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SNAP 10A THERMOELECTRIC PUMP
FINAL REPORT

By
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ABSTRACT

The SNAP 10A power system is a thermoelectric, direct power conversion system for space application using a nuclear reactor as the heat source. The heat is transferred from the reactor to the thermoelectric converter by circulation of the liquid metal, NaK.

This report describes the pump used to circulate the NaK. The description covers the development, manufacturing, testing, post-test examination, and application in flight systems including the space flight, SNAPSHOT.

The pump consists of a liquid metal dc conduction pump powered by an integrally mounted thermoelectric generator.

I. INTRODUCTION

A. SNAP 10A SYSTEM

The SNAP 10A system is a 500-watt thermoelectric power generator for space applications. In this system, the heat from a nuclear reactor is transferred to a thermoelectric generator by a liquid metal, the eutectic of Na and K (NaK). A schematic diagram of the system is shown in Figure 1.

The type of NaK pump which seemed best suited to this application had not been developed at the time of the initiation of the SNAP 10A project. The selected pump concept involved the use of a dc conduction pump powered by a thermoelectric generator.^(1, 2, 3) The concept included the use of the hot NaK as the heat source for the pump's thermoelectric generator and a radiator to dissipate the heat and thereby maintain the required temperature drop across the thermoelectric elements.

A study of the system configuration and operating requirements showed that the conduction pump and thermoelectric generator could be closely coupled to form an integral generator-pump unit.⁽⁴⁾ The advantages of close coupling include not only the factors involved in transmission line weight and power loss reduction, but also a favorable pumping rate-to-NaK temperature response, which eliminates the problems associated with response time delays during transient period operation. The pump of this design, designated the "thermoelectric pump," was developed and successfully used in the SNAP 10A system.^(5, 6)

B. DC CONDUCTION PUMP

The dc conduction pump consists of a channel with electrodes on opposite sides and a magnet mounted so that the magnetic field is perpendicular to the electric current passing through the NaK in the channel. The resulting force on the NaK, causing it to flow, is proportional to the current, magnetic field, and channel width.

The operating principle of the conduction pump is the same as that of a conventional dc motor in that a conductor carrying a current while in a magnetic field experiences a force proportional to the product of the magnetic field, electric current, and length of conductor. To use this principle in creating a pump,

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Figure 1. SNAP 10A System and Cycle

it is sufficient to pass a magnetic field across the channel carrying the liquid metal while in the same region an electric current is passed through the liquid by electrodes attached to the channel walls. The interaction of the electric current and magnetic field produce force on the liquid metal and cause it to flow. The configuration is illustrated in Figure 2. The electric current and thermal paths are shown in Figure 3. Such a pump is inherently simple and reliable and can be made very efficient.

The pump channel is formed of 1-in. stainless steel (SS) tubing with copper electrodes brazed to the outside channel walls with a 1750°F braze alloy. The magnetic field is supplied by a pair of stock Alnico 5 permanent magnets fitted with iron pole faces.

C. THERMOELECTRIC GENERATOR

To supply current for the pump with a minimum transmission line loss, the thermoelectric elements are mounted on the electrodes. The electrodes thereby also serve as the "hot junction" of the thermoelectric generator. A pair of P-type lead-tin-telluride elements are mounted on the "negative" electrode and a pair of N-type lead-telluride elements are mounted on the "positive" electrode.

A voltage is generated by the elements as the result of the Seebeck effect. The magnitude of the voltage developed is the product of the temperature difference and Seebeck coefficient, a property of the thermoelectric material. Thermoelectric materials are designated P-type or N-type to indicate conduction properties of the material in accordance with the practice in other semiconductor materials. In thermoelectric generators, such as used in the pump, the voltage polarity is indicated by the type. The electrical circuit consists of an N and a P element connected in series to produce a total voltage equal to the sum of the voltages of each element. Two such identical circuits are used in the SNAP 10A pump to meet the current requirements. This is also illustrated in Figure 3.

The elements are 0.16 in. thick, 0.9 in. wide, and 3.0 in. long. To achieve the desired thermoelectric properties at the operating temperature, the P-elements are "doped" with 1 at.% Na, and the N-elements are "doped" with 0.055 mol % PbI_2 . Since the properties of the lead-telluride and lead-tin-telluride thermoelectric materials are sensitive to very small amounts of

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Figure 2. Basic Configuration of a DC Conduction Pump

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Figure 3. SNAP 10A Thermoelectric Pump Configuration Schematic

impurities, the contacting material must be carefully selected. Iron is one of the few suitable contacting materials since, at the typical operating temperatures, it does not react with the thermoelectric material and does not alter the thermoelectric properties.

The assembly of an element is illustrated in Figure 4. To minimize contact resistance, the elements are made of a layer of powdered thermoelectric material placed between two layers of powdered iron, all of which is cold pressed and then sintered at 1300°F. By compacting the powders in this manner an excellent contact between the iron and thermoelectric material is achieved thereby reducing the contact resistance and the effects of differential expansion. By using the iron in this way, the sensitive thermoelectric material is protected from the harmful effects of contact with copper. The edges of the thermoelectric elements are coated with a ceramic material to inhibit deterioration.

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Figure 4. SNAP 10A Thermoelectric Pump Elements

Heat flowing through the elements is transmitted to space by four aluminum fins connected to the thermoelectric elements; the fins extend radially outward. Each fin, 6 by 8 in. in area, is coated with two special materials to achieve the desired heat radiation properties. The undercoat, with its high emittance was selected to radiate heat; however, since it also has a high solar absorptance, a

top coating, with a low solar absorptance must be used to reduce the effect of heat from the sun. In addition, the top coating is transparent in the high temperature infrared region. The combined properties of the double coating result in an optimum radiator surface for space applications.

All of the parts used in the pump are shown in Figure 5.

D. THERMOELECTRIC PUMP REQUIREMENTS

In selecting materials for the pump, a number of materials properties required careful consideration. Since the pump was to be located on top of the nuclear reactor where the radiation field is high, all parts had to be invulnerable to the damaging effects of radiation. The forces involved during launch into space established strength requirements and general structural features for all components. In addition, most parts were subject to careful selection on the basis of electrical, thermal, and magnetic conduction properties as these were critical factors in achieving the desired performance.

The detailed requirements of the pump are given in Reference 7; briefly, these include:

- 1) Delivery of 13.2 gpm of 1010° F NaK at a pressure of 1.1 psi,
- 2) Delivery of at least 10.4 gpm at the end of one year,
- 3) A means of measuring flow rate,
- 4) Delivery of 0.26 gpm when operated at 90° F from a 40 amp dc power source,
- 5) A weight of 22 lb or less, and
- 6) The ability to withstand the environmental conditions imposed by vehicle launch.

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Figure 5. SNAP 10A Thermoelectric Pump Components Prior to Final Assembly

II. SUMMARY OF PUMP DEVELOPMENT

The pump development program and results obtained were described in an interim report.⁽⁵⁾ The report presented an analysis of the dc conduction pump and the thermoelectric generator and of their integration to form the thermoelectric pump. Included in the discussion were the basic design equations, the design factors, and the effect of varying the parameters about the optimum values.

A description of the design and manufacturing methods and a discussion of the test results for each development pump was presented in chronological order showing the development sequence followed to achieve the desired objectives. Included were the post-test examination and material analysis of several pumps.

At the time the interim development report was issued, the main design objectives had been achieved, the design fixed and the pump drawings, and specifications for production, qualification test, and acceptance test were complete. The initial production of pumps for qualification and for system use had been initiated.

Reviewing the development report in greater detail, work began with the study of design equations, and a review of the properties and fabrication techniques of applicable materials in relation to the general objectives. The pump development was to be based on materials and techniques available at that time, and the initial problem was the selection best suited to the application. After some study and experimentation, the following choices were made:

- 1) Channel: Type 347 SS tubing; the material choice being based primarily on corrosion resistance and general suitability for long reliable life in the proposed service.
- 2) Electrodes: OFHC copper, brazed to the channel sides; so chosen for high conductivity, ease of brazing and suitability at the operating temperature.
- 3) Magnet: Alnico 5 stock magnets, selected for suitable magnetic properties, satisfactory behavior under the temperature and radiation environment, and ready off-the-shelf availability.

4) Thermoelectric elements: lead-telluride N, and lead-tin-telluride P; chosen on the basis of high figure of merit at the operating temperature relative to other materials, and demonstrated suitable fabrication technique.

5) Radiator: aluminum tapered fin coated with the tailored coating AI93 for thermal control; chosen for best conductance-to-weight factor, and otherwise well suited. The thermal control coating was developed for this type application and was readily available. This coating consists of a subcoat of chromium-cobalt-nickel spinel bonded with aluminum phosphate and a top coat of stannic oxide bonded with aluminum phosphate.

Given these initial selections, which established a number of the values used in the design equations, the problem then was to provide an optimum design, consistent with high reliability and the limitations of space, configuration, and weight.

While the design equations involving each part were well known and relatively simple, the overall design was complicated by the interdependency of the equations. Hence, an iterative process was used. Curves were prepared showing the various trade offs involving channel dimensions, magnetic flux density, thermoelectric element dimensions, and radiator dimensions.

Figures 6, 7, and 8 show the effect of channel dimensions on the power losses in the dc conduction pump. Since a high efficiency was desired, the objective was to choose dimensions giving low loss. Other factors, particularly those relating to the thermoelectric generator efficiency and radiator efficiency, also were involved so that the maximum dc pump efficiency was not necessarily the optimum. The dimensions finally selected are identified as the reference dimension in these figures. Figures 9, 10, and 11 show the effect of channel dimensions on the power radiated as heat. Based on these curves and practical fabrication and space limitations, the dimensions chosen were: length, 3 in.*, width, 1 in., and height, 0.4 in.

*The 3-in. length is the length of the channel to which the electrodes are brazed, hence it determines the conduction area. The overall length of the channel which includes the rectangular-to-round transition sections and length for mounting brackets is 8.55 in.

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Figure 6. Total Power Loss as Function of Length

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Figure 7. Total Power Loss as Function of Cross-Section Area

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Figure 8. Total Power Loss as Function of Height-to-Width Ratio

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Figure 9. Pump Power vs Channel Height and Magnetic Field

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Figure 10. Pump Power vs Channel Width and Magnetic Field

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Figure 11. Pump Power vs Thermoelectric Thickness

The results of the study of the effect of thermoelectric element thickness are shown in Figure 11. It was shown that the thickness was not critical so far as heat radiation power levels were concerned, so the thickness was chosen on the basis of satisfying the conductance requirements consistent with the space (volume) available for the thermoelectric elements. A satisfactory choice was 0.100 in. thick, by 3.0 in. long, by 0.90 in. wide. With these dimensions (two paralleled N elements in series with two paralleled P elements) the generator resistance was 46.5 μ -ohms. This resistance, plus the 9 μ -ohm bus bar resistance between the elements gave an effective generator resistance of 55.5 μ -ohms. This provided a very good resistance match for the dc conduction pump at the design operating conditions.

The minimum heat radiation requirement was shown to be at a magnetic field strength of 2560 gauss. This value was satisfactory regarding other factors so it was selected as the design value. In operation, the magnet is at 500°F, which reduces its flux density to approximately 2400 gauss. Analysis showed that the pump performance was relatively insensitive to the value of magnetic field over this range of values.

The radiator fin length was limited to 8.5 in. by system envelope requirements. The study of fin length and thickness resulted in the graph shown in Figure 12. The minimum height was shown to be 7.5 in. and the thickness required was 0.25 in. The analysis was based on a simple tapered fin design. The effect of cutting a hole in the fin to pass the magnet through raised the thickness and area requirements. In the final flight design, the fin length was 8.5 in. and the base thickness was 0.60 in.

Based on the described design, the thermoelectric pump electrical circuit (under design operating conditions) had the calculated values shown in Figure 13. Pump tests substantiated these values.

The pump test facility consisted of a liquid-metal test loop fitted with temperature, flow rate, and pressure measuring capabilities. The loop was arranged so that the test pump was operated in a vacuum to simulate space conditions.

A number of pumps were produced and tested. The first 11 pumps produced were not designed for flight but were intended to provide design data. Following

Figure 12. SNAP 10A Thermoelectric Pump Radiator Fin Analysis

that series was a group of 9 preliminary flight design pumps with the dimensions previously described. They were generally satisfactory except for being slightly underpowered. This was corrected by increasing the radiator fin base thickness to 0.6 in. Moreover, the quality control had not been established and specifications were in a preliminary stage. The final design modifications resulted in a series of satisfactory pumps which showed evidence of meeting the qualification requirements. The pressure vs flow characteristics of the first of this series are shown in Figure 14.

Having met the initial pumping requirement, primary attention was then given to the operating lifetime or degradation. The pumping performance as a function of operating time is shown in Figure 15 for five typical development pumps. The results indicated that the degradation rate was sufficiently low, and was within system requirements.

Upon completion of the tests, several development and preliminary flight design pumps were sectioned and various parts were examined metallographically. The conclusions were:

NOTE: RESISTANCES ARE INDICATED IN MICROOHMS (10^{-6} ohms); VOLTAGES ARE INDICATED IN MILLIVOLTS (10^{-3}); ALL VALUES ARE AT STANDARD OPERATING TEMPERATURE.

- I - TOTAL CURRENT
- E_P - OPEN CIRCUIT VOLTAGE OF P ELEMENT
- E_N - OPEN CIRCUIT VOLTAGE OF N ELEMENT
- E_C - COUNTER EMF
- R_P - RESISTANCE OF P ELEMENT
- R_N - RESISTANCE OF N ELEMENT
- R_n - RESISTANCE OF NaK IN THE CHANNEL
- R_w - RESISTANCE OF CHANNEL WALL (BOTH SIDES) SHUNTING CURRENT THROUGH THE NaK
- R_1 - RESISTANCE OF CHANNEL WALL (SERIES)
- R_2 - RESISTANCE OF COPPER "ELECTRODE"
- R_e - RESISTANCE OF ELECTRODE CONSISTING OF $R_1 + R_2$
- R_b - RESISTANCE OF BUS BAR (PART OF THE RADIATOR)

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Figure 13. Thermoelectric Pump Electrical Circuit

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Figure 14. Pressure vs Flow at Indicated NaK Temperatures for Pump SN-010

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Figure 15. SNAP 10A Pump Life Test Data at 1010°F NaK Temperature

1) The copper electrode-to-SS channel braze joint in the early development pumps was unsatisfactory. The braze foil used in these pumps was HH Premabraz 615.* Later pumps using WGP Nicoro 80† had satisfactory braze joints. Use of Nicoro 80 was recommended for flight design pumps.

2) The diffusion bond between the electrodes and the element copper shoes was satisfactory; however, the bonds to the iron powder surfaces appeared to provide good quality contact but not a very strong bond.

3) There was a significant difference between N elements and P elements in the behavior of the braze foil (HH 615) at the hot-iron-powder to copper-metal-block joint. Extensive reaction of the diffusion bonded joint was observed in P elements, but there was little reaction in the N elements. There was evidence that tellurium vapor had penetrated the P element hot-iron powders and reacted with the braze foil. The presence of tin in the P-type telluride probably accounted for the greater degree of reaction noted in P-type elements. Microprobe studies confirmed the presence of tellurium at the bonding interface.

4) Some of the N elements separated at the hot-iron-powder to telluride interface during sectioning, but practically all the P elements failed at that interface. Since this interface represents the line of maximum differential expansion under operating conditions, it was concluded that there is a possibility of failure here, which could be a factor in pump degradation.

5) The N and P elements showed copper contamination in the telluride material after operation in pump tests. The copper was more or less distributed throughout the lead telluride. Copper in the P elements was concentrated in the colder side of the lead-tin-telluride material. The extent of copper contamination in the P elements was much more severe than in the N elements. Copper poisoning of the thermoelectric materials probably was a significant factor in pump degradation.

*Manufactured by Handy and Harman Company, composition: 14.5% In, 24% cu, balance Ag.

†Manufactured by Western Gold and Platinum Company, composition: 3% Ni, 15.5% cu, balance Au.

6) The N elements showed no evidence of contamination by silver, but the P elements showed significant amounts of silver contamination concentrated in the cold side of the lead-tin-telluride material. It was concluded that silver poisoning of the P thermoelectric material also was probably a significant factor in pump degradation.

7) Very little evidence of contamination was found in the cold-iron powders except at the interface of the telluride material. The braze foil in the cold side of the elements appeared to have been unaffected. It was concluded, therefore, that the copper and silver poisoning came from the hot side of the elements.

8) Attempts to polish the P element specimens revealed that this material is significantly more friable or brittle than the N material. It was concluded, on the basis of working with this P material, that its present poor mechanical properties may result in fracturing of the elements during service and thus contribute to pump degradation.

A summary of these and later post-test examinations is presented in Section III-G.

III. PUMP QUALIFICATION

A. SCOPE

Since the issuance of the development report,⁽⁵⁾ most of the effort was expended on pump production and testing. The object was to produce pumps for qualification testing, installation in SNAP 10A systems, and special tests. Along with this, efforts to make certain improvements were continued. The subjects included design equations, specifications, quality assurance, and special tests, particularly those to determine pump susceptibility to damage.

B. PUMP MANUFACTURING

When the testing and post-test examination of the early flight design pumps confirmed a satisfactory design, the drawings and specifications⁽⁸⁾ were updated and production of flight design pumps was initiated. The requirements included a pump and a spare for each SNAP 10A system, three pumps for formal qualification test, and additional pumps for special tests. A total of 18 pumps were manufactured in this part of the program.

The fabrication of these pumps was essentially the same as that described in the development report. The updating of drawings and specifications consisted primarily of matters such as selecting more appropriate values of tolerances on parts, and establishing formal quality control procedures. This resulted in the production of pumps which were nearly identical in performance and characteristics.

All the pump parts are displayed in Figure 5. Beginning with the 1-in. SS formed tubing as the duct or channel, the first step in fabrication is to weld the aft support to it. The aft support is simply a structural part which provides a base for mounting the magnet assembly and serves as a base for the outriggers which provide lateral support during vibration at launch. The copper electrodes are brazed (at 1900° F) to the sides of the channel. The electrodes conduct heat from the NaK to the thermoelectric elements, and conduct electricity from the elements to the NaK. Two pairs of thermoelectric elements are diffusion bonded to the electrode faces. The radiators are then placed in contact with the elements and held by the compression bar assembly while the radiators are bonded to the

elements. Since this bond and the elements have little mechanical strength, the compression bar assembly is left in place as a part of the pump. The magnet, consisting of two C-shaped Alnico 5 magnets and two pole faces, is assembled around the channel; this assembly is held in place by several structural members. The magnet provides the magnetic field necessary for the operation of the thermoelectric pump, the prestartup pump, and the flowmeter. The radiator is coated to provide high emittance and low solar absorptance to dissipate heat and thereby maintain the desired temperature across the thermoelectric elements. Upon completion of these processes, the magnet is magnetized to the desired flux density.

A completed pump is shown in Figure 16. The manufacturing process is described in detail in Reference 8, which also references specifications and drawings.

In addition to the pump production described, two additional pumps were manufactured as development pumps. They were identical except that a different magnet material and configuration were used; the material was a grain oriented Alnico 5 alloy. This pump, (Figure 17) weighs 15 lb and is interchangeable with the standard production pumps which weigh 22 lb.

Figure 16. SNAP 10A Flight-Type Pump

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a. Side View

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b. End View

Figure 17. SNAP 10A Modified Pump

NAA-SR-11879

C. PUMP TESTING

The pumps were tested in essentially the same manner as described in the interim report. The details are described in the qualification,⁽⁹⁾ and acceptance⁽¹⁰⁾ test specifications. The tests are reviewed briefly as follows:

1. Pressure Test and Helium Leak Check

This test is performed with standard equipment and techniques to verify that the channel is sound.

2. Environmental Test

The pump is mounted in standard test machines and subjected to the mechanical forces of vibration, shock, and acceleration at levels required in the specification. This is to verify the structural soundness of the pump under conditions anticipated during launch of the SNAP 10A system.

3. Performance Test (Acceptance Test)

The pump is installed in a NaK loop which is fitted with instrumentation to measure:

- 1) pump flow rate
- 2) pump pressure rise
- 3) NaK temperature in the pump channel
- 4) radiator temperature
- 5) heat sink temperature
- 6) thermoelectric element temperatures
- 7) thermoelectric element voltages and pump terminal voltage
- 8) pump flowmeter voltage
- 9) pre-orbital startup current
- 10) pump ambient pressure
- 11) NaK pressure (static).

Figure 18 is a view of the pump in a test loop. The NaK loop test stand includes a vacuum chamber surrounding the pump to provide a vacuum environment and a controlled temperature heat sink (Figure 19).

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Figure 18. SNAP 10A Mounted in Test Loop

The test is started by heating the NaK in the loop. This heat operates the pump; heating is continued to 800°F, a temperature sufficiently high to ensure "wetting" of the walls. After allowing the NaK to return to room temperature, it is heated again and data are recorded as the temperature is increased to 1010°F, the nominal pump operating temperature. The flow rate as a function of NaK temperature is recorded, and a typical plot is shown in Figure 20.

After the temperature is stabilized at 1010°F, a valve in the test loop is slowly closed and flow and pressure are measured. In addition to the main objective of obtaining pressure vs flow data, other measurements are recorded. The NaK temperature is reduced to 900°F and then to 800°F and the pressure vs flow characteristics at each of these temperatures are obtained. Typical data obtained are shown in Figure 21.

The NaK is then returned to 1010°F and pump operation is continued for 20 hr. After completing the 20-hr test the NaK temperature is reduced to nominally 90°F and the pre-orbital startup test is performed. This consists of applying 40 amp to the pump and obtaining pressure vs flow data under these conditions. The sink (vacuum vessel walls) is maintained at nominally 90°F. Typical data taken are shown in Figure 22.

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Figure 19. View of Two Pump Test Stands

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Figure 20. Pumping Rate as a Function of NaK Temperature
(SN-027 in test loop had hydraulic characteristics of
SNAP 10A system)

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Figure 21. Pump Pressure vs Flow Characteristics at NaK Temperatures of 1010°F (Design value), 900°F and 800°F (Data from SN-027)

Figure 22. SN-027 Pressure vs Flow Characteristics at Pre-Orbital Startup Conditions (90°F NaK, 40 amp applied to pre-orbital startup electrodes)

Upon completion of these tests, further disposition of the pumps depended upon their ultimate use:

- 1) Pumps destined for use in SNAP 10A systems were delivered to the system upon the satisfactory completion of the acceptance test.
- 2) Pumps destined for qualification testing were processed through the qualification test to be described.
- 3) Pumps selected for special testing were subjected to various tests and the course of each pump was unique. Some of these special tests are described in the following text.
4. Life Test (Qualification Test)

The pump is installed in a NaK test loop whose facilities and characteristics are essentially the same as the loop described for acceptance testing except that a provision for measuring pump pressure is not included. However, it has the additional capability of providing a rapid, controlled heating rate and the associated recording data for use in the thermal cycle tests.

The qualification test includes the acceptance test. Following the acceptance test is the thermal cycle test. The thermal cycle test consists of raising the

NaK temperature from 100°F to 1010°F and returning to 100°F at specific rates for 10 times. Data are recorded each time the temperature is at 1010°F. The flow rate at each cycle for a typical pump is shown in Figure 23.

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Figure 23. Flow of SN-031 as a Function of Thermal Cycles
(Data normalized to SNAP 10A system
hydraulic characteristic)

When the thermal cycle test is complete, the pump is removed from the NaK loop and mounted on the environmental test machine. The pump is again subjected to the mechanical forces, vibration, shock, and acceleration values given in the qualification specification.

Following the environmental test, the pump is reinstalled in the NaK test loop, which is adjusted to equal the SNAP 10A system hydraulic characteristic, and the NaK temperature and sink (vacuum vessel walls) are set at nominally 90°F. With the application of 40 amp to the pump, the resultant flow rate is measured. This test is continued for 24 hr. A flow rate of 0.26 gpm or greater is required for satisfactory completion of this prestartup test.

The orbital startup and life test is begun by raising the NaK temperature to 1010°F at a specified rate. After attaining 1010°F, and steady-state values are

approached, the loop hydraulic characteristic is adjusted to simulate the system characteristic. After final adjustments are made, the NaK and sink temperatures are maintained constant and the temperature, flow, and voltage data are recorded throughout the life test. The flow rate as a function of time for the three qualification pumps is shown in Figure 24. Performance of a typical pump at each stage in the testing sequence is shown in Figure 25.

Figure 24. Pumping Rate as a Function of Operating Lifetime (Qualification pumps)

5. Special Tests

In some instances deviations were made in the standard test procedure to obtain supplementary data. Generally, the special tests were nondestructive:

- 1) Repeat tests, sometimes under slightly different conditions or with different variables.
- 2) Additional measurements.

In addition, there were requirements for data on the susceptibility of the pump to some condition not treated in the standard tests. Generally these tests were destructive or potentially damaging. Pumps which had not been selected for system or qualification use were used in this manner. The tests included:

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Figure 25. Performance (flow at system conditions) at Each Significant Event in Qualification Test

- 1) Life time operation at a NaK temperature of 1100° F,
- 2) Operation at temperatures above 1100° F to determine the upper limit,
- 3) Handling, transportation, and corrosive environment test,
- 4) Operation in air,
- 5) Operation at very low pressure (static) in the NaK to induce cavitation.

D. PUMP TEST RESULTS

The detailed results of the pump tests are presented in the references listed in Appendix A. The tests performed and utilization of the pump are summarized in this report in Table 1. More detailed data on a typical pump (SN-027, assigned to Flight System-3 (FS-3) are presented in Table 2.

1. Flight Design Pumps (Final Production Models)

Three flight design pumps were processed through the formal qualification test. These pumps met all requirements except the pre-orbital startup requirement. They did not provide sufficient flow, when operated from a separate power supply, to meet the requirements existing at the time of test. However, since that time, work on the SNAP 10A system requirements showed that the initial pre-orbital requirements were unnecessarily high. Upon redefining the pre-orbital requirements all pumps satisfactorily passed the pre-orbital startup test. (Subsequent system tests, including the flight test, confirmed the reduced requirements.) Life test data of these pumps are presented in Figure 24.

2. Flight Design Pumps (Early Models)

Life test data on early pumps are shown in Figure 26. The SN-011 and -013 pumps are early flight design models and differ from the later production units only in details of fabrication. At the time of their manufacture the specifications were not firm, manufacturing and materials quality control were not rigorous, so the two pumps do not have identical characteristics.

3. Experimental Pumps

Pumps SN-016 and -018 were experimental. They were identical to the early model flight design units except in the fabrication and mounting of the thermoelectric elements. In these experimental pumps an iron foil was placed between

TABLE 1
SUMMARY OF TESTS AND UTILIZATION OF FLIGHT-DESIGN PUMPS

	Pump Serial Number	Acceptance Test	Examination of Product	Proof Pressure and Leak Check	Acceptance Level Vibration	Performance Test	Prestartup Performance Test	Qualification Test	Thermal Cycling	Qualification Level Vibration	Shock	Acceleration	Prestartup Performance Test	Startup Performance Test	Life Test	Remarks
022	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	All tests completed satisfactorily
023	X	X	X	X	X	X										Special tests and high temperature life tests
024	X	X	X	X	X	X										Installed in FSM-4. Later was damaged and replaced
025	X	X	X	X	X	X										Sectioned in metallurgical lab for examination
026	X	X	X	X	X	X										Installed in FSM-4. Later was damaged and replaced
027	X	X	X	X	X	X										Installed in FS-3 and operated in system qualification test
028	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	All tests completed satisfactorily
029	X	X	X	X	X	X										Installed in FS-4 and operated in space
030	X	X	X	X	X	X										Installed in FSM-4
031	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	All tests completed satisfactorily
032	X	X	X	X	X	X										High temperature life test
033	X	X	X	X	X	X										Special tests
034	X	X	X	X	X	X										Special tests
035	X	X	X	X	X	X										Special tests
036	X	X	X	X	X	X										FS-4 spare pump
037	X	X	X	X	X	X										Special tests
038	X	X	X	X	X	X										Special tests
039	X	X	X	X	X	X										Installed in FS-5, system is in storage

TABLE 2
DETAILED DATA ON TYPICAL THERMOELECTRIC PUMP
(SN-027)

Operating Time (hr)	Pressure (psi)	Flow (gpm)	Pump Flow-meter (mv)	Pump Wall Voltage (mv)	Pump Inlet NaK Temperature (°F)	Pump Outlet NaK Temperature (°F)	Radiator Fin Temperature (°F)		Radiator Fin Temperature Resistance (°F)		Sink Temperature (°F)
							TC 24	TC 25	Thermometer 17	Thermometer 18	
Pre-orbital Startup											
	0.0059	0.41	0.425	0.440	89	90	89	90	89	89	87
	0.0312	0.30	0.314	0.338	89	90	89	90	89	89	87
	0.0527	0.20	0.216	0.242	89	90	89	90	89	89	87
	0.0723	0.10	0.125	0.153	89	90	89	90	89	89	87
	0.0917	0.00	0.024	0.054	90	91	90	90	90	90	87
Orbital Startup											
	0.001	0.06	0.054	0.08	97	95	90	90	90	89	80
	0.006	0.57	0.545	0.834	140	139	105	105	106	103	80
	0.013	0.78	0.790	1.164	185	184	144	142	144	140	86
	0.025	1.20	1.229	1.820	223	221	165	164	166	160	79
	0.038	1.58	1.655	2.476	258	257	190	185	190	183	93
	0.061	2.35	2.500	3.725	305	304	213	206	214	203	90
	0.130	4.00	4.344	6.767	400	399	265	256	265	250	82
	0.223	5.93	6.500	10.20	503	501	315	305	315	300	92
	0.360	8.00	8.900	14.56	600	599	353	344	354	335	83
	0.537	10.09	11.29	18.74	705	704	401	390	404	382	91
	0.666	12.14	13.20	23.62	797	796	444	434	445	424	91
	0.821	13.75	15.22	28.24	898	895	480	470	481	459	91
	1.084	16.30	18.06	34.47	1010	1006	525	520	529	505	93
Pressure vs Flow at NaK Temperature of 1010°F											
	1.07	16.32	18.10	34.56	1011	1006	525	520	529	505	93
	1.13	16.00	17.80	34.22	1014	1009	527	520	530	506	93
	1.23	15.00	16.92	33.15	1012	1007	527	520	530	507	93
	1.33	14.00	16.04	32.05	1011	1007	527	521	530	507	93
	1.43	13.00	15.25	31.06	1011	1006	527	523	531	507	93
	1.53	12.00	14.36	30.00	1014	1006	528	523	531	509	93
Pressure vs Flow at NaK Temperature of 900°F											
	0.93	14.60	16.03	29.68	898	895	483	479	487	465	88
	1.01	14.00	15.46	29.05	900	895	485	480	487	466	89
	1.12	13.00	14.55	27.88	899	894	484	480	487	466	89
	1.21	12.00	13.70	26.85	900	894	485	480	487	466	90
	1.31	11.00	12.86	25.83	900	893	485	479	488	466	90
	1.41	10.00	12.01	24.77	900	893	485	479	488	466	90
Pressure vs Flow at NaK Temperature of 800°F											
	0.770	13.00	13.97	25.07	800	800	449	441	450	430	87
	0.871	12.00	13.10	24.05	801	799	448	441	450	430	91
	0.981	11.00	12.23	23.04	801	799	449	441	450	430	93
	1.092	10.00	11.36	22.01	801	797	449	440	450	430	94
	1.192	9.00	10.47	20.96	800	797	449	441	450	430	95
	1.290	8.00	9.61	19.94	801	799	449	441	450	430	97
20-hr Life Test											
0	1.090	16.32	18.05	34.55	1011	1006	526	522	530	510	90
4	1.094	16.41	18.10	34.66	1011	1008	528	522	531	508	89
8	1.094	16.44	18.10	34.65	1010	1008	528	524	532	510	90
12	1.091	16.37	18.00	34.50	1010	1005	529	525	533	510	93
16	1.105	16.44	18.15	34.85	1012	1008	530	524	533	510	93
20	1.096	16.41	18.06	34.65	1010	1005	530	525	533	510	96

Figure 26. Pumping Rate as a Function of Operating Lifetime (Experimental and development pumps)

the element shoes and the contacting surfaces to prevent migration of copper and silver into the thermoelectric material. Auxiliary tests have shown that the barrier is effective in eliminating the copper contamination, but the life test data indicate no significant improvement in lowering the initial degradation rate. This matter is discussed in the description of the post-test examination, in Section III-G.

Tests of the modified pump, designated Y1 (Figure 17), showed that its performance was the same as that of the production flight models. This pump is interchangeable with the standard production pumps and differs only in that an improved magnet design permits magnet weight reduction, and a more efficient use of the radiator area with the consequent radiator weight reduction. The net result is a weight reduction of 32%, and a cost reduction.

4. Special Tests

Several special tests were performed to obtain data needed in analysis or to satisfy other requirements. Generally, these tests consisted of recording some additional data during a standard test or repeating a test under slightly different conditions. Such tests were nondestructive and were performed concurrently with the standard tests.

Some tests were required to determine the susceptibility of the pump to conditions not imposed in the standard tests but which could exist in practical system use. Such tests were potentially damaging so expendable pumps were used for these tests.

a. High Temperature Life Test

Two pumps were operated in a life test which was substantially identical to the standard life test except that the NaK temperature was raised to 1100°F (standard nominal temperature is 1010°F). The life data on these two pumps are shown in Figure 27. The general behavior is the same as that for the standard temperature but the initial degradation rate is higher. After a few hundred hours of operation the degradation rate decreased as is usual for pumps tested at lower temperatures. The reason for the rapid flow-rate decrease in SN-032 after 2500 hr is uncertain. A test facility malfunction occurred at that time.

Figure 27. Pumping Rate as a Function of Operating Lifetime
(Qualification pumps in life test at a NaK temperature of 1100°F)

b. Upper Temperature Limit

After SN-037 had been through the acceptance test, it was tested for high temperature endurance by raising the NaK temperature slowly beyond the standard

1010°F. Figures 28 and 29 show the performance of the pump at the higher temperatures. The performance continued to increase until a temperature of 1255°F was reached. At 1300°F the performance became poor and the test was discontinued. Analysis of the data showed that during the 1250°F to 1300°F interval the N-element resistance increased 30%. The poor performance above 1255°F is attributed to this resistance increase.

c. Operation in Air

Pump SN-038 was exposed to a limited amount of air during the thermal cycle test to determine the effect of air on pump operation. This caused noticeable damage. After completion of the sequence of standard tests, the pump was placed on life test in air (that is, with no vacuum vessel around the pump) to provide additional data on the effect of air on the pump operation. The pump performance increased markedly during the first 300 hr and then began degrading. After 2200 hr the degradation decreased as shown in the graph in Figure 30. After 2278 hr of operation the pump was removed from test to examine the extent of oxidation and correlate this with operating test data.

d. Cavitation

One of the factors which affects the performance of a thermoelectric pump is the absolute pressure of the liquid at the pump entrance. When this pressure approaches that of the vapor of the liquid being pumped, cavitation occurs. Several effects result, one being higher resistance in the pump channel due to the vapor. This limits the electric current, which reduces pumping power. Tests with SN-037 demonstrated this behavior by showing that when the NaK pressure (cover gas pressure) was reduced, cavitation began at 1.8 psia; with the pressure reduced to 1.08 psia, the flow rate dropped 50%.

e. Handling, Transportation, and Corrosive Environment Test

To be successful, SNAP 10A pumps must be capable of withstanding the conditions to be encountered after standard testing. This includes, handling, transportation, and storage in a seaside atmosphere for many days prior to launch. To obtain a degradation factor for this part of the operation, SN-034 was shipped to Vandenberg Air Force Base and stored for 33 days in a manner simulating the expected environment of the SNAP 10A system. The pump was then returned to

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Figure 28. Pressure and Efficiency as a Function of Flow at Different NaK Temperatures

Figure 29. Pump Power Output and Efficiency as a Function of NaK Temperature

Figure 30. SNAP 10A Thermoelectric Pump Life Test (SN-038), Air Operation, 1010°F

the test laboratories and pump operation was checked. It was found that the power had decreased 11%. Analysis showed that this decrease was attributable to mechanical factors (slight damage to elements or the contacts) rather than corrosion.

E. PUMPS IN FLIGHT SYSTEMS

1. Installation

The thermoelectric pump is mounted on top of the reactor. The pump channel is welded to the reactor head at the outlet stub. To prevent excessive forces on this support during lateral vibration, four compression outrigger supports are provided. These are installed after the pump is welded to the reactor head and fit into sockets in the head and the pump aft support. The pump outlet is welded to the system piping. A typical installation is shown in Figure 31.

Power to the prestartup electrodes is delivered by a pair of cables brazed to the electrode terminals. The pump flowmeter and thermoelectric generator/pump terminal voltage (wall voltage) leads are brazed to the terminals provided. Temperature sensors are bolted onto each radiator fin. The thermocouples for reading high temperatures (temperatures at full power) are attached to one pair of fins. Resistance thermometers for reading low temperatures prior to reactor startup are bolted onto a pair of radiator fins. Since resistance thermometers provide a better temperature indication than the thermocouples at low temperature they were selected for use at prestartup.

2. SNAP 10A FS-3 System

The FS-3 system was the first complete SNAP 10A system placed in operation. It was operated in a ground test facility simulating space operation as nearly as practical. Pump SN-027, installed in the FS-3 system, is shown in Figure 32.

a. Prestartup

The requirement for prestartup was a flow rate of 0.26 gpm or greater. The flow rate indicated during this phase of the operation was 0.45 gpm. This value is in excellent agreement with the value, 0.43 gpm, obtained during pump acceptance test.

Figure 31. Installation of Thermoelectric Pump on Reactor Head in SNAP 10A System

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Figure 32. Installation of Thermoelectric Pump
in SNAP 10 System in FS-3

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b. Startup

During the startup phase of the operation, the pump responded to the rising NaK temperature in the usual manner. No anomalous behavior was shown.

c. Full Power, Active Control

After attaining the nominal initial operating temperature, reactor power level adjustments were made for a 72-hr period. During this period, the pump was required to pump NaK at a rate of at least 13.2 gpm. The nominal rate during this period was 14.3 gpm. The actual value varied in the normal manner in response to NaK temperature changes caused by the reactor power level adjustments, but the flow rate was always above the minimum requirement.

d. Full Power, Passive Control (Life Test)

After completion of the power level adjustments, the system was placed on passive control. The NaK temperature was 1049°F and the pumping rate was 15.08 gpm. Thereafter, the NaK temperature gradually dropped toward the nominal value of 1010°F, and the pumping rate, which is a function of temperature, decreased also. In addition to the pumping rate decrease resulting from the temperature drop, there is a characteristic degradation of the thermoelectric generator, which contributes to the pumping rate decline. This generator degradation is greatest during the first 1000 hr of operation and thereafter is nearly negligible. The pumping rate as a function of operating life time is shown in Figure 33. The data are normalized to a NaK temperature of 1010°F to eliminate the effect caused by the decaying reactor power, and to facilitate comparison with other data. The required pumping rate during the first 90 days of passive control is 11.2 gpm, and 10.4 gpm thereafter until the completion of 1 year of operation. This graph shows that the pumping rate was always in excess of the requirement. Throughout the life test, the pump showed no anomalous behavior.

3. SNAP 10A FS-4 System

The FS-4 was the first SNAP 10A system to operate in space; SN-029 was used in the FS-4 system.*

*A preliminary report on this flight is given in Reference 6. A final report is in preparation.

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Figure 33. Flow Rate as a Function of Operating Time (SN-027 in FS-3 on earth), Data Normalized to Reactor Core Outlet Temperature of 1010° F

The requirements for the pump in the FS-4 system were the same as those given in the discussion on the FS-3 system. During operation in space, the pump behavior was satisfactory and was substantially identical to the behavior of pumps operating on earth in the qualification tests and in the FS-3 system. Some small apparent deviations were observed but analysis showed these were simply the normal response of the pump to slightly different conditions rather than anomalous behavior of the pump. For example, prior to liftoff the entire system was maintained at a temperature several degrees higher than the nominal 90° F NaK temperature used in pump prestartup tests. As a result the pre-startup flow rate was relatively high (a desirable condition). In analyzing the flight data, emphasis was placed on finding anomalies or deviations from ground test data.

a. Prestartup

During the prestartup period, the flow rate was much greater than the minimum required and greater than obtained in ground tests. However, in flight, the battery current was higher, the NaK temperature was higher, and the effective heat sink temperature was lower than in ground tests. These three factors contributed to the higher flow rate and when the ground test input values were corrected by

the higher values obtained in the flight, the flow rate as measured in flight was as predicted. Hence, the pump prestartup performance in flight is consistent with the performance on the ground and the apparent high performance is the result of more favorable input values in flight.

b. Startup

The pump performance and behavior during startup to full power was as observed during ground tests. The pump properly responded to the rise in NaK temperature and no anomalous behavior was evident.

c. Active Control

During the active control period, the pump was required to pump NaK at a minimum rate of 13.2 gpm. The initial flow rate was 15.6 gpm. During this period the flow rate changed in the normal response to the NaK temperature changes resulting from the reactor control-drum steps.

d. Passive Control

The performance and behavior of the pump during the passive control period was comparable to that observed during ground tests. When the desired reactor power level adjustments had been completed and the system was placed on passive control, the NaK temperature was 1056°F and the pumping rate was 14.4 gpm. Thereafter the NaK temperature gradually decreased in the normal manner and the pumping rate declined correspondingly. In addition, the pumping rate decreased as the result of the normal initial pump power degradation.

The pumping rate during the system operation is shown in Figure 34. To permit comparison of the FS-4 flight data with the FS-3 ground test data, and to review the data without NaK temperature change effects superimposed, the data are normalized to a constant NaK temperature of 1010°F. A comparison of these data indicates that there was a negligible difference between the pump operating in space and operating on earth. During the passive control period, the flow rate required by specification was a minimum of 13.2 gpm initially, 11.2 gpm at 2160 hr (90 days), and 10.4 gpm at the end of 1 year. For the duration of the system operation, the flow rate exceeded the minimum requirement and showed no anomalous behavior.

Figure 34. Thermoelectric Pump Operating in SNAP 10A Systems
 (Flow as a function of operating time, flow rate normalized
 to NaK temperature, 1010° F)

A criterion for anomalous behavior is the plot of terminal voltage as a function of flow rate. The terminal voltage is the voltage input to the conduction pump and is the output voltage of the generator at the pump load. The theoretical relation is discussed in Section III-4, which follows. The voltage vs flow rate curve drawn at an expanded scale is shown in Figure 35 with values from flight test data. The slope of the band of data points is in agreement with the theoretical value and analysis shows that the data scatter from the line is not much greater than that expected from data scatter alone. Also there is no trend of the later data (lower flow rate and lower terminal voltage) falling further to one side of the confidence limit lines. The average deviation from the theoretical line is small, less than 5%. The data points on pumps in ground test using calibrated flowmeters of laboratory accuracy generally are closer to the theoretical line than those shown in Figure 35 for the flight test. (For comparison, see Figure 38 showing ground test data.) It is probable that this deviation in the flight data is indicative of a slight error in the in-flight flow measurement.

The flowmeter (integral with the pump) showed no calibration change from the time of acceptance testing to operation at full power in flight. Pumps in

Figure 35. SNAP 10A Thermoelectric Pump
Terminal Voltage vs NaK Flow Rate

qualification test showed a significant calibration change, which was the result of the environmental test. This lack of change in the flight test may indicate that the potentially damaging forces involved in flight are much less than those imposed in environmental test.

F. THERMOELECTRIC PUMP PERFORMANCE ANALYSIS

A simple thermoelectric pump performance analysis technique has been developed to facilitate pump performance evaluation and to assist in identifying defects and anomalous behavior. The curves and equations are useful also in pump design.

The approach is based on considering the dc conduction pump and the thermoelectric generator separately.

1. DC Conduction Pump

The basic equation is the familiar equation relating the force on the electric current carrying conductor in a magnetic field. The load against which this force operates consists of the external hydraulic load (the useful load), the pump internal hydraulic load, and the internal magnetic braking load. The algebraic manipulation of the pertinent equations is presented in the following text. The numerical values applicable to the SNAP 10A pump are shown in brackets; CGS units are used:

$$F = BIW \times 10^{-1}$$

$$P = \frac{F}{A} = \frac{F}{HW} = \frac{BI}{10H}$$

$$P = \text{External hydraulic load} + \text{internal hydraulic load} + \text{magnetic brake load}$$

$$= k_1 Q^n + k_2 Q^m + k_3 Q$$

$$I = \frac{10PH}{B} = \frac{10H}{B} (k_1 Q^n + k_2 Q^m + k_3 Q)$$

$$E_W = IR_n + E_c$$

$$E_c = \frac{BQ}{H \times 10^8}$$

$$E_W = \frac{10HR_n}{B} (k_1 Q^n + k_2 Q^m + k_3 Q) + \frac{BQ}{H \times 10^8}$$

$$I_W = \frac{E_W}{R_w}$$

$$I_T = I + I_w$$

$$V_T = E_w + I_T R_e$$

where,

F = force (dynes)

B = magnetic flux density (gauss), [2400 gauss at operating temperature]

W = channel width (cm), [2.54 cm]

H = channel height (cm), [1.015 cm]

A = channel cross-sectional area (cm²), [2.58 cm²]

P = pressure developed (dynes/cm²), (dynes/cm² x 1.45 x 10⁻⁵ = psi)

k₁ = constant, [0.416]

k₂ = constant, [0.0758]

k₃ = constant, [0.097]

Q = volumetric flow rate (cm³/sec), (gpm x 63.3 = cm³/sec)

n = constant, [1.8 (experimentally determined)]

m = constant, [1.8 (experimentally determined)]

E_c = counter emf, back emf (volts)

E_w = wall voltage (volts), (measured to inside wall surfaces)

I = current through liquid, NaK, (amp)

I_w = current through channel walls shunting current through the liquid
(amp)

I_T = total current from power source (amp)

R_w = channel wall resistance (ohms), [306 x 10⁻⁶ ohms (both walls)]

R_n = NaK resistance in channel (ohms), [20.6 x 10⁻⁶ ohms]

R_e = electrode resistance (ohms), [1.57 x 10⁻⁶ ohms (both electrodes)]

W_o = mechanical power out (watts), P x Q x 10⁻⁷

W_i = electrical power in (watts), V_T x I_T

η = efficiency (%), W_o / W_i

For the case of the pump operating in a hydraulic system, where the various dimensions are constant and the only variable is the applied voltage, or terminal voltage (V_T), the values of terminal voltage, current, pressure, power, and efficiency as a function of flow rate are conveniently computed when organized in a table such as shown in Table 3. From this table, the graph shown in Figure 36 is drawn. For a given pump, a quick test of the correlation between the theoretical values and experimental values is obtained by plotting the measured terminal voltage as a function of the resultant flow rate. (The two qualification pumps, SN-022 and -031 were within $\pm 1/2\%$.) This test is useful for pumps on life test. As long as the data points follow the terminal voltage vs flow rate curve, it may be assumed that the dc conduction pump is not undergoing any change or deterioration. If the terminal voltage is essentially constant also, then the electrical power source, the thermoelectric generator, is not degrading.

TABLE 3
SNAP 10A THERMOELECTRIC PUMP ANALYSIS SUMMARY

Q (gpm)	0	2	4	6	8	10	13.2	16
$Q \text{ (cm}^3/\text{sec)}$	0	127	254	380	506	633	835	1013
Q^n	0	0.0614×10^5	0.214×10^5	0.44×10^5	0.60×10^5	1.11×10^5	1.82×10^5	2.56×10^5
$k_1 Q^n$	0	0.0256×10^5	0.0891×10^5	0.1837×10^5	0.307×10^5	0.459×10^5	0.758×10^5	1.068×10^5
$k_2 Q^m$	0	0.0046×10^5	0.0162×10^5	0.0334×10^5	0.0450×10^5	0.0844×10^5	0.138×10^5	0.1944×10^5
$k_3 Q$	0	0.0266×10^5	0.0534×10^5	0.0800×10^5	0.1068×10^5	0.1334×10^5	0.176×10^5	0.2135×10^5
$P \text{ (dynes/cm}^2)$	0	0.0568×10^5	0.1587×10^5	0.2971×10^5	0.4703×10^5	0.676×10^5	1.07×10^5	1.475×10^5
$E_c \text{ (volts)}$	0	2.985×10^{-3}	5.98×10^{-3}	8.97×10^{-3}	11.96×10^{-3}	14.93×10^{-3}	19.72×10^{-3}	23.9×10^{-3}
$\frac{10HR}{B} n_P$	0	0.496×10^{-3}	1.385×10^{-3}	2.595×10^{-3}	4.11×10^{-3}	5.90×10^{-3}	9.38×10^{-3}	12.9×10^{-3}
$E_w \text{ (volts)}$	0	3.481×10^{-3}	7.36×10^{-3}	11.56×10^{-3}	16.07×10^{-3}	20.83×10^{-3}	29.1×10^{-3}	36.8×10^{-3}
$I \text{ (amp)}$	0	24.1	67.3	126	200	286	455	626
$I_w \text{ (amp)}$	0	7.9	24.0	37.8	52.5	68.2	95.3	120
$I_T \text{ (amp)}$	0	32.0	91.3	164	252	354	550	746
$I_T R_e \text{ (volts)}$	0	0.05×10^{-3}	0.14×10^{-3}	0.26×10^{-3}	0.40×10^{-3}	0.56×10^{-3}	0.86×10^{-3}	1.2×10^{-3}
$V_T \text{ (volts)}$	0	3.53×10^{-3}	7.50×10^{-3}	11.82×10^{-3}	16.47×10^{-3}	21.39×10^{-3}	29.96×10^{-3}	38.00×10^{-3}
$W_o \text{ (watts)}$	0	0.0325	0.2262	0.6980	1.551	2.900	6.330	10.82
$W_i \text{ (watts)}$	0	0.113	0.685	1.94	4.15	7.57	16.48	28.32
$\eta \text{ (%)}$	-	28.8	33.1	36.0	37.4	38.3	38.4	38.2

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Figure 36. SNAP 10A Thermoelectric Pump-dc Conduction Pump

Generally a thermoelectric generator degrades noticeably during the first few hundred hours and the terminal voltage decreases correspondingly. After the initial degradation, the rate diminishes.

2. Thermoelectric Generator

In an operating thermoelectric pump, access to the thermoelectric generator to measure its performance is generally not feasible. While some measurements may be made without much difficulty, the two quantities, (1) open circuit voltage, and (2) electric current, cannot be measured directly. However, by considering the dc conduction pump as a calibrated load, the equations and method shown for the dc conduction pump analysis may be used.

By changing the mechanical load on the pump, the electrical load is changed on the generator. This enables computation of the quantities of interest in the generator. Supplementary equations used are:

$$R_{gb} = \frac{V_{T2} - V_{T1}}{I_{T1} - I_{T2}}$$

$$R_g = R_{gb} - R_b$$

$$E_g = V_T + I_T R_{gb}$$

$$E_b = I_T R_b$$

$$S = \frac{E_g}{\Delta T}$$

where,

$$\left. \begin{array}{l} V_{T1} = \text{terminal voltage (volts) at flow rate } Q_1 \\ V_{T2} = \text{terminal voltage (volts) at flow rate } Q_2 \\ I_{T1} = \text{terminal current (amp) at flow rate } Q_1 \\ I_{T2} = \text{terminal current (amp) at flow rate } Q_2 \end{array} \right\} \text{ at } S\Delta T = \text{constant}$$

R_{gb} = generator resistance (ohms). Subscripts g and b signify generator and bus and indicate total resistance viewed at voltage measurement terminals. Included are generator resistance and bus bar resistance

R_b = bus bar resistance (ohms), [in SNAP 10A, radiator fin-to-fin, effective value for both circuits, 9×10^{-6} ohms]

E_b = voltage drop across bus bar

E_g = generator emf, open circuit voltage (volts), (NOTE: E_g is assumed constant and must be nearly constant over the flow range Q_1 to Q_2 in order for the equations to be valid)

ΔT = temperature across thermoelectric element

S = Seebeck coefficient of the pair (N and P) of thermoelectric elements. Nearly same ΔT across each element is assumed.

The supplementary curve for computing bus bar resistance is shown in Figure 37.

For computing the various generator values, Table 3 is used with some modifications. As stated earlier, the pump is treated as a calibrated electrical load on the generator. In this case, the net pressure (P) is measured as a function of flow rate (Q) as the hydraulic load on the pump is changed. Using these values of P and Q, the other values are computed by the relations given. Table 4 shows the values at 10, 13.2, and 16 gpm where the change in flow rate is achieved by a loading change (a valve in the hydraulic loop). As an example, a complete analysis of SN-022 (the first qualification pump) is presented.

Beginning with the dc conduction pump, the terminal voltage as a function of flow rate is plotted. This is shown in Figure 38. The values from the acceptance test and from the qualification test are shown. The points at high voltage and high flow rate were obtained early in the pump life and as the various factors causing degradation became effective, the voltage and flow decreased. The fact that they followed the theoretical curve is evidence that the dc pump performance was as described by theory and continued unchanged (without degradation) throughout the tests. As the result of the close correlation of experiment and theory, the values of voltage, current, power, and efficiency for any flow rate can be read directly from data in Table 3 or on the graph of Figure 34.

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Figure 37. SNAP 10A Thermoelectric Pump Bus Bar Resistance

TABLE 4
PUMP 022 ANALYSIS SUMMARY

Q (gpm)	10	13.2	16
$Q \text{ (cm}^3/\text{sec)}$	633	835	1013
Q^n	1.11×10^5	1.82×10^5	2.56×10^5
$k_1 Q^n$	1.18×10^5	0.942×10^5	0.724×10^5
$k_2 Q^m$	0.0844×10^5	0.138×10^5	0.1944×10^5
$k_3 Q$	0.1334×10^5	0.176×10^5	0.2135×10^5
$P \text{ (dynes/cm}^2\text{)}$	1.398×10^5	1.256×10^5	1.13×10^5
$E_c \text{ (volts)}$	14.93×10^{-3}	19.72×10^{-3}	23.9×10^{-3}
$\frac{10HR_n P}{B}$	12.20×10^{-3}	10.95×10^{-3}	9.88×10^{-3}
$E_w \text{ (volts)}$	27.13×10^{-3}	30.67×10^{-3}	33.78×10^{-3}
$I \text{ (amp)}$	593	532	480
$I_w \text{ (amp)}$	88.7	100.3	110.3
$I_T \text{ (amp)}$	682	632	590
$I_T R_e \text{ (volts)}$	1.07×10^{-3}	0.99×10^{-3}	0.93×10^{-3}
$V_T \text{ (volts)}$	28.20	31.66×10^{-3}	34.71×10^{-3}

Analysis of the thermoelectric generator is accomplished by measuring the terminal voltage while changing the flow rate by changing the hydraulic load (as with a valve) and measuring the pressure developed by the electric current. The values obtained are shown in Table 4 with the other values computed.

Hence, at:

$$Q_1 = 10 \text{ gpm}$$

$$V_{T1} = 28.20 \times 10^{-3} \text{ volts}$$

$$I_{T1} = 682 \text{ amp,}$$

and at

$$Q_2 = 16 \text{ gpm}$$

$$V_{T2} = 34.71 \times 10^{-3} \text{ volts}$$

$$I_{T2} = 590 \text{ amp,}$$

and using the formulas given previously

$$R_{gb} = \frac{(34.71 - 28.20) \times 10^{-3}}{682 - 590} = 70.8 \times 10^{-6} \text{ ohms}$$

$$R_g = 70.8 \times 10^{-6} - 9 \times 10^{-6} = 61.8 \times 10^{-6} \text{ ohms}$$

$$E_g = 31.66 \times 10^{-3} + 632 \times 70.8 \times 10^{-6} = 76.36 \times 10^{-3} \text{ volts}$$

$$S = \frac{76.36 \times 10^{-3}}{314} = 242 \times 10^{-6} \text{ volts/}^\circ\text{F (note that this is the sum of N and P)}$$

$$R_L = \frac{31.66 \times 10^{-3}}{632} = 50.1 \times 10^{-6} \text{ ohms (load on the generator, i.e., the dc conduction pump)}.$$

After 3500 hr of operation, the terminal voltage as a function of flow rate was measured again with the following results:

$$R_{gb} = \frac{(31.8 - 24.68) \times 10^{-3}}{682 - 590} = 77.4 \times 10^{-6} \text{ ohms}$$

$$R_g = 77.4 \times 10^{-6} - 9 \times 10^{-6} = 68.4 \times 10^{-6} \text{ ohms}$$

$$E_g = 28.50 \times 10^{-3} + 632 \times 77.4 \times 10^{-6} = 77.4 \times 10^{-3} \text{ volts}$$

$$S = \frac{77.4 \times 10^{-3}}{342} = 226 \times 10^{-6} \text{ volts/}^\circ\text{F}$$

$$R_L = \frac{27.10 \times 10^{-3}}{487} = 55.7 \times 10^{-6} \text{ ohms}$$

This shows that during the 3500 hr, which included several kinds of tests, the generator resistance increased by 6.6×10^{-6} ohms while the Seebeck value decreased by 16×10^{-6} volts/ $^\circ\text{F}$. This is the source of the pump degradation. The effect of the decreased output of the thermoelectric generator is mitigated by the increase in load resistance R_L by 5.6×10^{-6} ohms. This increase in R_L is simply the result of the decreased pressure against which the pump works at the lower flow rates. This is one reason why the pump power degradation becomes less after a few hundred hours of operation.

Using the data obtained in conjunction with the appropriate temperature data, the generator Carnot efficiency (η_c), generator efficiency (η_g), and device efficiency (η_d), $\eta_g = \eta_c \times \eta_d$, are computed and shown in Figure 39. On this graph

Figure 39. SNAP 10A Thermoelectric Pump (SN-022)
Thermoelectric Generator Efficiency

are shown the theoretical generator efficiency (η_t) and the material efficiency (η_m). The device efficiency (η_d) differs from the material efficiency to the extent of the losses associated with contacts.

G. POST-TEST EXAMINATION OF THERMOELECTRIC PUMPS

1. Background

In addition to the evaluation of the pumps by measured performance, a program of post-test examinations was established to determine the behavior of the components and materials under the various test conditions. While the measured performance indicated acceptable behavior, the post-test examination was needed to indicate any incipient failure and to determine the adequacy of the safety factors allowed in the design. Reports presenting detailed descriptions and analyses of the pumps examined are identified in Appendix B. The discussion here is based primarily on the data in those reports.

In previous discussions of pump development, attention was directed toward sizing to meet the various performance, weight, and size requirements. In this discussion, the development is divided into the stages listed; attention is directed toward the factors related to degradation and reliability:

1) Early Development Pumps. Copper electrodes were brazed to the SS channel at 1325°F with HH Premabraz 615. Elements were diffusion bonded to the copper electrodes. The N and P elements were PbTe.

2) Preliminary Flight Pumps. Same as Item 1 except that the P elements were PbSnTe

3) Flight Pumps. Copper electrodes were brazed to the Type 347 SS channel at 1750°F with WGP Nicoro 80. Elements were diffusion bonded to the copper electrodes. The N elements were PbTe and the P elements were PbSnTe.

4) Experimental Element Barrier Pumps. Same as flight design pumps except that a barrier in the form of an iron foil is interposed between the element iron contacts and the copper shoes.

The changes indicated in the listing were made in response to the findings in post-test metallurgical examinations. The first change, replacing the PbTe P elements with PbSnTe P elements, was based on expected better mechanical properties (less fragile) of the PbSnTe P material. The second change, replacing the Premabraz 615 with Nicoro 80, was made after the discovery that the copper electrode-to-SS channel bond made with Premabraz 615 was poor and potentially unreliable.

The third change, the use of an iron foil barrier, was made to prevent the reaction of the thermoelectric material with the braze material and copper shoes. As discussed later, this change was not imposed on the flight design, hence remained in the experimental stage.

Metallographic examination of the pumps was limited to potential problem areas. These involved the components, and especially, the joints required to pass heat and electric current. The heat and electric current paths (shown in Figure 3) identify the potential problem areas. The elements (flight design) are shown in greater detail in Figure 4. Other parts of the pump, such as magnet assembly and mounting brackets, did not require any post-test examination other than cursory visual inspection.

2. Description of the Condition of the Components

The potential problem areas are discussed in the sequence of their position beginning with the channel.

1) Channel. The channels were entirely satisfactory; they all showed excellent resistance to intergranular corrosion or attack by NaK. This includes operation for more than 16,000 hr at the normal operating temperature (1010°F) and for more than 3000 hr at 1100°F.

2) Channel-to-Electrode Braze Joint. After the change to Nicoro 80 braze material (81.5% Au, 2% Ni, 16.5% Cu, with a braze temperature of 1750°F), this joint was excellent in all cases, i.e., over 16,000 hr operation at the normal operating temperature and more than 3000 hr at 1100°F.

3) Copper Electrode. This part was entirely satisfactory in all cases.

4) Electrode-to-Copper Shoe Bond (Hot). This diffusion bond, using Premabraze 615, was entirely satisfactory in all cases.

5) Copper Shoe (Hot). This component was generally satisfactory. However, in two pumps (SN-031 and -032) the copper shoes of the N elements were contaminated to a depth as great as 0.045 in. This contamination was not uniformly distributed but was greater closer to the channel (the heat source), and greater with depth of penetration.

Analysis showed that the contamination consisted of two phases. One phase was rich in lead and tellurium, and analysis indicated 48 wt % Pb, 48 wt % Te although it is probable that it was stoichiometric PbTe. The other phase was rich in copper and tellurium with some silver in isolated regions of the phase. The copper-tellurium-silver phase was about 50 wt % Cu, 40 wt % Te, and 10 wt % Ag. Further study indicated a two-phased structure of Cu-Te and Ag-Te particles. The phase diagrams for the Cu-Te and Ag-Te systems are not complete but tentative identification of the phases is Ag_2Te and CuTe .

The mechanism by which the lead telluride thermoelectric material and the silver from the Premabraze diffuses into the copper is not satisfactorily understood. It is related to the more general problem involving the entire

element, which will be discussed later. This contamination in the copper shoe (hot side) was observed in the N elements only.

A panoramic view beginning at this copper shoe is shown in Figure 40. This view is a composite of photomicrographs from one copper shoe to the other, thereby presenting a cross-sectional view of the element. Some of the features discussed in the following paragraphs are illustrated in this view.

6) Copper Shoe-to-Iron Bond (Hot). In early development pumps there was no particular problem with this bond; it was formed by diffusion bonding using Premabrazo as the bonding material. The thermoelectric material was lead telluride in the N and P elements. In the later pumps, using lead telluride for the N elements, and lead-tin-telluride for the P elements, a definite reaction at this bond occurred in elements using Premabrazo as the bonding material.

In N elements where copper foil was used instead of the Premabrazo, there was no reaction. In P elements the substitution of copper foil did not eliminate the reaction.

In elements using iron foil between the iron and copper shoes there was no reaction. The iron foil functioned as a barrier (as intended) by preventing passage of thermoelectric material constituents to the copper shoe (or braze foil).

A comparison of the discussed findings with the bond used in the flight design (Figure 4) raises a question about the choice made. This is treated in the discussion at the end of this section.

In flight-design N elements the reaction mentioned previously results in a depletion of the Premabrazo as a function of time and temperature. This is illustrated by comparing the Premabrazo thickness in an unused element (Figure 41) with the thickness in a pump operated 9387 hr under normal conditions (Figure 42). As the Premabrazo is depleted, the Premabrazo bond thickness decreases and silver and copper appear elsewhere [in the copper shoe as CuTe, previously described, in the iron shoes (hot), in the thermoelectric material, and particularly at the thermoelectric material iron shoe (cold) interface].

Cu-Ag-Te
AND PbTe
PHASES

PREMABRAZE 615

HOT Cu SHOE

NOTE ABSENCE
OF BRAZE

HOT Fe SHOE

N-TYPE
ELEMENT

PRECIPITATED
PHASES

COLD Fe SHOE
PREMABRAZE 615

COLD Cu SHOE

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Figure 40. Panoramic View from
Hot Cu Shoe to Cold Cu Shoe of
Specimen from SN-032,
N-Type (100X)

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Figure 41. Copper Hot Shoe-Iron Hot Shoe Diffusion Bond Region of As-Fabricated N-Type Assembly

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Figure 42. SN-031 N-Type Assembly

In flight-design P elements, the iron shoes are diffusion bonded directly to the copper shoes. Examination shows contamination at this interface similar to that seen in the N elements, in addition, there are large voids.

7) Iron Shoe (Hot). The condition of this region varied considerably from pump to pump. In N elements, where copper foil was used to bond the iron shoe to the copper shoe, there was no contamination. In N elements where Premabrazed was used, the iron shoes were contaminated with Premabrazed. The penetration was predominantly in the voids between the iron grains with very little penetration of the iron grains. The amount of contamination was slight in some elements and extensive in others. In pumps using the iron-foil barrier there was no contamination.

In P elements there was contamination of the iron shoe with the use of copper foil and with Premabrazed as the bonding material. Generally the contamination in the P elements was similar to that in the N elements but the amount was greater. In pumps using the iron-foil barrier there was no contamination. Also the contamination was less in the early development pumps using PbTe as P material.

8) Element-to-Iron Interface (Hot). In N elements, the contact at this interface was always good. In P elements the contact was relatively poor (separation and voids) in the early development pumps using PbTe as P material. This contact was poor also in some later pumps using PbSnTe as the P material. In the most recent pumps of the final flight design and of the iron-foil barrier design, this interface has been good in the P elements as well as in the N elements.

9) Element. In N elements, the contamination was generally slight throughout the body of the element. There was no contamination in elements using the iron-foil barrier. In P elements, the contamination was slight when PbTe was used as the P material. The contamination was much greater in pumps using the PbSnTe material. The distribution was similar in all PbSnTe P elements: a high density or accumulation at the cold interface with iron, and a diminishing density in the direction of the hot interface.

The amount of contamination and the density at the cold interface was a function of operating time and temperature. In one pump, a preliminary

flight model using Premabrazz, operating at 1100°F NaK (1010°F standard), the amount of contaminants entering the element was so great that the element thickness increased. The contamination was identified as a Cu-Sn alloy with some Te present and a Te-rich phase with significant amounts of Cu and Sn.

10) Element-to-Iron Interface (Cold). Generally, the contact at this interface was satisfactory in both the N and P elements. In the N elements, using the copper foil as bonding material between the iron and the copper shoes there was no significant contamination at the interface.

In N elements using Premabrazz, a well defined layer of this material was evident at the interface. By appearance and position it appeared as if the Premabrazz foil had been placed at this interface at the time of element fabrication. The layer thickness was a function of several factors, two of which were operating time and temperature. In some elements the thickness was as great as 0.002 in. In elements using the iron-foil barrier there was no such contaminating layer.

In the P elements there was no well defined layer as described for the N elements, but as stated in paragraph 9) the contamination density is greatest at this interface and extends into the element. In elements using the iron-foil barrier there was no contamination.

11) Iron Shoes (Cold). This component was satisfactory in all elements, although slight contamination was observed in a P element used in a preliminary flight-design pump operated at 1100°F NaK (1010°F NaK is standard).

12) Copper Shoe-to-Iron Bond (Cold). This bond was good on all early pumps, and on the later flight-design pumps having relatively short operating times. In flight-design pumps having long operating times, the N elements had a Cu-Ag precipitate at this bond and the P elements had significant voids at this bond. In elements using the iron-foil barrier there were no problems at this interface.

13) Copper Shoe (Cold). This component was entirely satisfactory in all pumps.

14) Radiator-to-Copper Shoe Bond (Cold). This bond was generally satisfactory. It was considered fair in SN-015 and -017. These pumps were operated for only a very short time (SN-015 for 42 hr and SN-017 for 125 hr). In all other pumps the bond was good.

The formation of the intermetallic joint is a function of time and temperature. The typical thickness was about 0.003 in. on the N side and 0.002 in. on the P side. The N side operates at a temperature about 25°F higher than the P side, and this probably accounts for the consistently thicker reaction zone on the N side.

15) Radiator Base. The aluminum radiator fin base had a satisfactory appearance in all pumps. The creep resulting from the initial high compressive loading at the radiator fin base operating temperature of nominally 600°F resulted in a typical deformation of 0.002 in. deep where the compression bar structure contacted the fin base.

16) Encapsulant. The encapsulant was generally satisfactory. It is an essential part of the element used to inhibit the sublimation and escape of tellurium vapor. In some elements the encapsulant was slightly cracked but there was no overall deterioration. In a few instances the encapsulant was darkened, presumably by the tellurium vapor.

3. Discussion of the Findings

The post-test examinations have shown that there is no evidence of incipient failure in any of the pump components and that there is an adequate safety factor.

The description of the condition of the components clearly indicates that, metallographically, all except the thermoelectric element show satisfactory behavior. The data show that the N and P elements undergo a change and since this change is indicated for pumps operating for as short a time as 46 hr it may be concluded that the observed phenomenon begins during the bonding cycle (during pump fabrication). At that time the element temperature is 980°F, which is significantly higher than the element operating temperature; hence, the various reactions, being temperature dependent, certainly begin during fabrication. Pump operation simply enables the reactions to proceed toward the end point of the possible reactions.

The exact nature of the mechanisms involved in the reactions observed has not been determined. It appears that tellurium vapor diffuses through the iron shoe to the interface of Premabrazed in N elements or to the copper in P elements. Tellurium, alloyed with either copper or silver, has a melting point below the existing temperature at the hot side. The resulting liquid metal diffuses through the iron shoe in the direction of the heat sink. In the N elements, precipitation occurs only at the PbTe-to-iron shoe (cold) interface. In the P elements, the precipitation is densest at the cold interface but is distributed with decreasing density toward the hot side. Shadow effects, that is, absence of precipitation near a void, indicate that the distribution follows the lines of conduction. A complete analysis of the phenomenon was beyond the scope of the pump development program.

It is well known that the properties of a thermoelectric material are very sensitive to changes in composition. Hence the changes observed must have changed the thermoelectric properties. This conclusion is confirmed in the analysis of pump data, which shows that all degradation in thermoelectric pumps is traceable to the thermoelectric generator and thence to the elements.

However, all pumps tested degraded in essentially the same manner. That is, the degradation was rapid during the first 1000 hr, diminished thereafter, and beyond 3000 or 4000 hr the degradation nearly ceased. Since pumps using the iron-foil barrier also showed this behavior it is concluded that the rapid initial degradation is not the result of the massive contamination described.

Two other views are considered. One of these is the effect of contamination by trace quantities. Other investigators^(11 through 16) have shown that the trace amounts affect the properties in an amount corresponding to the observed changes in thermoelectric properties. The massive contamination observed does not necessarily produce proportional changes in the thermoelectric properties. Hence the damage (degradation) may have been caused by the nearly unseen contamination, and the massive, obvious contamination may have added very little damage. The metallurgical report of no contamination in elements using the iron-foil barrier must be interpreted as a relative statement. That is, in comparison with elements having no barrier there was "no contamination." Under careful scrutiny, a "few spotty areas" of contamination were found in the

P elements of SN-017. This contamination was considered to have been in the original raw stock.

While the explanation described is plausible and, no doubt, trace quantities of impurities are present and affect the behavior, several types of behavior have been observed which are not so easily explained on the basis of contamination.

The other factor to consider is the generation of microcracks as the result of thermal stresses and creep. The initial mechanical load on the elements is relatively high at the center and negligible at the ends. During heating, the pressure at the center increases as the result of thermal expansion. Operation for a period of time results in creep of the materials under stress (the aluminum fin base, the elements, and the copper electrode compressed in an Inconel X compression bar structure) with the probable accompanying development of microcracks. During the development of the microcracks, the observed degradation is presumed to occur. With the progress of creep, the loading becomes more nearly uniform and the creep stops when the mechanical load becomes sufficiently low and uniformly distributed. The main experimental experience which supports this explanation of degradation is that after a pump has operated many hundreds of hours and the degradation has nearly stopped, raising the operating temperature starts the degradation again and after a few hundred hours the degradation nearly stops. This indicates that raising the temperature, resulting in thermal expansion, establishes a new higher mechanical load, and as this load is relieved by creep, more microcracks are generated until a new mechanical equilibrium is attained and the creep stops.

This behavior, that is, the renewal of rapid degradation followed by a slowing down of the degradation, is characteristic of all pumps, including those with the iron-foil barrier.

The efforts to study the degradation were made concurrently with the pump development and testing program and were a byproduct. That is, observations were made on pumps produced to meet qualification test and production requirements rather than to provide fundamental data on the mechanism of thermoelectric generator degradation. This policy was followed since, even with the slight degradation and with contamination, the success of the pump in meeting the system requirements was not in question. Subsequent testing, including the operation in the two operating SNAP 10A systems have substantiated this policy.

IV. CONCLUSIONS AND RECOMMENDATIONS

The thermoelectric pump for SNAP 10A systems has been successfully developed, produced (in small quantities), and operated in various tests including a flight test. All performance objectives have been achieved and excellent reliability has been demonstrated.

The pump program has been completed. Several pumps which had completed the specified life test were allowed to continue operation. Some were allowed to operate 2 years or longer (the longest was 2.3 years, or 20,037 hr for SN-011) and at the time of shutdown were performing well.

While the pumps have been satisfactory in meeting the requirements, several possible improvements became evident and were tested during the later part of the program. Since they were too late for convenient incorporation in the final design, and since the existing requirements had been satisfied, these improvements remain in the "recommendation stage" for pumps of this type which may be designed in the future. The desirable improvements are described in the following paragraphs.

The flowmeter accuracy and repeatability can be improved by moving the flowmeter electrodes farther from the thermoelectric pump electrodes and extending the magnetic field so that the electrodes are in a uniform field region.

Tests conducted late in the program showed that the prestartup, auxiliary power electrodes can be eliminated and the auxiliary power can be applied directly to the main thermoelectric pump electrodes. By the use of a temperature controlled magnet, the current required can be reduced to 9 amp. The main advantage of this improvement is a savings of ~40 lb of battery weight.

By using a magnet material with a higher energy product and higher coercive force, magnet weight can be reduced and the configuration changed to permit an improved radiator design. Late in the pump program, two pumps, using this improvement, were made and the resultant weight savings was 7 lb. The performance was the same as that of the present design. The main advantage is in the weight reduction, particularly in the radiator. The radiator is supported by the thermoelectric elements, and this weight saving is of significance during vibration.

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APPENDIX A
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4. C. M. Quirk and T. M. Funakura, "SNAP 10A PbSnTe T/E Pump S/N-023, Acceptance Test," NAA-SR-TDR No. 10279, August 10, 1964
5. C. M. Quirk and T. M. Funakura, "SNAP 10A PbSnTe T/E Pump S/N-026, Acceptance Test," NAA-SR-9877, May 5, 1964
6. C. M. Quirk and T. M. Funakura, "SNAP 10A PbSnTe T/E Pump S/N-027, Acceptance Test," NAA-SR-TDR No. 10143, June 24, 1964
7. C. M. Quirk and T. M. Funakura, "SNAP 10A PbSnTe T/E Pump S/N-028, Acceptance Test," NAA-SR-TDR No. 10144, June 26, 1964
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9. C. M. Quirk and T. M. Funakura, "SNAP 10A PbSnTe T/E Pump S/N-030," NAA-SR-TDR No. 10181, July 8, 1964
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15. C. M. Quirk, "SNAP 10A PbSnTe T/E Pump S/N-037 Acceptance Test," NAA-SR-TDR No. 10562, October 16, 1964
16. C. M. Quirk and T. M. Funakura, "SNAP 10A PbSnTe T/E Pump S/N-038, Acceptance Test," NAA-SR-TDR No. 10667, November 4, 1964

17. C. M. Quirk and T. M. Funakura, "SNAP 10A PbSnTe T/E Pump S/N-039, Acceptance Test," NAA-SR-TDR No. 10795, December 14, 1964
18. T. M. Funakura and C. M. Quirk, "SNAP 10A PbSnTe T/E Pump S/N-022, Qualification Test," NAA-SR-TDR No. 11548, July 30, 1965
19. T. M. Funakura and C. M. Quirk, "SNAP 10A PbSnTe T/E Pump S/N-028, Qualification Test," NAA-SR-TDR No. 11470, June 23, 1965
20. T. M. Funakura and C. M. Quirk, "SNAP 10A PbSnTe T/E Pump S/N-031, Qualification Test," NAA-SR-TDR No. 11549 (in publication) 1965

APPENDIX B
REPORTS OF METALLURGICAL EXAMINATIONS AND
RELATED DEGRADATION STUDIES

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2. E. L. Reed and N. H. Katz, "Fabricate and Post-Test Evaluation of SNAP 10A Thermoelectric Pumps," NAA-SR-MEMO-9447 (Classified Report) July 6, 1964
3. M. A. Perlow, "SNAP 10A Thermoelectric Pump Development," NAA-SR-9486 (Classified Report) June 3, 1964
4. E. L. Reed, "Post-Test Examination of T/E Pump 10-FSM-1," NAA-SR-MEMO-10299 (Classified Report) October 1, 1964
5. W. L. Cockrell and E. L. Reed, "Metallographic Examination of SNAP 10A Pump, Number DEV 6," NAA-SR-MEMO-9271 (Classified Report) May 5, 1964
6. E. L. Reed, "Post-Test Examination of SNAP 10A T/E Pump 010," NAA-SR-MEMO-10952 (Classified Report) March 11, 1965
7. E. L. Reed, "Post-Test Examination of P-Elements in T/E Pumps DEV-4 and DEV-5," NAA-SR-MEMO-11225 (Classified Report) April 5, 1965
8. E. L. Reed, "Post-Test Examination of T/E Pump FQ-4," NAA-SR-MEMO-TDR-No. 10518 (Classified Report) December 21, 1964
9. E. L. Reed, "Post-Test Examination of T/E Pump FQ-3," NAA-SR-MEMO-10517 (Classified Report) November 16, 1964
10. W. L. Cochrell and E. L. Reed, "Post-Test Examination of SNAP 10A Thermoelectric Pump Number-017, NAA-SR-TDR No. 9712 (Classified Report) April 15, 1964
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17. K. A. Davis, "Liquid Metal Pump, Powered by Lead Telluride Thermoelectric," NAA-SR-7258, April 2, 1962
18. R. M. Willard, "Post-Test Examination of SNAP 10A T/W Pumps Nos. 016, 031, and 032," NAA-SR-TDR No. 11841 (Classified Report) February 9, 1966