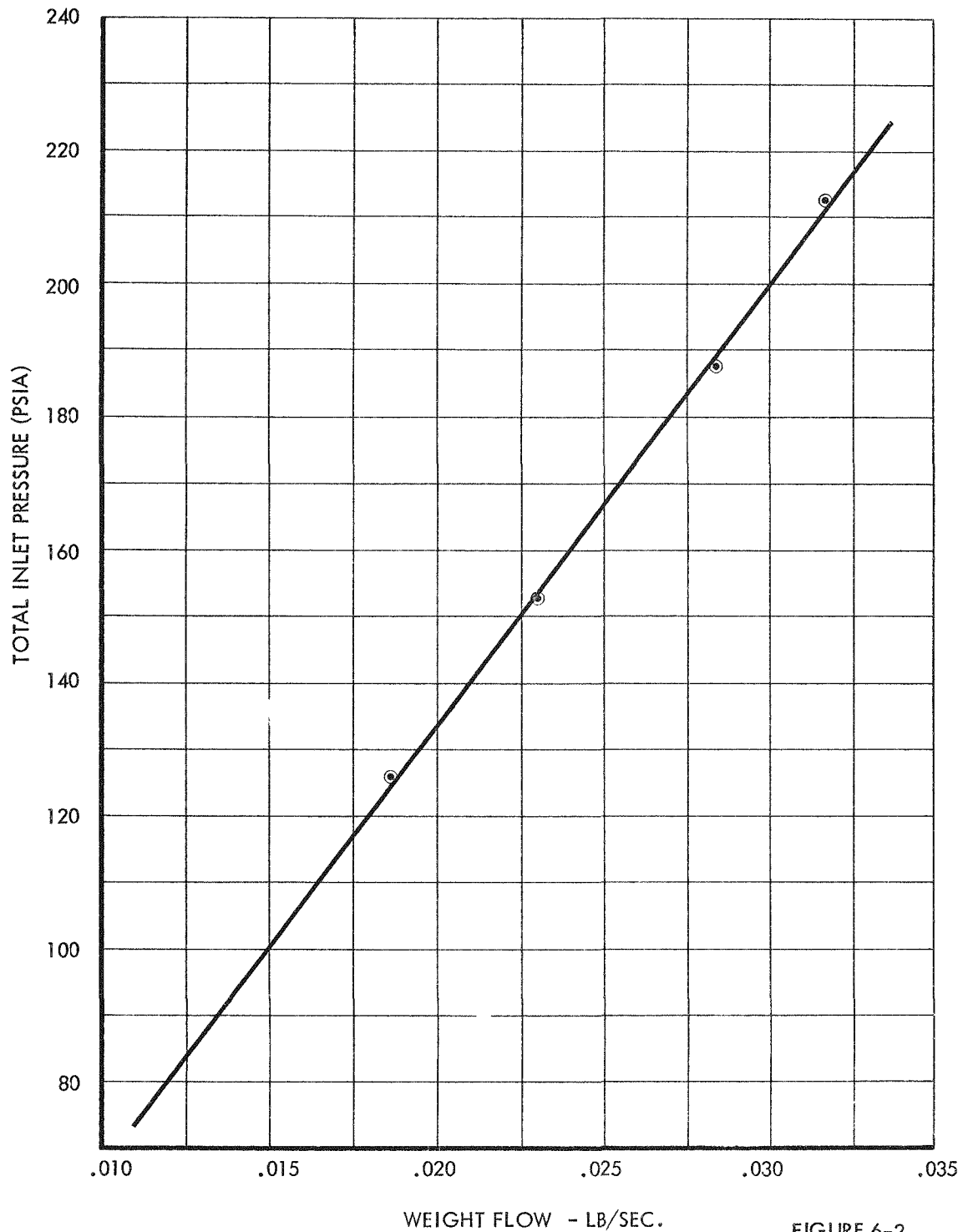
FLOWS CORRECTED TO 1300°F

WEIGHT FLOW – LB/SEC.

FIGURE 6-2

PROTOTYPE TEST PACKAGE 48 HOUR ENDURANCE RUN
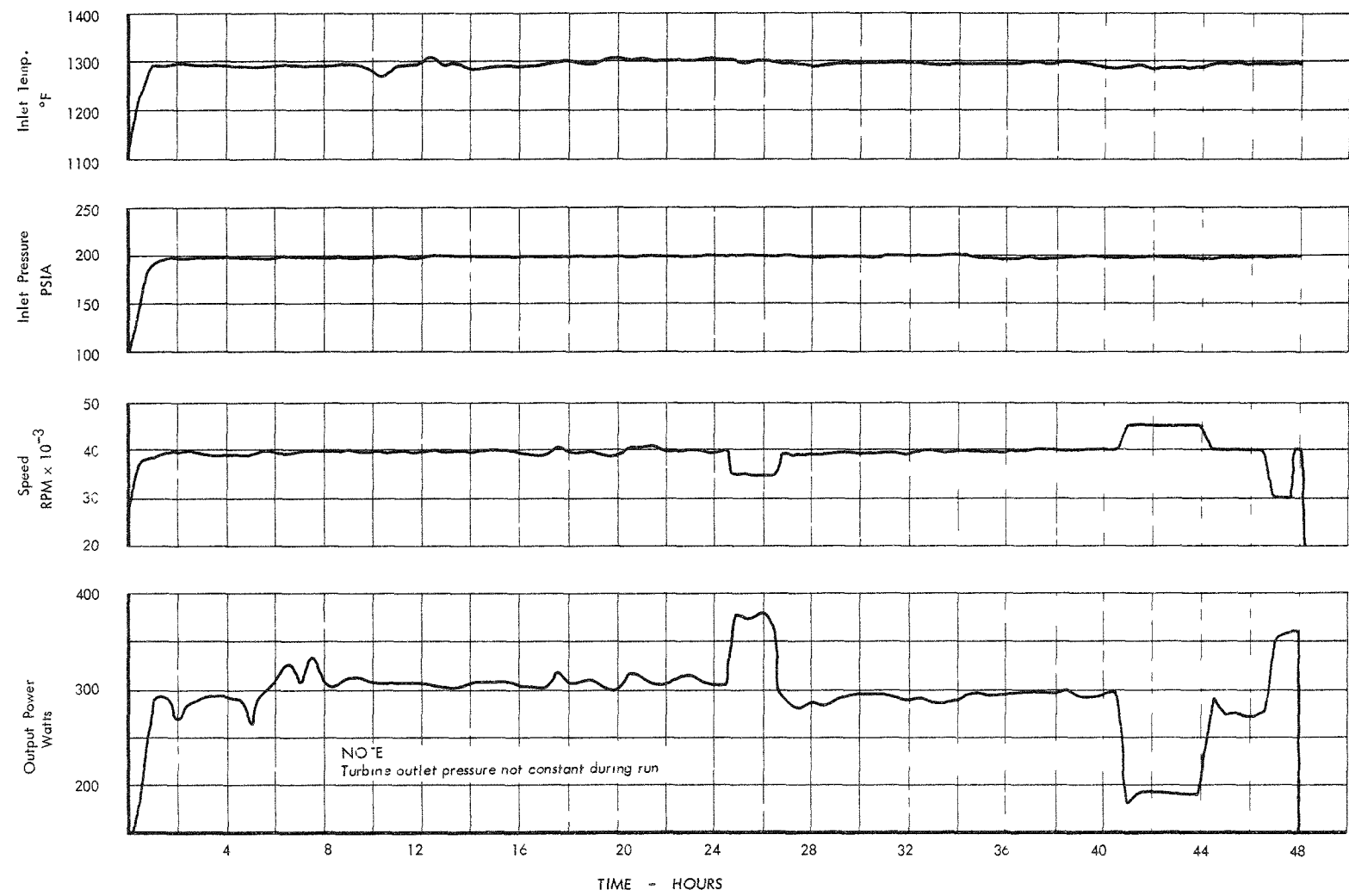
NOTE
Turbine outlet pressure not constant during run

TIME — HOURS

While two Prototype Test Packages were built during the program, essentially all of the performance and endurance testing was accomplished on the first unit. Although PTP-2 was built and operated on mercury vapor, the required scope of the SNAP I effort did not permit sufficient running time at design conditions to obtain valid performance data. This was unfortunate since PTP-2 had certain design changes which would have resulted in performance superior to that of PTP-1.

PTP-1 was assembled using second and third stage turbine nozzles whose areas were known to be greater than design. While it was recognized that this would result in lower turbine performance, other aspects of the SNAP I program required that the unit be placed into service without correcting these deficiencies. PTP-1 also used the first prototype permanent magnet alternator built. The alternator incorporated in PTP-2 had design modifications that resulted in its conversion efficiency being several points higher than that used in PTP-1. Primarily for these two reasons, the efficiency of the turbomachinery package was expected to be significantly greater in PTP-2 than it was in PTP-1.

Figure 6-4 is a performance map obtained from PTP-1 test data. For design turbine inlet temperature and condenser pressure, the power output of the package is shown as a function of turbine inlet pressure and speed. That this performance was obtained from a turbomachinery package with known deficiencies, using components with efficiencies less than those known to be attainable, and with no system optimization performed, attests to the performance potential of not only the turbomachinery, but of this method of producing electrical power in space.

Developmental problems that appeared during the testing of these two packages were corrected within the restrictions of the limited program. One was the replacement of the rotating annulus type of bearing flow restriction with the fixed capillary type originally used in TATP. It was found that while the annular type of orifice did tend to be self cleaning, it was more susceptible to lubricant contamination than was the fixed capillary type of restriction. Therefore, the turbine end bearing flow restriction was replaced with a fixed capillary type. Improvements in materials selection, parts cleaning and mercury filtering techniques were also responsible for an alleviation of lubricant contamination present in the system. Contributing heavily to the amount of contamination were the cleaning procedures based upon the use of acids. By substituting cleaning procedures utilizing degreasing techniques only, the amount of products of mercury corrosion that would contaminate the liquid mercury was substantially reduced.

Difficulty was also experienced in obtaining a completely sealed package. The metallic o-rings used to seal the several joints were found to require significantly higher torques on the retaining bolts than were specified by the manufacturer. While higher screw friction torques were partly responsible for this, several flanges had to be redesigned for closer bolt spacing and higher strength bolts specified. When it was determined that PTP would not be used in a nuclear radiation environment, this problem was eased by substituting high temperature rubber o-rings in several places.
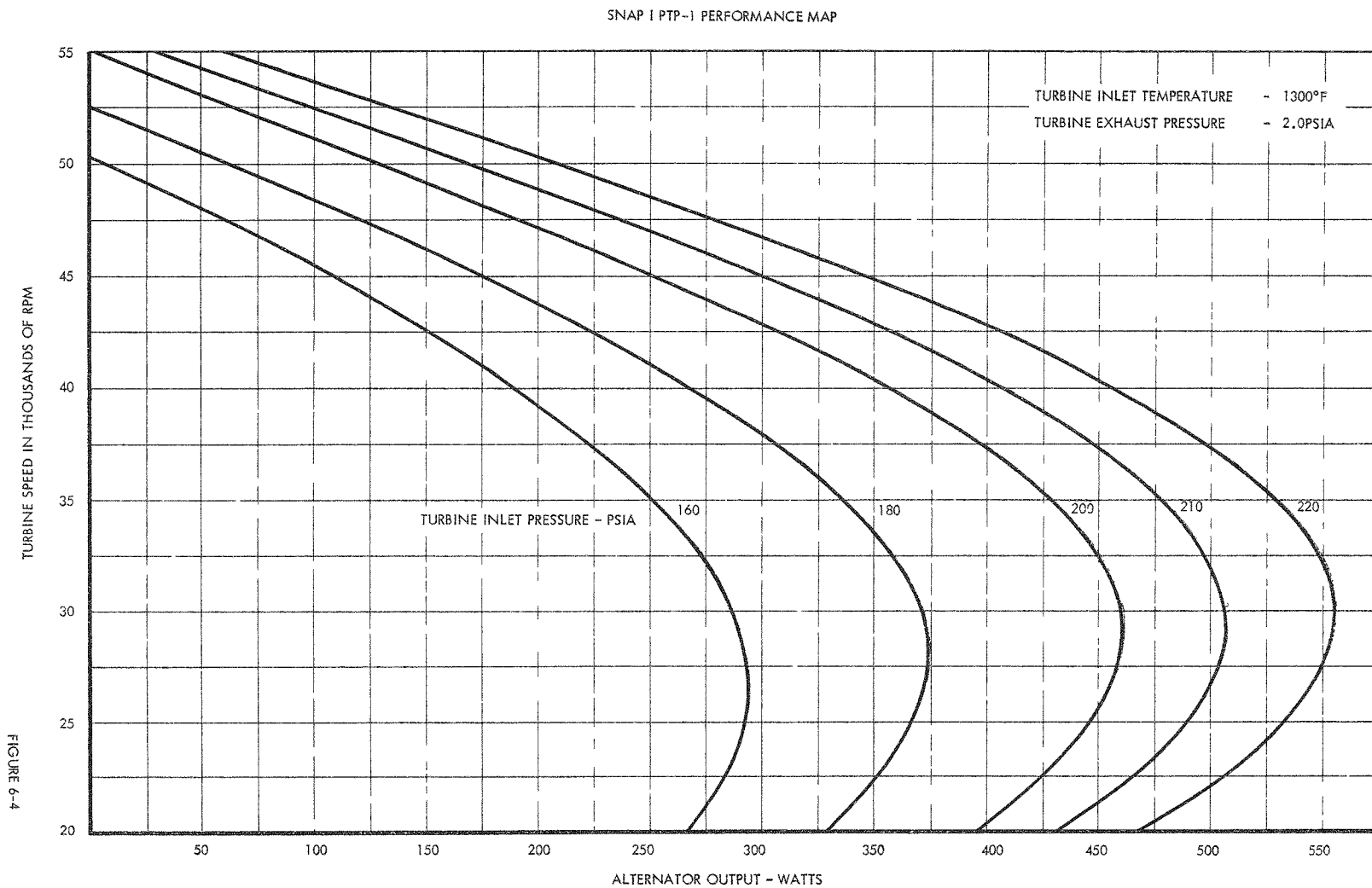
SNAP I PTP-1 PERFORMANCE MAP

FIGURE 6-4

7.0 SNAP I GROUND TEST SYSTEM

The Ground Test System represented the first integration of the several components developed under the SNAP I program. This section will describe the design considerations upon which this unit was based, the tasks it was designed to fulfill, and a summary of significant test results obtained.

7.1 Purpose

As is true of all aspects of the SNAP I development program, the Ground Test System was required to investigate new areas of technology. Since the GTS was the first system of mercury Rankine space power components, its role to the continuing development of SNAP I as well as future Rankine space power systems was a vital one. Specifically, the GTS was required to investigate the following areas:

1. Performance of the system
2. Control dynamics
3. Component interrelationships
4. Startup techniques
5. Endurance capabilities
6. System problem areas

7.2 Design and Fabrication

The design philosophy of the Ground Test System can be summarized as: GTS was to be a flight-type of mercury Rankine space power system specifically tailored to ground testing. This meant that it was to be capable of meeting the envelope requirements imposed by a given satellite vehicle configuration, and require no major system changes as it evolved into later versions that would incorporate radioisotope boilers, a radiant cooled condenser, leading to the final SNAP I flight test system. Reductions in scope and subsequent termination of the formal SNAP I development program resulted in modification to this concept. Since the flight requirement for SNAP I had been cancelled, the considerations for packaging the system to match a given vehicle configuration were no longer essential.

The original GTS design combined the two half power boilers provided by The Martin Company, with the Prototype Test Package and a compact air cooled condenser. These major components, together with the SNAP I control components, required auxiliaries and instrumentation, made up the GTS. The over-all configuration of the components was designed to be compatible with the satellite vehicle intended to utilize SNAP I. Figure 7-1 shows this general configuration and 7-2 shows how later versions of the SNAP I system could evolve into flight configuration with no major redesign.

For convenience in assembly and testing the turbomachinery package – PTP – together with the miscellaneous system components, they were mounted on a platform together

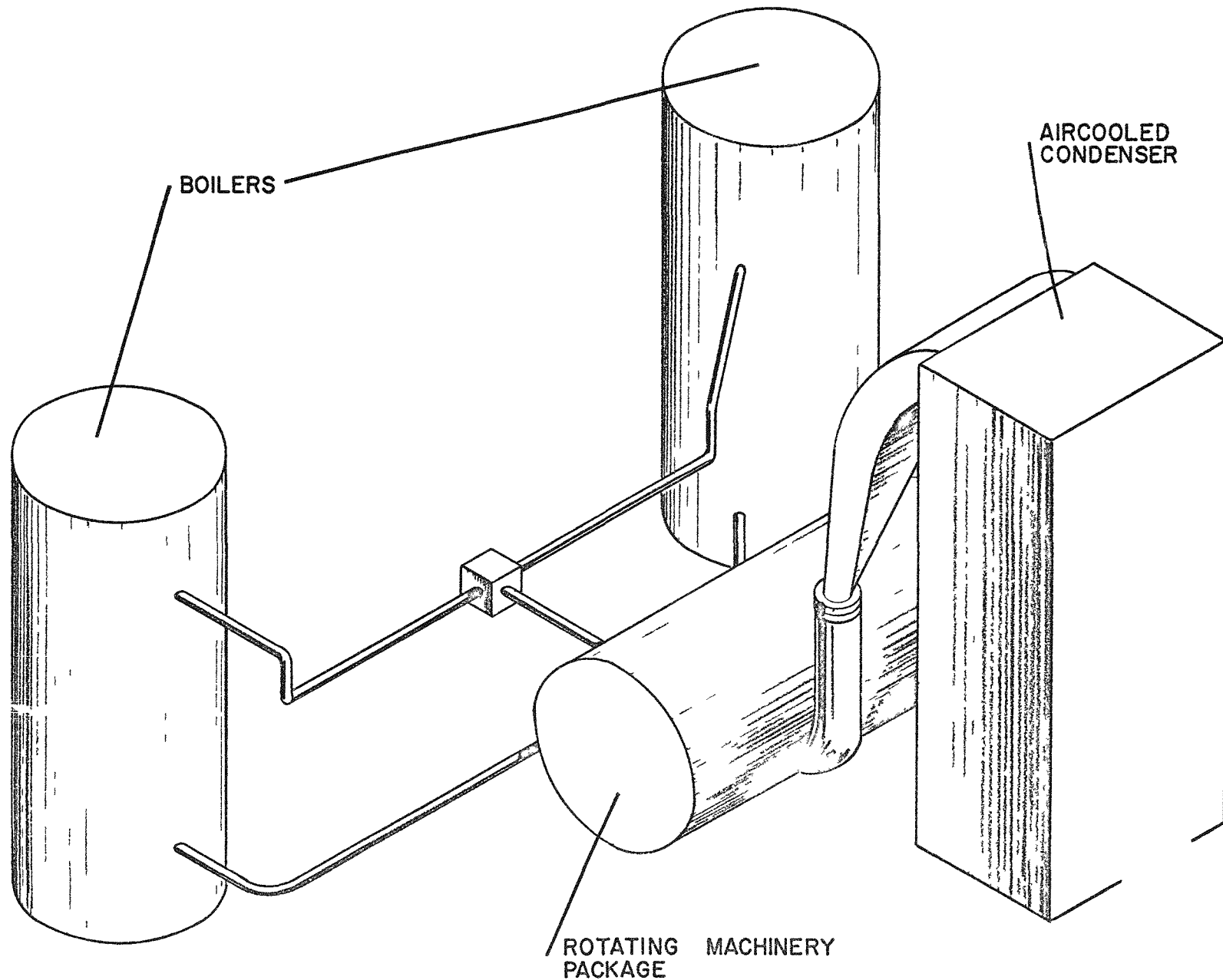# GROUND TEST SYSTEM COMPONENT ARRANGEMENT

BOILERS

AIRCOOLED CONDENSER

ROTATING MACHINERY PACKAGE

FIGURE 7-1

TAPCO GROUP △ Thompson Ramo Wooldridge Inc.

FLIGHT TEST SYSTEM COMPONENT ARRANGEMENT

BOILERS
(ENCLOSED WITHIN
BIOLOGICAL SHIELDS)

ROTATING MACHINERY
PACKAGE

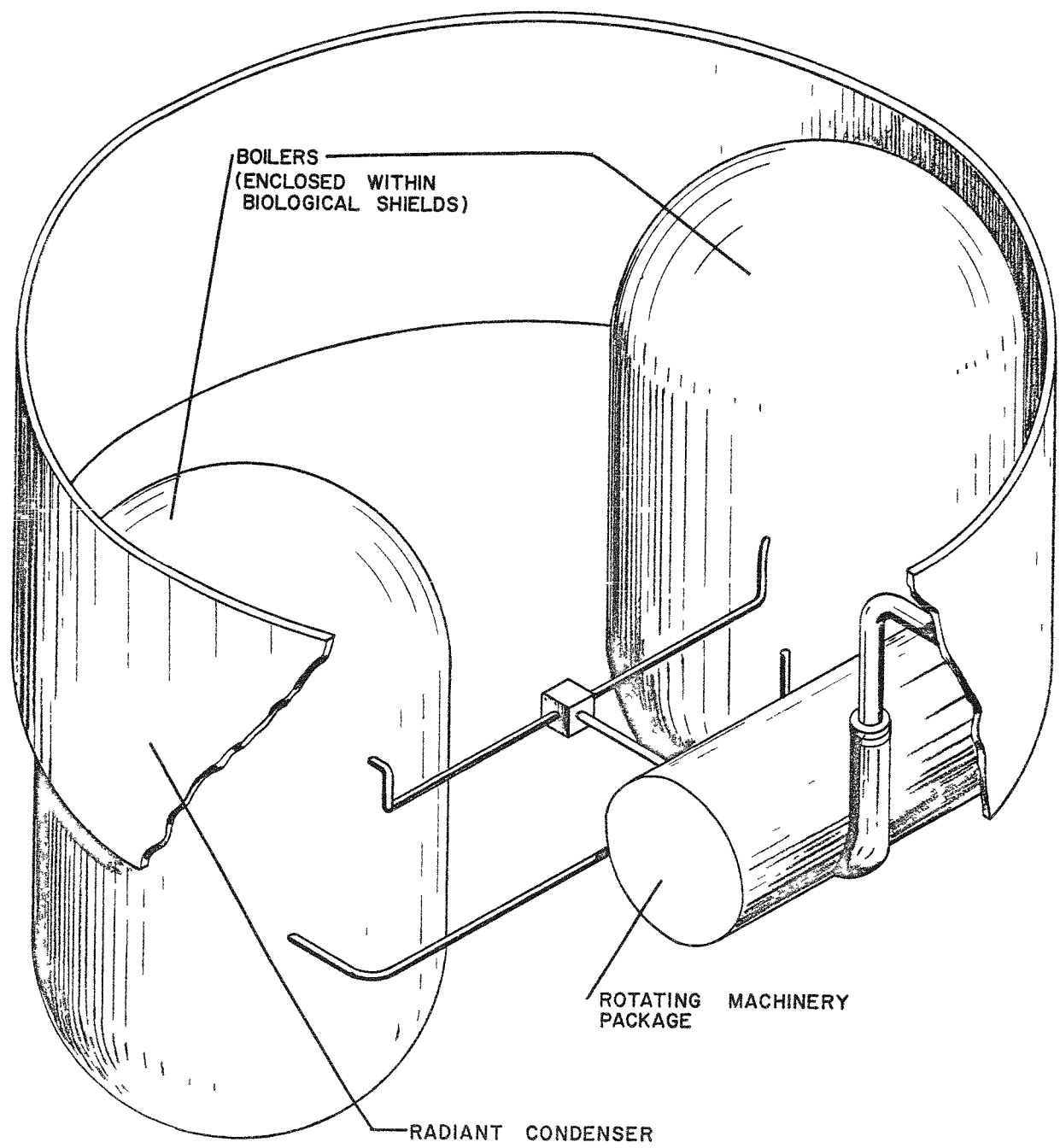RADIANT CONDENSER

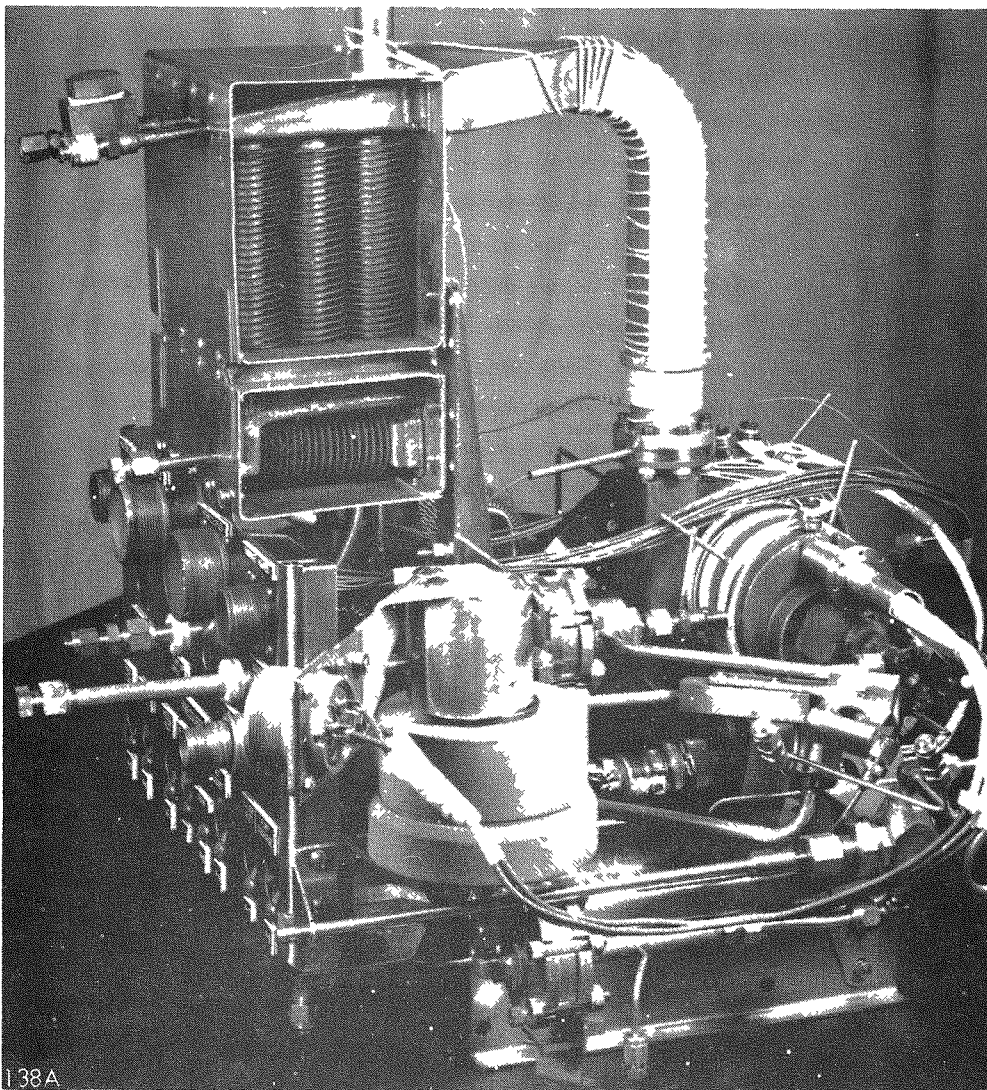FIGURE 7-2

TAPCO GROUP △™ Thompson Ramo Wooldridge Inc.

with the compact condenser. Figure 7-3 shows this package. Since it was expected that the turbomachinery and system auxiliaries would present the greatest need for modification and adjustment during testing, this modular design permitted maximum utilization of the test facility by allowing for a rapid replacement of this portion of the system.

Figure 7-4 is a schematic of the Ground Test System showing the flow paths of the fluid throughout the system. Flow from the package pump is metered through a venturi and supplied through a filter - assembly to the bearings of the turbomachinery package. Pump outlet flow also passes through another filter and venturi flow meter to the boiler inlet pressure regulator. The liquid mercury discharging from the pressure regulator is divided and enters the half power boilers; separate flow meters are provided at the inlets of each boiler to control this flow division. Vapor from the boilers is supplied through an insulated line to the turbine inlet, and the turbine exhaust vapor flows to the condenser, is condensed, and enters the subcooler. Lubricant flow from the bearings is collected in a manifold and enters a liquid mercury jet pump. This jet pump utilizes a small portion of the high pressure mercury from the package pump as the driving fluid. It's purpose is to lift the spent lubricant back to the subcooler where it is mixed with the incoming condensate, cooled, and supplied to the package pump inlet.
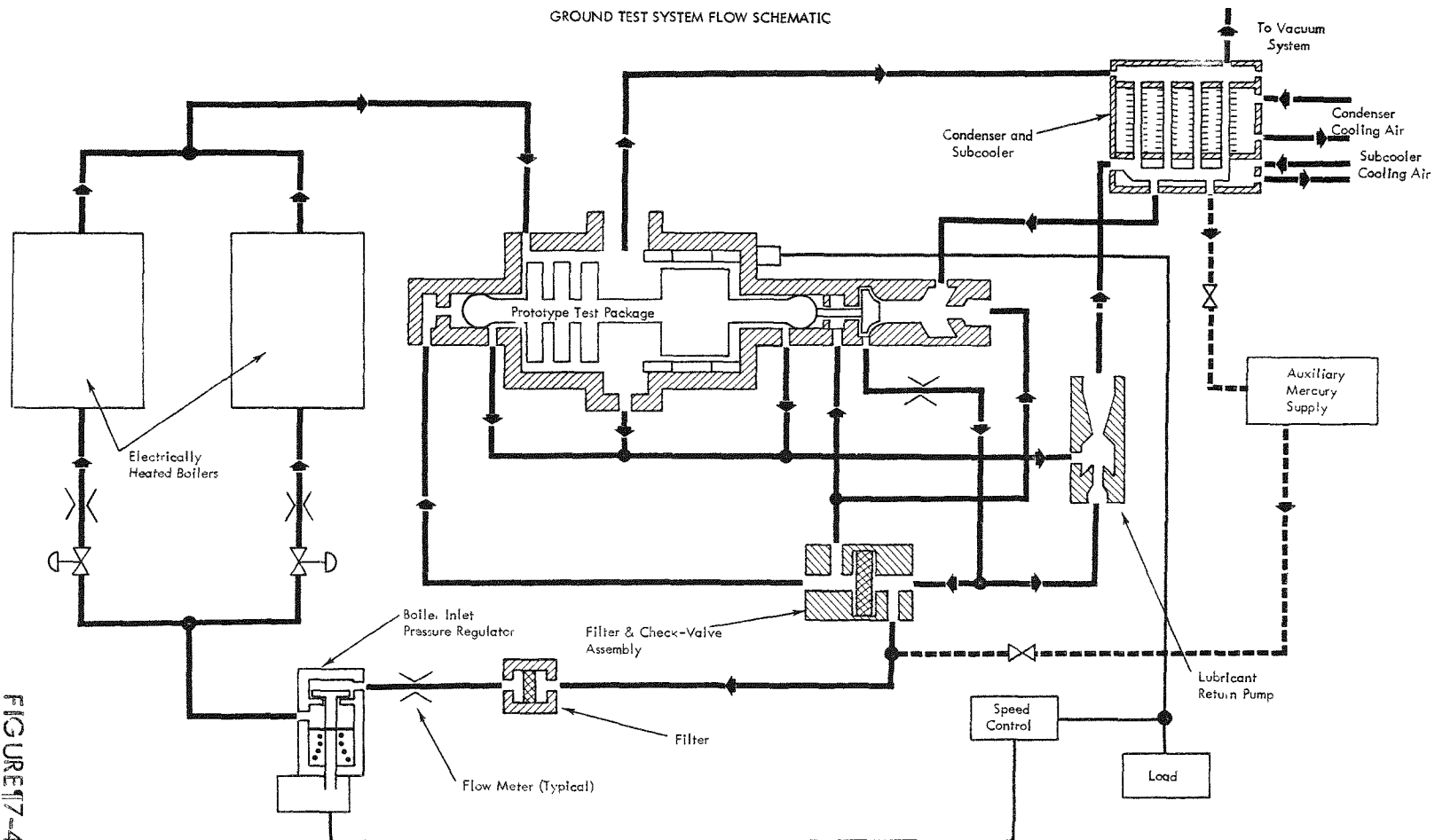
An auxiliary mercury supply provided by the test facility is used to fill the system with mercury, and, depending upon the startup method utilized, provides lubricant flow to the bearings until the turbomachinery is at sufficient speed to supply its own needs. A line is connected to the condenser in order that the test facility vacuum system can initially evacuate the system and draw off noncondensibles that may be evolved. The alternator output of the system is dissipated in a load bank which is part of the test facility. Also a part of the GTS is the electronic portion of the speed control, consisting of the frequency discriminator and magnetic amplifier to provide the modulation of the pressure regulator. GTS instrumentation provided for static and dynamic measurement of the pressure, temperature, flow rates, into and out of each major component, as well as measuring system electrical output and electrical input to the various system heaters.

As in the case of the Prototype Test Package, the design of the Ground Test System considered the effects of the nuclear environment in which it was to operate. However, program redirection away from the flight requirement resulted in no need for such considerations and hence, the design requirements for GTS were eased. This same program redirection eliminated the requirement for integration to a given vehicle and permitted more flexibility in component arrangements while still keeping the concept of a system potentially capable of use in space. The most significant results of this concept change was the substituting of a single boiler for the two half-power boilers after test experience had shown that these boilers did not fully meet system requirements. The single pass boiler of internal configuration, similar to a prototype boiler for use in space, was packaged for convenience of supplying heat, instrumentating, and installing. It was with this boiler that the bulk of GTS operating experience was obtained.

GROUND TEST SYSTEM PACKAGE

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FIGURE 7-3

GROUND TEST SYSTEM FLOW SCHEMATIC

To Vacuum
System

Condenser
Cooling Air

Subcooler
Cooling Air

Condenser and
Subcooler

Prototype Test Package

Auxiliary
Mercury
Supply

Electrically
Heated Boilers

Boiler Inlet
Pressure Regulator

Filter & Check-Valve
Assembly

Lubricant
Return Pump

Filter

Flow Meter (Typical)

Speed
Control

Load

7.3 GTS Testing

While the formal SNAP I development program had ceased at the end of Fiscal 1959, it was recognized that the components developed were the first of similar items for mercury Rankine space power systems to come. In order to provide further experimental background upon which these later systems could be efficiently developed, it was decided that SNAP I could make a major contribution in the area of endurance development. Beginning in July of 1959, then, the goal of the SNAP I program was to obtain a maximum amount of endurance testing of the Ground Test System to demonstrate the endurance capabilities of mercury Rankine space power hardware, to uncover possible problem areas, and to point toward their solution. During July and August, 1959, this effort was directly funded by the AEC under prime contract AT(30-1)-2559. Beginning September 1, 1959 this endurance testing program was continued under the SNAP II prime contract AT(11-1)-GEN-8 with the TRW work being performed under subcontract to Atomics International, a division of North American Aviation.

Prior to initiation of complete Ground Test System testing, a series of boiler, condenser, and control tests were run to determine steady state and dynamic performance of these components. The two half power boilers provided by The Martin Company supplied vapor to a turbine nozzle which throttled it to condenser pressure. Excess heat was removed in the desuperheater and the condenser returned the fluid to the auxiliary mercury supply. Preheated mercury from the auxiliary supply passed through the boiler inlet pressure regulator to the boiler pair. Commercial controllers installed at the inlet of each boiler enabled the flow division between the two boilers to be controlled automatically or manually.

The original purpose of this test series was to obtain information on dual boiler outlet pressure and temperature response as a function of changes to boiler inlet conditions. This was not completely achieved due to two characteristics of the dual boiler: They were found to produce a surging type of instability that resulted in oscillations in outlet pressure; part of the boiler discharge vapor was determined to be wet rather than superheated.

The manifestation of the boiler instability was in the form of a discharge pressure variation of approximately 20 psia with 10 sec. period. The boiler outlet moisture condition as determined by heat balances and measurements of inlet liquid flow vs vapor outlet flow was found to be approximately 20% wet. Modifications were made by TRW which consisted of auxiliary preheaters and preboilers mounted at the inlet to the dual boilers. The addition of 5 ft. of electrically heated tubing to the inlet of each boiler resulted in an improvement in the outlet moisture condition and a complete elimination of the instability problem. It was found that dry vapor could be produced with flows up to about 80% of design, but that wet vapor was obtained for flows in excess of this.

While the boilers would not permit the desired full power operation of the complete system, the turbomachinery portion of the GTS was integrated with the heat transfer and control

components and the initial system operation was begun. These first system runs demonstrated that the GTS was capable of stable, full speed operation. It also brought to light certain practical difficulties and pointed toward their solution. As discussed in section 6, the rotating annulus type of hydrosphere bearing flow restriction was found to be more sensitive to lubricant contamination. Therefore, a capillary type of flow restriction was incorporated in the turbomachinery package. Air and other noncondensibles leaking into the low pressure portions of the GTS were found to interfere with proper operation and modifications to insure more positive sealing and yet permit proper instrumentation and assembly techniques were incorporated. The early runs also resulted in the shakedown and improvement of the Systems Test Enclosure insuring consistent, reliable operation.

Concurrently with the initial GTS testing and the modifications being made to improve boiler performance, a single boiler suitable for system testing was designed and fabricated by TRW. This electrically heated boiler was built in order that GTS testing could continue in the event that the performance of the half power boilers could not be improved to permit design point system operation, or if mechanical failures of these boilers should occur. When such a failure did occur, in the form of a mercury leak from one of the boilers, the replacement boiler was completed, installed and tested. This boiler consisted of a helical coil immersed in liquid lead which served as the thermal bond to electrical heaters also immersed in it. Heat transfer testing of this boiler was very successful. Tests showed that it exceeded the requirements of the SNAP I system. However, before this boiler could be integrated with the GTS, a leak developed which proved to be the result of lead stress corrosion.

A second replacement boiler was built which utilized an identical boiler coil but was heated with high temperature radiant heaters rather than the lead bath. This boiler also demonstrated heat transfer capabilities in excess of those required and no mechanical difficulties were present. After the successful checkout of this boiler, the remainder of the GTS components were reassembled in preparation for endurance testing of the system.

The endurance running, described in the following paragraphs was performed subsequent to the program actually conducted under AEC Contract AT(30-3)-217. The endurance testing was initiated, however, under AEC Contract AT(11-1)-GEN-8, as previously explained, and the results are briefly summarized herein for sake of completeness.

On January 25, 1960, the first Ground Test System, made up of the TRW electrically heated boiler, the first SNAP I turbomachinery package (PTP-1), the compact air-cooled condenser, controls, and auxiliaries, began endurance testing. Satisfactory system performance was established and maintained for 200 continuous hours when a mercury vapor leak from an instrumentation line caused shutdown. Throughout this run the rotor speed had been limited to 32,000 rpm rather than 40,000 rpm due to a low setting of the boiler inlet pressure regulator. After repairing the instrumentation and resetting the pressure regulator to allow full design speed, the system was placed back in operation with no maintenance performed on the turbomachinery package or on any other portion of the system.

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The endurance test continued, under sponsorship by the AEC, until approximately the middle of March. At this time the 1000 hour objective of the AEC program was achieved and AEC funding was terminated. The endurance testing of the system continued, without interruption, under Air Force Contract AF 33(616)-6625.

The system was run at full speed and full power until May 19, and accumulated a total of 2510 hours of operation. Upon passing the 2500 hour objective, the GTS was voluntarily shut down, with no indication of any impending failure.

At the time of preparation of this report, no inspection of the system has been performed. However, several significant achievements of this test can be stated based upon measured parameters from the test.

1. Bearing performance entirely satisfactory, no noticeable deterioration.

2. No major effect of corrosion or mass transfer observed on the performance of the turbomachinery.

3. Turbine performance excellent. No reduction in performance observable.

4. Alternator performance good. Non-metallic bore seal material appears satisfactory.

5. Pump performance promising for first endurance attemtp. Slight outlet pressure deterioration observed but thought to be due to air leakage into system.

6. No indications of impending failure were present when the system was voluntarily shut down.

By nearly doubling the design life requirement of SNAP I, the Ground Test System has made a major contribution to the development of mercury Rankine space power systems. The information obtained during this run will make direct and substantial contributions to the design of future Rankine space power systems, as well as to the design of test rigs for evaluating such systems.

8.0 SYSTEM TEST FACILITIES

Of vital importance to any advanced technology development program are the facilities used to evaluate the chosen designs. Test facilities for such programs require that much ingenuity and engineering skill be utilized in their design and construction. The test facilities used during the SNAP I development are examples of this. This section will describe these test facilities and discuss how their difficult requirements were satisfactorily met.
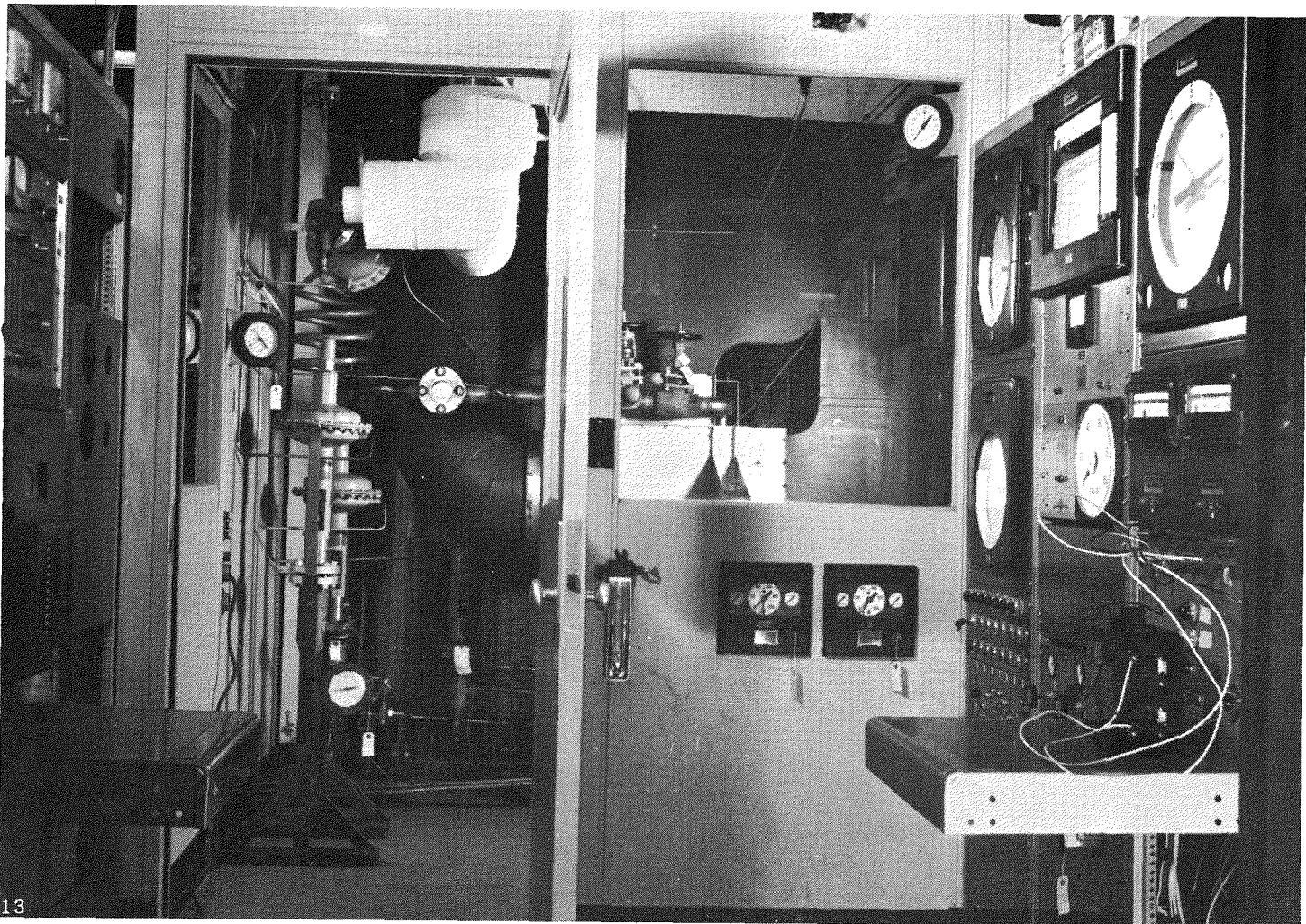
8.1 Breadboard Test Rig

The primary purpose of the SNAP I Breadboard Test Rig was to provide a facility capable of evaluating the performance of mercury vapor turbomachinery packages. It was also capable of evaluating heat transfer apparatus such as boilers and condensers, and other components requiring a flow of high temperature mercury. The requirements of this rig were to provide a high temperature, high pressure mercury vapor supply over the full range of turbomachinery requirements and to supply liquid mercury at the required temperatures and pressures. Provision was also made for accepting the turbine exhaust and condensing it. Elaborate instrumentation was required to obtain the required data for proper evaluation of operating parameters. Adequate auxiliaries and control devices were also required.

Common to all of the SNAP I test facilities designed and built at TRW were the precautions taken to insure the safety of test personnel. As well as the usual care taken in the design of high temperature, pressurized components and plumbing, special techniques were required to guard against the hazards due to the toxic characteristics of mercury vapor. This was accomplished by enclosing all mercury containing apparatus within a metal-walled room or enclosure. Blowers were used to exhaust air from the 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.
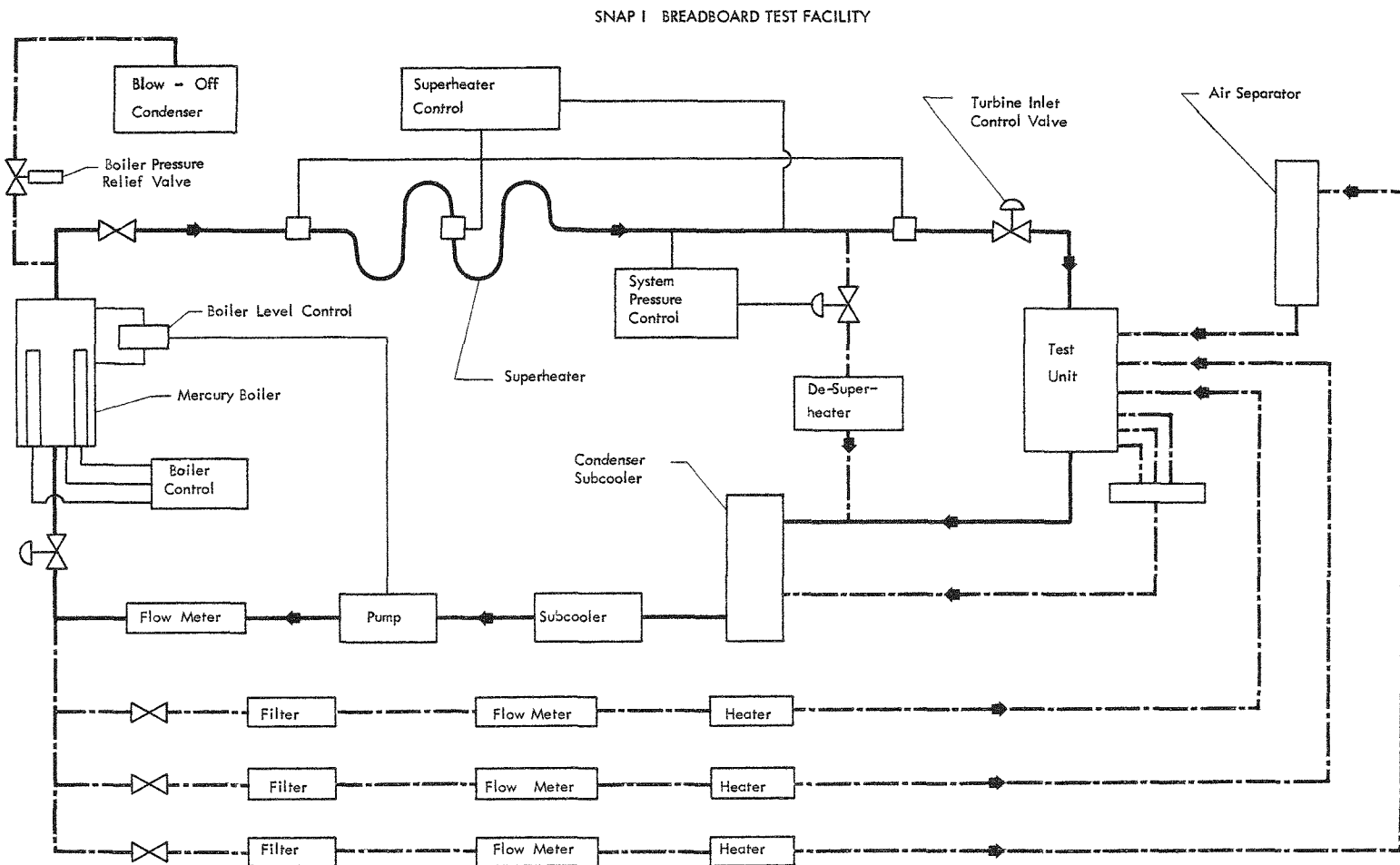
Figure 8-1 is a photograph of the SNAP I Breadboard Test Facility showing the enclosure with the associated instrumentation and operating controls.

A schematic of the breadboard test rig is included in Figure 8-2. Starting at the pump, liquid mercury flows through the accumulator which dampens out the pulsations of the positive displacement pump. The total pump flow is metered and divided between the boiler flow and the liquid mercury supply. Mercury is evaporated in a pool-type boiler consisting of vertical stainless steel pipe, three inches in inside diameter by five feet long. Electrical immersion heaters within this pipe supply the heat to the mercury which enters at the bottom. Superheating of the vapor is accomplished in an electric inline type resistance heater. System pressure is controlled with a vapor by-pass control valve actuated by a pressure control in the superheated vapor line. This valve controls the amount of by-pass

BREADBOARD TEST RIG – ENCLOSURE AND INSTRUMENTATION

FIGURE 8-1

FIGURE 8-2

flow through a de-superheater and back to the condenser, thus maintaining system pressure at the desired level. The superheated mercury vapor passes through two turbine inlet control valves prior to the turbine inlet. The exhaust vapor flows to an air-cooled condenser where it is condensed and subcooled. The subcooled mercury returns to the pump inlet. At the pump, a mercury reservoir is provided for filling and draining the system.

The liquid mercury supply consists of liquid flow meters, filters, preheaters, and control valving to provide several sources for liquid mercury at desired pressures and temperatures. An air separator is provided in the supply to the turbomachinery pump inlet. The inlet pressure to the pump is controlled by adjusting the mercury level in this air separator. The turbomachinery drain is vented directly to the condenser just above the liquid vapor inter-face. Various by-pass lines not shown in the schematic are provided for by-passing pump and bearing flows to provide for flexibility in test operations.

In addition to the mercury plumbing shown in Figure 8-2, a vacuum system is included to evacuate the system, remove non-condensables from the condenser and the air separator. An inert gas system (nitrogen) is included to provide a means to cold gas test the turbine and provide a non-corrosive cover gas during shut-down. A water supply, drainage system and compressed air supply have been included in the design of the breadboard.

A complete system of pressure and temperature measuring equipment is included to measure the system and test rig parameters. Also, a turbine speed sense and over-underspeed cut out is provided. Dynamic instrumentation is provided to measure and record transient data. Heater power controls, liquid level controls, and safety devices are an integral part of the design. Table 8-1 is a listing of the key capabilities of this test facility.

TABLE 8-1

Breadboard Test Rig Capabilities

Mercury flow –	liquid	40 lbs/min
	vapor	3 lbs/min
	pressure	300 psia, maximum
	temperature	1200°F vapor
		350°F liquid
Heat rejection –	condenser	16,000 Btu/hr
	subcooler	6,000 Btu/hr
Instrumentation –	pressure	static, Bourdon gages
		dynamic, strain gage transducers
	flow	manometers and calibrated orifices
		for all critical system flows
	temperature	192 channels of thermocouple loggers
	speed	recorder and counter
	alternator output	volts, amperes, and watts from
		25 to 2000 cps

8.2 Systems Test Enclosure

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.
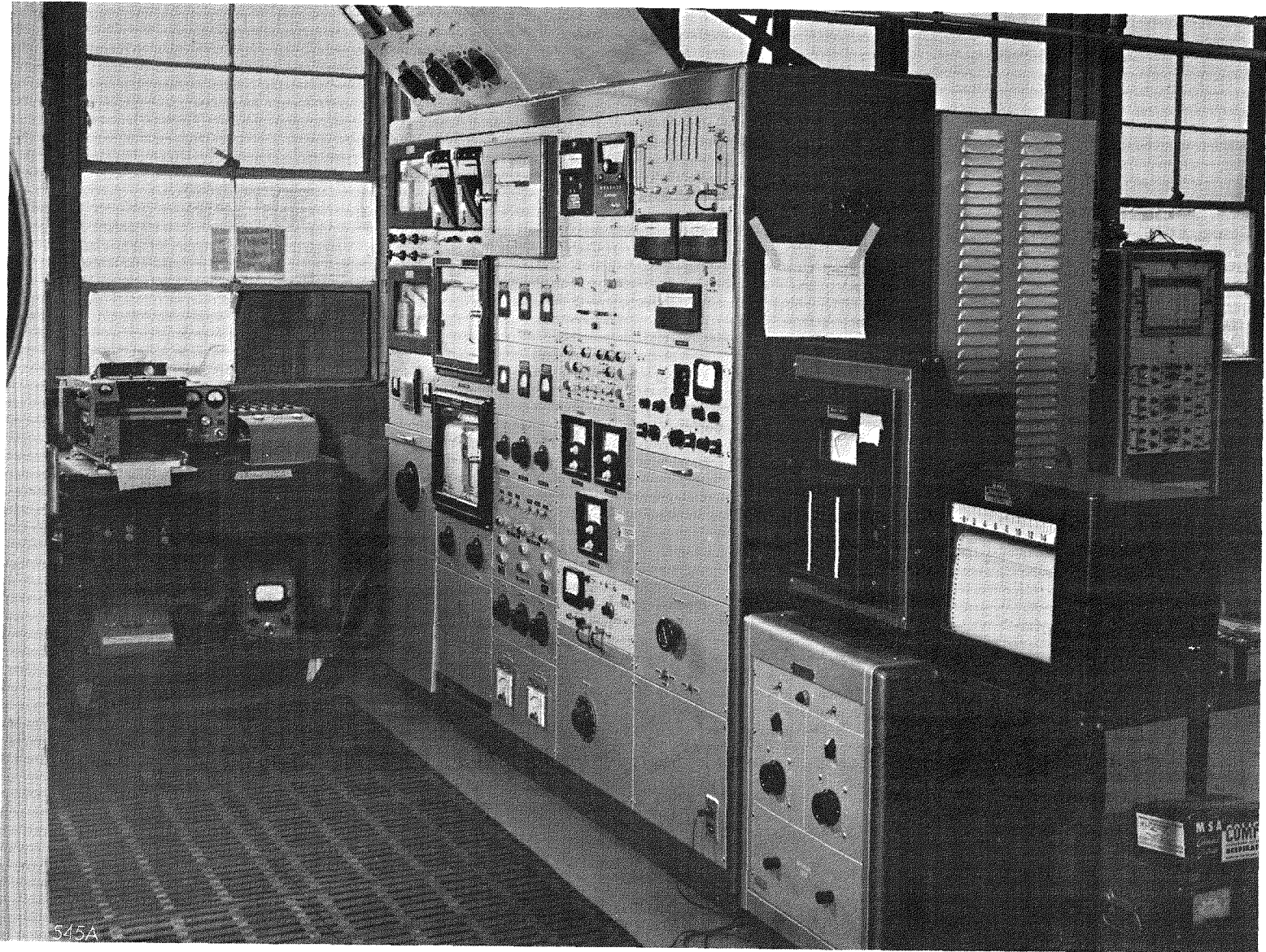
The STE consists of a metal walled enclosure approximately 14 by 12 and 9 feet in height, with consoles of instrumentation and controls. Provisions for the safe operation with high pressure and temperature mercury containing equipment similar to those described in section 8.1 were included. Figure 8-3 shows the control console with some of the associated instrumentation and Figure 8-4 is a view of the enclosure showing instrumentation mounted to it. Through the windows of the enclosure may be seen the Ground Test System.

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. Table 8-2 is a compilation of the capabilities of the STE.
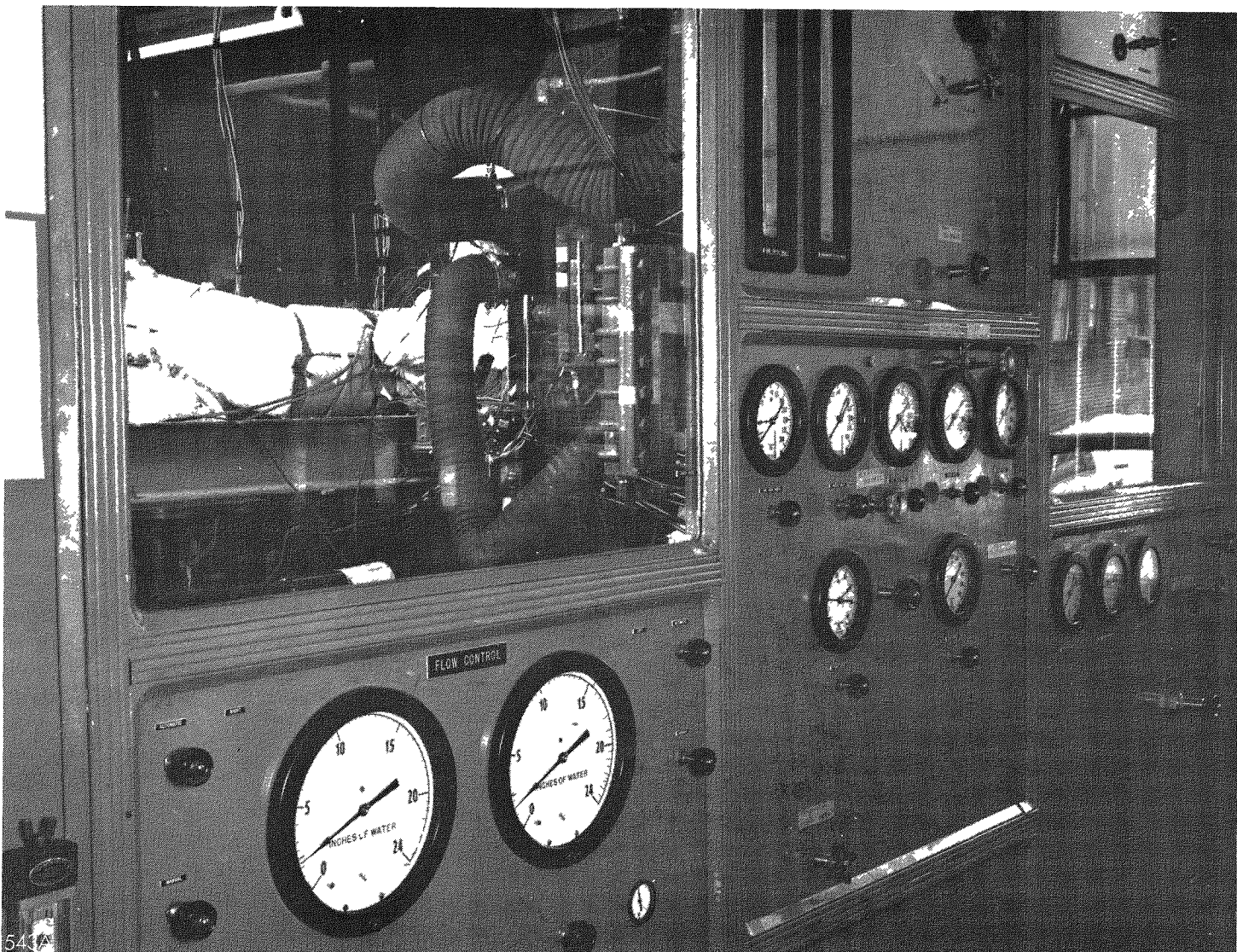
FIGURE 8-3

TAPCO GROUP

Thompson Ramo Wooldridge Inc.

SNAP-1 SYSTEMS TEST ENCLOSURE CONTROL CONSOLE

SNAP-I SYSTEMS TEST ENCLOSURE

TABLE 8-2

Systems Test Enclosure Capabilities

Mercury flow –	liquid	50 lb/min
	pressure	250 psia
	temperature	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

9.0 CONCLUSIONS

The requirements imposed on the SNAP I system as a result of its mission and environment, necessitated a coordinated developmental effort which significantly advanced the state-of-the-art in several fields. Notable contributions were made in understanding the requirements of dynamic power generation in space, developing long lived, high performance auxiliary power systems and developing materials compatible with high temperature liquid metals. Since SNAP I pioneered the application of long life turbo-electric power generation in space, it has been in the unique position of indicating future improvements and applications of this method of power generation.

9.1 Accomplishments of the SNAP I Power Conversion System Development Program

How well the SNAP I program achieved the original developmental goals is shown in Table 9-1. This table lists component performances experimentally achieved for comparison with the original requirements. The over-all efficiency shown, while not experimentally achieved, would be obtained if these components were integrated in an optimum manner. As stated in section 6.3, however, the over-all efficiency of a turbomachinery package made up of components with performances lower than these was very close to the value shown in this table.

Specific accomplishments of the SNAP I program of greatest significance are listed below:

> The Rankine power conversion method for obtaining electrical power in space was shown to be more feasible than other dynamic methods.

> Mercury was shown to be the optimum working fluid for the first generation of Rankine space power systems.

> Performance and endurance testing of the SNAP I Power Conversion System has furnished experimental proof of the feasibility and potential of this method of obtaining electrical power in space for long durations.

> All dynamic components of a mercury Rankine space power conversion system were successfully developed and integrated into a turbomachinery package with but one moving part.

> High speed mercury vapor turbines were designed and experimentally showed that efficiencies greater than 40% could be obtained with high pressure ratio, multistage, impulse machines for power outputs of less than one horsepower.

> A permanent magnet alternator, capable of producing up to 1200 watts while operating uncooled in a $550^\circ F$ mercury vapor environment, was developed and demonstrated efficiencies greater than 85%.

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TABLE 9-1

SNAP I PERFORMANCE ACCOMPLISHMENTS

COMPONENT	ORIGINAL GOAL	PARAMETER	EXPERIMENTALLY ACHIEVED
Turbine	40	Efficiency – %	46
Alternator	90	Efficiency – %	86
	20	Overload cap. – %	50
	7	Harmonics – %	5.5
Bearings	40	Power Absorption – watts	110
	20	Radial Load – lbf	25
	20	Axial Load – lbf	25
	10	Lube. flow req'd. – lbm/min	7
Pump	20	Efficiency – %	27
	1.86	Inlet Pressure – psia	1.86
	287	Outlet Pressure – psia	380
	12	Flow rate – lbm/min	14
Control	25	Power Absorption – watts	15
Turbomachinery Package	10	Efficiency – %	9.4
	25	Weight – lbm	13
	60	Life – days	104*

* voluntarily shut down

A jet-primed, centrifugal pump was developed to successfully operate at 40,000 RPM, and inlet pressures less than 2 psia while supplying the system with mercury at the required flow and pressure.

Mercury lubricated shaft bearings were developed and demonstrated reliable, low power consumption performance, for over two and one half thousand hours of full speed operation.

Analytical and experimental investigations of control modes for a radioisotope fueled, Rankine space power system showed solutions to be straightforward.

The feasibility of collecting condensate in zero gravity without mechanical devices was analytically and experimentally demonstrated.

Added data on mercury boilers for Rankine space power systems was obtained by developing a boiler to enable Ground Test System operation.

Testing of engineering materials in the mercury environment of SNAP I showed several classes of metallic and non-metallic materials to be compatible with requirements.

9.2 Potential Improvements to SNAP I

Although SNAP I was designed to match the power requirements, and space and weight limitations of a given vehicle and mission, it does not represent the ultimate in radioisotope fueled Rankine cycle auxiliary power systems. Areas in which notable achievements may still be made include performance, weight, compactness, and operational lifetime. Several studies have been performed which indicate the gains which may be realized in more sophisticated versions of the SNAP I system.

A SNAP I turboelectric package of considerably higher performance would have resulted if the component development programs had been carried to their conclusions. Unfortunately, funds were not available to do this. Several elements of the turbomachinery package would have benefited from more extensive development programs, particularly the turbine.

The full potential of the SNAP I system can be realized only when new design concepts and fabrication techniques are incorporated into the existing SNAP I technological structure.

9.2.1 Heat Source

Endurance testing which has been accomplished to date indicates that the specified SNAP I lifetime of 60 days can be far exceeded. To match this greater lifetime, an increased radioisotope heat source capacity would be required, since the power output of the original Cerium 144 source will not satisfy full power system needs after a 60 day operational period.

9.2.2 Modular Design

More compact system configurations can be achieved with the radioisotope heat source than is evident from the SNAP I arrangements which have been considered to date. A module concept, illustrated in Figure 9-1, probably is near the ultimate in perfection of component organization. This concept involves attaching the turbomachinery package directly to the heat source and surrounding the entire system with a container which would double as the condenser-radiator.

The major feature of the modular system is the combining of the heat source, turbomachinery package, and associated plumbing into a single unit. In addition to compactness, this arrangement will result in a more efficient system. Mounting the turbine housing directly to the boiler can allow heat conduction from the boiler to the turbine housing from which heat is transferred by convection to the working fluid. Calculations indicate that sufficient temperature potential and heat transfer area exist to allow this method of reheating to be used. This would result in higher efficiencies and lower possibility of erosion.
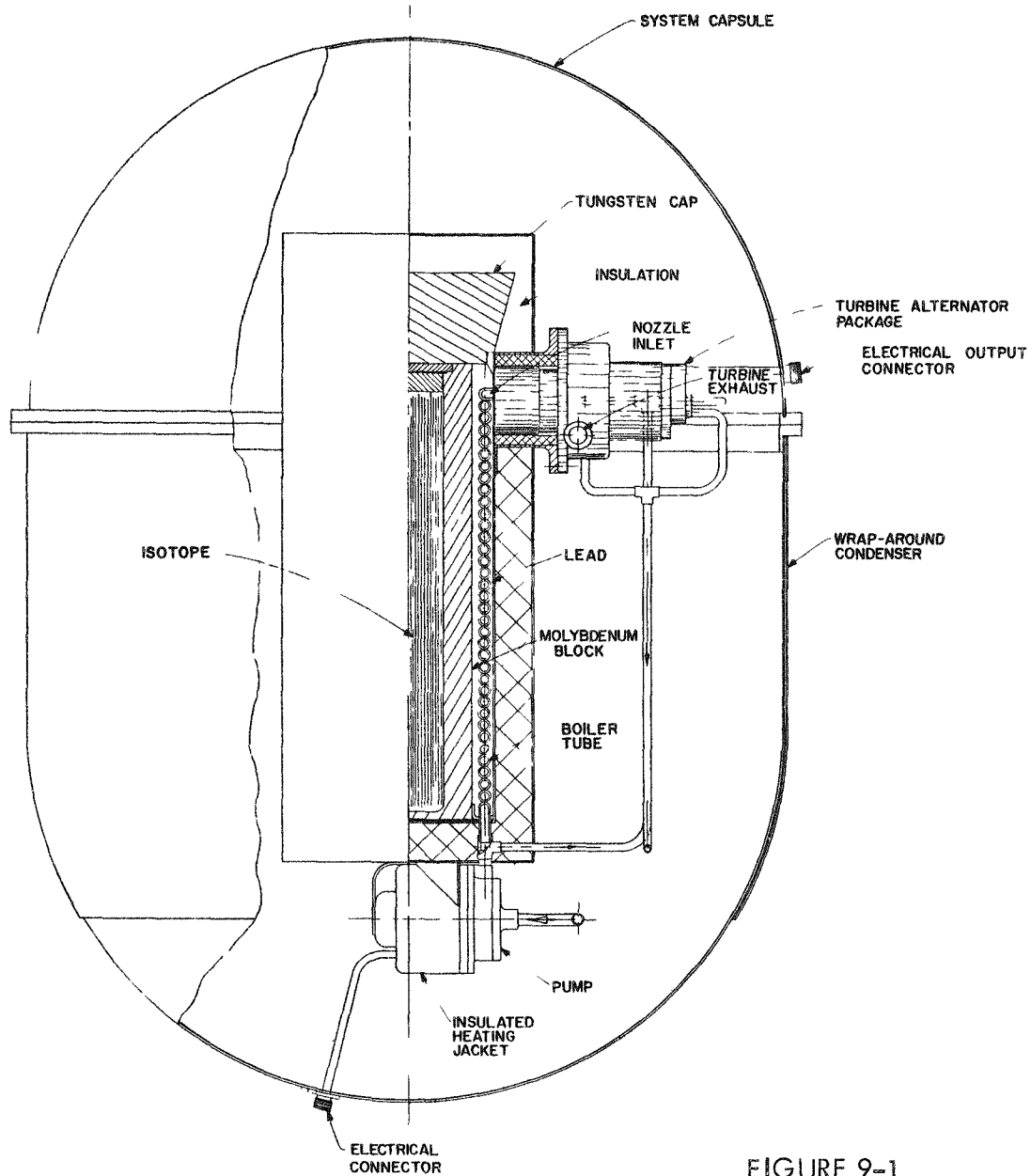
IMPROVED SNAP I SYSTEM

FIGURE 9-1

The shell containing the system would serve a second function in that it would contain a liquid biological shield prior to launching of the carrier vehicle. The weight of the shield necessary to protect humans from the radiation given off from a radioisotope source could be prohibitively heavy so far as a flying system is concerned. It, therefore, must be removed during countdown. A liquid shield is most convenient since it can be drained easily and rapidly. Mercury, being an excellent gamma ray absorber, is the natural choice.

9.2.3 Startup

SNAP I was to have been started prior to launch of the carrier vehicle. Since the system pump is mounted on the shaft, an external supply of mercury for the bearings was necessary for the bearings until the shaft was up to speed. Several complications are involved in this method of startup. Positively sealed fittings would be necessary to allow removal of the auxiliary startup system from a remote location. Since a reasonably large quantity of heat must be rejected from the condenser during pre-launch run-up and launch operation, an adequate ground and launch cooling system would be required. During launch, the operating power system would be subjected to accelerations, vibrations and shock loads. To be operable during this period requires larger bearings and other refinements which would not be incorporated into a system which would be subjected only to a zero-g environment or normal gravitational forces. Studies to determine the feasibility of a system startup in orbit have been conducted and have shown that a system could be designed for orbital startup by several techniques.

BIBLIOGRAPHY

No.	Title	Date	Classification
EN-529	SNAP I Startup Arrangements	4-10-59	Secret
EN-574	Test Summary, PTP No. 1, 48-Hour Endurance Test	5-15-59	Secret
EN-597	Effect of Increasing Turbine Inlet Pressure For PTP #2, Test #1	6-9-59	Secret
EN-600	PTP 1 Pump and Bearing Performance	6-8-59	Secret
EN-613	The Effect of Stage Pressure Distribution on PTP Turbine Output	6-23-59	Secret
EN-313	Effect of Rotor on Attitude Stability	11-12-58	Secret
EN-336	PP & TATP Test Analysis	12-2-58	Secret
TM-971	Satellite Attitude Stability	3-29-57	Secret
TM-1283	Selection of a Start-Stop System for the SPTP System of the VIP-I Program	8-14-58	Secret
TM-1387	Study to Determine the Feasibility of Using Conductive Turbine Reheat to Improve SNAP I System Performance	4-28-59	Secret
TM-1430	Test Summary GTS #1 Initial Test in STE	7-1-59	Secret
ER-2994	Feasibility Study of Rankine and Brayton Cycle for Satellite Vehicle Nuclear Power	3-26-56	Secret
ER-3052	Appraisal of Radioisotopes for Possible Application to Power Conversion Apparatus	7-2-56	Secret
ER-3053	Program for Evaluation of Power Conversion Apparatus for Isotope Heat Sources	7-2-56	Secret

BIBLIOGRAPHY (Continued)
Page 2

No.	Title	Date	Classification
ER-3099	Conceptual Design of a Low Power, Mercury Vapor, Power Conversion Apparatus	10-9-56	Secret
ER-3187	Preliminary Design of a Mercury Vapor Power Conversion System, Volume I	3-25-57	Secret
ER-3200	Proposal for Glenn L. Martin, Power Conversion System	1-19-57	Secret
ER-3547	Dynamic Control Study and Simulation of a One-Half Kilowatt Mercury Power Conversion Unit	5-7-58	Secret
ER-3653	Various Aspects of the Gamma Radiation Associated with the SNAP I APS	1-28-58	Secret
ER-3693	Preliminary Proposal for Zero-G Condenser Test	1-26-59	Secret
AE-93M	SPTP-P-001 Prototype Test Package Specification	8-20-58	Secret
AE-131M	Proposed Electrical Boiler Specification	10-16-58	Secret
AE-137M	SPTP-P-002 Prototype Test Package Specification	10-21-58	Secret
AE-167M	GTS-S-001 Ground Test System Specification	12-19-58	Secret

The reports listed in the bibliography are not available for general distribution. Any inquiries concerning the availability of this information should be directed to the AEC.