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MASTER

SNAP-21B PROGRAM, PHASE I

DEEP SEA RADIOISOTOPE-FUELED
THERMOELECTRIC GENERATOR
POWER SUPPLY SYSTEM

FINAL SUMMARY REPORT

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SNAP-21B PROGRAM, PHASE I

DEEP SEA RADIOISOTOPE-FUELED THERMOELECTRIC GENERATOR POWER SUPPLY SYSTEM

FINAL SUMMARY REPORT

Published June 1966

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FINAL SUMMARY REPORT

SNAP-21B PROGRAM, PHASE I
DEEP SEA RADIOISOTOPE-FUELED
THERMOELECTRIC GENERATOR
POWER-SUPPLY SYSTEM

ABSTRACT

During Phase I of the SNAP-21B Program, an operational mockup of the isotope-fueled thermoelectric generator power-supply system has been designed, fabricated, and placed on long-term test in a simulated deep-sea environment. In addition, the six major components of the system have been developed and tested: Hastelloy-C fuel capsule, U-8% Mo biological radiation shield, high-vacuum super-insulation system, 48-couple flatplate thermoelectric generator, dc-dc converter regulator, and titanium alloy pressure vessel. The mockup system substitutes an electric heater block for the isotope fuel capsule, and a stainless steel radiation shield and pressure vessel.

The electrically "fueled" mockup has successfully completed a simulated 5-year mission, and has been operating at a stable trouble-free level for more than 1 year with a thermoelectric materials efficiency of 9.7 percent, generator efficiency of 8.75 percent, converter efficiency of 89 percent, and over-all system efficiency of 5.2 percent. The mockup system has demonstrated that the power output, efficiency, reliability, maintenance, safety, weight, and environmental requirements of the SNAP-21B design can be met.

Further work will be done on maintaining insulation vacuum, improving generator cold-end heat transfer, insuring stability and interface compatibility of the radiation shield, developing and loading the fuel capsule, and testing a Sr-90 fueled system prototype under high-pressure, long-term operational conditions.

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FINAL SUMMARY REPORT
SNAP-21B PROGRAM, PHASE I
DEEP SEA RADIOISOTOPE-FUELED
THERMOELECTRIC GENERATOR
POWER-SUPPLY SYSTEM

SUMMARY

The purpose of the SNAP-21B Program is to design, develop, fabricate, and test a small-size, lightweight, long-life, highly efficient and reliable, Sr-90 fueled thermoelectric generator power-supply system for deep-sea and ocean-bottom applications. In Phase I of the program, two major tasks have been accomplished: the six major system components and auxiliary hardware have been developed and tested; and an operational mockup of the SNAP-21B system has been placed on long-term test in a simulated deep-sea environment. The test is providing engineering data on the performance of the various components when integrated into the power-supply system, and is experimentally verifying the ability of the system to provide a continuous 10-watt, 24-volt dc output over a 5-year period.

The Hastelloy-C fuel capsule has been designed, fabricated, and successfully safety tested. Post-test analysis has validated the capsule design and insured the integrity of the capsule under all conditions of credible use.

A lightweight U-8% Mo biological radiation shield has been designed to limit the nuclear radiation of the isotope fuel within acceptable levels. Long-term compatibility tests of shield samples have shown good results.

A high-vacuum super-insulation system has been designed, fabricated, and tested to insure minimal thermal conductivity. System testing indicates a conductivity of 0.0008 Btu/hr-ft-°F during operational life. Several modifications of the insulation-system liner have been made to achieve vacuum integrity under high-temperature, high-vacuum conditions.

Four 6-couple thermoelectric modules and six prototype thermoelectric generators have been designed, built, and placed on long-term test. The modules are continuing to show satisfactory efficiency and stability after more than 15,000 hours of operation. Because of an abnormal rise in cold-junction electrode temperature, the generators have demonstrated an initially rapid increase in power output followed by a more gradual decrease. However, the units are exhibiting relatively stable performance after more than 9000 hours of testing.

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Five power conditioners which can convert the 5.1-volt dc thermopile output to 24-volts dc with a system load of 57.6 ohms have been fabricated and placed on test. After more than 11,000 hours of failure-free performance, the converters are operating at 89-percent efficiency, and the voltage regulators are showing excellent stability.

A lightweight pressure vessel (titanium 721 alloy) has been designed, developed, and fabricated to contain the power-supply system under all operating conditions at an ambient seawater pressure of up to 10,000 psi. The pressure vessel has successfully completed all mechanical and hydraulic pressure tests.

The SNAP-21B-1 system mockup has undergone a simulated 5-year mission. The results indicate that the system is capable of a 11.65-watt beginning-of-life (BOL) output and a 10.4-watt end-of-life (EOL) output, 0.4 watts above the design requirement, at an over-all system efficiency of 5.2 percent. Except for the cold-end temperature rise and the inability to maintain insulation vacuum, the system is still functioning on a stable, trouble-free basis after more than 10,000 hours of operation.

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FINAL SUMMARY REPORT

SNAP-21B PROGRAM, PHASE I
DEEP SEA RADIOISOTOPE-FUELED
THERMOELECTRIC GENERATOR
POWER-SUPPLY SYSTEM**INTRODUCTION**

This report summarizes the work conducted for the United States Atomic Energy Commission by the 3M Company under Contract AT(30-1)3321 for development of the SNAP-21B deep-sea power-supply system. During Phase I of the program, which extended from April 1964 through June 1965, the 3M Company designed, developed, and fabricated a power-supply system that is capable of operating in a deep-sea or ocean-bottom environment according to the specified objectives and requirements.

The general objectives have been to develop a power-supply system with high efficiency and reliability, long life, and minimum size and weight. The system (Figure 1) has been designed to meet the following specific requirements:

- Continuous 10-watt, 24-volt-dc output for a minimum period of 5 years with unattended operation.
- Maximum radiation level of 200 mr/hr at the surface of the system and 10 mr/hr at 1 meter from the surface.
- Easy removal and replacement of the thermoelectric generator and power conditioner without the use of hot-cell facilities and without exceeding personnel radiation exposure limits.
- Containment of strontium-90 titanite fuel under all conditions of intended use and credible accidents for a minimum period of 300 years.

The power supply system must be capable of performing under the following environmental conditions:

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Figure 1.
SNAP-21B Deep Sea Thermoelectric
Generator (PD-37-1287). See
Section 6.0 for re-design of
insulation envelope neck tube and
liners.

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- Ambient air temperature of -40° to 130°F
- Ambient water temperature of 28° to 41°F
- Ambient air pressure of 10 to 32 in. Hg
- Ambient seawater pressure of up to 10,000 psi
- One-hundred percent relative humidity in a salt atmosphere.

Phase I of the SNAP-21B Program was organized into six developmental areas according to the six basic system components. The following is a brief design summary of the components and the over-all SNAP-21B system. For a detailed design summary, see Appendix A.

Fuel Capsule (Section 3.0)

The design objectives for the fuel capsule are: (1) easy encapsulation of strontium-90 titanate fuel at the fueling facility; (2) fuel-capsule temperature after fueling not to hinder insertion of the capsule in the biological radiation shield; (3) ability to withstand external pressures of up to 10,000 psi in a salt-water environment; and (4) absolute fuel containment for 300 years.

The fuel capsule (Figure 1) is designed to generate 187 thermal watts of power, with a power density of 0.8 watt/cc of fuel. For ease of handling and decontamination, the fuel pellet is doubly encapsulated with a thin, 316L stainless-steel inner capsule, and a thicker, Hastelloy-C outer capsule. The inner capsule slips inside the outer, with the end plates fitting flush against the inner capsule. The outer-capsule end plates are welded in place in a helium atmosphere. A double-cup outer capsule liner of chromium-plated copper provides for separation of the fuel capsule and the biological radiation shield, and is compatible with Hastelloy-C and uranium.

The outer fuel capsule has been constructed to withstand all safety tests. Heat flux analysis indicates that thermal expansion of the fuel capsule at 700°F after fueling will not hinder insertion of the capsule into the biological radiation shield.

Biological Radiation Shield (Section 4.0)

The design objectives of the biological radiation shield are to: (1) limit the nuclear radiation level to 200 mr/hr at the surface of the power supply system, and 10 mr/hr at 1 meter from the surface; (2) permit easy thermoelectric subsystem repair or replacement without hot-cell facilities, and without exceeding the maximum permissible AEC radiation exposure limits.

The U-8% Mo shield (Figure 1) is designed for minimum weight (241.75 lbs) and employs a cylindrical, rounded-end configuration to enclose the cylindrical fuel capsule. The U-8% Mo shield end-plug is bolted into place so that it can be easily removed and replaced without radiation leakage.

To protect against oxidation and eutectic formations, and to insure dimensional compatibility between the outer fuel capsule and the shield, and between the thermal insulation liner and the shield, a 0.010-inch-thick copper cylinder (not shown in Figure 1) is fitted between the fuel capsule and the shield, and a 0.032-inch-thick electroplated copper cladding is used on the exterior of the shield. The copper cylinder and cladding are in turn plated with a 0.0005-inch-thick flashing of chromium.

The shield will limit the radiation level to the desired limits when the fuel capsule is loaded with 30,000 curies of Sr-90.

Insulation Envelope (Section 6.0)

The objectives in designing the insulation envelope were to: (1) insure proper mechanical and thermal interfacing between the insulation envelope and the other power-supply system components; (2) establish the interface boundary and environmental conditions necessary to maintain the insulation system vacuum, minimize movement of the radiation shield, and limit the thermal conductivity of the insulation envelope to 0.0005 Btu/hr-ft-°F during the 5-year operational life of the system.

To meet the design objectives, three basic insulation-envelope models have been developed. Common to all three are: an outer shell of 316L stainless-steel; an evacuated super-insulation system composed of microquartz fibers and metallic reflection sheets wrapped in layers; and a getter material that absorbs the gases evolved by the super-insulation materials. These basic items are indicated in Figure 1.

In Design I, and also in both versions of Design II, the inner envelope liner (Figure 1) consists of a shell made from Inconel X750. This shell forms a leak-tight internal pressure housing, and provides a point of attachment between the radiation shield and the shield support structure. The support structure for Design I (see Section 6.0) consists of a thin-walled tube at the lower end of the shield and a bellows assembly at the upper end.

The bellows assembly has failed to provide the necessary mechanical support for the shield. However, long-term tests with Design I, after replacing the bellows assembly with a thin tube, have shown a thermal conductivity rate of 0.0008 Btu/hr-ft-°F, using a higher heat-source temperature than originally anticipated. Heat loss through the support tube is 7.0 watts, and that through the support tube is 21.0 watts. The entire heat balance analysis for the SNAP-21B-1 system is given in Appendix C.

In Design II (Figure 1) the bellows and lower support tube were replaced with a thin-walled, monocoque, cylindrical neck tube. The inner shell design, which consists of lower and upper heads joined by a single circumferential weld, remained the same. During vacuum processing at elevated temperatures, the inner shell failed at the circumferential weld; and the heat loss through the shield support structure increased to 28.0 watts.

To reduce the thermal expansion stress on the inner shell, the clearance between it and the shield was increased, and the shell assembly was changed to two shallower heads and a central cylinder joined by two circumferential welds

(see Section 6.0). However, the inner shell again failed during vacuum processing at elevated operating temperatures. To lower the heat loss, the neck tube was increased in length and reduced in thickness, resulting in a loss of only 21.2 watts through the support structure.

In Design III, which has not been tested, the inner shell has been eliminated by extending the neck tube (Inconel X750) into the fuel capsule cavity as an inner insulation system liner (see Section 6.0). The radiation shield will be securely bolted to a flange machined onto the neck tube. It is expected that the over-all heat loss will total 32 watts, including the 7.0 watts lost through the super-insulation system.

Thermoelectric Generator (Section 1.0)

Two objectives were involved in designing the thermoelectric generator: (1) developing a generator which can be removed from the power supply system and replaced without hot-cell facilities and with a minimum of special equipment, and which will provide a continuous, net system output of 10 watts at 24-volts dc for a minimum period of 5 years; (2) developing a thermoelectric leg subsystem which has an efficiency of at least 10 percent when integrated into the generator.

In its position above and outside the fuel capsule, radiation shield, and insulation system, the generator can easily be removed and replaced without a hot-cell facility by unbolting the top hemisphere of the pressure vessel (Figure 1). The generator case serves as a connection between the hot and cold frames, and maintains an hermetic seal for the generator assembly. A back-up ring is used to reinforce and join the two case sections. The case material, 0.005-inch-thick 347 stainless-steel, has high temperature strength and low thermal conductivity. After the generator is installed, the case is evacuated, back-filled with xenon gas, and sealed by welding.

The generator mounting plate (Figure 1) serves as the mounting mechanism for the thermoelectric generator, acts as the bearing plate from the segmented centering ring to the pressure vessel, and transfers heat from the generator cold frame to the centering ring and pressure vessel. The mounting plate material, 2024 aluminum, has a high thermal conductivity. The captive-bolt and spring arrangement provides the bearing pressure between the mounting plate and the centering ring for system support and thermal contact.

The segmented centering ring positions and retains the insulation envelope and radiation shield within the pressure vessel, and provides additional heat transfer area at the pressure vessel walls. The centering ring is segmented to allow for circumferential decreases in vessel diameter during operational cycling from sea level pressure to 10,000 psi. The convex surface of the centering rings matches the concave surface of the insulation envelope, allowing rotation of each ring segment to accommodate for radial deflection of the pressure vessel wall. Integral extensions on the generator mounting plate are spring-loaded to each centering ring segment for better heat-transfer contact.

Heat is transferred from the radiation shield to the generator hot frame by radiation and conduction through the air gap (Figure 1). The air gap isolates the generator assembly from the shield - minimizing direct transmission of shock and vibration to the thermoelectric legs, eliminating movements of the legs due to pressure vessel deflection, improving generator reliability because the hot and cold frames cannot shift with respect to each other except through differential expansion, and preventing possible eutectic formations between the radiation shield and the generator components.

Boron nitride, which has a low coefficient of expansion, comprises the hot-side electrical insulation disc between the hot frame and hot-junction electrodes.

Forty-eight thermoelectric couples are series connected through the hot- and cold-junction electrodes. The ball-type cold-junction electrodes are connected

by soft-soldered copper wire, and will not fracture and break electrical contact under unusual shock conditions. MIN-K 1301 provides thermal insulation around the thermoelectric couples.

Hardcoated aluminum followers and stainless-steel positioning springs, arranged between the cold-junction electrodes and the cold frame, maintain pressure contact between the hot-junction electrodes and the hot frame.

Several design iterations have been required to develop legs which provide maximum efficiency within the temperature limits of the leg materials and the environmental constraints imposed on the generator. The current leg design (Section 1.0), which accounts for Thompson heating terms and a 10-percent extraneous electrical loss in the generator, has the following characteristics:

- 1) N- and P-legs of different lengths but equal diameters.
- 2) N-legs of PbTe, with the hot end doped to a different level than the cold end.
- 3) P-legs with a hot end of PbSnTe and a cold end of BiSbTe.
- 4) Leg segments powder pressed simultaneously and joined so that the leg lengths correspond to the optimal operating temperature for the leg materials.

These design features provide maximum efficiency over the selected operating temperature range, which extends from a 115°F cold-junction electrode temperature to an 1100°F hot-junction electrode temperature. The present P-leg design has a materials efficiency of 10.6 percent and the N-leg an efficiency of 11.7 percent. Forty-eight couples, instead of the original 42, increase over-all system efficiency by providing higher voltage output from the generator to the dc-dc converter.

Power Conditioner (Section 5.0)

In designing the power conditioner, the objectives were to develop a unit that would: (1) convert the 5.1-volt dc thermopile output to 24-volts dc with a maximum ripple of 0.1 volt (peak-to-peak), and with a system load of 57.6 ohms; (2) operate at a minimum efficiency of 85 percent at the rated EOL output; and (3) have a 5-year operating life at an ambient, system operating temperature of $40^{\circ} \pm 5^{\circ}\text{F}$, and at a storage temperature range of -65° to 150°F .

The power conditioner (Figure 1) consists of three major components: a dc-dc converter, a voltage regulator, and an aluminum case and cover.

The converter (see Section 5.0) has been designed to operate from a three-terminal thermopile. The third terminal provides starting and operating bias to the converter, and eliminates the need for a resistive divider or a separate drive oscillator to obtain the bias voltage. This design feature and the over-all simplicity of the converter have resulted in measured conversion efficiencies of 88 to 89 percent.

Because packaged, commercial voltage regulators have been tested with inconsistent results, a 3M-built regulator is being used. This unit, which is made from components with known reliability characteristics, provides more room for the component leads and uses silicon planar-zener diodes. Operating efficiency has been greater than 99 percent.

The power conditioner case maintains the gas-filled atmosphere in which the conditioner operates, serves as a stable mounting for the conditioner within the pressure vessel (Figure 1), and provides an excellent heat-flow path from the converter components to the pressure vessel wall.

Pressure Vessel (Section 2.0)

The pressure vessel has been designed to: (1) contain the power-supply system under all operating conditions for a minimum period of 5 years; (2) not

leak during placement and operation; (3) have provision for external instrumentation and power leads; and (4) withstand all specified temperature, shock, vibration, corrosion, and pressure conditions, including a relative humidity of 100 percent in a salt atmosphere, and an ambient seawater pressure of up to 10,000 psi.

The major pressure-vessel components are illustrated in Figure 1:

- A lower cylinder which houses the fuel capsule, radiation shield, insulation system, and thermoelectric generator.
- An upper hemisphere which houses the power conditioner.
- Double O-ring seals for joining the cylinder and hemisphere.
- An electrical feed-through fitting for power leads and external instrumentation.

The pressure vessel and feed-through fitting are made of titanium 721 alloy, which has a high strength-to-weight ratio, high resistance to saltwater corrosion, minimum brittleness in thick sections, and is readily forged and machined using standard processing procedures.

The geometric configuration of the cylinder and hemisphere eliminates the need for internal stiffeners, and provides a minimum moment at the sealing joint to protect the vessel sealing mechanism.

The power conditioner mounting in the upper hemisphere (Figure 1) provides a heat sink that is remote from the generator heat sink, and which maintains the electronic components at reliable operating temperatures. The mounting also allows easy access to the power conditioner during assembly and servicing. The mechanical test summary for the pressure vessel is presented in Appendix B.

System Test (Section 8. 0)

The objectives of the SNAP-21B-1 system test are to obtain performance data on the various system components, and to verify the system's ability to provide a continuous 10-watt, 24-volt dc output from BOL through EOL conditions.

In the test setup (see Section 8. 0), a stainless-steel cartridge - heater block assembly simulates the fuel capsule and the U-8% Mo shield plug; a stainless-steel shield simulates the U-8% Mo shield.

Insulation System I (with the lower support tube and modified upper bellows) is being used. However, the super-insulation system is being continuously evacuated with a pump to maintain the desired low-pressure vacuum.

The prototype thermoelectric generator demonstrated over 1400 hours of stable bench-test performance prior to being installed in the test system. Similarly, the prototype power conditioner exhibited over 800 hours of trouble-free performance on bench test.

The cast, stainless-steel pressure vessel conforms closely to the final titanium model, and a 2-foot-long stainless-steel tube provides electrical instrumentation access to the pressure vessel and other system components. The auxiliary system equipment is described in Section 7. 0.

A thermally insulated steel tank, containing 185 gallons of refrigerated water, provides a cooling system and maintains the ambient water temperature at 40°F.

On April 29, 1965, electrical heater power was first supplied to the system. On May 25 the 1100°F hot-junction electrode temperature was established, the system test circuit activated, and the power conditioner loaded to 24-volts dc. During the next 1000 hours of operation, the system input power was reduced, in steps, by the same fractions that Sr-90 would exhibit at the end

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of 1, 2, 3, 4, and 5-year periods. In this way data was obtained on the BOL, intermediate, and EOL performance characteristics of the system and its components.

At the 3500-hour mark, the system input power was returned to the BOL level, where it remained until April 29, 1966 - one year from the start of system testing. The test data included in this report extend through June of 1966.

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1.0 SNAP-21B THERMOELECTRIC GENERATOR

1.1 PROGRAM OBJECTIVES

The Phase I objectives of the SNAP-21B Program were to design, develop, and fabricate a thermoelectric generator which could:

- Provide a continuous, net system output of 10 watts at 24-volts dc for a minimum period of 5 years.
- Be removed from the power-supply system and replaced without hot-cell facilities and with a minimum of special equipment.
- Have a thermoelectric-leg subsystem efficiency of at least 10 percent when integrated into the generator.
- Withstand the specified environmental conditions (see the Introduction).

1.2 PROGRAM ACCOMPLISHMENTS

The following accomplishments have been made during Phase I of the SNAP-21B Program:

- A thermoelectric generator capable of at least a 10-watt, 24-volt dc output for a minimum period of 5 years has been designed, fabricated, and put on test.
- The generator has been designed for removal and replacement in the power-supply system without hot-cell facilities and with a minimum of special equipment.
- Three thermoelectric-generator modules and five prototype generators are continuing to perform well in laboratory life tests after as much as 10,000 hours of continuous operation.
- A laboratory environment simulating the specified ambient water temperatures (see the Introduction) has been designed and built. One of the prototype generators has been operating satisfactorily in the system test environment for more than 8,000 hours and has successfully completed a simulated 5-year mission.

1.3 THERMOELECTRIC LEGS

1.3.1 Basic Design Factors

In the current design of the SNAP-21B thermoelectric generator, segmented thermoelectric couples are operated in series to provide the required power, voltage, and current at the load (see Appendix A). Initial couple designs used N- and P-legs with identical diameters and lengths. However, a more optimum couple design has been obtained by adjusting the length-to-area ratios (L/A) of the legs so that optimum current is simultaneously provided to both legs. The desired L/A can be conveniently achieved by making the N- and P-legs with different diameters and equal lengths or equal diameters and different lengths. In the later SNAP-21B designs (Table 1-1), the N- and P-elements have equal diameters and different lengths.

Temperature operating points for thermoelectric couples are selected primarily on the basis of: (1) The temperature limits of the thermoelectric materials, and (2) the environmental constraints imposed upon the generator. A BOL hot-electrode temperature of 1100° F and a cold-electrode temperature of 115° F were selected for the SNAP-21B generator.

After the generator design constraints were defined, thermoelectric materials with maximum efficiency over the selected temperature range were chosen. The following discussion illustrates the rationale behind the materials selection process. For a detailed discussion of how the SNAP-21B thermoelectric materials have been evaluated and selected, see References 1 to 6.

The efficiency (η) of a thermoelectric material is determined by three fundamental thermoelectric properties:

$$S = \text{Seebeck coefficient, where } S = \frac{\Delta E \text{ (volts)}}{\Delta T \text{ (° F)}}$$

Table 1-1. Thermoelectric Leg Specifications for the Six-Couple Modules and Prototype Generators

Leg	Module 3M-37-A1	Module 3M-37-A2	Module 3M-37-A3	Module 3M-37-A4	Prototype 3M-37-P1	Prototype 3M-37-P2	Prototype 3M-37-P3	Prototype 3M-37-P4	Prototype 3M-37-P5	Prototype 3M-37-P6	Prototype 3M-37-P7
P-LEG SIZE	0.188 in. dia. 0.578 in. lg.	0.188 in. dia. 0.578 in. lg.	0.188 in. dia. 0.578 in. lg.	0.188 in. dia. 0.446 in. lg.	0.188 in. dia. 0.446 in. lg.	0.188 in. dia. 0.446 in. lg.	0.188 in. dia. 0.446 in. lg.	0.188 in. dia. 0.446 in. lg.	0.188 in. dia. 0.446 in. lg.	0.188 in. dia. 0.411 in. lg.	0.188 in. dia. 0.411 in. lg.
MATERIAL:											
HOT SEGMENT	M-74 0.197	M-76 0.197	M-15 0.197	M-15 0.243	M-15 0.243	M-15 0.243	M-76 0.243	M-15 0.243	M-15 0.243	M-76 0.267	M-76 0.267
COLD SEGMENT	M-29 0.381	M-29 0.381	M-29 0.381	M-29 0.203	M-29 0.203	M-29 0.203	M-29 0.203	M-29 0.203	M-29 0.203	M-29 0.144	M-29 0.144
MANUFACTURING METHOD	Segments Simul. Powder Pressed	Segments Simul. Powder Pressed	Segments Individ. Powder Pressed Then Bonded	Segments Individ. Powder Pressed Then Bonded	Segments Individ. Powder Pressed Then Bonded	Segments Individ. Powder Pressed Then Bonded	Segments Simul. Powder Pressed	Segments Individ. Powder Pressed Then Bonded	Segments Individ. Powder Pressed Then Bonded	Segments Simul. Powder Pressed	Segments Simul. Powder Pressed
N-LEG SIZE	0.188 in. dia. 0.578 in. lg.	0.188 in. dia. 0.578 in. lg.	0.188 in. dia. 0.578 in. lg.	0.188 in. dia. 0.600 in. lg.	0.188 in. dia. 0.600 in. lg.	0.188 in. dia. 0.600 in. lg.	0.188 in. dia. 0.600 in. lg.	0.188 in. dia. 0.600 in. lg.	0.188 in. dia. 0.600 in. lg.	0.188 in. dia. 0.571 in. lg.	0.188 in. dia. 0.571 in. lg.
MATERIAL:											
HOT SEGMENT	M-10 0.356	M-10 0.356	M-10 0.356	M-10 0.368	M-10 0.368	M-10 0.368	M-10 0.368	M-10 0.368	M-10 0.368	M-10 0.371	M-10 0.371
COLD SEGMENT	M-13 0.222	M-13 0.222	M-13 0.222	M-13 0.232	M-13 0.232	M-13 0.232	M-13 0.232	M-13 0.232	M-13 0.232	M-13 0.200	M-13 0.200
MANUFACTURING METHOD	Segments Simul. Powder Pressed	Segments Simul. Powder Pressed	Segments Simul. Powder Pressed	Segments Simul. Powder Pressed	Segments Simul. Powder Pressed	Segments Simul. Powder Pressed	Segments Simul. Powder Pressed	Segments Simul. Powder Pressed	Segments Simul. Powder Pressed	Segments Simul. Powder Pressed	Segments Simul. Powder Pressed

ρ = resistivity, in micro-ohm inches

K = thermal conductivity, in watts/in. -hr-° F.

For a single material a fourth, derived parameter, the figure of merit (Z) is related to the three basic properties by

$$Z = \frac{S^2}{K\rho} .$$

In turn, the efficiency of the thermoelectric material is related to Z by

$$\eta = \frac{\Delta T \left[1 + Z \left(\frac{T_2 + T_1}{2} \right) \right]^{1/2} - 1}{T \left[1 + Z \left(\frac{T_2 + T_1}{2} \right) \right]^{1/2} + \frac{T_1}{T_2}}$$

where for a single couple,

$$Z = \frac{(S_P - S_N)^2}{\left[(K_N \rho_N)^{1/2} + (K_P \rho_P)^{1/2} \right]^2}$$

and where N and P refer to the thermoelectric properties of the N- and P-materials, respectively. Thus, for maximum material efficiency the average

value of $Z \frac{T_2 + T_1}{2}$ must be made as large as possible.

As Figures 1-1 and 1-2 indicate, Z and the thermoelectric properties S , ρ , and K are temperature dependent, such that the maximum Z value for any given material occurs only at one particular temperature. In the ideal case, maximum efficiency over an entire temperature gradient could be achieved by forming each thermoelectric leg from an infinite number of segments, so that the maximum possible Z value would occur at each point in the leg. The performance of this ideal thermoelectric leg would be approximated by the envelope of figure-of-merit curves whose maximum values are depicted by the dotted curve in Figure 1-1.

In the practical case, as much as 95 percent of the maximum material efficiency can be realized by forming each thermoelectric leg from two homogeneous segments that differ in doping level or composition. The lengths of the two segments are usually chosen to obtain optimum leg efficiency for a given hot-junction temperature, cold-junction temperature, and current. However, if the intersegment temperature at the optimum leg performance level exceeds the maximum safe-operating temperature, greater leg reliability at only a slight loss in efficiency can be achieved by shortening the cold-end segment and lengthening the hot-end segment.

For example, all N-type elements in the SNAP-21B thermoelectric modules and prototypes (Table 1-1) have been formed from differently doped segments of PbTe, the hot segment consisting of M10 material and the cold segment of M13. Figure 1-1 shows that the M10-M13 leg gives a higher figure-of-merit over a wider temperature range than the originally proposed, non-segmented M11 leg. The superior Z values are particularly apparent in the 5-year operating temperature ranges of the SNAP-21B generator, which are 115° to 165° F at the cold-junction and 1100° to 990° F at the hot-junction. Similarly, all the P-type elements (Table 1-1) have been formed from segments with different compositions. Figure 1-2 indicates that the M29-M15 leg produces a much higher figure of merit over the generator operating temperature than a non-segmented M29 or M15 leg. The primary difference between

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Figure 1-1. Figure of Merit vs. Temperature for N-Type Material (PbTe)

Figure 1-2. Figure of Merit vs. Temperature for P-Type Material

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the M29-M15 and M76-M15 combinations used in the final prototype designs (Table 1-1) is in the method of manufacture. Both legs have nearly the same thermoelectric characteristics.

1.3.2 Design Development

The initial thermoelectric generator design, as proposed, consisted of a 42-couple generator with segmented P-type and non-segmented N-type thermoelectric legs. Generator efficiency was calculated to be 10.2 percent, with the generator defined as the series connection of thermoelectric legs, hot-end electrodes, and output wires. The proposed generator design was re-evaluated on the basis of a more accurate materials measurement and found to have a lower generator efficiency than originally calculated.

An attempt was made to increase thermoelectric leg efficiency by also segmenting the N-type leg as discussed in Section 1.3.1. A new 48-couple-module thermoelectric generator was designed with the P- and N-legs segmented, resulting in a calculated efficiency of 9.49 percent. The efficiency change of approximately -0.7 percent represented the combination of a new materials measurement (negative effect), segmenting of the N-type leg (positive effect), and increased electrode losses (negative effect). The difference between the original and revised design represented an effort to regain total system efficiency by providing higher voltage output from the generator to the dc-dc converter. A summary of the initial and revised designs is shown in Table 1-2 and the test results for the first single-couple designs are shown in Table 1-3.

The single-couple tests showed that the power output from Designs 1 and 2 was 15 to 20 percent lower than expected. The power was low due to a higher than expected resistance associated with the P-leg. Possibilities for the high P-leg resistance were:

- 1) Oxidation of the hot-end pressure contact
- 2) High resistivity in the P-leg material
- 3) Fabrication problems when P-leg segmented units were powder-pressed simultaneously.

Table 1-2. Thermoelectric Couple Design Dimensions

Type Design	Type Leg	Dia. (In.)	Area (In. ²)	Length (In.)	LE/L	L/A
1. 42-Couple Design	N	3/16	0.0276	0.470	0.471	17.02
	P	3/16	0.0276	0.388	0.581	14.06
2. 48-Couple Initial Design	N	3/16	0.0276	0.578	0.384	20.94
	P	3/16	0.0276	0.578	0.659	20.95
3. 48-Couple Design "A"	P	3/16	0.0276	0.446	0.455	16.15
	N	3/16	0.0276	0.600	0.386	21.73
4. 48-Couple Design "B"	P	3/16	0.0276	0.411	0.350	14.89
	N	3/16	0.0276	0.571	0.350	20.68

To control Items 2 and 3, the P-leg segments were pressed separately, then joined with a metallic intersegmental disc. Tests indicated that this fabrication method did not completely eliminate the power problem. Further investigation showed that a computer analysis used to determine leg dimensions was not properly programmed and that improper material properties input cards were used for the P-leg.

On the basis of the above factors, the thermoelectric couple was redesigned and one N-type and two P-type materials were selected for extended testing. The materials selected are listed in Table 1-4 and the resultant geometrical dimensions are given in Design "A" of Table 1-2.

Table 1-3. Test Results for Single Thermoelectric Couples Using Designs 1 and 2

Type Design	Type Leg	Couple Number	T_h	T_c	E_o	R_i	P_o
1. Measured	N	3	950	105	103.7	0.0162	0.161
Calculated			950	100	109.6	0.0172	0.175
1. Measured	P	3	950	111	80.7	0.169	0.095
Calculated			950	110	82.6	0.0104	0.164
2. Measured	N	1	955	100	103.0	0.0173	0.153
Calculated			950	100	105.7	0.0185	0.144
2. Measured	P	1	955	95	82.7	0.0215	0.076
Calculated			950	100	82.7	0.0151	0.114

T_h = Hot electrode temperature, °F

T_c = Cold electrode temperature, °F

E_o = Open EMF, millivolts

R_i = Internal resistance, milliohms

P_o = Power output, watts

Table 1-4. Thermoelectric Materials for Couple Design "A"

Location	N-Type	P-Type 1*	P-Type 2**
Hot Segment	M10, PbTe	M15, (PbSn)Te	M76 (PbSn)Te
Cold Segment	M13, PbTe	M29, (BiSb) ₂ Te ₃	M29 (BiSb) ₂ Te ₃

*Individually pressed and bonded

**Simultaneously pressed

Advances in thermoelectric computer technology revealed a need to include Thomson heating terms in performance analyses of the thermoelectric legs. Design "A" was therefore re-evaluated using advanced techniques.

A comparative analysis of Designs "A" and "B" is presented in Table 1-5. In addition to accounting for Thomson heating effects, Design "B" includes a 10-percent (instead of 5-percent) extraneous electrical loss in the generator, and incorporates a lower segmenting temperature for the P-leg. Table 1-5 shows that Design "A" results in an EOL efficiency of 10.00 percent compared to 10.58 percent for Design "B".

Figure 1-3 and Table 1-2 list the dimensions for Designs "A" and "B". Elements of Design "A" were used in six-couple module 3M-37-A4 and prototypes 3M-37-P1 through -P5; elements of Design "B" were used in prototypes 3M-37-P6 and -P7 (see Table 1-1).

1.4 SIX-COUPLE MODULES

1.4.1 Design

A six-couple test module was designed to aid in establishing the short- and long-term performance characteristics of the thermoelectric materials and designs. It was expected that the data obtained from this type of module would be used to determine the final design of the thermoelectric generator used in the Phase I prototype system.

A cut-away sectional schematic of the six-couple test module and its associated instrumentation is shown in Figure 1-4. Figure 1-5 indicates the location of the thermocouple temperature sensors, while Figure 1-6 shows the electrical circuitry. Figures 1-7 through 1-11 illustrate the various module components.

Four six-couple modules, 3M-37-A1 through -A4, were built and put on test. The physical and chemical characteristics of the thermoelectric elements used in these modules are listed in Table 1-1.

Table 1-5. Comparative Analysis of Two 10-Watt, 24-Volt-DC Thermoelectric Generators Using Leg Designs "A" and "B"

		Design "A"	Design "B"
T_{hBOL}	$^{\circ}F$	1100	1100
T_{hEOL}	$^{\circ}F$	950	950
T_{cBOL}	$^{\circ}F$	120	120
T_{cEOL}	$^{\circ}F$	100	100
T_{SNBOL}	$^{\circ}F$	472	439
T_{SNEOL}	$^{\circ}F$	400	376
T_{SPBOL}	$^{\circ}F$	629	557
T_{SPEOL}	$^{\circ}F$	550	476
N	No. of Couples	48	48
$(L_c/L)_N$		0.383	0.350
$(L_c/L)_P$		0.455	0.350
$(L/A)_N$		21.73	20.7
$(L/A)_P$		16.15	14.9
D	Inch	0.1875	0.1875
L_N	Inch	0.600	0.571
L_{CN}	Inch	0.230	0.200
L_P	Inch	0.446	0.411
L_{CP}	Inch	0.203	0.144
Q_{SBOL}	Watts	138.6	142
Q_{SEOL}	Watts	124.3	125
$\eta_{TE_{EOL}}$	%	10.00	10.58

Figure 1-3. Dimensions for Thermoelectric Leg Designs "A" and "B"

Figure 1-4. Six-Couple Test Module

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Figure 1-5. Six-Couple Module Instrumentation

Figure 1-6. Six-Couple Module External Electrical Circuit

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Figure 1-7. Six-Couple Test Module Components

Figure 1-8. Basic Six-Couple Module Assembly Components

Figure 1-9. Six-Couple Module Assembly Less the Case

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Figure 1-10. Typical Thermoelectric Couple Assembly

Figure 1-11. Typical P-Leg Assembly

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1.4.2 Testing

Six-couple modules 3M-37-A1, -A3 and -A4 are continuing on test at the present time. Testing of module 3M-37-A2 was terminated after 4,560 hours due to a sudden, catastrophic degradation in performance. It was strongly suspected that an external temperature perturbation was responsible for the ultimate failure of this module, rather than a degradation of the thermoelectric elements. A careful analysis of the data from this module shows that a severe overheating, caused by a change of the input-power measuring equipment, could have taken place.

Performance curves of the four modules are shown in Figures 1-12 through 1-15, which indicate that modules A1, A3, and A4 are continuing to operate satisfactorily after 15,000, 14,000, and 13,000 hours of testing, respectively, and that module A2 performed well until it was overheated. The raw performance data is listed in Reference 7.

1.5 PROTOTYPE GENERATORS

1.5.1 Components

The layout for the SNAP-21B prototype generators is shown in Figure 1-16. The thermoelectric generator case connects the hot frame to the cold frame as a structural member and maintains a hermetic seal for the thermoelectric subassembly. The design criteria established for this component are to: 1) maintain a hermetic seal, 2) provide structural strength, and 3) minimize extraneous heat losses.

On the basis of its high temperature strength and low thermal conductivity, 347 stainless steel was selected as the case material. Heat losses through the generator case could be reduced by decreasing the wall thickness. It was determined that fabrication technique restrictions and allowable stresses would permit a minimum wall thickness of 0.005 inch.

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Figure 1-12. Performance of Six-Couple Module 3M-37-A1 (input power reduced at 10,536 hours)

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Figure 1-13. Performance of Six-Couple Module 3M-37-A2
 $(T_h = 1100^\circ \pm 10^\circ\text{F}; T_c = 115^\circ \pm 5^\circ\text{F})$

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Figure 1-14. Performance of Six-Couple Module 3M-37-A3
(input power reduced at 8496 hours)

Figure 1-15. Performance of Six-Couple Module 3M-37-A4 (input power reduced at 9360 hours)

Figure 1-16. Prototype 48-Couple Thermoelectric Generator Assembly

It was first believed that electron-beam (EB) welding could be used to seal the generators. To determine whether EB welding would be feasible, three non-operating generators were made and successfully welded. However, when actual prototype generators were EB welded they failed to seal. EB welding appeared to be inadequate; thus, the generator case was redesigned using tungsten in gas (TIG) welding and silver brazing as the closing technique. The case was designed for two parts, with the final closure being a TIG weld at the case mating joint. Three sample cases were made and test welded at this joint. Three additional cases were made to fabricate complete experimental enclosures. Welding of these units revealed a buckling problem at the case mating joint as shown in Figure 1-17. This problem was solved by providing a mechanical backup ring to resist deformation. The reinforced case design was applied to the final three prototype generators, all of which were fabricated with complete success. The two prototypes that failed to seal with EB welding were O-ring sealed. Figure 1-18 shows the sealing mechanism.

Because of its low coefficient of expansion, boron nitride was selected for the hot-side electrical insulation disc between the hot electrodes and the hot frame (Figure 1-16). Tellurium copper was chosen for the cold frame because the cold frame was to be welded to the case rather than silver brazed. Thermal insulation chosen for the generators was Min-K 1301. Case interiors were to be evacuated and backfilled with xenon gas. First generator designs called for 48 thermoelectric couples, series connected through the hot-junction electrodes and ball-type, copper cold-end electrodes with 20-gauge silver leads between couples. A spring-follower arrangement between the cold electrodes and cold frame provided force to maintain pressure contacts at the hot frame and at the hot-junction of the thermoelectric legs. The first thermoelectric generator constructed is shown in Figure 1-19, with a mounting frame and electrical heater for laboratory testing.

1.5.2 Assembly

A fixture was designed to assemble the generator and to hold the unit while the case was welded to the hot and cold frames. Two other fixtures were

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Figure 1-17. Welded Experimental Generator Cases

designed and fabricated to aid in generator assembly. During assembly the fixture (Figures 1-20 and 1-21) maintains the relative position of the hot and cold frames while the thermoelectric legs are installed. The fixture is then used to compress the thermoelectric leg subassembly. After compression, the fixture holds the partially assembled generator while electrical connections are being completed, thermal insulation is packed into place, and the generator case is fitted into position. During welding, the fixture is connected to an external drive system which rotates the generator under the welding beam.

A compression yoke (Figure 1-22) is installed on the generator while the generator is in the assembly fixture. This yoke holds the generator in compression for handling, shipping, and removal from the assembly fixture prior to welding. The case sleeve (Figure 1-23) fits over the exterior of the generator case during vacuum processing to prevent collapse of the case.

Figure 1-18. Generator O-Ring Installation

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Figure 1-19. Exterior View of Initial Prototype Generator

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Figure 1-20. Thermoelectric Generator Assembly Fixture

Figure 1-21. Assembly Fixture with Welded Generator in Place

Figure 1-22. Thermoelectric Generator with Compression Yoke

Figure 1-23. Sleeve Assembly for Generator Case

To prepare the copper cold frame for TIG welding to the case, a short section of the generator case is silver brazed to the cold frame. This brazing is done in a controlled hydrogen-atmosphere furnace at 1450° F.

The thermoelectric generator is assembled with the use of the assembly and welding fixture. The hot and cold frames are attached to the fixture. The fixture is then adjusted so that the hot and cold frames are separated a prescribed distance. At this distance the leg compression springs exert just enough pressure to hold the thermoelectric couples in position. The generator is assembled by installing one thermocouple at a time, starting from the center of the generator and working out to the periphery. When all the thermocouples are in place, the subassembly is compressed by moving the hot and cold frames together. Electrical connections are then made to feed-through terminals in the cold frame. Thermal insulation is then packed around the thermoelectric legs and surrounding void spaces.

The generator case is then slipped into position over the hot and cold frames. At this point, preliminary assembly is complete and the compression yoke is attached to the assembled generator so the unit may be removed from the assembly fixture.

For welding, the assembly fixture is mounted in a controlled atmosphere welder. The generator assembly (with yoke) is replaced in the fixture and the compression yoke is removed. The case is then joined to the hot frame and to the small section that is prebrazed to the cold frame.

The welded generator is then removed from the fixture. The case sleeve is installed and the generator is leak checked to determine if a hermetic seal has been established. The generator is then processed, evacuated, backfilled with xenon gas, and sealed.

1. 5. 3 Testing

Seven 48-couple prototype thermoelectric generators, 3M-37-P1 through -P7, were built; however, only five were put on test. Severe electrical shorting within prototype P1 caused it to be scrapped, and EB welding difficulties with P2 caused it to be disassembled. The thermoelectric subassembly of P2 was subsequently used in P5. EB welding difficulties with P3 and P4 were resolved by using an O-ring to establish the necessary hermetic seal. P5, P6, and P7 were all successfully sealed using the TIG welding - silver brazing technique described in Section 1. 5. 2.

The physical and chemical characteristics of the thermoelectric elements used in the prototype generators are listed in Table 1-1. Prototypes P3, P5, P6, and P7 are continuing on bench tests at the present time. The bench test of P4 was terminated after 1416 hours to make this generator available for use in the SNAP-21B-1 system. Since being installed, generator P4 has accumulated an additional 9000 hours of testing.

Normalized performance data for the four prototypes continuing on bench test are shown in Figures 1-24 through 1-27. The raw performance data are listed in Reference 7. The results show that the prototypes are relatively stable and are operating satisfactorily despite a gradual rise in cold electrode temperature. The gradual decrease in output power for those prototypes (not shown in the normalized data) has primarily been caused by the rising cold-electrode temperatures, although a small portion of the decrease has been caused by other factors. Test data from the six-couple modules shows that the thermoelectric devices on test for this program appear to go through a 2000- to 4000-hour settling out period.

Since prototypes P6 and P7 represent the final Phase-I design effort it is of interest to note the performance of these generators. If the measured EOL

Figure 1-24. Performance of Prototype 48-Couple Generator 3M-37-P3
(E = voltage, R = resistance, P = power, x = experimental,
c = computer)

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Figure 1-25. Performance of Prototype 48-Couple Generator 3M-37-P5
(E = voltage, R = resistance, P = power, x = experimental,
c = computer)

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Figure 1-26. Performance of Prototype 48-Couple Generator 3M-37-P6
(E = voltage, R = resistance, P = power, x = experimental,
c = computer)

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Figure 1-27. Performance of Prototype 48-Couple Generator 3M-37-P7
(E = voltage, R = resistance, P = power, x = experimental, c = computer)

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temperatures of $T_h = 990^\circ \text{F}$ and $T_c = 165^\circ \text{F}$ were imposed upon these generators, and if they continued to operate at their present level of performance, they would deliver about 9.8 and 9.3 watts of power, respectively. This, of course, is substantially less than required for EOL conditions. However, if the cold electrode temperature can be reduced to about 125°F , the two generators should deliver about 11.0 and 10.4 watts of power, respectively. With a conversion efficiency of 90 percent in the power conditioner, these generators would very nearly deliver the required 10-watt power output. It is thus apparent that the cold-end heat transfer mechanism must be improved. This problem is slated for examination in Phase II.

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1.6 REFERENCES

1. Report No. NYOO(3321)-3. SNAP-21B Program Quarterly Report No. 1 (9 March to 30 June 1964). AEC Contract AT (30-1)3321 (August 1964).
2. --- MMM(3321)-7. --- No. 2. (1 July to 30 September 1964).
--- (October 1964).
3. --- MMM(3321)-11. --- No. 3. (1 October to 31 December 1964).
--- (January 1964).
4. --- MMM(3321)-13. --- Bimonthly Report (1 January to 28 February 1965).
--- (March 1965).
5. --- MMM(3321)-14. --- Monthly Report No. 8 (March 1965).
--- (April 1965).
6. --- MMM(3321)-15. --- Monthly Report (1 April to 30 April 1965).
--- (May 1965).
7. SNAP-21B Test Summary Letter No. 19, 3M Isotope Power Laboratory. AEC Contract AT (30-1)3321 (9 May 1966).

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2.0 SNAP-21B PRESSURE VESSEL

2.1 PROGRAM OBJECTIVES

The program objectives are to design and fabricate a pressure vessel which will:

- Completely contain the system under operating conditions for a minimum five-year period at pressures up to 10,000 psi.
- Withstand environmental corrosive conditions and incur no leakage during corrosive conditions or during placement and design-life operation.
- Have provision for external instrumentation and power leads.
- Withstand the conditions specified in the Introduction, including mechanical vibrations of 5 to 32 cps, having an excursion within 0.054 to 0.066 inch or an excursion producing 3 g's.

2.2 PROGRAM ACCOMPLISHMENTS

The following program accomplishments were achieved during Phase I:

- The prototype pressure vessel design was completed.
- Fabrication procedures, vendor qualifications, material suppliers, and quality requirements were established.
- A 1/4-scale titanium pressure-vessel model was fabricated and tested to destruction to validate the empirical design.
- One full-scale, prototype, titanium pressure vessel was forged and sectioned for mechanical testing.
- A second full-scale prototype was fabricated and tested to the 10,000-psi requirement.
- A full-scale stainless-steel pressure vessel was fabricated for system integration and thermal analysis testing.

2.3 PRESSURE VESSEL DESIGN

After early preliminary discussion with David Taylor Model Basin personnel, titanium alloy 721 (7Al, 2Cb, 1Ta) was selected as the most desirable material for constructing the pressure vessel. Alloy 721 has good welding properties, high strength, acceptable stress corrosion characteristics, and brittleness does not occur in thick sections (one inch or over) as it does in other titanium alloys.

Design criteria based on the physical properties of 721 titanium were established as follows:

- 1) Vessel to be operated at 10,000 psi
- 2) Cylinder interior to be smooth (no stiffeners)
- 3) Minimum moment at the seal joint to protect the seal mechanism
- 4) Safety factor of 1.5
- 5) Inclusion of a suitable penetration for an electrical lead-through in one hemisphere.

The most difficult vessel to design for high external pressures is a cylinder with semi-infinite length. The ratio of the actual elastic buckling pressure (P_E) to the theoretical collapse pressure (P_T) approaches unity as the ratio of vessel length to diameter increases. Stiffeners are then used to introduce safety factors and to increase operating pressures while maintaining light weight.

The preliminary cylindrical length dimension of the SNAP-21B pressure vessel was approximately 12 inches - short enough to use a smooth cylinder with ample safety. Since the safety factor could be applied to the smooth cylindrical section without stiffeners, the balance of the design was accomplished in the following manner:

- 1) Align the geometric center lines of the hemispheres with those of the cylinder to eliminate bending moments at the seal joint.
- 2) Equate stresses and moments at the penetration so that the hemisphere will respond as if no penetration exists.
- 3) Calculate all dimensions using the following empirical and theoretical approaches:

Cylinder

- (a) Determine $\frac{P_E \text{ (elastic buckling pressure)}}{P_{THEO} \text{ (theoretical collapse pressure)}}$

from the empirical curve of $\frac{P_E}{P_{THEO}}$ versus

$\frac{L \text{ (length of cylinder)}}{D \text{ (diameter of cylinder)}}$. In this case, P_E/P_{THEO} was selected as 2 to provide additional cylinder safety (recommended since no empirical data was available on cylinders of this particular size).

- (b) Calculate P_{THEO} (Ref. 1) and determine P_E :

$$P_{THEO} = \frac{2 E}{1 - \mu^2} \frac{(t)}{(D_o)} \frac{(t)^2}{(D)} \quad (1)$$

where:

- E = Young's modulus
 μ = Poisson's ratio
 t = Cylinder thickness
 D_o = Outside diameter
 D = Mean diameter.

Since P_{THEO} , t , D_o , and D are unknown, cycling solutions are required using the criterion that P_{THEO} must be greater than 15,000 psi (10,000 psi operating pressure times 1.5 safety factor) and that the inside diameter of the vessel is fixed. In addition, the solution for P_{THEO} and cylinder thickness (t) must be compatible with the hemisphere design in order to maintain geometric centerlines for zero bending moments at the vessel seal. Values obtained in this calculation must also agree with steps (c) and (d) below in determining the actual collapse pressure.

P_{THEO} for the preliminary SNAP-21B pressure vessel was calculated to be 18,675 psi; therefore P_E , from (a), is 37,350 psi.

- (c) By assuming that the plastic buckling strength of a semi-infinite cylinder is analogous to the plastic buckling strength of a column, the plastic collapse pressure P_t is (Ref. 2):

$$P_t = \frac{E_t}{E} P_E \quad (2)$$

where:

E = Young's Modulus

E_t = Tangent modulus at the critical stress level

P_E = Elastic buckling pressure.

This equation is a conservative approximation of Gerard (Ref. 3) who includes the second modulus in determining plastic collapse pressure:

$$P_t = \frac{E_t}{E} P_E - P_t = \frac{E_s E_t}{E} P_s + \frac{E_T}{E} P_t \quad (3)$$

As Figure 2-1 illustrates, determination of P_t accounts for modulus reduction when the vessel material exceeds its proportional limit under P_E .

- (d) If the Hencky-Von Mises yield criterion (Ref. 2) is assumed to apply in the plastic range, the actual plastic collapse pressure can be determined, as in Figure 2-1, by plotting P_t (Equation 2) as a function of P_E versus the Hencky-Von Mises stress intensity:

$$\sigma_i = \left[\sigma_\phi^2 + \sigma_x^2 - \sigma_\phi \sigma_x \right]^{1/2} \quad (4)$$

where:

σ_i = Hencky-Von Mises stress intensity

σ_ϕ = pR_o/h = circumferential stress

σ_x = $pR_o/2h$ = longitudinal stress

p = applied pressure = 15,000 psi

R_o = outside radius

h = shell thickness.

Solving for σ_i ,

$$\sigma_i = \sqrt{\frac{3}{2}} \frac{R_o}{h} p \quad (5)$$

which is a straight-line curve for any given vessel and is a function of p only.

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Figure 2-1. Graphical Determination of the Actual Pressure-Vessel Collapse Pressure

- (e) By redundant calculations of Equations (1), (2), and (4), cylinder thickness was optimized at 0.998 inch for the preliminary vessel. This resulted in an actual collapse pressure of 15,300 psi giving a cylinder efficiency of 98 percent:

$$100 \frac{P_{\text{Design}}}{P_t} \text{ percent eff.} = \frac{15,000 \text{ psi}}{15,300 \text{ psi}} 100 = 98 \text{ percent.} \quad (6)$$

By using different titanium alloys, the cylinder efficiency is reduced due to the values of E_t .

Hemispheres

- (a) By employing an empirical equation for titanium (Ref. 2), the elastic buckling pressure P_E is determined by

$$P_E = 0.84 E \frac{(h)^2}{(R_o)} \quad (7)$$

where:

h = hemisphere thickness

R_o = hemisphere outside radius.

P_E for the preliminary SNAP-21B pressure vessel was calculated to be 76,700 psi.

- (b) By using Equations (2) and (4) and applying the same graphical principle, the actual collapse pressure of the hemispheres was determined as 16,667 psi, yielding approximately 90-percent hemisphere efficiency.

- (c) Sacrificing hemisphere efficiency for higher cylinder efficiency was a compromise with vessel weight, since the bulk of the material is in the cylinder. Total weight of the designed vessel is approximately 126 pounds.

The pressure vessel design was completed with provisions for mounting a dc-dc converter, with selection of O-ring seal material, and with selection of an electrical feed-through fitting. The mounting location for the dc-dc converter is on the opening (penetration) for the feed-through connector inside of the hemisphere. This mounting provides:

- 1) A flat heat-transfer surface to the pressure vessel.
- 2) A heat sink remote from the generator heat sink area, so that converter and regulator heat is dissipated while the electronic components are maintained at reliable operating temperatures.
- 3) Easy access to the dc-dc converter during assembly and servicing.

The O-ring seal material selected was Viton (Minnesota Rubber compound 514AD), a fluorelastomer capable of long-term exposure to atmosphere and seawater over the complete range of specified ambient and elevated temperatures experienced by the operating system.

A 12-pin electrical feed-through fitting was selected and made of titanium alloy 721 to prevent galvanic corrosion between the pressure vessel and the fitting. The fitting is designed to withstand 10,000-psi external pressure with a minimum safety factor of 1.5. A single O-ring seal is used between the fitting and the vessel. The fitting was produced by the D. G. O'Brien Co. of Framingham, Mass.

2.4 PRESSURE VESSEL FABRICATION

2.4.1 One-Quarter-Scale Pressure Vessel Model

An approximately one-quarter (0.2436) scale model was fabricated at the David Taylor Model Basin. All known structural details of the prototype were incorporated into the model, which was machined from a 4-inch-diameter bar stock of 721 titanium alloy. An average yield strength, based on a 0.2-percent offset of 120,805 psi, was determined for the model from two samples taken from the bar stock.

The model was not large enough to close the penetration into the hemispherical end in the manner to be used for the prototype vessel; that is, an electrical feed-through fitting sealed with an O-ring and bolted to the penetration. Therefore, the penetration was closed with a flat circular plate and made pressure tight by using a rubber-based sealing compound. Figures 2-2 and 2-3 show the one-quarter-scale pressure vessel prior to testing.

2.4.2 Stainless Steel Full-Scale Pressure Vessel

A stainless steel vessel (Figures 2-4 and 2-5) was fabricated for use in system thermal analysis and in system integration testing. The unit was cast, welded, and machined from CF-8C (AISI type 347) stainless steel. All machining conforms to the design specifications of the prototype pressure vessel with the following exceptions:

- 1) The outside of the lower hemispherical surface (body) and the outside of the upper hemispherical surface (cover) were left in as-cast condition to eliminate a time-consuming and costly contour machining operation.
- 2) The outside of the cylindrical surface (body) was only partially turned to dimensions since insufficient material remained after casting shrinkage.

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Figure 2-2. Components of the One-Quarter-Scale Pressure Vessel

Figure 2-3. Assembled One-Quarter-Scale Pressure Vessel

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Figure 2-4. Exterior of the
Stainless-Steel Pressure Vessel

Figure 2-5. Interior of the Stainless-Steel Pressure Vessel

- 3) The inside hemispherical surfaces of the body and cover were only rough-machined (125 finish) to meet minimum thermal test requirements.

2.4.3 Prototype Titanium Pressure Vessel

Two prototype 721 titanium pressure vessels were fabricated by the Taylor Forge and Pipe Works Co. of Chicago, Ill. (Figure 2-6). The vessel covers were made from 8-inch-diameter and the vessel bodies from 12-inch-diameter titanium billets. Steps in the fabrication process were as follows:

- 1) Each billet was coated with a special high-temperature lubricant and forged in a closed die at 1950° to 1980° F.
- 2) Vapor blasting and crack inspection were performed after the initial forging operation.
- 3) Each piece was again coated and forged a second time at the same temperature as in Step (1). This second forging operation was the final forging for the pressure vessel covers.
- 4) The pressure-vessel bodies were back-extrusion press-forged to final shape.
- 5) The bodies and covers were heated to 1925° F after forging and then water quenched. They were then rough inspected, stress relieved at 1400° F $\pm$ 50° F for 1 hour, and air cooled.
- 6) Conditioning and inspection for cracking was performed.
- 7) Qualifying machine cuts were taken on all four forgings to determine the depth of cracking.
- 8) Test rings were cut from each cover and body and then rough machined.

Figure 2-6. Prototype Titanium Pressure Vessel

2.5 PRESSURE VESSEL TESTS

2.5.1 One-Quarter-Scale Pressure Vessel Model

A series of hydrostatic pressure tests was conducted on a one-quarter-scale model of the prototype pressure vessel (Ref. 4). These tests were conducted to validate the empirically based mechanical design of the prototype vessel. Three categories of pressure testing were conducted on the vessel, including deflection rate under external loading, creep rate under loading, and testing to final destruction.

A detailed report on test procedures and results is given in Monthly Report No. 2 (Ref. 5). The following information outlines the mode of testing and test conclusions:

2.5.1.1 Deflection

Local strain (inches of deflection per inch) versus external loading pressure (psi) was determined at selected locations on the interior and exterior of the model pressure vessel. Seventy-six strain gages were used to detect local stress, and two multi-channel plotters were used to record strain data. The instrumentation system is shown in Figures 2-7 and 2-8. The series of tests was designed to determine the manner in which the pressure vessel would bend or distort with various degrees of external pressure. Particularly, the distortion profile at the 10,000-psi operation pressure was desired for design purposes. Three deflection tests were conducted at 0 to 5000, 0 to 10,000, and 0 to 12,000 psi, respectively.

The test results showed that all portions of the pressure vessel deformed very nearly as predicted. The only high-stress area of concern was on the inside of the upper hemisphere near the heat-sink flange. In this area, unexpected high-longitudinal compressive stresses were observed; however, it appeared that these stresses were very localized, and as such were re-distributed by the mechanism of cold flow. Because these stresses were

Figure 2-7. Strain Gage Instrumentation

Figure 2-8. Data Recorders and Pressurization System

localized, there was little chance of a premature failure at the stress location. This fact was demonstrated when the pressure vessel was loaded to failure and failure occurred elsewhere.

2.5.1.2 Creep

A short-term creep test was conducted to determine how the pressure-vessel deflection profile would change over a period of time when the vessel was subjected to a constant external pressure. The same instrumentation as described above was used to monitor the creep strains. Creep data were taken every 15 minutes for 4 hours with an external pressure of 12,000 psi.

From the test results, it appears that creep will be no problem after allowance is made for the initial deformation of the vessel (the deformations observed when loading the vessel from 0 to 10,000 psi). The creep observed in this test is denoted "short-term" creep as opposed to the "long-term" (extremely slow) creep observed for most metallic materials. The effects of long-term creep cannot be predicted from this experiment; however, the material was selected on the basis of the negligible long-term creep it exhibits.

2.5.1.3 Failure

To determine the correlation between the empirically determined failure pressure and that actually realized in practice, the vessel was subjected to increasing external pressures until failure occurred. All strain-gage instrumentation was removed prior to this test, because the strain data obtained beyond the yield point of the material would have little or no value for design or analysis purposes. In addition, the presence of the numerous strain-gage wires would have caused a problem in sealing the testing chamber at the anticipated failure pressure.

The loading schedule for this test was 100-psi pressure increments, starting from 12,000 psi to the failure pressure. The vessel was loaded from 0 to 12,000 psi in about 12 minutes. A 30-second stabilization period was observed between application of the 100-psi pressure increments.

Failure of the vessel at 17,500 psi indicated that no difficulty should occur in achieving the desired operating pressure of 10,000 psi with the prototype pressure vessel. As designed, the vessel could have failed at any location at the predicted failure pressure. The location of the failure was in the lower hemisphere (Figure 2-9), and there were no unexpectedly high stresses recorded in the failure area prior to the destruction test.

Figure 2-9. Fracture in One-Quarter-Scale Pressure Vessel

The close agreement between the predicted and experimentally determined deflections and failure pressure provided confidence in the predicted performances for design purposes. It appears that the critical deflections will be about as predicted and that there should be no difficulty in achieving the desired operating pressure.

2.5.2 Stainless Steel Full-Scale Pressure Vessel

The stainless steel pressure vessel was not mechanically or hydrostatically tested because it was to be used for a system test only and would not be subjected to extreme hydraulic forces.

2.5.3 Prototype Titanium Pressure Vessel

2.5.3.1 Chemical Analysis

Table 2-1 lists the chemical composition specifications and the analyses of the supplier and the two testing facilities.

Table 2-1. Chemical Analysis of 721 Titanium Base Alloy

Element	Chemical Composition (1) Specifications	Titanium Metals Corporation	Taylor Forge & Pipe Works	Charles C. Kawin Co. for 3M
Aluminum	6.6 - 7.3	6.90	6.84	6.96
Columbium	2.0 - 2.75	2.50	2.61	2.55
Tantalum	0.8 - 1.2	1.30(2)	1.26(2)	1.60(2)
Carbon	0.030	0.026	0.029	0.020
Nitrogen	0.012	0.005	0.005	0.0056
Iron	0.180	0.12	0.12	0.10
Oxygen	0.080	TOP-0.075	0.0741-0.077	0.074
Hydrogen	0.008	---	0.0051-0.0039	0.0036
Other	0.50	(3)	(3)	(3)
Titanium	87.94	89.05(4)	89.05(4)	88.69(4)

- (1) Percent, maximum unless a range is shown or unless otherwise stated.
- (2) Out of specification, was accepted by the 3M Co.
- (3) Residuals were not analyzed.
- (4) Includes small unanalyzed residuals.

2.5.3.2 Mechanical Testing

Mechanical testing of the full-scale, prototype, titanium pressure vessel was made by the Taylor Forge and Pipe Works. Illustrations of how test samples were taken from the two forgings, locations of test samples, and mechanical test results are presented in Appendix B.

The Charles C. Kawin Company, acting on behalf of the 3M Company, substantiated the results of the Taylor Forge and Pipe Works' mechanical testing data. The Kawin Company did not completely retest the pressure vessel but rather "spot checked" Taylor Forge and Pipe Works' results. The Kawin Company results will also be found in Appendix B.

2.5.3.3 Hydraulic Pressure Testing

The full-scale, prototype, titanium pressure vessel was tested at the David Taylor Model Basin. Figure 2-10 shows the pressure vessel at the test location. The instrumentation and test procedure for the prototype were very similar to those of the one-quarter-scale model (Section 2.5.1) with the following exceptions:

- a. The prototype model was proof-tested to 10,000 psi in saltwater and was not tested to failure, whereas the one-quarter-scale model was proof-tested to 12,000 psi in oil and later tested to failure.
- b. The prototype model had a limited instrumentation of 12 strain gages, whereas the one-quarter-scale model had 76 gages. The prototype model had pairs of gages located at 6 different positions on the inside surface as follows:
 - (1) At the intersection of the penetration and hemisphere.
 - (2) At the intersection of the heat sink and hemisphere just off the fillet. Two pair of gages were placed 180° apart.

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Figure 2-10. Titanium Prototype Pressure Vessel on Test Site at David Taylor Model Basin (Strain relief plug and receptacle clearly visible in lower photos.)

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- (3) Same region as in (2), but on the center of the fillet.
- (4) At the mid-span of the cylinder.
- (5) At the apex of the hemisphere without a penetration.
- c. The creep test applied to the prototype model was at a pressure of 10,000 psi for a duration of 48 hours, whereas the creep test applied to the one-quarter-scale model was at a pressure of 12,000 psi for a duration of 4 hours.
- d. Each O-ring of the double O-ring seal on the prototype model was tested to 10,000 psi for a duration of 2 hours, whereas each O-ring of the double O-ring seal on the one-quarter-scale model was tested to 5,000 psi for 15 minutes.
- e. The penetration in the prototype model was closed by means of an electrical receptacle bolted to the penetration and sealed with an O-ring, whereas the penetration in the one-quarter-scale model was closed with a flat circular plate and made pressure tight with a rubber-based sealing compound. The receptacle was bolted to the penetration during both O-ring tests.
- f. The prototype model was first tested using a strain-relief plug, furnished by the 3M Company, which was to make a pressure-tight connection with the receptacle and provide a method to bring the strain-gage wires to the outside of the pressure tank.
- g. To check for surface cracks after the end of the tests, the prototype model was dye-checked on the inside surface of the hemisphere at its intersections with the penetration and heat sink, whereas the one-quarter-scale model was not.

2.5.3.4 Prototype Test Results

The elastic strain behavior of the prototype model was identical to the one-quarter-scale model, and any conclusions concerning elastic strain data made from the one-quarter-scale model also apply to the prototype model.

From information provided by the Taylor Forge & Pipe Works, the prototype model material (titanium) appears to have a minimum yield strength of 107,000 psi as compared to 120,800 psi for the one-quarter-scale model. Based on a direct ratio of yield strengths and a collapse pressure of 17,500 psi for the one-quarter-scale model, the prototype model has a projected collapse pressure of 15,500 psi.

Figure 2-11 shows the results of the creep test for the gage that recorded the highest amount of strain during the 48-hour period at pressure. These measurements were recorded from a meridional gage located off the fillet of the hemisphere near the heat sink.

Test results show that the receptacle and each O-ring will sustain 10,000 psi.

During the initial test of the prototype model at a pressure of 3300 psi, the strain-relief plug was flooded at the receptacle. However, this test is inconclusive because the leakage may have been attributed to an electrical splice to bring strain-gage leads from the strain-relief plug to the outside of the pressure tank.

The dye-check made at the conclusion of the tests did not reveal any surface cracks.

Figure 2-11. Prototype Pressure Vessel Creep Test Results

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2.6 REFERENCES

1. Sturm, R. G., University of Illinois Experimental Station, Bulletin No. 12 (November 1941).
2. Krenzke, M. A., Structural Development of a Titanium Oceanographic Vehicle for Operating Depths of 15,000 to 20,000 Feet, DTMB Report 1677 (September 1963).
3. Gerard, G., Plastic Stability Theory of Thin Shells, Journal of the Aeronautical Sciences, Vol. 24, No. 4 (April 1957).
4. Couch, William, Design of Radioisotope Pressure Vessel and Test Results of One Quarter Scaled Model, DTMB - SML No. TR720-3 (April 1965).
5. Report No. MMM (3321)-15. SNAP-21B Program Monthly Report (1 April to 30 April 1965). AEC Contract AT (30-1) 3321 (May 1965).

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3.0 FUEL CAPSULE

3.1 PROGRAM OBJECTIVES

The objectives of the SNAP-21B program were to:

- Design and fabricate a fuel capsule capable of absolute fuel containment under all conditions of intended use and credible accidents for a minimum period of 300 years.
- Design and fabricate a fuel capsule which will permit strontium-90 titanate fuel to be easily encapsulated at a fueling facility.
- Verify the fuel capsule design by conducting a test program using the prototype capsules.

3.2 PROGRAM ACCOMPLISHMENTS

- Fuel capsules have been designed and fabricated that are capable of absolute fuel containment under all conditions of intended use and credible accidents for a minimum period of 300 years.
- The fuel capsule is designed to permit easy encapsulation of strontium-90 titanate fuel.
- Nineteen fuel capsules were tested to determine the integrity of fabrication and to verify the required containment of fuel.

3.3 FUEL CAPSULE DESIGN

In providing for a fuel capsule with a high degree of fuel containment integrity, special attention has been given to selection of the encapsulating materials. High-strength, highly anti-corrosive materials were particularly important in view of the 10,000-psi external pressures to which the fuel capsule could be exposed when the power supply system is implanted at operational depths. Compatibility of the fuel capsule materials with the fuel and shield materials has also required careful evaluation.

The prototype fuel capsule (Figure 3-1) is designed for 187 watts generation with a power density of 0.8 watts/cc of fuel. Once the required fuel volume of 234 cc was determined, the fuel pellet was designed to give a length-to-diameter (L/D) ratio of 1. The pellet dimensions are 2.63 inches square, and the weight is 1.8 pounds. Revised fuel loading requirements will necessitate minor dimensional changes for fueled units.

For ease of handling and decontamination, ORNL suggested that the pellet be doubly encapsulated. A thin capsule of 316L stainless steel with an 0.018-inch wall is used as an inner liner. It is 2.688 inches in diameter, 2.732 inches long, and weighs less than 0.2 pound. For ease of fuel encapsulation the capsule has a 0.010-inch clearance on the radius and a 0.015-inch clearance on each end.

The outer fuel capsule is constructed to withstand the required safety tests. It is made of Hastelloy C alloy with a 0.250-inch wall thickness. The capsule has an outside diameter of 3.198 inches and a length of 3.332 inches. The inner capsule liner slips inside the outer capsule (Figure 3-2) with the end plates fitting flush against the inner capsule. The end plates of the outer capsule are welded in place in a helium atmosphere. The weight of the capsule and liner is 4.0 pounds, and the completed fuel capsule weighs 5.8 pounds.

3.3.1 Fuel Capsule Temperature Determination

To assure interface fits during assembly, an analysis was made of the fuel capsule temperature rise after fueling. The findings indicated that thermal expansion of the capsule at 700° F will not hinder its insertion in the biological radiation shield. The analytical method was as follows:

Assumptions:

- 1) The fuel capsule is loaded with 187 watts of strontium-90 fuel
- 2) The capsule is surrounded by still air
- 3) Heat transfer is by free convection to air and by radiation to surroundings.

Figure 3-1. SNAP-21B Fuel Capsule and Liner Assembly

Figure 3-2. Inner and Outer Fuel Capsule Components

For steady state conditions a heat balance on the capsule then yields:

$$Q_{\text{fuel}} = Q_{\text{convection}} + Q_{\text{radiation}} \quad (1)$$

$$Q_{\text{convection}} = f(N_u, G_r) \text{ capsule} \quad (2)$$

$$Q_{\text{radiation}} = f(\epsilon, A, T) \text{ capsule} \quad (3)$$

where

Q = Heat flow (Btu/hr)

N_u = Nusselt number (dimensionless)

G_r = Grashof's number (dimensionless)

ϵ = Emissivity (dimensionless)

A = Heat transfer area

T = Temperature ($^{\circ}$ R).

Assuming that the fuel capsule is small in comparison to the surroundings, the heat loss through radiation is (Ref. 1).

$$Q_{\text{radiation}} = \sigma A_{\text{capsule}} [T_{\text{surface}}^4 - T_{\text{surroundings}}^4] \quad (4)$$

where σ = Stefan-Boltzman constant.

The heat loss through free convection varies as the geometrical attitude of the capsule varies. Therefore, three different situations were assumed:

- 1) The capsule was assumed to be vertically oriented.

The heat loss could then be evaluated using the following expression (Ref. 2) and Equation (6) below:

$$N_u = 0.378 (G_r)^{1/4}. \quad (5)$$

- 2) The capsule was assumed to be horizontally oriented. The heat loss could be evaluated by using Equation (5) and by letting $X = 2.5d$, where

X = characteristic length (feet)

d = capsule diameter (feet).

- 3) For ease of calculation and good approximation, the capsule was assumed to be a sphere of equal area and the heat loss was evaluated (Ref. 3).
Sample calculations, Case 1:

$$Q/A = \phi = 1970 \text{ Btu/hr-ft}^2$$

$$\phi = (h\Delta T)_{\text{convection}} + [\delta\epsilon(T_1^4 - T_2^4)] \text{ radiation} \quad (6)$$

where: h = film coefficient of heat transfer.

Assume $T = 300^\circ \text{F}$; then

$$N_u = \frac{hX}{k} = 0.378 (G_r)^{1/4} = 16.4$$

$$h = 1.2 \text{ Btu/hr-ft}^2 \cdot ^\circ \text{F}$$

$$\phi = 1.2 (300) + 0.173 \times 10^{-8} \times 0.4 \times 3.96 \times 10^{11}$$

$$\phi = 641 \text{ Btu/hr-ft}^2.$$

Therefore, the calculated heat flux is lower than the actual flux and the assumed temperature difference is too low. Iterating by assuming a new ΔT results in a more correct answer.

Using the procedure outlined above, the surface temperature of the fuel capsule at rest was predicted to reach a maximum temperature of 700° F.

3.3.2 Fuel Capsule Elevated Temperature Evaluation

Use of radiative rather than conductive heat transfer from the biological shield to the thermoelectric generator requires the capsule to operate at approximately 1350° F rather than 1175°F. An analysis was conducted to determine the structural strength of the capsule at the elevated temperature.

The principal stresses evaluated in the fuel capsule design are: collapsing stress, shear stress on the end plate, and rupture stress on the end plate.

The formulas used to determine the stresses are:

$$\text{Collapsing stress (Ref. 4)} \quad S_c = \frac{2P_o r_o^2}{r_o^2 - r_i^2} \quad (7)$$

$$\text{Shear stress (Ref. 5)} \quad S_s = \frac{P_o r_i}{2t} \quad (8)$$

$$\text{Rupture stress (Ref. 5)} \quad S_r = \frac{3P_o r_i^2}{8t^2} (1 + \mu) \quad (9)$$

where:

P_o = external pressure

r_o = outside radius

r_i = inside radius

t = thickness

μ = Poisson's ratio.

The ultimate tensile strength of Hastelloy C was assumed as 115,000 psi at room temperature, and 80,000 psi at 1400° F. The calculated stresses at an operating pressure of 10,000 psi are:

Failure	Stress (psi)	Calculated Safety Factor	
		Hot	Cold
Collapse	69,300	1.15	1.66
Shear	26,900	1.49	1.92
Rupture	35,000	2.26	3.25

Elevated temperature operation of the fuel capsule will induce an exothermic, eutectic formation between the Hastelloy C fuel capsule material and the uranium-8 molybdenum biological-shield material. To prevent eutectic formation, the double-cup outer liner (Figure 3-1) was designed. This liner provides physical separation of the capsule and shield. Titanium was selected as the outer liner material since it is compatible with uranium and Hastelloy C. Copper might also be used for this liner, since experimental work indicates it is also compatible.

3.4 FABRICATION

The fuel capsule components were fabricated at the 3M Company according to drawings B-PD-37-1027 through -1033. Hastelloy C was used for the outer capsule and 316L stainless steel for the inner capsule. The 3M Company Laboratory verified the composition of the Hastelloy C material by comparing it with a known sample of Hastelloy C in an emission spectrograph. The chemical composition and strength of the material, as certified by the vendors, are listed in Table 3-1.

Each capsule component was measured with a micrometer caliper and then matched with appropriately measured counterparts. The main components of the capsule (cylindrical body, two end plates) were then each stamped with an identical number. Each measurement was compared to the design dimensions, which are listed in Table 3-2 and illustrated in Figure 3-3.

Fifteen matched sets of fuel capsule components were forwarded to ORNL for fabrication, while four additional assemblies, quality rejected for dimensional and appearance anomalies, were used to develop the capsule welding procedure. The preliminary weld specimens were metallographically acceptable with respect to weld integrity, and the specified minimum weld penetration of 0.100 inch was achieved.

ORNL which will perform the actual fueling, established the weld parameters and closed the test capsules as follows:

The inner containers and end plugs were cleaned with trichlorethylene for oil removal. The cylinders and one end plug were then welded in a pressure-pot type welder at 9 amperes, 10 volts, 1 rpm in 65 percent argon, and 35 percent helium under 0.5 atmosphere pressure. The welding electrode was 0.040-in. diameter, 2-percent thoriated tungsten. After loading the dummy source material, the containers were sealed in the same manner. In both steps the welding chamber was purged three times by evacuating to 300 microns pressure and back-filling with the gas mixture.

Table 3-1. Chemical Composition and Strength of Hastelloy C

	Bar Stock (end cap)	Tubing (cylinder wall)
Molybdenum	15.93%	15.82%
Chromium	15.49%	15.89%
Iron	5.23%	5.40%
Tungsten	3.75%	4.42%
Cobalt	0.74%	0.62%
Silicon	0.55%	0.73%
Manganese	0.45%	0.64%
Vanadium	0.18%	0.22%
Carbon	0.08%	0.06%
Phosphorus	0.01%	0.006%
Sulfur	0.007%	0.007%
Nickel	Balance	Balance
Yield Strength, psi Room temperature	53,800	59,350
Tensile Strength, psi Room temperature	114,150	126,750
800°F	87,100	103,000
1600°F	29,450	31,800

Table 3-2. Fuel Capsule Component Dimensions (also see Figure 3-3)

Capsule Number	A	B	C	D	E	F	G	B ¹	E ¹	F ¹	G ¹	Disposition
1	2.696	2.949	3.198	3.337	0.247	0.352	2.771	2.946	0.249	0.351	2.771	Fueling Facility weld evaluation
2	2.693	2.949	3.203	3.338	0.247	0.349	2.773	2.947	0.248	0.350	2.772	Fueling Facility weld evaluation
3	2.694	2.948	3.200	3.336	0.246	0.351	2.774	2.948	0.249	0.351	2.772	Electrically-heated prototype
4	2.695	2.948	3.197	3.338	0.246	0.351	2.779	2.947	0.248	0.350	2.773	Not welded
5	2.694	2.948	3.198	3.337	0.247	0.353	2.775	2.947	0.249	0.351	2.774	Electrically-heated prototype
6	2.695	2.948	3.196	3.336	0.247	0.351	2.773	2.947	0.249	0.349	2.771	Hydrostatic pressure test
7	2.697	2.948	3.193	3.337	0.247	0.352	2.775	2.948	0.249	0.352	2.770	Hydrostatic pressure test
8	2.696	2.948	3.197	3.337	0.246	0.351	2.775	2.948	0.248	0.349	2.767	Hydrostatic pressure test
9	2.695	2.948	3.202	3.336	0.247	0.350	2.776	2.947	0.248	0.349	2.767	Fire test
10	2.696	2.948	3.197	3.336	0.246	0.350	2.775	2.945	0.249	0.350	2.772	Fire test
11	2.696	2.948	3.204	3.337	0.248	0.352	2.775	2.947	0.248	0.351	2.774	Not welded
12	2.695	2.947	3.196	3.336	0.247	0.351	2.776	2.947	0.249	0.351	2.775	Thermal shock test
13	2.695	2.947	3.212	3.333	0.246	0.352	2.775	2.947	0.249	0.350	2.773	Vibration test
14	2.696	2.948	3.199	3.336	0.246	0.351	2.775	2.947	0.249	0.349	2.772	Hydrostatic pressure test
15	2.696	2.948	3.194	3.336	0.245	0.350	2.775	2.947	0.249	0.350	2.772	Save for future testing
16	2.695	2.948	3.196	3.335	0.248	0.352	2.775	2.947	0.249	0.351	2.770	Save for future testing
17	2.697	2.947	3.192	3.336	0.246	0.352	2.774	2.946	0.249	0.350	2.771	Save for future testing
18	2.697	2.948	3.207	3.338	0.247	0.352	2.772	2.946	0.249	0.351	2.766	Thermal shock test
19	2.694	2.948	3.203	3.336	0.246	0.351	2.775	2.947	0.249	0.349	2.773	3M weld evaluation

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Figure 3-3. Fuel Capsule Component Dimensions (see Table 3-2)

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The outer container top plugs were welded in place, re-machined in the top area to the original inside diameter, and cleaned with trichloroethylene. A small V-groove was cut in the side of the bottom plug to aid in pump-down. After inserting the inner containers, the bottom plugs were welded in an AIRCO welder at 10 psig, 65 percent argon, 35 percent helium pressure, and purged as mentioned above. Capsules No. 7, 8, 9, 14, and 15 were welded at 130 amperes, 10 volts, 1 rpm, single pass, using a 3/32-inch diameter, 2-percent thoriated tungsten electrode. Capsules No. 12, 16 and 17 were welded in two passes, one pass at 110 amperes, 12 volts, and the other pass at 95 amperes, 12 volts, 1 rpm, and also using a tungsten electrode identical to that described above. The other capsules were welded in two passes, the first pass at 100 amperes, 10 volts, and the second at 80 amperes, 11 volts, 1 rpm, using an electrode the same as described above.

The capsules were leak-tested by submerging them in water within a vacuum desiccator and evacuating to 28 in. Hg. No leaks were observed. Two outer capsules were sectioned and examined for depth of weld penetration. The two specimens each showed a minimum fusion-weld penetration of 0.100 inch as specified.

At the conclusion of the test program, four capsules were sectioned, each in two places through their fusion welds. Three capsules had less than 0.100-inch weld penetration. The units with less penetration than originally specified were adequate in that all capsules remained integral throughout testing. A deeper penetration can be obtained by slightly champering the capsule plug before closure. Weld parameters will be re-established for this welding method prior to actual fueling of capsules. One of the four capsules had its filler weld sectioned in two locations. Weld penetration was 0.2 inch approximately or 80 percent of plate thickness. Fueled capsules will be fabricated from solid bar stock to eliminate the filler weld and the separate end plate.

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Late in the program the Battelle Northwest Laboratory performed ultrasonic tests on several SNAP-21B prototype fuel capsules. The tests demonstrated their ability to accurately detect and measure structural defects in the capsules. Because these tests can be performed in a hot cell, it is expected that they can be used on fueled units to verify weld penetration and uniformity.

3.5 FUEL CAPSULE TESTING

A fuel capsule test program was conducted to verify the capsule design and insure capsule integrity under credible conditions of transport and use.

Table 3-3 summarizes the program.

3.5.1 Fuel Simulant

For testing purposes, the strontium-titanate fuel was simulated with a pellet of AlSiMag 614 (Figure 3-4) a product of American Lava Corporation. The pertinent physical properties of strontium titanate and AlSiMag are compared in the following table.

Physical Properties	AlSiMag 614	SrTiO ₃
Density	0.134	0.134
Coefficient of expansion, °F ⁻¹	4×10^{-6}	6×10^{-6}
Compressive strength, lb/in ²	315,000	---
Thermal conductivity (1500° F), Btu/hr-ft-° F	4.8	2.4
Melting point, ° F	3000	3450

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Table 3-3. SNAP-21B Fuel Capsule Test Summary

Test	Number of Capsules to be Tested	Description	Requirements
Hydrostatic Pressure	4	The fuel capsule will be closed at both ends and inserted into an isostatic hydraulic press. The external pressure will be raised until the capsule ruptures or until the press limit of 29,500 psi is reached.	Visual and metallographic examinations of failure. Metallographic examinations of weld structure if no failure occurs. Redesign and re-test if results so indicate.
Fire	2	Capsule is placed in a furnace and subjected to conditions as outlined in the two-hour fire test, ASTM E 119-61.	Visual examination for failure. Hydrostatic pressure check for failure. (Weigh for detection of fluid intrusions.) Helium leak check.
Thermal Shock	2	Capsule is heated to maximum fire test conditions (1850° F) and is held until equilibrium is reached. The capsule is then removed and dropped into 50° F water.	Visual examination for stress cracking. Hydrostatic pressure check for failure. Helium leak check.
Vibration	1	Capsule will be tested for a 1-hour period. Maximum loading will be 16 g's with frequency varying from 10 ± 0 10,000 cps.	Visual examination for failure. Helium leak check.
Total Number of Capsules	9		

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3.5.2 Fire Test

Two capsules (Nos. 9 and 10) were fire tested as outlined in the specifications of the American Society for Testing and Materials (ASTM E 119-61). A thermocouple (chromel-alumel) placed adjacent to a capsule was used to register temperature. The two capsules were introduced into a pre-heated furnace and fired as indicated in Table 3-4. Upon removal from the furnace with subsequent air cooling, it was noted that the once shiny surfaces of the capsules were oxidized black. However, no cracks, blisters, or blemishes were discernable.

To verify the apparent maintenance of integrity, the capsules were hydrostatically pressurized to 10,000 psi. Possible fluid intrusion was checked by accurate weighings of the capsules on a triple-beam balance before and after pressure application. The weight of capsule No. 9 changed from 2526.89 to 2526.90 grams, while that of capsule No. 10 remained at 2508.44 grams. The very slight change in weight of capsule No. 9 is within the ± 0.05 -gram accuracy of the balance. The fact that neither capsule incurred a significant weight gain indicated that integrity had been maintained.

Figure 3-4. Simulated Fuel Pellet
(AlSiMag 614)

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A dye penetrant system, General Mills "Spotcheck", was applied generously to each capsule surface (particularly the weld areas) and permitted to stand for 10 minutes. The excess was wiped off with a dry cloth; then a cleaner (part of the General Mills kit) was used to complete the removal of the unused penetrant. A special developer applied to the surfaces which had been coated with the crimson dye penetrant revealed no surface cracks or unnatural pores. (The color of the developer was white and any penetrant which may have seeped into a crack was intended to be drawn out by the developer; in this manner the location of the crack could be pinpointed as a line of vivid crimson.)

As a third and final verification of capsule integrity, a helium leak-test was performed. The capsules were pressurized with helium in a chamber made of 3-1/2-inch (nominal) schedule-40 pipe fitted with end caps and valves. A

Table 3-4. Fuel Capsule Fire Test Temperature Data

Time (minutes)	Temperature (°F)	Time (minutes)	Temperature (°F)
0	969	65	1760
1	1040	73	1837
3	1065	74	1850
8	1130	83	1850
13	1184	103	1850
18	1249	134	1852
23	1308		(power turned off;
28	1368		capsules remained
33	1418		in furnace)
38	1479	138	1832
43	1535	303	1276
48	1609	444	1053
53	1641		(capsules removed
59	1700		from furnace)

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helium pressure of 300 psig was applied to the capsules for 20 minutes. After pressure relief, the capsules were removed from the pipe and placed in a vacuum dessicator. The dessicator was connected to a Consolidated Electrodynamics Corporation Type 24-110-A helium leak detector. After removal of the air surrounding the capsule within the dessicator, the exhaust from the dessicator was "sniffed" for a possible helium concentration which would indicate a capsule leak. Both capsules had a leak rate of less than 5×10^{-8} std cm³/sec of helium. This figure, an extremely small flow rate, probably was due to an evolution of helium entrapped in surface pores.

In summary, hydrostatic pressure application with weighings before and after the test, dye-penetrant checks, and helium leak checks all served to verify that the fire test had failed to breach the capsule integrity. Capsule No. 10 was sectioned and then a small wedge of the fusion weld area was cut out and mounted for examination. After polishing, the cross section of the weld area was photomicrographed (Figure 3-5), showing that a penetration of 0.081 inch had been accomplished.

Figure 3-5. Capsule No. 10 - Fusion Weld Section
(10X left, 150X right)

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3.5.3 Thermal Shock Test

Two capsules (Nos. 12 and 18) were individually subjected to thermal shock. With their temperatures registered by a thermocouple (chromel-alumel), the capsules were brought to equilibrium at 1850° F in a furnace. A capsule (glowing a bright cherry red) was removed from the furnace and immediately dropped into a vessel of 50° F water. The capsule continued to glow for several seconds after submersion; a great deal of localized boiling was evident around the capsule. The other capsule was also quenched in 50° F water with similar observations noted. Upon removal from the water, the capsules turned a dull black with a slight greenish cast (Figure 3-6).

Figure 3-6. Capsule No. 12 after Thermal Shock Test

No stress cracking was evident on either capsule. Each capsule was hydrostatically pressurized to 10,000 psi. The weight of capsule No. 12 changed from 2502.37 grams before pressure application to 2502.41 grams afterward; the weight of capsule No. 18 increased from 2517.87 to 2517.89 grams. The variance in weights in both cases was within the balance accuracy of ± 0.05 gram. It was concluded that no fluid had intruded during pressurization; therefore, capsule integrity had been maintained throughout each thermal shock test.

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Dye penetrant, applied as stated previously, revealed no cracks or weld faults. A helium leak check, resulting in an indicated leak rate of less than 5×10^{-8} std cm³/sec for each capsule, verified that neither capsule had been breached during the thermal shock test.

A section was cut from the fusion weld area of capsule No. 18. The photomicrographs (Figure 3-7) indicate a weld penetration of about 0.034 inch.

Figure 3-7. Capsule No. 18 - Fusion Weld Section
(10X left, 150X right)

3.5.4 Vibration Test

A vibration test was performed on capsule No. 13 at Environ Laboratories, Minneapolis, Minnesota. A sine-wave vibration from 5 to 28 cps with a 0.4-inch displacement, followed by a variation from 28 to 3000 cps at 16 g's

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acceleration was applied to the capsule. The capsule was securely fastened between two recessed aluminum plates, with one of the plates fastened, in turn, to the shaker platform. Some resonance was noted (apparently due to shifting of the fuel simulant).

After vibration, the capsule was weighed (2531.39 grams) and then subjected to 10,000 psi in the hydrostatic press. A following weight of 2531.43 grams revealed the absence of intruded fluid. Dye penetration and a helium leak-rate of less than 5×10^{-8} std cm³/sec confirmed that the vibration test had not damaged the capsule integrity. The piece was mounted in plastic, polished, and then photomicrographed. The picture (Figure 3-8) revealed a weld penetration of 0.053 inch, which did not meet the specified 0.100-inch minimum.

Figure 3-8. Capsule No. 13 - Fusion Weld Section
(10X left, 150X right)

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3.5.5 Hydrostatic Pressure Test

Four capsules (Nos. 6, 7, 8, and 14) were pressurized in an isostatic press to 29,500 psi (the limit of the press). The pressure was increased manually at a 100-psi/min rate. Any deformation which occurred was relatively minor and not immediately apparent. A micrometer caliper revealed a 0.020- to 0.030-inch depression radially and a similar depression lengthwise. A triple-beam balance was used to weigh the capsules for possible fluid intrusion. The recorded weights are listed below.

Table 3-5. Capsule Weights Before and After Hydrostatic Pressure Application

Capsule	Weight before (grams)	Weight After (grams)
6	2508.71 $\pm$ 0.05	2508.66 $\pm$ 0.05
7	2503.27 $\pm$ 0.05	2503.24 $\pm$ 0.05
8	2506.69 $\pm$ 0.05	2506.67 $\pm$ 0.05
14	2507.72 $\pm$ 0.05	2507.67 $\pm$ 0.05

None of the four capsules gained weight during the tests, indicating that no breeches had occurred. Dye penetrant applied to the surface of each capsule revealed no cracks. A helium leak check of each capsule showed that none "leaked" more than 5×10^{-8} std cm³/sec. Thus, the integrity of each capsule was maintained as verified by the dye penetration and helium leak tests. Photomicrographs (Figure 3-9) of a fusion weld area of capsule No. 14 revealed a weld penetration of 0.1 inch. An area of the filler weld is shown in Figure 3-10.

3.5.6 Corrosion

Among the several desirable properties of Hastelloy C is its extremely low rate of corrosion in salt water. Samples of Hastelloy C submerged in salt water have been extensively studied by others, and the corrosion rate for the material (10^{-4}) inch/year is well known (Ref. 6). Therefore, no additional research was done in this area.

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Figure 3-9. Capsule No. 14 - Fusion Weld Section
(10X)

Figure 3-10. Capsule No. 14 - Filler Weld Section
(10X)

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3.6 REFERENCES

1. Introduction to Heat Transfer, 3rd Edition, Brown and Marco - McGraw Hill.
2. Heat and Mass Transfer, 2nd Edition, Eckert and Drake - McGraw Hill.
3. Laminar Free Convections from a Sphere, Chiang, Ossin and Tien - ASME 63-WA-103.
4. Design of Machine Elements, 2nd Edition, Spotts - Prentice-Hall.
5. Mechanical Engineering Handbook, 6th Edition, Marks - McGraw-Hill.
6. As determed by the Wrightsville Beach Corrosion Center, North Carolina, MND-P-2835-SNAP7D (15 March 1964).

4.0 BIOLOGICAL RADIATION SHIELD

4.1 PROGRAM OBJECTIVES

The program objectives for the biological radiation shield are to:

- Limit the nuclear radiation level to 200 mr/hr at the system's surface, and to 10 mr/hr at 1 meter from the surface.
- Permit easy thermoelectric subsystem repair or replacement without hot-cell facilities and without exceeding the maximum permissible radiation exposure limits established by the AEC.

4.2 PROGRAM ACCOMPLISHMENTS

- The interface between the shield and the insulation envelope was defined, and the shield dimensions established.
- Protection methods and materials were evaluated for compatibility with various shield-system interfaces, and a cladding approach was determined.
- Fabrication of the radiation shield was completed.

4.3 BIOLOGICAL RADIATION SHIELD DESIGN

4.3.1 Design Configuration and Material Selection

The final design configuration and material selection for the biological radiation shield were based upon radiation analysis and radiation-attenuation analog experiments as reported in Reference 1. The design analysis and experimentation indicated that a uranium alloy (U-8% molybdenum) was the most acceptable shield material.

The choice of U-8% Mo offers several distinct advantages. Pure, depleted uranium metal is the best low-weight shield material, but has an undesirable phase change at the system operating temperature. U-8% Mo alloy eliminates this problem and the resultant density loss is negligible. U-8% Mo retains more than 90 percent of the density of unalloyed uranium and offers improved

physical and chemical properties, including higher strength, ductility, and corrosion resistance. The stabilized gamma structure of U-8% Mo is body-centered cubic and much of the anisotropic behavior of alpha uranium is eliminated. U-8% Mo has good high-temperature strength characteristics with a yield strength of 5000 psi at 1600° F.

The radiation shield was designed for minimum weight. Using a cylindrical fuel capsule, the shield geometry that offers the least weight is a cylinder with rounded ends. To minimize the heat loss from the insulation, it was decided to load the fuel capsule into the shield from the thermoelectric generator end; thus it was necessary to design an end plug which would be easy to remove and replace without radiation "leakage." Figure 4-1 shows the configuration of the radiation shield, which is designed to limit the system radiation level to 200 mr/hr at the surface of the pressure vessel when the fuel capsule is loaded with 30,000 curies of strontium-90 titanate.

4.3.2 Shield Interface Protection

At the inner and outer surfaces of the radiation shield, two critical interfaces exist. At the outer interface between the shield and the insulation envelope, oxidation protection, mechanical support, and maintenance of high vacuum within the insulation envelope must be assured. At the inside interface between the shield and the fuel capsule, protection against oxidation and possible eutectic formations must be provided because of the high operating temperatures.

The problem then was to physically separate the fuel capsule (Hastelloy C) and the insulation system (Inconel X) from the radiation shield (U-8% Mo) by using a compatible material as a separating layer. Copper met these requirements, but is subject to rapid oxidation at operating temperature. The final design solution was to use a 0.032-inch electroplated copper cladding on the exterior of the shield and a 0.010-inch copper cylinder fitted between the capsule and the shield. The cladding and cylinder were plated with a thin (0.0005-inch) flashing of chromium.

Figure 4-1. SNAP-21B Shield and Plug Assembly

The problems of mechanical support and retention of high vacuum within the insulation system are discussed in Section 6.0.

4.3.3 Integration of the Shield and the Insulation System

Because the position of the radiation shield with respect to the insulation envelope is unique, the effect of temperature upon their compatibility must be carefully evaluated. Thermal expansion and thermal stability related to thermal cycling are particularly important in maintaining the desired fit between the two components. The shield must be prevented from moving during shock and vibration, and provision must be made for differential expansion of the shield and insulation shell.

The National Lead Company confirms that the U-8% Mo shield material is of the annealed or gamma stabilized form. Wilkinson (Reference 2) states that "being isotropic, gamma-uranium alloys might be expected to be more resistant to thermal cycling and irradiation damage than nonisotropic compositions. . . This applies to the metastable as well as to the stable gamma alloys . . . In the molybdenum system, the gamma phase was once thought to be stabilized to room temperature in the vicinity of 12.5 to 17.0 w/o of molybdenum, but it is now known to be metastable in this composition range below 575° to 600°C, even though normal cooling of alloys containing more than 9.8 w/o molybdenum retains the gamma . . . The critical alloying addition of molybdenum that will just retain the gamma structure in uranium on quenching in water is 7.0 w/o . . . The key to dimensional stability is found in the (time-temperature-transformation curve, Figure 4-2) which shows the proper transformation time for maintaining the desired phase condition . . . Inasmuch as these alloys are metastable, long time annealing at 550°C causes the metastable gamma to decompose forming alpha plus delta."

Enclosing the radiation shield within the insulation envelope reduces the cooling rate. This condition does not pose a problem during initial heating of the shield, but an auxiliary method of cooling may be required to prevent long

residence at temperatures between 300° and 580° C. However, because the shield is presently in the gamma phase, any changes that might occur would reduce the shield size and create a looser fit between the shield and the insulation shell.

Figure 4-2. Time, Temperature, Transformation Curve for 8 Wt. Percent Molybdenum-Uranium

The thermal expansion coefficients, as given by the Handbook of Thermophysical Properties of Solid Materials, are:

$$8.75 \times 10^{-6} \text{ units/unit/}^{\circ}\text{F from } 70^{\circ} \text{ to } 1350^{\circ}\text{F}$$

$$8.88 \times 10^{-6} \text{ units/unit/}^{\circ}\text{F from } 70^{\circ} \text{ to } 1500^{\circ}\text{F.}$$

The insulation system requires outgassing at a temperature equal to or greater than that experienced at operating conditions. The following precautions were taken for processing the system fabricated around the uranium radiation shield. The center of the copper heater block was instrumented to indicate the temperature. The maximum temperature allowed was 1500°F, and the power was adjusted so that the block temperature did not exceed 1500°F. Processing was done in an argon atmosphere. The processed system was allowed to cool to

200°F or less before being exposed to an air atmosphere. Approximately 40 hours were required to reach 1500°F. Although precautions were taken to ensure that the electrical leads did not short circuit, two heater blocks failed during processing. Considerably shortened life results if the heaters are operated at temperatures above their maximum-rated sheath temperature of 1350°F. In the future, therefore, longer processing time at 1350°F will be used.

The most recent insulation envelope design (Figure 6-5) greatly simplifies the shield cladding problem in that the dimensional requirements for the exterior surface of the shield are greatly relaxed. It is anticipated that the inner liner - neck tube of the insulation envelope could be made of titanium; or if a material susceptible to eutectic formations were used, a flame-sprayed cladding could be applied to the neck-tube area in contact with the shield. The effect of shield outgassing upon this envelope design has not been evaluated.

4.4 BIOLOGICAL RADIATION SHIELD FABRICATION

The biological radiation shield was fabricated from U-8% Mo alloy at the Nuclear Metals Division of the National Lead Company. Fabrication proceeded through alloying and casting processes (Figures 4-3 and 4-4). When fabrication was completed, radiography revealed a void in the bottom of the shield. The void was plugged by machining a rod and inserting it into the void. The completed shield, with plug and assembly bolts, weighed 255 pounds prior to cladding.

A copper cladding to protect against oxidation and eutectic was specified for the shield. The cladding was provided by plating a 0.032-inch layer of copper to the exterior of the shield, and by fitting a copper cylinder to the shield cavity. The copper plating and cylinder were given a 0.0005-inch flashing of chromium to prevent oxidation of the copper at operating temperatures.

Figure 4-3. Shield Casting with Sprue Attached

Figure 4-4. Shield Casting Showing Capsule Cavity

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When fabrication was completed, the radiation shield was shipped to the Linde Division for enclosure in the insulation envelope. Final weight was 241.75 pounds for the main cask and 16.25 pounds for the plug. The total weight of 258.3 pounds includes the six plug-retainer bolts. The certified analysis of the uranium alloy is as follows:

Table 4-1. Uranium Alloy Analysis Data

Uranium	92.5 percent
Molybdenum	7.5 percent
Density	17.48 g/cc
Tensile strength	126,500 psi
Yield strength	122,250 psi
Elongation	5 percent minimum
Expansion	6.5×10^{-6} units/unit/°F at 70°F nominal

Upon arrival at Linde five or six small cracks and two blisters were present in the plating. National Lead indicated that the defects were not present at the time of shipment. While stress cracking is a common phenomenon with heavy electroplate (upon some substrates), close examination pointed to the possibility that electrolyte had been entrapped under the cladding. The shield was heated to 350°F to see if additional cracking and blistering occurred. The low temperature was chosen to avoid precipitation of the alpha phase. Oxidation was reduced to a minimum, and the eutectic problem was eliminated entirely, permitting the use of the stainless-steel heater block already available at Linde. After this heating, several more cracks appeared and two new blisters formed (one quite large at 2.3 inches diameter). The cladding appeared to be intact.

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4.5 BIOLOGICAL RADIATION SHIELD SAMPLE PLATING TESTS

A number of shield material samples were plated by National Lead and sent to 3M for evaluation. Two specimens each of six different platings were received. One of each pair was sent intact, while the other was sectioned. The sectioned pieces had been heat-treated at a pressure of 10 microns mercury for 4 hours at 1300°F, and then furnace-cooled to 800°F before air exposure. The plating thickness appeared uniform in all instances.

At National Lead the first four specimens were plated in a copper cyanide bath. However, the plating efficiency was poor and the samples tended toward severe treeing. All subsequent plating was done in a copper sulfate bath. Half the specimens received a nickel strike of about 0.001 inch before the 0.025-inch copper plating. The other specimens were plated with 0.025 inch of copper directly on uranium. The nickel strike reduced the adherence of the copper plate and seemed to induce blistering. As a result, the nickel strike was eliminated from all production components. Several specimens received a 0.001-inch plating of chromium over the copper plate.

On receipt from National Lead, the samples (0.50-inch-diameter cylinders) were sealed in an argon atmosphere inside quartz ampoules, one sample to an ampoule, and were then fired at 1500°F for 200 hours. The best appearing samples were those which had received a chromium plate over the copper with no nickel substrate. The samples are shown in Figure 4-5.

Four of the sectioned specimens exhibited materials compatibility under the test conditions. Samples No. 1 (Figure 4-6) and No. 2 (Figure 4-7) were plated in a cyanide bath. After heating, Sample No. 1 showed a more irregular profile than No. 2 (Figures 4-8 and 4-9). The remaining samples were plated from a sulfate bath. Except as noted, all samples received a 0.0005-inch over-plate or flashing of chromium.

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Figure 4-5. Plated and Heated Radiation-Shield Test Samples

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Figure 4-6. Electroplated Shield Specimen
Sample No. 1
U-8% Mo Clad with Ni-Cu-Cr
(plated in CN^-)

Figure 4-7. Electroplated Shield Specimen
Sample No. 2
U-8% Mo Clad with Cu-Cr
(plated in CN^-)

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Figure 4-8. Cross Section of U-8% Mo
Sample No. 2, 2-1/2X
(see Figure 4-7)

Figure 4-9. Cross Section of U-8% Mo
Sample No. 2, 30X
(see Figure 4-7)

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Sample No. 3 (Figure 4-10) was plated in the same manner as the radiation shield. Sample No. 4 (Figure 4-11) was identical except for the nickel base plate. While both samples had an excellent appearance, Sample No. 4 did not appear to be quite as good as the Cu-Cr sample, and therefore was not used in the actual shield plating process.

Samples No. 5 and 6 were plated as comparative samples without the chromium flashing. Sample No. 5 (Figure 4-12) consisted of only a copper plate, while Sample No. 6 (Figure 4-13) had a nickel base. Although the photographs show some mottled effects on Sample No. 5, it actually was little affected. However, Sample No. 6 (Figures 4-13, 4-14, and 4-15) showed a severe change in the exterior surface which possibly reflected a eutectic or melting condition in the shield alloy. Sectioning showed that this was not the case. It was therefore surmised that entrapped electrolyte had caused most of the surface cracking and blistering.

Sample No. 3 was heated at 1500°F for 1887 hours. It was then sectioned, mounted, and polished for metallographic analysis. A cursory examination revealed a zone at the U-8% Mo - copper interface where migration had taken place between the two metals. The composition of the resulting alloy has not been determined. Sample No. 4 remained at 1500°F for 3015 hours. It was then lowered to 1375°F where it has been exposed for an additional 3438 hours. Two other samples have also been exposed to 1375°F for more than 5000 hours. While some diffusion has occurred, the plating appears quite functional. Additional test data on the suitability of copper as a cladding material has been provided by more than 6000 hours of SNAP-23 system operation.

Although the use of copper as a cladding material appears quite feasible at the present time, the effect of diffusion upon barrier properties has not been determined. It is expected that from the diffusion rates of the above samples, and from the use of thinner cladding specimens which will provide accelerated boundary movement, the effect of barrier diffusion can be clarified early in Phase II of the SNAP-21B program.

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Figure 4-10. Electroplated Shield Specimen
Sample No. 3
U-8% Mo Clad with Cu
(plated in SO_4^{-2})-Cr

Figure 4-11. Electroplated Shield Specimen
Sample No. 4
U-8% Mo Clad with Ni-Cu-Cr
(plated in SO_4^{-2})

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Figure 4-12. Electroplated Shield Specimen
Sample No. 5
U-8% Mo Clad with Cu
(plated in SO_4^{-2})

Figure 4-13. Electroplated Shield Specimen
Sample No. 6
U-8% Mo Clad with Ni-Cu
(plated in SO_4^{-2})

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Figure 4-14.
Cross Section of Sample No. 6
(see Figure 4-13) 2-1/2X
Magnification

Figure 4-15.
Cross Section of Sample No. 6
(see Figure 4-13) 30X
Magnification

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4.6 REFERENCES

1. Report No. NY00(3321)-3 SNAP-21B Program Quarterly Report No. 1 (9 March to 30 June 1964). AEC Contract AT(30-1)3321 (August 1964).
2. Uranium Metallurgy, by W. D. Wilkinson, Inter-Science Publishers, 1962.

5.0 DC-DC POWER CONDITIONER

5.1 PROGRAM OBJECTIVES

- The SNAP-21B Phase I objectives were to develop a power conditioner capable of converting the 5.1-volt dc thermopile output to 24 volts dc with a maximum ripple of 0.1 volt (peak-to-peak).
- With a minimum efficiency of 85 percent under a system load of 57.6 ohms at EOL generator output.
- With a 5-year life at an ambient operating temperature range of $40^{\circ} \pm 5^{\circ}\text{F}$, and at a storage temperature range of -65° to 150°F .

5.2 PROGRAM ACCOMPLISHMENTS

- Five power conditioners were placed on long-term test. The conditioners consist of a dc-dc converter, filter, and regulator. All units are exhibiting efficiencies above 85 percent.
- Four (Trio Laboratories) regulators were placed on long-term test. These regulators have displayed an acceptably small variation in regulated voltage.
- An automatic selector switch for redundant converter operation has been designed, breadboarded, and placed on test. The switch and two associated power conditioners are performing satisfactorily.

5.3 POWER CONDITIONER DESIGN AND ANALYSIS

5.3.1 Converter

The SNAP-21B converter was designed to operate from a three-terminal thermoelectric generator. Figure 5-1 shows the connection diagram for the generator. The third terminal provides starting and operating bias to the converter, resulting in an efficiency improvement of several percent over the more conventional technique of using a resistive divider to obtain the bias voltage.

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Figure 5-1. Connection Diagram for the 48-Couple Generator

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The converter (Figure 5-2) was selected for maximum efficiency and high reliability. Only standard 2N series transistors were used in the construction of the converters without pre-selection for special characteristics.

Early in the program two experimental converters, designated MP-A and MP-B, were designed and built (Figure 5-3). Three converters, designated MP-C, MP-D, and MP-E, were constructed and placed in a prototype housing. As Table 5-1 indicates, all converters exceeded the minimum efficiency requirement of 85 percent and met the electrical specifications.

5.3.2 Regulator

Because of the characteristic decay in the heat output of a radioisotopic-fueled thermoelectric generator, extra power is produced at the beginning of life. To absorb this power, to stabilize the output voltage against changes in load current, and to protect the generator under no-load conditions, a regulator is required. It was determined that the proposed zener-diode regulator would not meet the performance and reliability requirements of the SNAP-21B system. Therefore, two approaches were made: (1) investigation of a commercial regulator, and (2) development of a regulator from such discrete components as transistors, resistors, zener reference diodes, and capacitors.

A pre-packaged regulator (Figure 5-4) is manufactured by the Semiconductor Division of Trio Laboratories, Incorporated. The trade name of this device is "Super/Reg" and it is described as a "Synthesized Zener Diode." The device is a complete voltage regulator in a 0.5-inch-high by 1-inch-diameter transistor package. In March 1965, six Trio regulators designated A through F were put on long-term test. At a later date six additional regulators designated G through L were placed on long-term test in conjunction with the SNAP-21B converters.

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PARTS LIST

Q1-Q2	BENDIX	USA 2N1653
Q3-Q4	TEXAS INST.	2N3147
R1	DALE RH5	$6.81\Omega \pm 1\%$
R2	" "	$20\Omega \pm 1\%$
R3-R4	" "	$1.0\Omega \pm 1\%$
R5	" MF $\frac{1}{4}$	80K Ω - SELECT FOR 24.5 V-NO LOAD
C1-C2	MALLORY TSS396K010	PP-10V-39 MFD TO LEVEL R OF TSS100
C3-C4-C5-C6	" TSS476K035	PD-35V-47MFD TO LEVEL R OF TSS100
$\triangle$ REGULATOR: TRIO-LABS		75TE22
OR 3MDPD-37-1340A		
$\triangle$ TI-TRANS DWG DPD-37-1133-A		3M-T-MP-I

* INDICATES PART OF T1

Figure 5-2. Converter Circuit

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Figure 5-3. Experimental DC-DC Converter

Table 5-1. Performance of Converters MP-B, -C, -D, and -E

E_{in} volts	I_{in} amps	E_{out} volts	I_{out} amps	P_{in} watts	P_{bias} watts	P_{total} watts	P_{out} watts	Efficiency Percent	Converter Designation	Comment
4.83	2.47	24.00	0.446	11.91	0.107	12.01	10.70	89.1	MP-B	Breadboard converter, placed on long term test
4.90	2.31	24.27	0.421	11.31	0.105	11.42	10.21	89.1	MP-C	Bench test in case, with regulator
4.88	2.34	24.00	0.425	10.20	0.105	11.51	10.20	88.6	MP-C	
4.98	2.27	24.58	0.000	11.30	0.105	11.40	0.00	----	MP-C	As above, open circuit 70°F air temperature
4.87	2.24	24.00	0.402	10.89	0.105	11.00	9.66	88.7	MP-C	As above, loaded to 24 v, 150°F air temperature
4.95	2.17	24.42	0.000	10.74	0.105	0.00	0.00	----	MP-C	As above, no load, 150°F air temperature
4.90	2.32	24.00	0.421	11.38	0.105	11.48	10.11	88.1	MP-D	With regulator, before welding
5.01	2.25	24.58	0.000	11.25	0.105	0.00	0.00	----	MP-D	As above, no load
4.89	2.33	24.00	0.423	11.39	0.105	11.50	10.15	88.3	MP-D	As above, after welding
5.00	2.25	24.64	0.000	11.26	0.105	11.36	0.00	----	MP-D	As above, no load
4.90	2.30	24.15	0.418	11.28	0.105	11.38	10.11	88.8	MP-E	Bench test
4.88	2.34	24.00	0.425	11.40	0.105	11.50	10.19	88.5	MP-E	With regulator, before welding
5.01	2.24	24.70	0.000	11.22	0.105	11.32	0.00	----	MP-E	As above, no load
4.88	2.34	24.00	0.424	11.41	0.105	11.52	10.16	88.2	MP-E	As above, after welding
5.00	2.25	24.69	0.000	11.23	0.105	11.34	0.00	----	MP-E	As above, no load

Electrical Schematic

Exterior View

Figure 5-4. Trio Laboratories "Synthesized Zener Diode"

Early in testing, regulator B burned out because of a test-fixture short circuit. Shortly after being placed on test, the regulation voltage of Unit E changed excessively because of a resistor which open circuited at about 150°F. Regulators G, H, and J failed within 250 hours as the result of bad zener-reference diodes. In all cases of regulator failure, the malfunction was produced by a softening of the 'knee' which occurs when a diode has acceptable voltage at high current values, but excessively low voltage at low current values. As a zener diode deteriorates, its characteristic curve (Figure 5-5) tends to regress from one similar to Curve B to one similar to Curve A. The cause of the Trio diode 'knee' softening was assumed to be contamination on the surface of the junction, which could have resulted from bending the diode leads excessively close to the glass seal so that it cracked.

In view of the reliability shortcomings of the commercial regulators, the SNAP-21B regulators will be constructed from discrete components. Solutions to the problem of zener diode reliability will include:

- 1) Increasing the zener current from 0.0006 to 0.015 amperes
- 2) Using the saturation characteristic of a square loop core
- 3) Selecting, screening, and burning in standard diodes (assuming that the majority of failures occurs early).

In addition, a silicon planar-zener diode will be used for the reference voltage, and adequate room will be provided for component loads. This diode has a much sharper 'knee' than a standard zener diode, is assumed to degrade at a slower rate, and is less subject to the problems which result from a cracked glass seal.

Figure 5-6 shows the layout and schematic of the SNAP-21B regulator which has been designed. Preliminary reliability calculations indicate that a failure rate of 0.02 percent per 1000 hours should be possible, resulting in failure of 0.88 percent of the regulators over a 5-year, 44,000-hour operating life. Probability of regulator success would therefore be 99.12 percent.

Figure 5-5. Electrical Characteristics of the Zener Diode

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Electrical Schematic

Installation Layout

Figure 5-6. The SNAP-21B Regulator

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5.3.3 Automatic Selector Switch

To obtain power conversion reliability, an automatic selector switch was designed and constructed. The switch selects one of two converter-regulator combinations to provide redundant converter operation. This design may be used in later phases of the SNAP-21B program. Figure 5-7 is a block diagram of the selector circuit, which operates as follows:

When the power supply is turned on, the flip-flop will be in one state or the other. Power will flow through one of the current converters (box 4 or 5) to its corresponding switch. The switch connects the corresponding converter-regulator (box 8 or 9) to the thermoelectric generator and to the load. The path activated will depend on which state the flip-flop is in. If the sensing circuit detects an improper operating condition, such as high or low output voltage, the time delay will generate a pulse after approximately one second. This pulse will change the state of the flip-flop, turning off one converter and turning on the other. If the second converter does not come up to performance specification after the time-delay interval, the pulse generator will emit another pulse and the flip-flop will switch back to the first converter. This action will continue until one converter or the other begins to operate properly.

Figure 5-8 shows the various components in the automatic selector switch. This unit is on long-term test with power conditioners MP-A and MP-B.

5.3.4 Converter Case

Figures 5-9, 5-10, and 5-11 illustrate the design of the converter case. Sufficient space has been provided to house two converters, two regulators, and an automatic selector switch. Because redundant converter operation was not used in Phase I of the program, the present power conditioner housings contain only one converter and regulator.

Figure 5-7. Automatic Selector Switch for Redundant Operation of DC-DC Converters

Figure 5-8. Layout View of the Automatic Selector Switch

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Figure 5-9. Cover Installed on Converter Case

Figure 5-10.
Case and Converter with Cover Removed

Figure 5-11. Converter Removed from Case

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The enclosure of the converter case was designed to:

- 1) Provide a short heat-flow path from the converter components to the pressure vessel
- 2) Position and retain the converter within the pressure vessel
- 3) Provide maximum use of space in the top hemisphere of the pressure vessel.

The converter enclosure parts are constructed of 12-gauge aluminum that is heliarc welded to a 6061 aluminum base plate. The inside of the case has two 1/4-inch aluminum standards for mounting the pie-shaped converter base. The bottom of the case has a tubulation fitting so that the sealed case can be evacuated and backfilled with an inert gas. The enclosure is sealed by heliarc welding the cover in place.

A leak-rate specification for the case was determined as follows: If the minimum pressure in the converter case at -55°C (-67°F) is to be 0 psig, then the maximum internal pressure at 70°C (158°F) will be 23.6 psia. The maximum leak rate must not result in a pressure lower than 23.6 psia at 70°C if the converter case is held at 70°C over a 5-year period. If the initial pressure at 70°C is 30 psia, the maximum leak rate will be 7.22×10^{-6} cc/sec. Allowing a 5:1 safety factor and considering the helium content (2.77 percent) of the backfill gas, the maximum leak rate on a helium mass-spectrometer leak detector will be 10^{-8} cc/sec. The sensitivity of the leak detector is 10^{-9} cc/sec.

In addition to defining the permissible leak rate, a check of the radiation pressure buildup was made. Potting compounds have a tendency to decompose into gases in the presence of gamma radiation. Because potting compounds are used in constructing the converter, gas evolution was investigated. No gas evolution data was available for the potting compounds which were used, so a preliminary calculation was based on the outgassing rate of natural

rubber. This material is assumed to be a sufficiently accurate standard because it has one of the highest outgassing rates. Calculations indicate that a pressure increase of only 0.0002 psi in 30 psia will occur after 5 years of exposure to the BOL radiation dose of 200 mr/hr. Because the increase will be more than 3 orders of magnitude below what could be tolerated, no problem is expected.

5.4 POWER CONDITIONER FABRICATION

The fabrication procedure for the dc-dc converter is to:

- 1) Assemble regulator per print and adjust for proper voltage.
- 2) Install regulator assembly and bolt to case; test for proper voltage.
- 3) Connect the regulator leads to converter.
- 4) Connect regulator to converter.
- 5) Install converter and bolt to case.
- 6) Connect lead wires to cover and solder.
- 7) Test power conditioner for compliance to the specifications of Step 10.
- 8) Weld the cover to case by means of inert-gas-shielded electric arc welding.
- 9) Backfill with nitrogen gas containing 2.77 percent helium and leak test.
- 10) Test converter for input voltage, bias voltage input current, bias current, and output current. Measurements are to be made with the output voltage adjusted to 24.0 volts. If the efficiency of the converter is less than 88 percent, or if the input voltage is not between 5.0 and 5.2 volts when tested, the converter must be rejected or reworked.

5.5 POWER CONDITIONER TESTING

5.5.1 Test Fixtures

A converter test fixture, containing a regulated power supply, was designed to simulate two separate thermoelectric generators, including the characteristics of the bias tap. All measurement points are brought out to terminals on a front panel. Three types of measurements are made: voltage, current and temperature. The voltage and current are read out on a Fluke differential voltmeter, and current readings are obtained with a special 0.25-percent precision shunt. The temperature readings are obtained with iron-constantan thermocouples and a potentiometer accurate to $\pm 1^\circ\text{F}$. Parameters measured are input current, output current, input voltage, output voltage, bias voltage, temperature of the converter mounting base, and temperature of the ambient air inside the cabinet. A running-time meter is provided to accurately record the actual operating hours.

The regulator test fixture consists of a regulated power supply, ballast resistors, and heat sinks for the regulators. All measurement points are brought out to terminals on a front panel. The measurement techniques are similar to those used for the converter test fixture. Parameters measured are terminal voltage, regulator current, mounting base temperature, and ambient temperature.

5.5.2 Test Performance

Table 5-1 (Page 5-6) gives a performance description of the first three prototype converters (MP-C, MP-D, and MP-E) and experimental converter MP-B at various stages in the early part of the program. The life-test data in Table 5-2 shows that converter MP-B has been sufficiently stable. The long-term test results for converter MP-C are listed in Table 5-3. After 9490 hours the converter continues to exhibit high efficiency and stability.

Table 5-4 gives the performance of power conditioner MP-B (converter MP-B and regulator MPR-A-1). As can be seen, the no-load voltage continues to be stable.

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Power conditioner MP-A (converter MP-A and Trio Laboratory regulator L) and power conditioner MP-D (converter MP-D and Trio Laboratory regulator K) have been placed on long-term test with the automatic selector switch. The performance of this combination is presented in Table 5-5. The no-load voltage has been sufficiently stable.

A Trio Laboratory regulator designated Unit I has been operating in conjunction with converter MP-C. Table 5-6 presents the long-term test results. Again, the no-load voltage is sufficiently stable.

The first group of six Trio Laboratory regulators (A through E) and regulator HPR-A are undergoing long-term test in the fixture discussed in Section 5.3.1. The no-load voltage at 1.5 amperes is tabulated in Table 5-7. All regulators are exhibiting sufficient stability.

The performance of power conditioner MP-E, which is in the systems test, will be reported in Section 8.0.

A summary of the power conditioner converters and regulators is presented in Table 5-8.

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Table 5-2. Converter Performance of Power Conditioner MP-B

E_{IN} Volts	I_{IN} Amps	P_{IN}^* Watts	E_{OUT} Volts	I_{OUT} Amps	P_{OUT}^+ Watts	Efficiency Percent	Hours on Test
4.837	2.470	12.054	24.00	0.446	10.70	88.76	172
4.840	2.460	12.013	24.00	0.445	10.68	88.90	242
4.841	2.465	12.040	24.00	0.445	10.68	88.70	341
4.837	2.474	12.066	24.00	0.447	10.73	88.90	452
4.837	2.467	12.032	24.00	0.446	10.70	88.90	542
4.838	2.464	12.022	24.00	0.446	10.70	88.90	667
4.839	2.471	12.057	24.00	0.446	10.70	88.77	740
4.838	2.476	12.078	24.00	0.447	10.73	88.82	837
4.838	2.472	12.059	24.00	0.447	10.73	88.97	908
4.838	2.468	12.040	24.00	0.447	10.72	89.00	1006
4.838	2.475	12.074	24.00	0.448	10.74	88.96	1076
4.839	2.465	12.028	24.00	0.446	10.70	88.95	1196
4.839	2.463	12.018	24.00	0.445	10.68	88.88	1267
4.836	2.467	12.030	24.00	0.446	10.71	88.99	1341
4.838	2.476	12.079	24.00	0.448	10.74	88.91	1411
4.837	2.474	12.068	24.00	0.447	10.73	88.91	1501
4.839	2.473	12.068	24.00	0.447	10.73	88.91	1601
4.836	2.470	12.046	24.00	0.447	10.72	88.99	1637
4.839	2.476	12.082	24.00	0.447	10.74	88.89	1704
4.837	2.472	12.058	24.00	0.447	10.72	88.90	1823
4.836	2.476	12.075	24.00	0.448	10.75	89.03	1918
4.835	2.470	12.043	24.00	0.447	10.72	89.01	2018
4.836	2.492	12.051	24.00	0.451	10.82	89.04	2130
4.839	2.470	12.053	24.00	0.447	10.72	88.94	2254
4.838	2.468	12.040	24.00	0.447	10.72	89.03	2331
4.837	2.470	12.047	24.00	0.447	10.72	88.98	2401
4.839	2.469	12.047	24.00	0.447	10.72	88.96	2493
4.839	2.471	12.058	24.00	0.447	10.73	88.97	2568
4.839	2.462	12.015	24.00	0.445	10.68	88.89	2665
4.840	2.470	12.056	24.00	0.446	10.74	88.78	2711
4.836	2.462	12.007	24.00	0.445	10.68	88.95	2829
4.835	2.425	11.83	24.00	0.440	10.56	89.29	2878
4.838	2.458	11.99	24.00	0.444	10.66	88.86	2977
4.838	2.457	11.987	24.00	0.444	10.66	88.95	3049
4.836	2.472	11.954	24.00	0.448	10.74	89.16	3147
4.837	2.465	11.923	24.00	0.446	10.71	89.08	3215
4.839	2.469	12.048	24.00	0.447	10.73	89.06	3312
4.839	2.468	12.043	24.00	0.446	10.71	89.39	3382

* Includes approximately 0.105 watts bias power.

+ Includes regulator and filter losses.

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Table 5-2. Converter Performance of Power Conditioner MP-B (Continued)

<u>E_{IN}</u> <u>Volts</u>	<u>I_{IN}</u> <u>Amps</u>	<u>P_{IN}*</u> <u>Watts</u>	<u>E_{OUT}</u> <u>Volts</u>	<u>I_{OUT}</u> <u>Amps</u>	<u>P_{OUT}†</u> <u>Watts</u>	<u>Efficiency</u> <u>Percent</u>	<u>Hours</u> <u>on Test</u>
4.839	2.468	12.043	24.00	0.446	10.71	88.98	3498
4.839	2.469	12.048	24.00	0.446	10.72	88.97	3557
4.839	2.467	12.037	24.00	0.447	10.72	89.8	3648
4.841	2.467	12.041	24.00	0.446	10.704	88.8	3696
4.840	2.471	12.059	24.00	0.447	10.728	88.9	3816
4.839	2.470	12.052	24.00	0.446	10.704	88.8	3887
4.837	2.448	11.940	24.00	0.442	10.608	88.8	3982
4.838	2.468	12.040	24.00	0.446	10.704	89.8	4055
4.838	2.466	12.030	24.00	0.446	10.704	88.9	4152
4.839	2.466	12.032	24.00	0.446	10.704	88.9	4224
4.838	2.465	12.025	24.00	0.446	10.704	89.0	4345
4.838	2.468	12.040	24.00	0.446	10.704	88.9	4411
4.838	2.469	12.045	24.00	0.446	10.704	88.9	4497
4.838	2.468	12.040	24.00	0.446	10.704	88.9	4656
4.837	2.468	12.037	24.00	0.446	10.704	88.9	4731
4.838	2.470	12.049	24.00	0.466	10.704	88.8	4826
4.837	2.467	12.032	24.00	0.466	10.704	88.9	4915
4.838	2.468	12.040	24.00	0.466	10.704	88.9	5011
4.838	2.475	12.074	24.00	0.477	10.723	88.8	5086
4.837	2.471	12.052	24.00	0.477	10.723	88.9	5148
4.839	2.468	12.042	24.00	0.446	10.704	88.9	5247
4.841	2.465	12.033	24.00	0.445	10.680	88.8	5338
4.837	2.471	12.052	24.00	0.447	10.728	89.0	5411
4.838	2.469	12.045	24.00	0.446	10.704	88.9	5483
4.842	2.467	12.045	24.00	0.446	10.704	88.8	5604
4.841	2.478	12.095	24.00	0.448	10.752	88.8	5675
4.838	2.468	12.040	24.00	0.446	10.368	88.9	5772
4.837	2.466	12.028	24.00	0.446	10.704	88.9	5847
4.839	2.473	12.066	24.00	0.447	10.728	88.9	5916
4.837	2.466	12.028	24.00	0.446	10.704	88.9	6017
4.837	2.471	12.052	24.00	0.447	10.728	89.0	6083
4.839	2.467	12.037	24.00	0.446	10.704	88.9	6185

* Includes approximately 0.105 watts bias power.

† Includes regulator and filter losses.

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Table 5-2. Converter Performance of Power Conditioner MP-B (Continued)

E_{IN} Volts	I_{IN} Amps	P_{IN}^* Watts	E_{OUT} Volts	I_{OUT} Amps	P_{OUT}^+ Watts	Efficiency Percent	Hours on Test
4.838	2.470	12.050	24.00	0.446	10.704	88.8	6348
4.839	2.463	12.018	24.00	0.445	10.680	88.8	6446
4.840	2.467	12.040	24.00	0.446	10.704	88.9	6615
4.840	2.467	12.040	24.00	0.446	10.704	88.9	6707
4.840	2.463	12.020	24.00	0.445	10.680	88.9	6832
4.841	2.460	12.008	24.00	0.444	10.656	88.7	7024
4.840	2.465	12.030	24.00	0.445	10.680	88.7	7193
4.840	2.464	12.025	24.00	0.445	10.680	88.8	7380
4.840	2.467	12.040	24.00	0.446	10.704	88.9	7594
4.840	2.466	12.035	24.00	0.446	10.704	88.9	7745
4.841	2.469	12.052	24.00	0.446	10.704	88.8	7842
4.843	2.461	12.020	24.00	0.445	10.680	88.8	8032
4.840	2.469	12.051	24.00	0.447	10.728	89.02	8196
4.840	2.462	12.017	24.00	0.445	10.680	88.87	8387
4.841	2.468	12.048	24.00	0.446	10.704	88.84	8583
4.840	2.467	12.041	24.00	0.446	10.704	88.90	8723
4.839	2.467	12.039	24.00	0.446	10.704	88.91	8867
4.839	2.464	12.024	24.00	0.446	10.704	89.02	9039
4.840	2.467	12.041	24.00	0.446	10.704	88.90	9301
4.840	2.469	12.051	24.00	0.446	10.704	88.82	9396
4.841	2.466	12.039	24.00	0.446	10.704	88.91	9565
4.840	2.467	12.041	24.00	0.446	10.704	88.90	9729
4.840	2.468	12.046	24.00	0.446	10.704	88.85	9919

* Includes approximately 0.105 watts bias power.

+ Includes regulator and filter losses.

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Table 5-3. Converter Performance of Power Conditioner MP-C

<u>E_{IN}</u> <u>Volts</u>	<u>I_{IN}</u> <u>Amps</u>	<u>P_{IN}*</u> <u>Watts</u>	<u>E_{OUT}</u> <u>Volts</u>	<u>I_{OUT}</u> <u>Amps</u>	<u>P_{OUT}†</u> <u>Watts</u>	<u>Efficiency</u> <u>Percent</u>	<u>Hours</u> <u>On Test</u>
4.909	2.386	11.814	24.00	0.434	10.42	88.10	23
4.911	2.383	11.804	24.00	0.433	10.39	88.00	113
4.911	2.381	11.795	24.00	0.433	10.39	88.10	238
4.914	2.378	11.787	24.00	0.432	10.37	87.96	311
4.912	2.387	11.826	24.00	0.434	10.42	88.07	408
4.912	2.387	11.826	24.00	0.434	10.42	88.09	479
4.912	2.380	11.792	24.00	0.433	10.39	88.08	577
4.913	2.385	11.819	24.00	0.434	10.42	88.12	647
4.912	2.384	11.812	24.00	0.436	10.41	88.28	767
4.912	2.382	11.802	24.00	0.433	10.39	88.06	838
4.910	2.381	11.792	24.00	0.433	10.40	88.20	912
4.911	2.394	11.860	24.00	0.435	10.44	88.10	982
4.911	2.388	11.830	24.00	0.434	10.43	88.16	1072
4.913	2.390	11.845	24.00	0.434	10.42	87.97	1172
4.911	2.385	11.816	24.00	0.434	10.41	88.10	1208
4.913	2.391	11.850	24.00	0.435	10.44	88.10	1275
4.907	2.389	11.825	24.00	0.435	10.44	88.29	1394
4.916	2.391	11.856	24.00	0.436	10.45	88.14	1489
4.909	2.385	11.810	24.00	0.434	10.42	88.23	1589
4.910	2.404	11.907	24.00	0.438	10.51	88.27	1701
4.910	2.387	11.823	24.00	0.434	10.43	88.21	1825
4.912	2.394	11.861	24.00	0.436	10.46	88.19	1902
4.910	2.386	11.817	24.00	0.434	10.41	88.11	1972
4.909	2.388	11.824	24.00	0.435	10.43	88.22	2064
4.913	2.401	11.899	24.00	0.437	10.49	88.14	2139
4.911	2.381	11.796	24.00	0.433	10.39	88.10	2236
4.913	2.387	11.830	24.00	0.434	10.42	88.05	2282
4.912	2.368	11.632	24.00	0.432	10.37	88.35	2400
4.910	2.340	11.591	24.00	0.426	10.22	88.21	2449
4.909	2.392	11.845	24.00	0.435	10.44	88.14	2548
4.910	2.377	11.774	24.00	0.432	10.38	88.17	3049
4.910	2.385	11.710	24.00	0.434	10.42	88.27	3147
4.910	2.378	11.675	24.00	0.433	10.40	88.30	3215
4.912	2.383	11.808	24.00	0.434	10.43	88.33	2883
4.911	2.382	11.701	24.00	0.434	10.40	88.93	2953

*Includes approximately 0.105 watts bias power.

†Includes regulator and filter losses.

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Table 5-3. Converter Performance of Power Conditioner MP-C (Continued)

<u>E_{IN}</u> <u>Volts</u>	<u>I_{IN}</u> <u>Amps</u>	<u>P_{IN}*</u> <u>Watts</u>	<u>E_{OUT}</u> <u>Volts</u>	<u>I_{OUT}</u> <u>Amps</u>	<u>P_{OUT}†</u> <u>Watts</u>	<u>Efficiency</u> <u>Percent</u>	<u>Hours</u> <u>On Test</u>
4.908	2.383	11.798	24.00	0.434	10.42	88.30	3069
4.909	2.387	11.820	24.00	0.434	10.43	88.24	3122
4.911	2.384	11.809	24.00	0.434	10.41	88.20	3219
4.911	2.382	11.800	24.00	0.433	10.39	88.00	3267
4.910	2.386	11.817	24.00	0.435	10.44	88.30	3387
4.920	2.456	12.185	24.00	0.447	10.72	88.00	3458
4.906	2.363	11.694	24.00	0.430	10.32	88.20	3553
4.909	2.385	11.809	24.00	0.434	10.41	88.90	3626
4.910	2.380	11.787	24.00	0.433	10.39	88.16	3723
4.911	2.382	11.698	24.00	0.433	10.39	88.82	3795
4.911	2.381	11.795	24.00	0.433	10.39	88.10	3916
4.912	2.383	11.807	24.00	0.433	10.39	88.01	3982
4.913	2.382	11.804	24.00	0.433	10.39	88.03	4058
4.913	2.384	11.814	24.00	0.433	10.39	87.96	4227
4.911	2.383	11.804	24.00	0.433	10.39	88.03	4302
4.912	2.384	11.812	24.00	0.434	10.42	88.18	4397
4.910	2.384	11.792	24.00	0.433	10.39	88.12	4486
4.912	2.382	11.802	24.00	0.433	10.39	88.05	4582
4.912	2.388	11.831	24.00	0.434	10.41	88.03	4657
4.910	2.385	11.812	24.00	0.434	10.41	88.18	4719
4.911	2.384	11.707	24.00	0.433	10.39	88.00	4819
4.913	2.377	11.780	24.00	0.432	10.37	88.01	4909
4.910	2.380	11.787	24.00	0.433	10.39	88.16	4982
4.910	2.379	11.782	24.00	0.433	10.39	88.20	5054
4.910	2.377	11.773	24.00	0.432	10.37	88.06	5175
4.911	2.387	11.824	24.00	0.434	10.41	88.09	5246
4.910	2.375	11.763	24.00	0.432	10.37	88.14	5343
4.907	2.371	11.736	24.00	0.431	10.34	88.13	5418
4.911	2.378	11.780	24.00	0.432	10.36	88.01	5487
4.909	2.369	11.731	24.00	0.431	10.34	88.18	5588
4.909	2.375	11.760	24.00	0.432	10.36	88.16	5654
4.911	2.371	11.745	24.00	0.431	10.34	88.41	5756
4.910	2.374	11.759	24.00	0.432	10.36	88.17	5919
4.910	2.363	11.602	24.00	0.429	10.30	87.89	6017
4.910	2.368	11.626	24.00	0.430	10.32	87.98	6186
4.910	2.368	11.759	24.00	0.430	10.32	87.76	6278
4.910	2.363	11.705	24.00	0.429	10.29	87.96	6403
4.911	2.360	11.589	24.00	0.429	10.29	88.06	6595

*Includes approximately 0.105 watts bias power.

†Includes regulator and filter losses.

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Table 5-3. Converter Performance of Power Conditioner MP-C (Continued)

<u>E_{IN}</u> <u>Volts</u>	<u>I_{IN}</u> <u>Amps</u>	<u>P_{IN}*</u> <u>Watts</u>	<u>E_{OUT}</u> <u>Volts</u>	<u>I_{OUT}</u> <u>Amps</u>	<u>P_{OUT}†</u> <u>Watts</u>	<u>Efficiency</u> <u>Percent</u>	<u>Hours</u> <u>On Test</u>
4.910	2.365	11.715	24.00	0.430	10.32	88.09	6764
4.911	2.370	11.741	24.00	0.430	10.32	87.89	6951
4.910	2.372	11.749	24.00	0.431	10.34	88.04	7165
4.910	2.369	11.734	24.00	0.431	10.34	88.15	7316
4.911	2.374	11.761	24.00	0.431	10.34	87.95	7413
4.913	2.370	11.747	24.00	0.431	10.34	88.05	7603
4.910	2.373	11.754	24.00	0.432	10.37	88.20	7767
4.909	2.367	11.732	24.00	0.430	10.32	88.03	7958
4.910	2.373	11.754	24.00	0.431	10.34	88.00	8154
4.910	2.371	11.745	24.00	0.431	10.34	88.07	8294
4.909	2.371	11.742	24.00	0.431	10.34	88.09	8438
4.909	2.367	11.723	24.00	0.431	10.34	88.24	8610
4.910	2.373	11.754	24.00	0.432	10.37	88.21	8872
4.910	2.375	11.764	24.00	0.432	10.37	88.13	8967
4.909	2.366	11.718	24.00	0.430	10.32	88.07	9136
4.908	2.368	11.725	24.00	0.431	10.34	88.22	9300
4.908	2.369	11.730	24.00	0.431	10.34	88.18	9490

* Includes approximately 0.105 watts bias power.

† Includes regulator and filter losses.

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Table 5-4. Regulator Performance (Power Conditioner)

Conditioner: MP-B
Regulator: MPR-A-1

Conditioner: MP-B
Regulator: MPR-A-1

<u>Operating Hours</u>	<u>No Load Voltage</u>	<u>Operating Hours</u>	<u>No Load Voltage</u>
72	24.08	3903	24.08
149	24.08	4005	24.08
219	24.09	4168	24.08
311	24.08	4266	24.08
386	24.08	4435	24.08
483	24.08	4527	24.08
529	24.08	4652	24.08
647	24.08	4844	24.08
696	24.08	5013	24.08
795	24.08	5200	24.08
869	24.09	5414	24.08
967	24.08	5565	24.08
1039	24.08	5662	24.08
1132	24.08	5852	24.08
1202	24.08	6016	24.08
1318	24.08	6207	24.08
1377	24.08	6403	24.08
1468	24.08	6543	24.08
1516	24.08	6687	24.08
1636	24.08	6859	24.08
1706	24.08	7121	24.08
1802	24.08	7216	24.08
1875	24.08	7385	24.08
1972	24.08	7549	24.08
2044	24.08	7739	24.08
2165	24.08		
2231	24.08		
2307	24.08		
2476	24.08		
2551	24.08		
2646	24.08		
2735	24.08		
2831	24.08		
2906	24.08		
2968	24.08		
3067	24.08		
3158	24.08		
3231	24.08		
3303	24.08		
3424	24.08		
3495	24.08		
3592	24.08		
3667	24.08		
3736	24.08		
3837	24.08

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Table 5-5. Automatic Selector Switch Performance

<u>Hours</u>	<u>Out Put Voltage (Volts)</u>		<u>Condition</u>
	<u>Conditioner MP-A</u>	<u>Conditioner MP-D</u>	
0			
360	24.60	24.45	261 hours prior testing on con- ditioner MP-D
384	24.46	24.57	
504	24.48	24.58	
552	24.50	24.62	
648	24.47	24.58	
720	24.47	24.58	
816	24.45	24.58	
888	24.45	24.58	
984	24.46	24.59	
1056	24.47	24.59	
1176	24.47	24.58	
1224	24.47	24.58	
1320	24.47	24.58	
1368	24.45	24.58	
1488	24.46	24.58	
1560	24.46	24.58	
1656	24.43	24.56	
1824	24.43	24.56	
1968	24.46	24.49	
2136	24.45	24.65	
2304	24.46	24.58	
2472	24.48	24.58	
2568	24.48	24.58	
2640	24.48	24.58	
2736	24.44	24.58	
2832	24.44	24.57	
2903	24.49	24.59	
2975	24.48	24.59	
3095	24.46	24.59	
3167	24.46	24.58	
3263	24.47	24.59	
3335	24.48	24.59	
3407	24.48	24.59	
3503	24.48	24.58	
3575	24.47	24.59	
3671	24.45	24.58	Good, test continuing
3839	24.45	24.58	
3935	24.45	24.58	
4103	24.45	24.57	
4199	24.46	24.58	
4319	24.46	24.58	
4511	24.43	24.57	
4679	24.47	24.57	
4871	24.47	24.57	
5087	24.46	24.58	
5231	24.43	24.58	
5351	24.43	24.57	

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Table 5-5. Automatic Selector Switch Performance (Continued)

<u>Hours</u>	<u>Output Voltage (Volts)</u>		<u>Condition</u>
	<u>Conditioner MP-A</u>	<u>Conditioner MP-D</u>	
5519	24.41	24.55	261 hours prior testing on conditioner MP-D
5687	24.44	24.58	
5879	24.45	24.59	Good, test continuing
6071	24.47	24.58	
6215	24.44	24.58	
6359	24.47	24.59	
6527	24.48	24.59	
6791	24.45	24.57	
6887	24.45	24.56	
7055	24.44	24.56	
7223	24.52	24.59	
7415	24.44	24.56

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Table 5-6. Regulator Performance (Power Conditioner)

Conditioner: MP-C
Regulator: I

Conditioner: MP-C
Regulator: I

<u>Operating Hours</u>	<u>No Load Voltage</u>	<u>Operating Hours</u>	<u>No Load Voltage</u>
	24.58		
23	24.55	3916	24.53
113	24.52	3982	24.53
238	24.53	4058	24.53
311	24.54	4227	24.53
408	24.54	4302	24.53
479	24.53	4397	24.53
577	24.55	4486	24.53
647	24.53	4582	24.53
767	24.53	4657	24.53
838	24.54	4719	24.53
912	24.54	4819	24.53
982	24.52	4909	24.52
1072	24.53	4982	24.53
1172	24.52	5054	24.53
1208	24.53	5175	24.53
1275	24.52	5246	24.53
1394	24.53	5343	24.53
1489	24.54	5418	24.53
1589	24.54	5487	24.53
1701	24.54	5588	24.53
1825	24.53	5654	24.53
1902	24.53	5756	24.53
1972	24.54	5919	24.53
2064	24.53	6017	24.53
2139	24.53	6186	24.53
2236	24.53	6278	24.53
2282	24.53	6403	24.53
2400	24.52	6595	24.53
2449	24.56	6764	24.53
2548	24.53	6951	24.53
2620	24.54	7165	24.53
2716	24.54	7316	24.53
2788	24.53	7413	24.53
2883	24.53	7603	24.53
2953	24.53	7767	24.54
3069	24.53	7958	24.54
3122	24.53	8154	24.54
3219	24.53	8294	24.54
3267	24.52	8438	24.54
3387	24.53	8610	24.54
3458	24.53	8872	24.54
3553	24.52	8967	24.54
3626	24.53	9136	24.54
3723	24.53	9300	24.54
3795	24.53	9490	24.54

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Table 5-7. Regulator Performance (Test Fixture)

Operating Hours	No Load Voltage						Operating Hours	
	A	B	C	D	E	F	HPR-A	HPR-A
0	21.7	Bad	21.92	22.58	Burnt Out	21.96	26.78	0
168	21.84	Resistor	21.97	22.58	due to	22.02	26.79	96
312	21.82	-	21.96	22.55	test	21.97	26.76	168
384	21.83	-	21.97	22.58	fixture	22.04	26.71	283
480	21.81	-	21.95	22.55	short	22.02	26.65	331
552	21.82	-	21.96	22.56	-	22.04	26.67	451
648	21.83	-	21.97	22.57	-	22.03	26.75	499
698	21.80	-	21.94	22.56	-	22.01	26.77	595
794	21.80	-	21.94	22.55	-	21.96	26.72	667
866	21.81	-	21.96	22.56	-	22.00	26.70	955
981	21.82	-	21.96	22.54	-	21.99	26.73	1051
1029	21.83	-	21.98	22.56	-	22.08	26.76	1267
1149	21.82	-	21.97	22.57	-	22.04	26.80	1435
1197	21.81	-	21.94	22.56	-	22.00	26.77	1507
1293	21.80	-	21.92	22.54	-	21.95	26.76	1603
1365	21.82	-	21.95	22.55	-	21.99	26.74	1651
1653	21.81	-	21.93	22.54	-	21.98	26.78	1795
1749	21.78	-	21.89	22.51	-	21.95	26.81	1938
1965	21.82	-	21.93	22.55	-	21.98	26.78	2010
2133	21.81	-	21.92	22.55	-	21.97	26.76	2106
2205	21.82	-	21.93	22.56	-	21.97	26.78	2178
2301	21.81	-	21.92	22.55	-	21.96	26.77	2274
2349	21.80	-	21.92	22.55	-	21.98	26.79	2346
2493	21.81	-	21.92	22.55	-	21.99	26.78	2466
2637	21.80	-	21.91	22.55	-	21.98	26.79	2538
2709	21.80	-	21.90	22.54	-	21.99	26.79	2610
2805	21.81	-	21.92	22.55	-	22.00	26.81	2682
2877	21.82	-	21.93	22.56	-	21.97	26.77	2778
2973	21.80	-	21.91	22.54	-	21.97	26.79	2874
3045	21.80	-	21.89	22.54	-	22.00	26.76	2929
3165	21.80	-	21.89	22.54	-	21.97	26.80	3001
3237	21.80	-	21.89	22.54	-	21.96	26.77	3121
3309	21.80	-	21.90	22.55	-	21.98	26.73	3217
3381	21.80	-	21.90	22.55	-	21.97	26.73	3313
3477	21.81	-	21.91	22.55	-	21.98	26.69	3433
3573	21.80	-	21.89	22.53	-	21.94	26.76	3553
3627	21.80	-	21.91	22.55	-	21.97	26.75	3625
3699	21.80	-	21.90	22.55	-	21.98	26.79	3697
3819	21.80	-	21.90	22.55	-	21.99	26.76	3793
3915	21.82	-	21.92	22.55	-	22.01	26.75	3865
4011	21.82	-	21.92	22.56	-	22.02	26.78	3961
4131	21.83	-	21.94	22.56	-	22.03	26.79	4009
4251	21.81	-	21.91	22.55	-	22.01	26.73	4129
4323	21.81	-	21.92	22.55	-	22.01	26.78	4177
4395	21.81	-	21.91	22.56	-	22.02	26.77	4273
4491	21.81	-	21.91	22.55	-	21.98	26.78	4345

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Table 5-7. Regulator Performance (Test Fixture) (Continued)

Operating Hours							Operating Hours	
	A	B	C	D	E	F	HPR-A	HPR-A
4563	21.82	Bad Resistor	21.91	22.55	Burnt Out	22.01	26.79	4441
4659	21.81		21.90	22.54	due to	21.99	26.79	4513
4707	21.80		21.89	22.54	test	21.99	26.81	4609
4827	21.80		21.90	22.53	fixture	22.00	26.80	4681
4875	21.84	-	21.93	22.57	short	22.03	26.80	4801
4971	21.81	-	21.90	22.54	-	22.00	26.81	4849
5043	21.81	-	21.90	22.55	-	22.00	26.81	4945
5139	21.80	-	21.89	22.53	-	21.99	26.83	4993
5211	21.78	-	21.88	22.53	-	21.96	26.81	5113
5307	21.78	-	21.88	22.53	-	21.95	26.80	5185
5379	21.78	-	21.88	22.53	-	21.96	26.80	5281
5499	21.78	-	21.88	22.53	-	21.96	26.80	5449
5547	21.78	-	21.87	22.52	-	21.95	26.80	5521
5643	21.78	-	21.88	22.53	-	21.96	26.80	5641
5691	21.77	-	21.86	22.52	-	21.94	26.80	5713
5811	21.78	-	21.87	22.52	-	21.96	26.80	5784
5883	21.78	-	21.86	22.53	-	21.96	26.80	5952
5979	21.77	-	21.86	22.52	-	21.94	26.79	6025
6147	21.78	-	21.87	22.52	-	21.95	26.78	6121
6219	21.77	-	21.86	22.52	-	21.94	26.78	6217
6339	21.78	-	21.87	22.52	-	21.95	26.79	6313
6511	21.79	-	21.87	22.52	-	21.95	26.78	6385
6583	21.79	-	21.87	22.52	-	21.95	26.76	6457
6751	21.79	-	21.87	22.52	-	21.95	26.79	6553
6823	21.80	-	21.87	22.52	-	21.96	26.84	6649
6919	21.79	-	21.88	22.52	-	21.97	26.76	6720
7015	21.79	-	21.88	22.53	-	21.98	26.77	6792
7111	21.79	-	21.88	22.53	-	21.98	26.78	6913
7183	21.79	-	21.88	22.53	-	21.97	26.80	6985
7255	21.79	-	21.89	22.53	-	21.99	26.78	7080
7351	21.79	-	21.88	22.53	-	21.97	26.76	7153
7447	21.77	-	21.85	22.52	-	21.95	26.77	7224
7519	21.80	-	21.89	22.53	-	21.98	26.76	7321
7591	21.80	-	21.88	22.53	-	21.98	26.76	7393
7711	21.80	-	21.88	22.53	-	21.98	26.80	7489
7783	21.80	-	21.88	22.53	-	21.98	26.78	7657
7879	21.80	-	21.88	22.53	-	21.98	26.69	7753
7951	21.80	-	21.89	22.53	-	21.98	26.82	7921
8023	21.80	-	21.88	22.53	-	21.98	26.80	8017
8119	21.80	-	21.88	22.53	-	21.99	26.79	8137
8191	21.80	-	21.88	22.53	-	21.99	26.83	8329
8287	21.79	-	21.87	22.53	-	21.97	26.77	8497

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Table 5-7. Regulator Performance (Test Fixture) (Continued)

Operating Hours							Operating Hours	
	A	B	C	D	E	F	HPR-A	HPR-A
8455	21.79	Bad	21.88	22.53	Burnt Out	21.97	27.17	8684
8551	21.79	Resistor	21.88	22.53	due to	21.97	26.81	8905
8719	21.78	-	21.86	22.52	test	21.96	26.79	9049
8815	21.79	-	21.87	22.52	fixture	22.01	26.83	9163
8935	21.79	-	21.87	22.52	short	22.01	26.89	9336
9125	21.78	-	21.86	22.52	-	21.99	26.81	9504
9293	21.79		21.88	22.52		22.01	26.82	9696
9485	21.58		21.61	22.40		21.77	26.82	9870
9701	21.77		21.86	22.51		21.95	26.82	10,014
9845	21.78		21.87	22.51		21.95	26.78	10,158
9965	21.67		21.84	22.51		21.96	26.79	10,326
10,133	21.75		21.82	22.50		21.94	26.82	10,590
10,301	21.77		21.86	22.51		21.97	26.81	10,686
10,493	21.78		21.86	22.51		21.97	26.83	10,854
10,687	21.77		21.85	22.50		21.96	26.82	11,022
10,831	21.78		21.86	22.51		21.98	26.82	11,214
10,975	21.79		21.87	22.52		21.99		
11,143	21.79		21.87	22.52		21.98		
11,407	21.79		21.85	22.51		21.98		
11,503	21.79		21.86	22.52		21.98		
11,671	21.79		21.85	22.52		21.98		
11,839	21.79		21.85	22.51		21.98		
12,031	21.79		21.85	22.52		21.97

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Table 5-8. Power Conditioner, Converter, and Regulator Summary

Regulator	Converter	Location
A	MP-C	Regulator test fixture
B		Failed due to test fixture short
C		Regulator test fixture
D		Regulator test fixture
E		Failed
F		Not in use
G		Failed
H		Failed
I		Operated together on long-term test as power conditioner MP-C
J		Failed
K	MP-E	Operated together in system test as power conditioner MP-E
L	MP-A	Operated together as power conditioner MP-A; operating with automatic selector switch
M	MP-D	Operated together as power conditioner MP-D; operating with automatic selector switch
HPR-A-1	MP-B	Regulator test fixture
MPR-A-1		Operated together on long term test as power conditioner MP-B

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6.0 INSULATION ENVELOPE

6.1 PROGRAM OBJECTIVES

The Phase I program objectives were to develop an insulation envelope:

- With a thermal insulation conductivity not greater than 0.0005 Btu/hr-ft-°F during generator operation.
- That will interface mechanically and thermally with other generator system components.
- That will withstand the environmental conditions imposed on the power supply system, as defined by the technical provisions.

6.2 PROGRAM ACCOMPLISHMENTS

- A thermal conductivity of 0.0008 Btu/hr-ft-°F for the insulation was achieved using a somewhat higher heat source temperature.
- An insulation envelope was designed to interface mechanically and thermally with other generator system components.
- Three insulation envelopes were fabricated.
- Heat balance tests were conducted on two insulation envelopes.
- A complete thermal and mechanical analysis was performed on the insulation envelope design.
- One insulation envelope (Unit I) was fitted into the SNAP-21B-1 prototype system for thermal heat balance tests and long-term power system testing in a water tank.

6.3 INSULATION ENVELOPE DESIGN

The function of the insulation envelope in the SNAP-21B system is to insulate the heat source. The envelope surrounds the heat source and thermally insulates it except in the area where heat is supplied to the thermoelectric generator. The insulation envelope consists of a vacuum enclosure, heat-source support structure, insulation layers, reflective foil, and a vacuum-maintenance getter.

Development of the insulation envelope required early establishment of the interface boundary and environmental conditions. A preliminary design of the envelope (Figure 6-1) was conceived to establish the following conditions and capabilities:

- 1) An external shell temperature of approximately 50° to 68°F.
- 2) A heat-source surface temperature ranging from 1310° to 1323°F.
- 3) A thermal gradient of 1100° to 100°F for the generator case paralleling the thermal-insulation enclosure bellows.
- 4) An insulation envelope capable of withstanding 3-g vibration loads while supporting the shield at operating temperature conditions .
- 5) Shield motion, under conditions of vibration, restricted to 0.025-inch radially and 0.050-inch longitudinally.
- 6) A 2400-pound load applied by the hold-down ring to the insulation envelope.

The interface dimensions which apply to the completed system are defined by Figure 6-1.

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6.3.1 Mechanical Design and Analysis

The mechanical design for the insulation envelope is based on the following criteria:

- 1) Containment of vacuum
- 2) Support for the biological shield
- 3) Minimum heat transfer through the support structure
- 4) Minimum movement of the biological shield
- 5) Three-g vibration
- 6) Five-year life.

6.3.1.1 Initial Mechanical Design

The initial envelope design (Figure 6-2) was established to meet the interface requirements of the pressure vessel, shield, thermoelectric generator, and segmented centering ring. Components and structures not affecting interface fits were subject to optimization and modification in order to achieve the design objectives.

The insulation enclosure of the initial design consists of an inner and outer shell. The major enclosure components are as follows:

- Inner shell - upper head
- lower head
- Outer shell - center cylinder section
- upper head
- lower head
- Top ring
- Neck bellows.

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Figure 6-2. Initial Insulation Envelope Design

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The two heads comprising the inner shell form a leak-tight internal pressure housing and provide a point of attachment between the heat source (shield) and the support mechanism.

Inconel X750 was selected for the inner-shell material on the basis of high-temperature creep strength and available welding technology. A creep strength value of 16,000 psi (resulting in a 2 percent total elongation after 40,000 hours at operating temperature) was used in the design analysis.

Because the shield is held primarily by the support structure, the forces acting on the inner shell are caused by the difference between the internal (vacuum) and external (atmospheric) pressures. Although calculations indicated that a shell thickness of 0.0048 inch was satisfactory, fabrication considerations dictated the use of heavier material. The inner shell is 0.050-inch thick and each head weighs 1.6 pounds. This material thickness was based on the minimum required for proper welding, and resulted in a stress safety factor of 10.

Type 316 stainless steel was selected for the low-temperature outer-shell components of the envelope. A stress value of 30,000 psi at room temperature was used for this material.

The upper head of the outer shell serves as part of the enclosure and as the contact member to the segmented centering ring. The upper head has a concave circular surface which mates with the segmented centering ring. The head must withstand the mounting force (2400 pounds) of the ring and the vacuum of the insulation envelope. Because of its unusual configuration, simplifying approaches were used for the upper-head stress analysis (Ref. 1).

The first method of analysis was to assume that the upper-head was a flat, ring-shaped plate clamped at its outermost edge.

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The loading assumed to exist was that which would be present if the true load were projected downward on the flat ring. The results of the analysis indicated that an upper head thickness of 0.220-inch would provide a safety factor of 23.0.

The second method of analysis was to assume a beam with a rectangular cross section and unit width, cantilevered at one end and loaded with applicable forces on a per-unit length of circumference. The analysis indicated that a safety factor of 1.7 could be realized with an upper head thickness of 0.220-inch. Calculations also showed a large bending moment at the point of attachment to the cylindrical section of the outer shell. Because the analysis of this design configuration was necessarily restricted to mechanical approximations, the upper head was specified to be 0.220-inch thick, and the wall was extended into the cylindrical section to compensate for high bending moments.

The lower head is a partial hemisphere potentially subject to small-area contact due to pressure vessel deflection at operating pressure. Mechanical analysis indicated a safety factor of 2.3, with a wall thickness of 0.240-inch. This component weighs approximately 11.4 pounds.

Mechanical analysis of the cylindrical section of the outer shell and the top ring showed that relatively thin members could be used for these components. The design thicknesses were selected on the basis of weldability and resulted in a safety factor greater than 10.

The top ring functions as a simple flat-ring plate in joining the upper head of the outer shell to the bellows. The loading on the ring member is caused by external pressure. With a thickness suitable for welding, the stress safety factor was greater than 10.

The neck bellows forms a non-rigid, minimum heat transfer, vacuum-tight connection between the upper head of the inner shell and the top ring. The bellows is made of 0.008-inch-thick Inconel X.

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The design and selection of material for the insulation envelope support mechanism was most critical. This mechanism carries all the g-load forces on the inner shell and shield, and must be designed to minimize heat transfer.

6.3.1.1.1 Initial Envelope Support Design

A survey conducted on materials having a high strength-to-thermal-conductivity ratio indicated that sintered particles of silica formed into hollow tubes would be attractive for the support mechanism. A compression-type system was designed (Figure 6-2) to use the high compressive strength of the silica material. However, because this material cannot be fabricated into sections thinner than 0.125-inch, it could not be used in this application without excessive thermal losses.

Two alternate support mechanisms were evaluated. First, a series of truncated cones (telescoping tubes) was considered because a long conduction path could be obtained. However, the confined space between the enclosure walls limited the number of tube cycles, resulting in a total insulation-envelope heat loss of approximately 34 watts. Second, long wire supports were evaluated. Because of the elevated operating temperatures, the high strength normally developed in cold-drawn wire could not be realized, so this method was rejected.

6.3.1.1.2 Support Design of Insulation Unit I

The support structure finally selected for use in the first insulation envelope was a single thin-wall tube located at the bottom of the enclosure (Figure 6-3). The tube connects the inner shell-lower head to the outer shell-lower head and functions as a cantilevered beam. Inconel X750 was selected as the tube material. Stress analysis showed that the most critical tube load was bending (Ref. 1). With the support tube dimensions selected, a safety factor of 1.06 under a 3-g load was indicated. This safety factor would be augmented somewhat by the undetermined load-carrying ability of the thermal insulation and the neck bellows.

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Figure 6-3. Design of Insulation Unit I

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6.3.1.1.3 Support Design of Insulation Unit II

To reduce thermal heat loss and provide a greater safety factor, the inner vessel of the second unit is supported by a thin-walled monocoque cylinder (Figure 6-4). This supporting arrangement replaces the neck bellows as an enclosing member and eliminates the lower support tube of Unit I. The cylinder extends from the inner shell-upper head to the top ring.

Figure 6-4. Basic Design of Insulation Units II and III

Stress analysis of the thin-wall support member showed that the stress caused by transverse bending was also the most critical one (Ref. 2). Table 6-1 summarizes the calculated structural characteristics of the support structure.

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Table 6-1. Mechanical Strength Characteristics of the Support Structure for Insulation Unit II

Stress Mode	Stress (psi)	Failure Stress (psi)	Safety Factor	Maximum Deflection (inches)	Natural Frequency (cps)
Tensile	6,780	80,000	11.5	0.000715	675
Transverse Bending	28,100	43,200	1.54	0.0010	67
Compressive	2,770	32,700	11.5	0.0005	675
Torsion	6,470	26,300	4.0	0.0014	140

As the data indicates, the maximum support-tube deflections corresponding to 3-g accelerations are necessarily small relative to the allowable limits of 0.025-inch. Resonant magnification problems within the support structure are not anticipated for the specified 5- to 32-cps frequency band.

6.3.1.1.4 Support Design of Insulation Unit III

Use of an uranium-alloy radiation shield required increasing the clearances between the shield and the inner shell to prevent thermal expansion from overstressing the shell. Modification of the inner shell (Figure 6-4) was required because the existing inner heads were not large enough. The revised design consists essentially of two slightly shortened heads, a short cylindrical shell, and two circumferential welds - as opposed to the former arrangement in which two deep heads and a single circumferential weld were used. In addition, a longer and slightly thinner support tube is used.

6.3.1.2 Advanced Mechanical Design

After difficulties were encountered in obtaining a vacuum-tight enclosure, the initial envelope design concept was re-examined. In each case of vacuum loss, leakage was attributed to failure of the circumferential weld of the inner shell. Consideration was therefore given to eliminating the inner shell through the use of a neck tube (Figure 6-5) which would act as a support and would form part of

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Figure 6-5. Advanced Mechanical Design of the SNAP-21B Insulation Envelope

the enclosure. The neck tube would extend into the shield cavity and form a liner for the heat source. By machining this inner liner - neck tube in one piece, no welds would be required in the high-temperature area.

As Figure 6-5 shows, the shield is supported by bolting it to a flange machined onto the neck tube. Structural and thermal analyses for the third insulation envelope also apply to this design, and assembly of this insulation envelope will be similar to the three previous units.

After leak checking, the neck tube - inner liner will be fastened to the shield with bolts, and the subassembly will be placed on a mandrel and wrapped with super insulation. The remaining assembly and processing procedures will be the same as for Units II and III.

6.3.2 Thermal Insulation Design and Analysis

The insulation envelope is devised to thermally insulate the heat source so that most of its heat flows through the thermoelectric generator. Insulation is attained by using reflective shields, fibrous spacers, a high vacuum, and a getter to maintain vacuum during the design life of the system.

In a vacuum heat is transferred only by radiation. A series of reflective shields is used to reduce this mode of heat transfer. The shields are made from metal foil of aluminum for lower temperatures and from copper, stainless steel, or nickel for higher temperatures. The shields are thin enough for minimum weight and for flexible, contour fitting of the insulation. The fibrous mats that separate the shields are made of glass for lower temperature use and of quartz or ceramic for higher temperature use. A suitable vacuum level is maintained in the insulation envelope by using a high-capacity getter material.

The mode of heat transfer and the properties of the constituent insulating materials are temperature dependent. At higher temperatures, thermal radiation becomes increasingly important as compared to solid-conduction transfer through the fibrous spacer materials. The vapor pressure of the

materials increases at higher temperatures, tending to increase gaseous conduction by encroachment on the vacuum. In preparing the insulation envelope, high-temperature processing procedures must be used to sufficiently outgas the materials and to improve the emissivity of the biological radiation shield. A getter is included in the sealed system to incorporate residual outgassing and to maintain the vacuum at a proper level. The extent of processing and the quantity of getter used depends on the desired design life. At higher temperature applications, a vacuum approaching 10^{-3} mm Hg is maintained to keep gaseous conduction at low level. Above 10^{-2} mm Hg, gaseous conduction will appreciably increase the total heat transfer through the insulation envelope.

Calculation of the thermal loss through the super insulation was based on experimental data from laboratory tests. For example, Figure 6-6 shows the thermal conductivity of the super insulation as a function of hot-side temperature at a pressure of 15 microns of mercury or less. From this thermal conductivity data and the geometry of the insulation envelope, it was possible to calculate the heat loss through the super insulation. The calculated loss for a hot-side temperature of 1325°F and a cold-side temperature of 50°F was 7.2 watts.

In addition to the super insulation, heat is lost through the support structure and neck bellows of the insulation units. These losses were calculated on the basis of material thermal properties, the physical dimensions of the components, and the hot- and cold-side temperatures. The total heat losses are summarized in Table 6-2.

The experimental heat-balance results for insulation Units I, II, and III are presented in Table 6-3. The boundary temperatures noted are for the inner and outer shell surfaces. The discrepancy between the theoretical (Table 6-2) and experimental values (Table 6-3) for Unit I is attributed to partial collapse of the bellows (which reduced the heat-transfer path) and to the high view-factor value used in the experimental calculations. The

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Figure 6-6. Mean Apparent Thermal Conductivity of High-Temperature Super Insulation versus Hot-Side Temperature

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Table 6-2. Calculated Heat Losses for the Insulation Envelope Designs (Thermal Watts)

Heat Loss Component	Initial (Bellows and Fused Silica Support)	Unit I (Bellows and Thin-Wall Tube Support)	Unit II (Thin-Wall Neck-Tube Support)	Unit III (Modified Thin-Wall Neck Tube Support)
Super Insulation	7.2	7.2	7.2	7.2
Bellows	6.6	6.6	-	-
Support	8.4	14.2	28.0	21.2
Total	22.2	28.0	35.2	28.4

Table 6-3. Thermal Performance of Insulation Units I, II, and III at Design Temperatures

Mode of Heat Transfer	Heat Loss (Thermal Watts)		
	Unit I	Unit II	Unit III
Extraneous Losses			
Top-Plug Thermal Insulation	0.23	0.59	0.32
Thermocouple Wire	1.80	3.10	1.72
Heater Power Leads	2.20	2.00	5.43
Power Lead Insulation	-	1.90	2.53
Total	4.23	7.59	10.00
Insulation Envelope Losses			
Super Insulation	8.4	8.2	8.8
Bellows	14.2	-	-
Support	17.5	28.8	20.3
Total	40.1	37.0	29.1
Total System Losses	44.3	44.6	39.1
Total Experimental Power Input	38.0 ^(a)	46.0 ^(b)	45.0 ^(c)

The calculated values are based on experimental temperatures recorded at fixed points on the envelope, and on total power input.

The average boundary temperatures corresponding to the power inputs were: (a) 1180° to 90°F, (b) 1325° to 90°F, and (c) 1355° to 107°F.

difficulties with shorting of the electrical heater leads is reflected by increased lead losses resulting from the use of heavier lead insulation in Units II and III. As can be seen, however, reasonable agreement was obtained between the theoretical and experimental thermal performance values.

6.4 INSULATION ENVELOPE FABRICATION

As Section 6.3 indicates, three insulation envelopes were constructed for the SNAP-21B Program. The first two units were assembled on stainless-steel simulated shields, and the mechanical and thermal properties of the insulation envelopes were evaluated. The third unit was assembled on the prototype shield and incorporated design changes resulting from tests of the preceding two units. The insulation envelopes were of the same size and general configuration, and processing was in accordance with a five-year design life.

6.4.1 Insulation Unit I

The inner shell heads of Unit I were hydro-formed (Figure 6-7). The inner shell-upper heads were sent to the bellows manufacturer for attachment of the neck bellows. The support tube was machined from Inconel X750 bar stock. Two simulated biological shields were fabricated from stainless-steel. Two mating electrical-heater blocks were also manufactured and were used in assembling and processing insulation envelope Units I and II. Each simulated shield and heater block was instrumented with thermocouples so that temperatures could be monitored during insulation processing and testing.

In constructing Unit I the instrumented, simulated heat-source assembly was placed in the lower head of the inner shell (Figure 6-8). Instrumentation leads were extracted over the heater block cavity of the simulated shield, and the inner shell-upper head assembly was fitted over the simulated shield (Figure 6-9). The upper and lower heads were joined by a circumferential edge weld, and the bottom tube-support was welded to the lower head.

The inner shell was leak-checked after welding and had no leaks. The super insulation was then wrapped about the inner shell. After wrapping, the outer

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Figure 6-7. Bellows, Inner Shell - Upper Head, and Inner Shell - Lower Head Assemblies of Insulation Unit I

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Figure 6-8. Instrumented, Simulated Biological Radiation Shield Placed in the Inner Shell - Lower Head of Unit I

Figure 6-9. Bellows and Inner Shell of Unit Enclosing the Radiation Shield

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shell parts were fitted into place and welded to complete the super insulation enclosure. The enclosure was leak-checked and the electric heater bolted into position. The system was heated and vacuum pumping was started as part of the processing procedure. As processing continued, the temperature on the hot side was raised to 1550°F to increase the outgassing rate of the insulation material.

When processing was completed (as indicated by the dynamic pressure, and by the pressure rise with the pumps sealed off), a heat balance test was conducted (Ref. 2).

After testing, the system was cooled in preparation for final sealing. During cooling a leak was discovered in the bellows. Examination showed that the leak was caused by an arc from the electric-heater lead wires. The bellows was repaired by heliarc welding; however, it was subsequently found that the circumferential weld of the inner shell was cracked and leaked. Fortunately, the heat-balance test data was still valid.

A container was designed to replace the bellows (Figures 6-10 and 6-11). The container was machined from a solid block of 304 stainless-steel. By

Figure 6-10. Electric Heater Container

Figure 6-11. Modified and Repaired Insulation Unit I

having the container extend into the heater-block cavity of the stainless-steel simulated shield, only one weld joint was required to repair and seal the enclosure. Extensive leak testing confirmed the integrity of the seal.

Insulation envelope Unit I is being used in the SNAP-21B-1 system test. Continuous evacuation of the insulation envelope is necessary because the getter system was rendered inoperative by the earlier loss of vacuum integrity. Blank-off tests indicate that the insulation materials are out-gassing at a rate of 2 to 3 microns per hour. Results of the system test heat balance are included in Section 8.0.

6.4.2 Insulation Unit II

The second insulation envelope was fabricated from previously acquired piece parts. This envelope differed from the first in that a neck tube replaced the bellows and the lower support tube was eliminated (Figures 6-3 and 6-4).

Assembly and processing of Unit II was similar to that of Unit I. During vacuum processing at elevated temperature, the envelope developed a leak. Upon disassembly it was found that cracks had developed across the circumferential weld joint of the inner shell. Detailed analysis indicated that the probable cause of cracking was an interference fit of such magnitude as to create stresses which exceeded the tensile strength of the Inconel X750 shell.

When the leak was discovered, the heaters were turned off and the decrease in temperature with time was monitored. Insulation vacuum was maintained at the desired level by pumping continuously on the insulation space and the plug volume region. Estimation of thermal performance was possible from the cool-down data. The average cool-down rates for specified boundary temperatures were: 8.5°F/hr at BOL (1325° to 90°F), and 5.6°F/hr at EOL (1050° to 80°F). The transient thermal calculations were based on a 303 stainless-steel shield weight of 109.6 pounds, a 303 stainless-steel heater block weight of 13.7 pounds, an Inconel-X inner shell weight of 5 pounds, and an effective insulation weight of 5 pounds.

6. 4. 3 Insulation Unit III

With the possibility of overstressing the inner shell of Unit III, clearances between the shell and the U-8 percent Mo shield were increased. The revised design of the inner shell consisted essentially of two heads and a cylindrical shell portion, as opposed to the former arrangement in which two deep heads and a single circumferential weld were used (Figure 6-4). A longer support tube (2.28 versus 1.70 inches) with a reduced thickness was used. After assembly of the inner shell around the shield, and before application of the insulation, the subassembly was heated to approximately 1025° in an argon atmosphere to verify the adequacy of clearance between members.

Vacuum processing during heating was carried out with the insulation-plug volume maintained in an argon atmosphere. Loss of vacuum integrity for the enclosure occurred at a shield temperature of approximately 1300°F. Leak testing revealed that the failure had occurred in the inner shell and was assumed to be similar to that which occurred in Unit II. Subsequent thermal tests were conducted by pumping continuously on the insulation space and the plug volume to maintain an operating vacuum of 15 microns of mercury or less.

6.5 REFERENCES

1. Report No. MMM(3321)-11. SNAP-21B Program Quarterly Report No. 3 (1 October to 31 December 1964), AEC Contract AT(30-1)3321 (January 1964).
2. Report No. MMM(3321)-13, SNAP-21B Program Bimonthly Report (1 January to 28 February 1964) --- (March 1965).

7.0 SNAP-21B AUXILIARY EQUIPMENT

7.1 SEGMENTED CENTERING RING

The segmented centering ring (Figures 7-1 and 7-2) serves two functions:

- 1) It positions and retains the insulation envelope and the heat source within the pressure vessel.
- 2) It provides additional heat-transfer area at the pressure vessel walls.

The mounting ring is segmented to allow for longitudinal and circumferential decrease in pressure-vessel dimensions during operational cycling from a normal atmosphere to a submergence pressure of 10,000 psi (Ref. 1). The convex surface of the mounting ring matches the concave surface of the insulation envelope to provide positioning and support for the envelope. The convex ring surface allows rotation of each ring segment to accommodate the radial deflection of the pressure-vessel wall by external pressure.

A captive bolt and spring arrangement provides bearing pressure between the mounting plate and the mounting ring for system support and thermal contact. Integral extensions on the mounting plate are spring-loaded to each ring segment for heat-transfer contact.

7.2 THE DESICCANT HOLDER

A desiccant holder (Figure 7-3) was designed to contain the desiccant and still allow good penetration of the moisture vapor on all sides. A number-20 stainless-steel mesh cloth is used to expose the desiccant to the pressure vessel atmosphere. The mounting for the holder will be on two of the thermoelectric generator mounting bolts.

The amount of desiccant required to lower a possible relative humidity of 100 percent to the 0 percent within the pressure vessel was determined to be 10 grams. The dessicant ("Drierite") is essentially calcium sulfate (CaSO_4).

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Figure 7-1. Pressure Vessel - Insulation Assembly with Segmented Centering Ring

Figure 7-2. Generator Mounting Plate with Segmented Centering Ring

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It has indicator coloring for moisture saturation conditions and is well activated as received from the manufacturer. It can be re-activated by baking at 200 to 225° C for 2 hours.

Figure 7-3. Desiccant Holder

7.3 HUMIDITY SENSOR

A Hydrodynamics, Inc. wide-range sensing element (Model #15-2001) and readout indicator (Model #15-3001) will be used to measure the relative humidity in the vessel cover. The readout indicator unit will be able to provide the power needed to supply the sensor unit and will have a voltage output tap for recording instrumentation. The system will readout the relative humidity in the sensor area and the temperature for correcting the indicated relative humidity during temperature excursions. When the vessel is sealed in high humidity conditions, a desiccant will be provided for reducing the humidity to within the range of the sensor. The sensor is capable of a 33 to 94 percent humidity range at 40° F, and a 21 to 83 percent humidity range at 120° F.

Excess moisture, which tends to dilute the salt-solution coating on the sensor grid, has the greatest detrimental effect on the humidity sensor.

To determine if there would be any poisoning effect from the desiccant on the sensor salt coatings, the desiccant (activated silica gel) and the sensor were

left in a sealed chamber for several days. Then moisture was added as a slow stream of vapor and in a dish at 68° F. No adverse effects were noted in either test. The response of the sensor was naturally faster with the vapor input. Response in either case was good as noted in Table 1-1. Table 1-2 shows the time required to lower the humidity in the chamber with 10 grams of desiccant enclosed in a No. 20 mesh stainless-steel screen.

7.4 RECEPTACLE AND PLUG

To transfer electrical energy from the SNAP-21B power supply to its electrical load, a receptacle and plug were designed and fabricated.

7.4.1 Receptacle

A stainless-steel receptacle with 28 pins was first designed and fabricated (Figure 7-4). The receptacle was supplied by the D. G. O'Brien Co. of

Top View

Bottom View

Figure 7-4. Stainless-Steel Electrical Feed-Through Receptacle

Table 7-1. Excess Moisture Test No. 1 (Vapor injected into a 500 cu. in. chamber)

<u>Elapsed Time (min.)</u>	<u>Relative Humidity (Percent)</u>	<u>Sensor Temperature</u>
0:00	1.0	68° F
0:15	86.0	73*
0:30	90.0	73

*Temperature increase due to vapor temperature

Table 7-2. Excess Moisture Test No. 2 (10 grams desiccant in a 500 cu. in. chamber)

<u>Elapsed Time (Hours)</u>	<u>Relative Humidity (Percent)</u>	<u>Sensor Temperature</u>
:0	95.0	68° F
:30	79.0	68
1:20	57.5	68
2:20	40.0	68
3:00	27.0	68
67:00	1.0	66

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Framingham, Massachusetts. Examination of the stainless-steel electrical feedthrough receptacle resulted in the following design and specification changes in the prototype titanium receptacles:

- 1) Bolt clearance holes were increased in size so that fabrication and assembly could be easily accomplished without using extensive tools and fixtures.
- 2) The locator key (Figure 7-4) will be attached to the inside wall of the receptacle by an interference fit rather than by brazing or bonding.
- 3) O-ring groove machining will conform to standard groove dimensions with edge and corner radius tolerances.
- 4) To prevent radial seal leakage, only concentric finish irregularities will be permitted.
- 5) Surface contamination of the titanium caused by glass fusing and plating processes will be removed during final machining.

Experiments in fusing glass to titanium (Figure 7-5) indicated that excellent bonding which withstood the design pressures could be obtained. Surface (hydrogen) contamination of the titanium is induced by the high-temperature glass sealing operation, but is not detrimental to the metal-to-glass bond. However, only sample receptacles containing a few pins could be made to withstand 10,000-psi pressure, whereas difficulty was experienced in making a pressure-proof 28-pin receptacle. Proper sealing between the glass and the pin and receptacle housing interfaces becomes critical with a large number of pins.

When it became apparent that a leak-proof 28-pin titanium receptacle could not be made without additional development extending beyond the program time limits, a 12-pin titanium receptacle (Figure 7-6) was fabricated (also by the D. G. O'Brien Co.). This titanium receptacle was tested to 10,000-psi pressure with no leakage or failure.

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Figure 7-5. Samples of Glass-Titanium Fusing

Bottom View

Top View

Figure 7-6. Twelve-Pin Titanium Receptacle

7.4.2 Plug with Strain Relief

A 28-pin plug with a strain relief that is compatible with the 12-pin receptacle was also designed and fabricated. The plug (Figure 7-7) has a length of cable attached and has been checked for electrical continuity with the receptacle.

Figure 7-7. Twenty-Eight Pin Plug with Strain Relief and Cable Assembly

7.5 O-RING SEALS

The O-ring seal material for the pressure vessel and receptacle is 90-durometer Viton. Dimensions of the vessel O-rings were established as follows:

	<u>Inside Diameter (inches)</u>	<u>Nominal Cross- Sectional Diameter (inch)</u>
Outside Vessel Seal	14.325 ± 0.030	0.25
Inside Vessel Seal	13.309 ± 0.030	0.25
Receptacle Seal	3.234 ± 0.031	0.125

The outside vessel seal is sized to provide a slight stretch-fit over the pressure vessel cover. This allows system assembly without interference from, or damage to, the seal. The receptacle and inside vessel seals are sized to be statically at rest in their respective grooves prior to assembly.

7.6 PRESSURE SENSOR

A Consolidated Electrodynamics Corporation, 0- to 50-psi, absolute pressure-range transducer (Type 4-312) will be used to sense pressure within the vessel cover. A Kepco, Inc. Model ABC-10 power supply will furnish a regulated dc voltage to the transducer. The millivolt output of the transducer can be recorded on any noncurrent-drawing millivolt meter or recorder. The system has been checked for stability at atmospheric pressure in the 3M laboratory.

7.7 PRESSURE VESSEL RACK

A pressure vessel rack (Figure 2-10) was made to hold the pressure vessel during outfitting and pressure testing. The rack will help prevent damage to the pressure vessel while installing and holding it in the pressure tank. The rack holds the vessel in such a manner that it will not influence vessel deflection when pressure is applied and relieved.

7.8 REFERENCES

1. Report No. MMM(3321)-7. SNAP 21-B Program Quarterly Report No. 2 (1 July to 30 September, 1964). AEC Contract AT(30-1)3321 (October 1964).

8.0 SNAP-21B-1 SYSTEM TEST

8.1 PROGRAM OBJECTIVES

The objectives of the SNAP-21B-1 system are to:

- Obtain a preliminary experimental verification of the ability of the proposed system to provide the required electrical output of 10 watts at 24 volts dc.
- Demonstrate delivery of the specified electrical performance at BOL and EOL thermal conditions.
- Obtain engineering information concerning the mechanical, electrical, and thermal performance of the various components when integrated into a complete system.

8.2 PROGRAM ACCOMPLISHMENTS

The test results show that:

- The system is capable of delivering the specified electrical performance under BOL and EOL thermal conditions.
- All individual system components under test are functioning as anticipated with the following exceptions:
 - a) The cold-electrode temperature of the thermoelectric generator is somewhat higher than expected.
 - b) The insulation envelope is incapable of maintaining its own vacuum.

During April 1965, the various components of the SNAP-21B-1 system were instrumented and assembled in preparation for the first system test. All system hardware used in this test was of first-generation prototype design.

First-generation hardware was used in the interest of obtaining an experimental

verification of the capability of the entire system at the earliest possible date. The difference between the first-generation and final hardware design specifications and their influence upon the performance of the system will be discussed in Section 8.6.

In addition to demonstrating over-all system capability, the test was designed to provide additional engineering information on the performance of the various system components. Prior to this time, component testing had been done only on an individual basis. Although the thermal and electrical response of the system was of prime concern, the test has also served as a shakedown for the various mechanical components.

At the time of writing, the SNAP-21B-1 system is continuing on test and has logged over thirteen months of continuous operation. The system is operating very satisfactorily and is extremely stable.

8.3 SYSTEM HARDWARE AND COMPONENTS

The system hardware and auxiliary support equipment used in the test are shown in Figure 8-1 and listed in Table 8-1.

8.3.1 System Components

Pressure Vessel. A cast, type-CF8C (AISI 347) stainless-steel pressure vessel is being used in this test. The vessel very nearly conforms to the geometrical characteristics specified on 3M prints PD-37-1014 (body) and PD-37-1015 (cover). The major deviations from these specifications are that the exterior of the vessel contains excess material on the two hemispherical surfaces, and that the entire exterior surface has been, for the most part, left in an as-cast condition. The excess material on the hemispherical surfaces resulted in wall thicknesses of about 1.0 inch rather than the prescribed 0.5 inch, and the as-cast exterior surfaces

Figure 8-1. SNAP-21B-1 System Test Hardware
(the components are identified on the
following page)

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Table 8-1. Test Hardware Nomenclature

1. Pressure Vessel
2. Insulation System
3. Thermoelectric Generator
4. Power Conditioner
5. Mounting-Alignment Assembly/
Segmented-Centering Ring
6. Biological Radiation Shield
7. Radiation Disc
8. Heater Block
9. Insulation
10. Support
11. Instrumentation Tube
12. Water Tank
13. Water
14. Cooling System

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resulted in a surface finish of 500 microinches rather than the prescribed 63 microinches. Neither of these factors would materially influence the thermal response of the system.

Insulation System. Linde high-temperature super-insulation Unit I is being used in this test. Unit I was originally intended to be fabricated per Linde print A607936; however, fabrication difficulties necessitated a mechanical modification. The revised system is described on 3M print PD-37-1258.

As a direct result of the system modifications, the interior of the insulation system was exposed to the atmosphere for a month and the gas getter system was never activated. Both these factors combined to result in an insulation system which had a high initial outgassing rate and could not maintain a sufficient vacuum once the initial outgassing had been completed. For these reasons it has been necessary to continuously pump on the insulation system to maintain a vacuum.

Thermoelectric Generator. Thermoelectric generator 3M-37-P4 is being employed in the test. This generator was originally intended to be hermetically sealed using electron-beam welding techniques; however, welding difficulties were encountered. To make the generator available for testing, the necessary hermetic seal was established using a conventional rubber O-ring (see Section 1.0). Although it was expected that this type of seal would be sufficient to determine the short-term performance characteristics of the generator system, it was not known what effects the seal would produce after extended periods of time. It should be noted that this generator exhibited over 1400 hours of stable performance on bench test prior to being installed in this system.

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Power Conditioner. Power conditioner MP-E is being used in the test system. This conditioner was fabricated per circuit diagram print PD-37-1180 and component assembly print PD-37-1214. The only deviation from print specifications was that the conditioner was not hermetically sealed when installed in the system. This was due to the fact that its voltage regulator had failed after 168 hours of bench testing and had to be replaced. At the time, it was suspected that the welding process used to establish the hermetic seal may have been responsible for the premature regulator failure; hence, the outer case was not re-sealed after the faulty regulator was replaced. Exposure to the atmosphere for relatively short periods of time was not expected to materially affect the performance of the conditioner. It should be noted that this conditioner exhibited 792 hours of stable performance under accelerated failure conditions prior to system installation.

Mounting-Alignment Assembly. The mounting-alignment assembly used in this test consists of a generator mounting plate which was fabricated per 3M print PD-37-1071, and a segmented centering ring which was fabricated per 3M print PD-37-1070. Both components are exactly per print except for a slight modification to accommodate the vacuum gauge and evacuation tube of the super-insulation system.

Biological Radiation Shield. A type 303 stainless-steel biological radiation shield is in the test system. The shield was fabricated per 3M print PD-37-1062 (Section 4.0) and is contained as an integral part of the high-temperature super-insulation system. The 303 stainless-steel simulates the U-8 percent Mo shield specified for the final prototype system.

Radiation Disc. A Hastelloy-C radiation disc was fabricated for this test system per 3M print PD-37-1121 (Section 7.0) and received a surface preparation per 3M specifications TPF-8 (surface finish) and TPO-45 (heat treatment). It should be noted that the hot frame of the generator also received a surface preparation per TPF-8, but was not heat treated.

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Heater Block. A type 303 stainless-steel heater block was fabricated per 3M print PD-37-1120 (Figure 8-3). The heater block contains two 115-volt 250-watt Watlow-Firerod heating cartridges. The block-cartridge assembly simulates the "hot" Hastelloy-C fuel capsule and the U-8 percent Mo biological shield plug.

Insulation. Pulverized Min-K 1301 thermally insulates the generator in the neck tube area of the super-insulation system.

8.3.2 Auxiliary Equipment

To provide the desired environmental conditions external to the system, the following auxiliary facilities are being used.

Support Stand. A small, four-legged, stainless-steel stand mechanically supports the system and thermally isolates the pressure vessel from its surrounding metallic environment.

Instrumentation Tube. A 2-foot length of 1-3/4 inch-diameter stainless-steel tubing provides electrical access to the pressure vessel for instrumentation purposes. This tubing is welded to a stainless steel flange which, in turn, is bolted to the penetration flange of the pressure vessel. A rubber O-ring provides the necessary watertight seal.

Water Tank. A 35-inch-diameter, 48-inch-deep steel tank holds the water which simulates the deep-sea environment. This tank is lined on the inside with an epoxide resin to prevent rusting, and is coated on the outside with 1 inch of polyurethane foam for thermal insulation. A 1/4-inch-thick disc of Masonite, also coated with 1 inch of polyurethane, serves as a cover for the open end of the tank.

Water. Approximately 185 gallons of ordinary (fresh) tap water simulate the deep-sea environment. It should be noted that the water is not

mechanically circulated so that heat transfer from the pressure vessel surface will take place primarily by free convection. This arrangement results in the most pessimistic heat transfer rates, and hence, the highest or maximum vessel skin temperatures.

Cooling System. A Freon 12 vapor-compression refrigeration system maintains the water bath at the estimated deep-sea temperature of 40° F. The evaporator of the refrigeration system is made of six coils of 5/8-inch-diameter copper tubing. The coils were submerged in the water bath to obtain the desired cooling. With a 40° F water temperature and a 70° F room air temperature, this system is capable of providing approximately 1/2-ton of refrigeration.

8.3.3 Instrumentation

The approximate locations of the thermocouple temperature sensors used in this test are shown in Figure 8-2. The exact locations of these thermocouples were recorded on engineering prints for heat-transfer calculation purposes. Three types of thermocouples were used to span the expected temperature spectrum:

<u>Thermocouple No.</u>	<u>Calibration</u>
1-24, 35 and 36	Type T (copper-constantan)
25-34, 37-40	Type J (iron-constantan)
41-44	Type K (chromel-alumel)

All thermocouples located in the interior of the pressure vessel mounting-alignment assembly and in the generator cold frame were "potted-in" with a copper oxide heat-transfer cement. All other thermocouples were surface bonded by welding or soft soldering, depending upon the local temperature. Figure 8-3 shows the thermocouple instrumentation of several systems components.

- a - in mounting plate
- b - in segment
- c - 26, 27, 30 and 31 on hot shoes
- d - 28, 29, 32 and 33 on cold shoes
- e - air space
- f - regulator
- g - transistor

Figure 8-2. Thermocouple Instrumentation Locations

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Pressure Vessel Cover

Pressure Vessel Body

Centering Ring Segment

Generator Hold-Down Plate

Heater Block

Thermoelectric Generator

Figure 8-3. Thermocouple Instrumentation of Test System Components

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Figure 8-4 is a schematic of the electrical instrumentation used in this test. The instrumentation is divided into two separate and distinct test circuits: (1) The generator test circuit, which is comprised of a load resistance and a current shunt, is used when the system is being heated or cooled. This circuit establishes the temperature level and operational characteristics of the thermoelectric generator. (2) The system test circuit is comprised of a current shunt between the generator and power conditioner, and a system load resistance and current shunt. This circuit is used when steady-state thermal conditions prevail, and is relied upon to establish the operational characteristics of the entire system. Both test circuits use two or more of seven voltage taps (three at the generator terminals and four at the power conditioner terminals).

With the instrumentation arrangement described above, it is possible to determine the generator output, the input to the conditioner, and the system output. However, this information is not gained without penalty. Extremely long current leads are necessary to bring the desired information to the instrumentation console, resulting in an appreciable power loss between the generator and power conditioner.

Quite obviously this excessive power loss would not be present if the instrumentation were removed. This power loss problem is not encountered with the system output measurements, because the current load resistance merely becomes a portion of the external load.

In addition to the loaded system measurements, provisions were made to determine the open- and short-circuit response. In Figure 8-4, the following nomenclature is used to describe the measurements made at the respective voltage taps:

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Figure 8-4. Electrical Schematic of the System Test Instrumentation

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E_{OS}	=	system open circuit voltage
E_{LS}	=	system load voltage
E_{SS}	=	system short-circuit voltage
E_{LPC}	=	conditioner primary input voltage
E_{LBC}	=	conditioner bias input voltage
E_{LPG}	=	generator primary load voltage
E_{LBG}	=	generator bias load voltage
E_{OPG}	=	generator primary open-circuit voltage
E_{OBG}	=	generator bias open-circuit voltage
I_{LS}	=	system load current
I_{SS}	=	system short-circuit current
I_{LPG}	=	generator primary load current.

Figure 8-5 is a series of photographs taken during the instrumentation assembly process. Figure 8-6 shows the completely assembled system submerged in the water bath, and Figure 8-7 demonstrates the entire test apparatus and instrumentation console.

8.4 TEST PROCEDURE

On April 29, 1965, electrical power was supplied to the system. During the following four weeks the system was slowly heated to its design BOL condition. During this time the temperature level and performance characteristics of the generator were continually monitored through the generator test circuit. In addition, the local temperature of all critical areas within the system was carefully monitored to prevent overheating.

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Figure 8-5. Assembly Sequence for the SNAP-21B-1 System

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Figure 8-6. Submerged Test System

Figure 8-7. Test Instrumentation Console

On May 25, 1965, the desired 1100° F generator hot-electrode temperature was established. At this time the system test circuit was activated. After the vacuum insulation envelope had been pumped down to an acceptable pressure level, and the system had reached a steady-state thermal condition, the power conditioner was loaded to 24 volts and a complete set of electrical and thermal data was recorded. The input power required to establish the desired hot-electrode temperature was 230 watts. Of the 230 watts, approximately 4 watts was consumed or rendered unavailable for conversion by the instrumentation system. This resulted in a net input power of 226 watts, which was then reduced by the same fraction that the Sr-90 isotope would experience in a 1-year period. After a new steady-state thermal condition had been established, the conditioner was again loaded to 24 volts and another complete set of data was recorded. This procedure was repeated four more times, thus establishing the BOL, EOL, and intermediate-year performance characteristics of the system. The input-power levels for each of the years are shown in the following table and in Figure 8-8.

Table 8-2. System Performance Characteristics Over a Five-Year Period

Year	Percent of BOL Power	Net Input Power (Watts)
0	100.0	226
1	97.5	220
2	95.1	215
3	92.8	210
4	90.5	205
5	88.3	200

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Figure 8-8. Performance Test Curves for SNAP-21B-1 Prototype Power-Supply System

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In addition to the 24-volt loading condition on the power conditioner, a set of data was recorded at several other loading conditions for each of the five years. This was done to establish the performance of the system under constant external resistance. Also, two insulation blank-off tests were conducted. Because the insulation envelope used in this test has no active getter, it was necessary to continuously pump on the envelope to maintain the desired vacuum. These blank-off tests were conducted to gain some insight into the rate of pressure increase resulting from leakage or from outgassing of the insulation materials. The tests were conducted at the BOL and EOL thermal conditions. After the 5-year EOL insulation blank-off test had been completed, the system was restored to its BOL condition for continued testing.

8.5 SYSTEM TEST RESULTS

Tables 8-3 and 8-4 indicate the thermal and electrical characteristics of the system at the various input power levels described in Section 8.4. This data and additional data are summarized in Table 8-5.

Table 8-3 contains the thermal data and should be used in conjunction with Figure 8-2. The data in Table 8-3 is self-explanatory except for the indications of Thermocouples 26 and 27. These two thermocouples were located on hot electrodes and were known to be contaminated by tellurium vapors. This type of contamination results in a false temperature indication. The average hot-electrode temperature of the generator was determined using Thermocouple 31, which was known to be providing reliable information. The cold-electrode temperatures and Seebeck voltages developed for adjacent pairings of the thermoelectric legs provided verification of the calculated average temperatures.

The data in Table 8-4 is also self-explanatory except for the two system power-input and power-output indications. The measured system power-input is the gross input and differs from the corrected value by the total power made unavailable for conversion due to the presence of instrumentation. This difference is mainly comprised of the heat conducted past the thermopile through

Table 8-3. SNAP-21B-1 System Test Thermal Data

Thermocouple Number	Temperature (°F)					
	BOL	Year 1	Year 2	Year 3	Year 4	EOL
1	81	81	80	79	78	77
2	75	74	74	74	73	72
3	74	74	74	72	72	71
4	68	64	64	62	65	63
5	64	63	63	61	62	61
6	60	57	57	56	57	57
7	47	45	45	43	46	44
8	43	41	42	41	44	42
9	43	41	41	41	44	41
10	44	42	42	42	43	42
11	50	49	48	47	49	47
12	50	49	48	47	49	47
13	52	50	50	50	49	49
14	50	48	49	48	49	47
15	62	62	61	60	61	60
16	52	50	51	49	50	50
17	44	43	43	41	41	41
18	44	43	43	41	42	41
19	43	41	43	41	42	41
20	45	44	44	42	44	42
21	38	36	37	35	37	37
22	39	38	38	37	39	38
23	40	38	38	38	39	39
24	39	38	39	38	39	38
25	1058	1037	1022	994	983	960
26	1070	1048	1030	1005	991	967
27	1072	1052	1034	1010	996	973
28	171	168	166	166	162	157
29	185	181	177	179	174	171
30	Out	Out	Out	Out	Out	Out
31	1090	1065	1051	1026	1012	989
32	179	175	172	173	168	163
33	180	179	175	173	173	167
34	115	112	109	110	108	103
35	67	65	65	63	65	62
36	54	52	52	49	52	51
37	1284	1256	1238	1212	1195	1151
38	145	142	141	140	135	132
39	47	45	47	48	48	44
40	47	45	47	48	48	44
41	1124	1099	1078	1049	1038	1023
42	1282	1258	1241	1212	1199	1184
43	1338	1314	1294	1265	1255	1239
44	1443	1419	1398	1368	1356	1336

Table 8-4. SNAP-21B-1 System Test Electrical Data

	BOL	Year 1	Year 2	Year 3	Year 4	EOL
Generator primary load voltage (volts)	5.23	5.22	5.21	5.18	5.18	5.16
Generator bias load voltage (volts)	0.73	0.73	0.72	0.72	0.72	0.72
Generator primary load current (amps)	2.48	2.41	2.36	2.27	2.23	2.19
Generator bias load current (amps)	0.15	0.14	0.14	0.13	0.13	0.13
Generator primary power output (watts)	12.97	12.58	12.30	11.76	11.55	11.30
Generator bias power output (watts)	0.11	0.10	0.10	0.10	0.10	0.09
Generator total power output (watts)	13.08	12.68	12.40	11.86	11.65	11.39
Conditioner primary voltage input (volts)	4.90	4.90	4.89	4.88	4.88	4.86
Conditioner bias voltage input (volts)	0.60	0.60	0.60	0.60	0.60	0.61
Conditioner primary current input (amps)	2.48	2.41	2.36	2.27	2.23	2.19
Conditioner bias current input (amps)	0.15	0.14	0.14	0.13	0.13	0.13
Conditioner primary power input (watts)	12.15	11.81	11.54	11.08	10.88	10.64
Conditioner bias power input (watts)	0.09	0.09	0.08	0.08	0.08	0.08
Conditioner total power input (watts)	12.24	11.90	11.62	11.16	10.96	10.72
System load voltage (volts)	24.00	24.00	24.00	24.00	24.00	24.00
System load current (amps)	0.45	0.44	0.43	0.41	0.41	0.40
System power output (measured) (watts)	10.90	10.56	10.34	9.94	9.79	9.60
System power output (corrected) (watts)	11.65	11.25	11.08	10.72	10.57	10.39
System power input (measured) (watts)	230	224	219	212	208	203
System power input (corrected) (watts)	226	220	215	209	205	200

Table 8-5. SNAP-21B-1 System Test Data Summary

	BOL	Year 1	Year 2	Year 3	Year 4	EOL
Generator hot electrode temperature (°F)	1100	1074	1048	1022	1006	990
Generator cold electrode temperature (°F)	179	176	173	172	169	165
Water temperature °F)	39	38	38	37	39	38
Generator load voltage (volts) ¹	5.23	5.22	5.21	5.18	5.18	5.16
Generator load current (amps) ¹	2.48	2.41	2.36	2.27	5.23	2.19
Generator total power output (watts)	13.08	12.68	12.40	11.86	11.65	11.39
Conditioner load voltage input (volts) ¹	4.90	4.90	4.89	4.88	4.88	4.86
Conditioner load current input (amps) ¹	2.48	2.41	2.36	2.27	2.23	2.19
Conditioner total power input (watts)	12.24	11.90	11.62	11.16	10.96	10.72
System load voltage (volts)	24.00	24.00	24.00	24.00	24.00	24.00
System load current (amps)	0.45	0.44	0.43	0.41	0.41	0.40
System power output (measured)(watts)	10.90	10.56	10.34	9.94	9.79	9.60
System power output (corrected)(watts) ²	11.65	11.25	11.08	10.72	10.57	10.39
System power input (measured)(watts)	230	224	219	212	208	203
System power input (corrected)(watts) ³	226	220	215	209	205	200
Conditioner efficiency (percent)	89	89	89	89	89	90
System efficiency (percent) ⁴	5.2	5.1	5.2	5.1	5.2	5.2

- (1) Primary circuit only.
 (2) Corrected for measured instrumentation losses.
 (3) Corrected for estimated instrumentation losses.
 (4) Based on corrected power input and output.

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thermocouple and heater lead wires, and of the power lost, due to Joule heating, in the heater leads between the wattmeter and the system.

The difference between the measured and corrected power output indications is also attributed to the presence of instrumentation; however, this correction is based on a measured loss rather than a calculated loss as was the case for the input power. As an example, examination of the BOL data shows a 0.33-volt drop in the primary circuit between the output terminals of the generator and the input terminals of the power conditioner. At 2.48 amperes this amounts to a 0.82-watt power loss, which is directly attributable to the instrumentation system as previously discussed. The 10.90-watt system power output is as measured and, as such, is influenced by the 0.82-watt power loss. The 11.65-watt power output is that which the system would deliver if the instrumentation were removed and replaced with "design" current leads. The validity of the output power correction scheme used was determined in a bench test using prototype P5 and power conditioner MP-F. The difference between the calculated corrected power output and the measured corrected power output was found to be less than 1.7 percent.

As was discussed in Section 8.4, the data presented in Tables 8-3, 8-4, and 8-5 pertains to a 24-volt loading condition on the power conditioner. The electrical response of the system to a constant external resistance is shown in Table 8-6. The loading condition used was approximately 55 ohms, which was the resistance necessary to establish a 24-volt conditioner output at EOL conditions. Table 8-6 shows that for each of the 5-year power input levels, the system voltage output was well within the 24 ± 1 volts specified in the technical provisions, and that the system power output was slightly greater than the specified 10 watts.

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Table 8-6. SNAP-21B-1 System Test Electrical Data (55-ohm External Load)

	BOL	Year 1	Year 2	Year 3	Year 4	EOL
Generator primary load voltage (volts)	5.34	5.32	5.31	5.26	5.22	5.16
Generator bias load voltage (volts)	0.74	0.74	0.74	0.73	0.74	0.72
Generator primary load current (amps)	2.44	2.36	2.30	2.25	2.20	2.19
Generator bias load current (amps)	0.15	0.15	0.14	0.14	0.13	0.13
Generator primary power output (watts)	13.03	12.56	12.21	11.83	11.47	11.30
Generator bias power output (watts)	0.11	0.11	0.11	0.10	0.10	0.09
Generator total power output (watts)	13.14	12.67	12.32	11.92	11.57	11.39
Conditioner primary voltage input (volts)	5.01	5.00	5.00	4.95	4.92	4.86
Conditioner bias voltage input (volts)	0.62	0.62	0.62	0.62	0.61	0.61
Conditioner primary current input (amps)	2.44	2.36	2.30	2.25	2.20	2.19
Conditioner bias current input (amps)	0.15	0.15	0.14	0.14	0.13	0.13
Conditioner primary power input (watts)	12.22	11.80	11.50	11.14	10.81	10.64
Conditioner bias power input (watts)	0.09	0.09	0.09	0.08	0.08	0.08
Conditioner total power input (watts)	12.31	11.89	11.59	11.22	10.89	10.72
System load voltage (volts)	24.61	24.59	24.60	24.38	24.21	24.00
System load current (amps)	0.42	0.41	0.41	0.41	0.40	0.40
System power output (measured)(watts)	10.26	10.08	10.09	9.98	9.75	9.60
System power output (corrected)(watts)	10.85	10.79	10.87	10.73	10.34	10.39
System power input (measured)(watts)	2.30	2.24	2.19	2.12	2.08	2.03
System power input (corrected)(watts)	2.26	2.20	2.15	2.09	2.05	2.00

The results of the BOL and EOL insulation blank-off tests are shown in Figures 8-9 and 8-10. These tests were conducted under the thermal conditions shown for BOL and EOL in Table 8-3. Figures 8-9 and 8-10 show that the pressure increased at a nearly constant 3 microns per hour throughout the life of the test at BOL conditions, and at a nearly constant 2 microns per hour throughout the life of the test at EOL conditions.

Because of the relatively low pressure-increase rates at both thermal conditions, it was suspected that the pressure increase was caused by outgassing of the insulation materials rather than by a leak in the vacuum enclosure. The difference between the two pressure increase rates can be explained by the difference in temperature.

Upon completion of the EOL insulation blank-off test, BOL input power was restored to the system. After a steady-state thermal condition had been established, a set of data was recorded for comparison with data previously recorded on BOL thermal conditions. These two sets of data are shown in Tables 8-7, 8-8, 8-9, and 8-10. Very close agreement exists between the two sets of data, indicating a very stable system. It should be noted that these two sets of data were taken 77 days (1848 hours) apart.

8.6 HEAT BALANCE ANALYSIS

Estimates of the quantity of heat required by the SNAP-21B system were reported early in the design phases of this program. The estimates were based on calculations which took into consideration component thermal properties, configurations, and temperature profiles. These temperature profiles were necessarily determined by analytical techniques. With the availability of data from the first system test, these calculations could again be made, this time using the same dimensional configurations, but thermal properties and temperature profiles based on experimental results. It was expected that the calculations based on the experimental data would more nearly represent the true performance of the system.

Figure 8-9. SNAP-21B-1 BOL Insulation Blank-Off Test

Figure 8-10. SNAP-21B-1 EOL Insulation Blank-Off Test

Table 8-7. SNAP-21B-1 System Test Comparison of Thermal Data-System Test Circuit

(Temperature in °F)		
Thermocouple Number	Old	New
1	81	82
2	75	77
3	74	76
4	68	66
5	64	65
6	60	60
7	47	45
8	43	43
9	43	42
10	44	43
11	50	49
12	50	49
13	52	50
14	50	49
15	62	63
16	52	52
17	44	44
18	44	44
19	43	44
20	45	45
21	38	38
22	39	39
23	40	39
24	39	39
25	1058	1057
26	1070	1057
27	1072	1067
28	171	174
29	185	189
30	Out	Out
31	1090	1084
32	179	182
33	180	180
34	115	111
35	67	66
36	54	54
37	1284	1251
38	145	143
39	47	46
40	47	48
41	1124	1120
42	1282	1274
43	1338	1330
44	1443	1439

Table 8-8. SNAP-21B-1 System Test Comparison of
Electrical Data-System Test Circuit

	Old	New
Generator primary load voltage (volts)	5.23	5.23
Generator bias load voltage (volts)	0.73	0.73
Generator primary load current (amps)	2.48	2.46
Generator bias load current (amps)	0.15	0.15
Generator primary power output (watts)	12.97	12.87
Generator bias power output (watts)	0.11	0.11
Generator total power output (watts)	13.08	12.98
Conditioner primary voltage input (volts)	4.90	4.89
Conditioner bias voltage input (volts)	0.60	0.60
Conditioner primary current input (amps)	2.48	2.46
Conditioner bias current input (amps)	0.15	0.15
Conditioner primary power input (watts)	12.15	12.03
Conditioner bias power input (watts)	0.09	0.09
Conditioner total power input (watts)	12.24	12.12
System load voltage (volts)	24.00	24.00
System load current (amps)	0.45	0.45
System power output (measured)(watts)	10.90	10.80
System power output (corrected)(watts)	11.65	11.67
System power input (measured)(watts)	230	230
System power input (corrected)(watts)	226	226

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Table 8-9. SNAP-21B-1 System Test Comparison of Summary
of Data System Test Circuit

	Old	New
Generator hot electrode temperature (°F)	1100	1091
Generator cold electrode temperature (°F)	179	181
Water temperature (°F)	39	39
Generator load voltage (volts) ¹	5.23	5.23
Generator load current (amps) ¹	2.48	2.46
Generator total power output (watts)	13.08	12.98
Conditioner load voltage input (volts) ¹	4.90	4.89
Conditioner load current input (amps) ¹	2.48	2.46
Conditioner total power input (watts)	12.24	12.12
System load voltage (volts)	24.00	24.00
System load current (amps)	0.45	0.45
System power output (measured)(watts)	10.90	10.80
System power output (corrected)(watts) ²	11.65	11.67
System power input (measured)(watts)	230	230
System power input (corrected)(watts) ³	226	226
Conditioner efficiency (percent)	89	89
System efficiency (percent) ⁴	5.2	5.2

(1) Primary circuit only.

(2) Corrected for measured instrumentation losses.

(3) Corrected for estimated instrumentation losses.

(4) Based on corrected power input and output.

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Table 8-10. Heat-Balance Summary for the SNAP-21B-1 System

<u>System Component</u>	<u>System at BOL</u>	<u>System at EOL</u>
Insulation Envelope		
Bottom Support Tube	17.4	15.8
Thickness of Getter Capsule	0.2	0.2
Super Insulation	7.4	5.9
Microquartz	2.8	2.5
Neck Tube	21.0	18.1
Generator		
Insulation Around Legs	5.8	5.2
Insulation Annular Ring	2.9	2.6
Outer Case	9.9	8.8
Legs	136.8	119.9
Insulation Between Generator and Neck Tube	0.4	0.3
Leads to System Power Input, Thermocouples	4.0	3.0
Total	208.6	182.3
Heat Input, Experimental	230.0	203.0

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A heat balance is an accounting of the quantity of heat which flows through each component from heat source to heat sink. The summation of these quantities for all components which surround the heat source should equal the quantity of heat which is being supplied to the system. It should be noted that the heat balances to be presented below are based on one-dimensional heat flow which results in some inherent error.

The results of the calculations of the heat flow through each component of the system at the BOL and EOL thermal conditions described in Section 8.5 are summarized in Table 8-11. See Appendix C for details of the calculations. The calculated heat fluxes and the measured power inputs show agreement to within 8 percent for the BOL and EOL thermal conditions. This was felt to be very acceptable on an over-all system basis, due to the inherent difficulty in making heat flux measurements. The discrepancy was probably the result of an accumulation of small errors in the calculations for each component rather than a gross miscalculation for any single item.

Table 8-11. SNAP-21B-1 System Test Comparison of Electrical Data Generator Test Circuit

	Old	New
Open Circuit Voltage (volts)	10.48	10.40
Load Voltage (volts)	5.23	5.23
Load Current (amps)	2.50	2.50
Internal Resistance (ohms)	2.10	2.07
Power Output (watts)	13.08	13.08

APPENDIX A

ENGINEERING DESIGN SUMMARY OF THE SNAP-21B DEEP SEA POWER SUPPLY SYSTEM

The SNAP-21B engineering design summary is based upon the Phase I design and experimental work completed on June 30, 1965. It was assumed in preparing this summary that the data presented would reflect the power supply system that could be constructed on July 1, 1965 and would exhibit the properties outlined below.

Contractor	Minnesota Mining and Manufacturing Co.
Contract No.	AT(30-1)-3321
Users and Missions	Not Available
Status	SNAP-21B-1 Systems Test Operational
Date Prepared	July 7, 1965

SYSTEM AND GENERATOR DATA

System Concept	PbTe — thermoelectric, flat-plate type
Fuel	Sr ⁹⁰ TiO ₃
Major System Assemblies	Pressure vessel, single-module generator, insulation envelope, fuel capsule and shield, and power conditioning equipment.

	<u>Total System</u>	<u>Generator</u>
Design Life (years)	5	5
Weight	516 ± 2 pounds	20 ± 1 pounds
Length (inches)	27.85	4.12
Diameter (inches)	15.836 OD, maximum	7.84 and 4.45
Volume (cubic inches)	3339	89.3

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WEIGHT OF THE SNAP-21B SYSTEM (ACTUAL UNLESS NOTED)
NOVEMBER 19, 1965

Total Pressure Vessel - - - - - 151.27 lbs

Receptacle	5.0 lbs
Top Dome	40.0
Bottom Dome and Cylinder	106.0
All Bolts	0.27

Total Insulation System- - - - - 50.25 lbs

Total Biological Shield - - - - - 258.09

Shield Body	241.75 lbs
Plug and Bolts	16.34

Total Thermoelectric Generator - - - - - 18.853 lbs

Weight of Cold Frame	15.2 lbs
MIN-K 1301 (calc.)	0.07
Microquartz (calc.)	0.02
Boron Nitride (calc.)	0.13
Hot Frame (calc.)	1.63
Case	0.203
48 Couples (0.034 lb x 48)	1.6

One Couple - - - - - 0.034 lb

- 2 springs
- 2 followers
- 2 legs
- 2 cold shoes
- 2 hot shoes
- Hot junction electrode

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Radiation Disc (calc.) - - - - -	1.45 lbs
Segmented Centering Ring (Complete)- - - - -	25.6 lbs
Total Heat Source - - - - -	5.8 lbs
Fuel	1.8 lbs
Fuel Capsule	4.0
Total dc-dc Converter - - - - -	5.121 lbs
Converter Housing	2.575 lbs
Converter Lid	0.632
Converter Components	1.44
Trio Lab Regulator and Bracket	0.113
8 Bolts	0.031
Potting Compound	0.33
Total SNAP-21B System Weight, Less Plug with Strain Relief-	516.434 lbs

ELECTRICAL CHARACTERISTICS OF THE SNAP-21B SYSTEM

	<u>Total System</u>		<u>Generator</u>	
	BOL	EOL	BOL	EOL
Electric Output, watts (e)	11.7	10.1	13.3	11.4
Thermal Input, watts (th)	203	179	152.3	135
Efficiency, percent	6.25	5.6	8.75	8.45
Specific Power, watts (e)/pound	0.23	0.20	0.70	0.60
Closed Circuit Voltage, volts	24	24	5.95 + 0.868	5.067 + 0.727
Design Voltage, volts	24	24	Same	Same
Design Current, amps	0.421	0.421	N/A	N/A

TEMPERATURE PROFILE (BOL)

Fuel, Maximum	1422°F
Fuel Capsule Surface	1412°F
Hot Junction, T_h	1100°F
Cold Junction, T_c	115°F
Thermionic, T_v	N/A
Generator Housing	1108° by 86°F
Tip of Fins	N/A
Converter Housing	N/A
Ambient Sea Water	41°F
Shield Surface, Average	1362°F

HEAT DISTRIBUTION

Total Thermal Input	203 watts	100%
Heat to T/E Legs	132	65
Heat Loss through T/E Insulation	8	4
Other System Heat Losses	63	31
Heat Rejected from Housing	71	37
Heat Rejected from T/E Couples	119	63
Heat Rejected - Total	190	100

Heat Requirement area:

Thermoelectric Legs	132.0 watts
Insulation Envelope	32.0
Other	39.0
Total	203.0 watts

SYSTEM ENVIRONMENTAL CAPABILITIES**OPERATIONAL ENVIRONMENT (INCLUDING TRANSPORTATION)**

Temperature	34.5° ± 6.5°F (nominal) -65° to 130°F (extreme range)
Pressure	10,000 psi; 22,500 feet (ocean depth)
Humidity	Minimum - 0% Maximum - 100% in salt atmosphere
Shock	As incurred in vibration
Vibration	5 to 32 cps having an excursion within 0.054 to 0.066 inch or an excursion producing 3 g's.
Acceleration	As incurred in vibration

STORAGE

Storage Life	5 years
Temperature	42.5° ± 97.5°F
Pressure	10 to 32 in. Hg
Humidity	100% relative humidity
Other	None

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SAFETY DATA

OPERATION, HANDLING, AND TRANSPORTATION – RADIATION DOSE RATES

	<u>In Operation</u>	<u>At System Surface in Transport</u>	<u>One Meter From System Surface</u>
Total Bremsstrahlung, mr/hr	200	200	10
Total Neutrons, mr/hr	None	None	None
Basis of Optional Data	Enclosed in pressure vessel		
Regulations Adhered To	AEC-ICC shipping regulations		

SYSTEM DESIGN TO MAINTAIN FUEL CAPSULE INTEGRITY

Accident	Rupture of pressure vessel
Maximum Temperature, °F	1425
Maximum External Pressure, psi	10,000
Impact Velocity (capsule intact)	Not applicable
Reentry Burnup	Not applicable
Long-Term Corrosion	Exposed to sea water at 10,000 psi
Design Life, years	300

FUEL SPECIFICATIONS USED IN DESIGN AND SAFETY ANALYSIS

Fuel Supplied By	ORNL
Isotopic Composition	Sr-90, > 75%; Sr-89, < 25%; Ce-144 < 1%
Chemical Form	SrTiO ₃

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Physical Properties:

Melting Point, °F	~ 3450
Boiling Point, °F	> 3450
Kindling Temperature, °F	> 3450
Maximum Continuous Operating Temperature, °F	1425
Density, gm/cm ³ at 70°F	3.7
Specific Activity, curies/gm	33
Specific Power, watt/gm	0.21
Power Density, watt/cm ³	0.8
Specific Heat, Btu/gm-°F	0.143
Thermal Conductivity, Btu/hr-ft ² -°F/in.	38.3
Limiting Factor	Capsule integrity

Nuclear Radiation

<u>Type</u>	<u>Half-Life (yrs)</u>	<u>Energy (mev)</u>	<u>%</u>	<u>Remarks</u>
Bremsstrahlung	30	2.18 max.	100	Primary beta absorbed in fuel, secondary bremsstrahlung radiation

Determined Dose Rates

<u>Type of Radiation</u>	<u>Dose Rate (mrad/hr)</u>	<u>Remarks</u>
Bremsstrahlung	200	At surface pressure vessel

Chemical Properties

Chemical Reactions

None applicable

Corrosion Effects

None

Health Data

Half-Lives:

Radiological, year

28

Biological, year

50

Effective, year

18

Maximum Permissible Body Burden, μCi

20

Maximum Permissible Concentration ($\mu\text{Ci}/\text{cm}^3$ in air)

$3 \times 10^{-10}/168$ hour
week

Maximum Permissible Concentration ($\mu\text{Ci}/\text{cm}^3$ in water)

$4 \times 10^{-6}/168$ hour
week

Toxicity

Insignificant

HEAT SOURCE

System

Thermal Input:

BOL, watt (T_h)

203.0

EOL, watt (T_h)

179.0

Capsules Per Generator

1

Isotope and Chemical Form

$\text{Sr}^{90}\text{TiO}_3$

Capsule (design must be modified)

Overall Length, in.	3.337
Overall Diameter, in.	3.198
Length/Area, in. ⁻¹	0.416
Fuel Loading Per Capsule, BOL (design must be modified)	187 watt (T _h)
	890 gm
	30,000 curies
Internal volume per capsule:	
Total, in ³	14.3
Fuel, in ³	14.3
Void (percent of total)	< 1
Internal Pressure (maximum psi at 1400°F after 1 year)	60
Design Pressure	Not applicable

	<u>Capsule</u>	<u>Capsule Liner</u>
Material	Hastelloy Alloy C	SS 316
Inside Diameter, in.	2.698	2.660
Inside Length, in.	2.737	2.680
Wall Thickness, Sides, in.	0.250	0.020
Wall Thickness, Ends, in.	0.250	0.030
Total Weight, lb	3.8	0.1
Melting Point, °F	2400	2500
Thermal Conductivity, Btu/hr-ft/°F	10.0 @ 1150°F	12.4 @ 932°F

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	<u>Capsule</u>	<u>Capsule Liner</u>
Linear Expansion Coefficient, $10^{-6}/^{\circ}\text{F}$	8.2 @ 70-1600°F	12.8 @ 1900°F
Density, lb/in ³	0.323 @ 72°F	0.290 @ 72°F
Strength-Tensile, psi	121,000 @ 72°F	75,000 @ 72°F
Yield, psi	81,000 @ 72°F	30,000 @ 72°F
Closure Method	Weld	Weld
Material	Hastelloy Alloy C	SS 316
Minimum Penetration, in.	0.100	0.020
Shear Strength, psi	30,000	Not Applicable

THERMOELECTRIC CONVERSION ASSEMBLY

Couples/Generator	48
Modules/Generator	1
Couples/Module	N/A
Electrical Resistance:	
Generator	1.32 ohms (EOL)
Module	N/A ohms
Couple	N/A ohms
Type of Circuit	Series
Thermoelectric Efficiency, %	10.0 (BOL)
Energy Conversion Efficiency, % (net, system)	6.25 (EOL)

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THERMOELECTRIC LEGS

	<u>P-Leg</u>	<u>N-Leg</u>
Thermoelectric Material (segmented)	(BiSb) ₂ Te ₃ -PbTe, SnTe	PbTe-PbTe
Fabrication Method	Powder pressed	Powder pressed
Hot Segment Length, inch	0.267	0.371
Cold Segment Length, inch	0.144	0.200
Total Leg Length, inch	0.411	0.571
Diameter, inch	0.188	0.188
Length/Area, inches ⁻¹	14.9	20.7
Hot Junction Temperature, °F	1100	1100
Cold Junction Temperature, °F	115	115
Segment Temperature @ Max. Eff., °F	548	425
Open Circuit Voltage, mv	105.8	125.8
Load Voltage @ Max. Eff., mv	62.8	72.8
Average Resistivity, μΩ-in.	1149	1042
Current @ Max. Eff., amps	2.5	2.5
Power @ Max. Eff., watt	0.16	0.18
Rate of Heat Rejection, watts	1.34	1.35
Rate of Heat Absorption, watts	1.50	1.53
Material Efficiency, %	10.5	11.7

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N-Leg					
Operating Temperature (°F)	T (°F)	S (mv °F)	P (μΩ - in.)	K (watts/in.°F)	Z* (°C ⁻¹ x 10 ³)
115	110	115	460	0.0325	1.59
425	cold				
	200	126	715	0.0274	1.46
	seg.				
	300	138	1050	0.0240	1.36
	400	149	1450	0.0219	1.26
	500	105	540	0.0258	1.42
	600	115	720	0.0233	1.42
	700	125	950	0.0213	1.39
	800	133	1200	0.0203	1.31
	900	134	1470	0.0205	1.07
1100	hot seg.				
	1000	130	1730	0.0225	0.78
1100	1100	120	1850	0.0250	0.56

$$*1.59 = Z \times 10^3$$

$$Z = 1.59 \times 10^3$$

$$Z = 0.00159$$

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P-Leg					
Operating Temperature (°F)	T (°F)	S (mv °F)	P ($\mu\Omega$ -in.)	K (watts/in.°F)	Z (°C ⁻¹ x 10 ³)
115	100	88.5	359	0.0140	2.80
	200	94.5	505	0.0130	2.44
	300	102.5	657	0.0129	2.22
	400	106.9	843	0.0140	1.74
548	500	105.3	1021	0.0161	1.22
	600	93.0	890	0.0180	0.97
	700	102.0	1070	0.0181	0.97
	800	111.0	1290	0.0190	0.90
	900	118.0	1520	0.0203	0.81
	1000	123	1750	0.0212	0.73
1100	1100	122	1830	0.0224	0.65

Hot Shoe

Material	Iron
Thickness, inch	0.020
Diameter, inch	0.228
Bond (material, thickness and method)	N/A
Diffusion barrier (material and thickness)	Note: Hot shoe serves this function; connected in series by copper electrode (0.544 long x 0.248 wide x 0.040 thick)

Cold Shoe

Material	Copper
Thickness, inch	0.175 and 0.334
Diameter, inch	0.188
Bond (material, thickness and method)	Tin Solder
Diffusion barrier (material and thickness)	N/A

Electrical Leads Between Couples

Material	Copper
Thickness, inch	N/A
Diameter, inch	0.033
Method of Attachment to Cold Junction	Solder

Thermal Contact

Method of Assuring Thermal Contact

Spring pressure

Materials and Dimensions

From 347-SS generator hot frame through boron-nitride electric insulation, copper hot strap, iron hot shoe, thermoelectric leg, copper cold shoe, aluminum follower to the generator cold frame

DC-DC CONVERTERS

Circuit Type

Modified Royer

Converters/System

1

Principal Components

Transistors, transformer, capacitors, resistors, zener diode

Weight, lb

 $5 \pm 1/2$

Length, in.

4.4

Impedance, ohms

N/A

Diameter, in.

10.2

Transistor Material

Germanium/silicon

Transformer Core Material

50% Ni-Fe

	<u>BOL</u>	<u>EOL</u>
Efficiency, %	N/A	89.0
Output Power, watt(e)	10.1	10.1
Output voltage, volts (s)	24.0	24.0
Output current, amps (s)	0.421	0.421
Input power, watt (e)	13.8	11.7

	<u>BOL</u>	<u>EOL</u>
Input voltage, volts (s)	N/A	5.1, 0.7*
Input current, amps (s)	N/A	2.22, 0.150*
Oscillating Frequency, cps	250	
Operating Temperature	70°F ± 5°F	
Voltage Regulation	±3.0%	
Transistor Losses, watt (e)	1.104 maximum	
Ripple, mv (peak to peak)	100	
Transformer Losses, watt (e)	0.326 maximum	

OTHER COMPONENTS

Fill Gas or Vacuum

Composition, Percent, and Purpose	Vacuum in space occupied by thermal insulation between shield and pressure vessel.
Pressure	1 to 15 x 10 ⁻³ mm Hg
Temperature Range	50° to 1350°F
Thermal Conductivity	0.0008 Btu/hr-ft-°F

Thermal Insulation between T/E Thermoelements or T/I Diode Insulation

Material and Dimensions	MIN-K 1301 insulation powder-packed and xenon backfilled in all generator void spaces. Microquartz insulation in felt form located in strategic locations to prevent powder shifting.
-------------------------	---

*3-wire input sealed in an aluminum enclosure.

Estimated Thermal Conductivity 0.0192 Btu/hr-ft°F

Electrical Insulation

Materials, Location Boron nitride on generator hot frame, aluminum hardcoat on thermoelectric leg spring-loaded follower

Housing (Pressure Vessel)

Material	721 Titanium
Coating	None
Outer Diameter, inches	14.675
Height, inches	27.850
Typical Thickness, inches	1.090
Flange: OD, inches	15.831
ID, inches	10.500
Typical Thickness, inches	2.665

Seals

<u>Type</u>	<u>No. Per System</u>	<u>Material</u>	<u>ID (in.)</u>	<u>Actual Thickness (diam)</u>	<u>Remarks</u>
O-ring	1	Vitron	3.234	0.139	Seal between vessel and receptacle
O-ring	1	Vitron	14.359	0.275	Outer seal between sections of pressure vessel
O-ring	1	Vitron	13.309	0.275	Inner seal between sections of pressure vessel

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Electrical Leadthroughs

Type, Number, Material

Through pressure vessel, 12 "Niron"
gold and copper plated pins; titanium
721; to be bolt attached to pressure
vessel penetration.

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Figure B-1. Diagram Depicting How Two Forged Titanium Pressure Vessels Were Sectioned for Mechanical Testing Purposes and Parts Used for Final Assembly

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TEST RING TESTS

ONE HALF TEST RING FOR CUSTOMER TESTS
ONE HALF TEST RING FOR TFPW TESTS

TEST IDENTITY	TEST DESCRIPTION
TT-1 THRU TT-4	0.252 DIA. R.T. TENSILE
RT-1; RT-2	0.252 DIA R.T. TENSILE
TC-1; TC-2; RC-1; RC-2	0.500 DIA x 1.5 R.T. COMPRESSION TEST
TI-1 THRU TI-3	V-NOTCH CHARPY TEST @ 32°F
TI-4 THRU TI-6	V-NOTCH CHARPY TEST @ -80°F
RI-1 THRU RI-3	V-NOTCH CHARPY TEST @ 32°F
RI-4 THRU RI-6	V-NOTCH CHARPY TEST @ -80°F
M-1; M-2	MICROSPECIMEN POLISH AND PHOTO

CROSS-SECTIONED FORGING TESTS

ONE HALF FORGING FOR CUSTOMERS TESTS
ONE HALF FORGING FOR TFPW TESTS

TEST IDENTITY	TEST DESCRIPTION
A	3/8 THICK MACROSLAB ETCH AND PHOTO
REMOVE AT SECTION "A-A"	
TT-1; TT-2; TT-3	0.252 DIA R.T. TENSILE
AT-1, 2, 3, 7	0.252 DIA R.T. TENSILE
AI-1 THRU 3	V-NOTCH CHARPY IMPACT TEST AT 32°F
AI-4 THRU 6	V-NOTCH CHARPY IMPACT TEST AT -80°F
AI-7 THRU 9	V-NOTCH CHARPY IMPACT TEST AT 32°F
AI-8 THRU 12	V-NOTCH CHARPY IMPACT TEST AT -80°F
TI-1 THRU TI-3	V-NOTCH CHARPY IMPACT TEST AT 32°F
REMOVE AT OR NEAR SECTION "B-B"	
TT-4	0.252 DIA R.T. TENSILE
AT-4, 5, 6, 8	0.252 DIA R.T. TENSILE
TC-1,2	0.500 DIA x 1.5 COMPRESSION TEST
AC-1,2	0.500 DIA x 1.5 COMPRESSION TEST
TI-4 THRU TI-6	V-NOTCH CHARPY IMPACT TEST AT -80°F
M-1 THRU M-4	MICROSPECIMENS ETCH AND PHOTO
AC-3; AC-4	0.500 DIA x 1.5 COMPRESSION TEST

Figure B-3. Pressure Vessel Body Test Specimen Locations

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Table B-1. Pressure Vessel Cover - Test Ring Serial No. 1

Forging Serial No.	Test Identity	Test Temp.	TENSILE TESTS				IMPACT TESTS		COMPRESSION TESTS
			0.2% Off Yield Strength (psi)	Ultimate Strength (psi)	% Elong. in 1"	% Reduction in Area	Charpy V Notch (ft-lbs)	Charpy V 3 Test Average	0.2% Off Yield Strength (psi)
1	TT-1	RT	119600	132000	14.0	31.0			
	TT-2	RT	117400	130000	17.0	31.0			
	RT-1	RT	112000	124200	17.0	29.0			
	RT-2	RT	111600	124200	19.0	30.0			
	TI-1	32°F					35		
	TI-2	32°F					31	34.3	
	TI-3	32°F					37		
	TI-4	-80°F					22		
	TI-5	-80°F					23	23.0	
	TI-6	-80°F					24		
	RI-1	32°F					33		
	RI-2	32°F					32	32.0	
	RI-3	32°F					31		
	RI-4	-80°F					28		
	RI-5	-80°F					21	24.0	
	RI-6	-80°F					23		
	TC-1	RT							129000
	TC-2	RT							114990
	RC-1	RT							119800
	RC-2	RT							119230
	RC-3	RT							121800

RC-3 RETEST AT RC-1 LOCATION

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Table B-2. Pressure Vessel Cover - Test Ring Serial No. 2

TENSILE TESTS							IMPACT TESTS		COMPRESSION TESTS
Forging Serial No.	Test Identity	Test Temp.	0.2% Off Yield Strength (psi)	Ultimate Strength (psi)	% Elong. in 1"	% Reduction in Area	Charpy V Notch (ft-lbs)	Charpy V 3 Test Average	0.2% Off Yield Strength (psi)
2	TT-1	RT	118000	131200	14.0	33.0			
	TT-2	RT	115200	127200	14.0	30.0			
	RT-1	RT	110800	123200	18.0	30.0			
	RT-2	RT	109900	121600	16.0	28.0			
	TI-1	32°F					34		
	TI-2	32°F					31	32.7	
	TI-3	32°F					33		
	TI-4	-80°F					23		
	TI-5	-80°F					24	23.7	
	TI-6	-80°F					44		
	RI-1	32°F					34		
	RI-2	32°F					32	32.0	
	RI-3	32°F					30		
	RI-4	-80°F					24		
	RI-5	-80°F					25	24.3	
	RI-6	-80°F					24		
	TC-1	RT							123600
	TC-2	RT							121300
	RC-1	RT							112400
	RC-2	RT							116420
	RC-3	RT							117620

RC-3 RETEST AT RC-1 LOCATION

T - Tangential
R - Radial
A - Axial

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Table B-3. Pressure Vessel Cover - Cross-Section Forging

Forging Serial No.	COMPRESSION TESTS						IMPACT TESTS		COMPRESSION TESTS
	Test Identity	Test Temp.	0.2% Off Yield Strength (psi)	Ultimate Strength (psi)	% Elong. in 1"	% Reduction in Area	CharpyV Notch (ft-lbs)	Charpy V 3 Test Average	0.2% Off Yield Strength (psi)
1	TT-1	RT	107600	116800	12.0	28.0			
	TT-2	RT	106400	120000	16.0	28.0			
	TT-3	RT	111600	122800	17.0	30.0			
	TT-4	RT	110800	123400	13.0	22.0			
	TT-5	RT	100800	114000	13.0	30.0			
	TT-6	RT	103200	115600	10.0	25.0			
	AT-1	RT	102800	116200	12.0	26.0			
	AT-2	RT	102800	119000	15.0	26.0			
	AT-3	RT	101200	117000	10.0	23.0			
	AT-4	RT	102700	116200	13.0	26.0			
	TI-1	32°F					35		
	TI-2	32°F					38	38.0	
	TI-3	32°F					41		
	TI-4	-80°F					23		
	TI-5	-80°F					31	26.3	
	TI-6	-80°F					25		
	AI-1	32°F					38		
	AI-2	32°F					39	40.3	
	AI-3	32°F					44		
	AI-4	-80°F					26		
	AI-5	-80°F					38	31.6	
	AI-6	-80°F					31		
	RC-1	RT							108570
	RC-2	RT							108650
	RC-3	RT							107290
	AC-1	RT							107740
	AC-2	RT							108650
	T - Tangential R - Radial A - Axial

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Table B-4. Pressure Vessel Body - Cross-Section Forging

MECHANICAL PROPERTY TABULATION

Forging Serial No.	Test Identity	Test Temp.	TENSILE TESTS				IMPACT TESTS		COMPRESSION TESTS
			0.2% Off Yield Strength (psi)	Ultimate Strength (psi)	% Elong. In 1"	% Reduction In Area	Charpy V Notch (ft-lbs)	Charpy V 3 Test Average	0.2% Off Yield Strength (psi)
2	TT-1	RT	106400	120000	13.0	23.0			
	TT-2	RT	105100	119200	12.0	27.0			
	TT-3	RT	101200	115200	11.0	27.0			
	TT-4	RT	105600	120000	16.0	30.0			
	AT-1	RT	106000	119200	14.0	29.0			
	AT-2	RT	105800	118600	16.0	29.0			
	AT-3	RT	107000	118200	13.0	24.0			
	AT-4	RT	106000	117900	14.0	21.0			
	AT-5	RT	105200	117600	13.0	30.0			
	AT-6	RT	105200	115600	15.0	34.0			
	AT-7	RT	103500	116000	12.0	36.0			
	AT-8	RT	107800	121200	13.0	21.8			
	TI-1	32°F					34		
	TI-2	32°F					37	34.0	
	TI-3	32°F					31		
	TI-4	-80°F					25		
	TI-5	-80°F					24	24.7	
	TI-6	-80°F					24		
	AI-1	32°F					35		
	AI-2	32°F					42	36.6	
	AI-3	32°F					33		
	AI-4	-80°F					24		
	AI-5	-80°F					28	25.3	
	AI-6	-80°F					24		
	AI-7	32°F					38		
	AI-8	32°F					35	35.3	
	AI-9	32°F					34		
	AI-10	-80°F					26		
	AI-11	-80°F					25	25.6	
	AI-12	-80°F					26		
	TC-1	RT							111450
	TC-2	RT							107634
	AC-1	RT							109407
	AC-2	RT							109725
	AC-3	RT							111026
	AC-4	RT							108707

T - Tangential
R - Radial
A - Axial

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Table B-5. Pressure Vessel Body - Test Ring Serial No. 1

Forging Serial No.	Test Identity	Test Temp.	TENSILE TESTS				IMPACT TESTS		COMPRESSION TESTS
			0.2% Off Yield Strength (psi)	Ultimate Strength (psi)	% Elong. in 1"	% Reduction in Area	Charpy V Notch (ft-lbs)	Charpy V 3 Test Average	0.2% Off Yield Strength (psi)
1	TT-1	RT	106000	118800	11.0	29.0			
	TT-2	RT	104000	119000	13.0	28.0			
	TT-3	RT	105600	119800	15.0	29.0			
	TT-4	RT	105600	120200	16.0	30.0			
	RT-1	RT	105600	119800	13.0	26.0			
	RT-2	RT	104400	118800	14.0	29.0			
	TI-1	32°F					36		
	TI-2	32°F					44	38.0	
	TI-3	32°F					34		
	TI-4	-80°F					26		
	TI-5	-80°F					23	24.3	
	TI-6	-80°F					24		
	RI-1	32°F					35		
	RI-2	32°F					31	34.0	
	RI-3	32°F					36		
	RI-4	-80°F					22		
	RI-5	-80°F					24	23.3	
	RI-6	-80°F					24		
	TC-1	RT							107400
	TC-2	RT							113590
	RC-1	RT							111100
	RC-2	RT							108770

T - Tangential
R - Radial
A - Axial

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Table B-6. Pressure Vessel Body - Test Ring Serial No. 2

TENSILE TESTS							IMPACT TESTS		COMPRESSION TESTS
Forging Serial No.	Test Identity	Test Temp.	0.2% Off Yield Strength (psi)	Ultimate Strength (psi)	% Elong. in 1"	% Reduction in Area	Charpy V Notch (ft-lbs)	Charpy V 3 Test Average	0.2% Off Yield Strength (psi)
2	TT-1	RT	107500	119400	14.0	29.0			
	TT-2	RT	106000	119600	15.0	29.0			
	TT-3	RT	108000	119800	15.0	26.0			
	TT-4	RT	105200	118800	14.0	28.0			
	RT-1	RT	106000	119000	13.0	27.0			
	RT-2	RT	104800	119000	13.0	28.0			
	TI-1	32°F					38		
	TI-2	32°F					34	35.6	
	TI-3	32°F					35		
	TI-4	-80°F					23		
	TI-5	-80°F					28	25.0	
	TI-6	-80°F					24		
	RI-1	32°F					31		
	RI-2	32°F					30	30.6	
	RI-3	32°F					31		
	RI-4	-80°F					22		
	RI-5	-80°F					24	23.0	
	RI-6	-80°F					23		
	TC-1	RT							111000
	TC-2	RT							116180
	RC-1	RT							112000
	RC-2	RT							115100
T - Tangential R - Radial A - Axial									

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APPENDIX C

HEAT BALANCE CALCULATIONS

Heat transfer calculations are presented for the B.O.L. and E.O.L. thermal conditions as described in Section 8.0.

I. Insulation System

System pressure was maintained at less than 10 microns at both the B.O.L. and E.O.L. conditions.

<u>Summary of Results</u>	Heat Flux (watts)	
	<u>B.O.L.</u>	<u>E.O.L.</u>
A. Bottom Support Tube	17.35	15.75
B. Reduced Insulation Thickness at Getter Capsule	.24	.22
C. Super Insulation	7.38	5.87
D. Micro Quartz	2.78	2.48
E. Neck Tube	<u>21.0</u>	<u>18.1</u>
TOTAL	48.75	42.42

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Material - Inconel (X) 750

Length = (3.090 - .625) + .625/12	BOL	EOL
L = 2.517 in.	$T_h = 1428^{\circ}\text{F}$	1331°F
Area = (4.223)(π)(.010)	$T_c = 50^{\circ}\text{F}$	47°F
A = .1331 in ²	Mean Temp. 744°F	689°F
	K = $117 \frac{\text{Btu}}{\text{hr ft}^{\circ}\text{F}}$	$114 \frac{\text{Btu}}{\text{hr ft}^{\circ}\text{F}}$

$$Q = \frac{KA(T_h - T_c)}{L}$$

$$Q_{\text{BOL}} = \frac{117(.1331)(1428-50)}{2.517(144)} = 59.3 \text{ Btu/hr} = 17.35 \text{ watts}$$

$$Q_{\text{EOL}} = \frac{114(.1331)(1331-47)}{2.517(144)} = 53.8 \text{ Btu/hr} = 15.75 \text{ watts}$$

B. Reduced Insulation Thickness at Getter Capsule

According to Linde, the loss is 0.22 watts for $\Delta T = 1275^{\circ}\text{F}$

$$Q = \frac{\Delta T_i}{\Delta T} (0.22)$$

$$Q_{\text{BOL}} = \frac{1378}{1275} (0.22) = .2377 \text{ watts}$$

$$Q_{\text{EOL}} = \frac{1284}{1275} (0.22) = .2215 \text{ watts}$$

C. Super Insulation

<u>BOL</u>	<u>EOL</u>
$T_h = \frac{1443 + 1285}{2} - 5 = 1359^{\circ}\text{F}$	$T_h = \frac{1336 + 1151}{2} - 5 = 1239^{\circ}\text{F}$
$T_c = 52^{\circ}\text{F}$	$T_c = 50^{\circ}\text{F}$
$K = .0008 \text{ Btu/hr ft}^{\circ}\text{F}$	$K = .0007 \text{ Btu/hr ft}^{\circ}\text{F}$

$$L = 1.72 \text{ in} = 0.143 \text{ ft}$$

$$A = 3.44 \text{ ft}^2$$

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$$Q_{\text{BOL}} = \frac{.0008(3.44)(1307)}{(0.143)} = 25.2 \text{ Btu/hr} = 7.38 \text{ watts}$$

$$Q_{\text{EOL}} = \frac{.0007(3.44)(1189)}{(0.143)} = 20.0 \text{ Btu/hr} = 5.87 \text{ watts}$$

D. Micro Quartz

$$K = .022 \text{ Btu/hr ft}^{\circ}\text{F} \quad \text{I.D.} = 4.780 \text{ in.}$$

$$L = 2.250 \text{ in} \quad \text{O.D.} = 6.000 \text{ in.}$$

$$A = 10.31 \text{ in}^2$$

BOL

EOL

$$T_h = 1271^{\circ}\text{F}$$

$$T_h = 1138^{\circ}\text{F}$$

$$T_c = 145^{\circ}\text{F}$$

$$T_c = 132^{\circ}\text{F}$$

$$Q_{\text{BOL}} = \frac{.022(10.31)(1271-145)}{2.250(12)} = 9.46 \text{ Btu/hr} = 2.78 \text{ watts}$$

$$Q_{\text{EOL}} = \frac{(.022)(10.31)(1006)}{2.250(12)} = 2.48 \text{ watts}$$

E. Neck Tube (304 Stainless Steel, PD-37-1216-A)

$$Q = KU\Delta T$$

$$T_h = 1271^{\circ}\text{F}$$

$$1138^{\circ}\text{F}$$

$$U = \frac{1}{1/u_1 + 1/u_2 + 1/u_3}$$

$$T_c = 145^{\circ}\text{F}$$

$$132^{\circ}\text{F}$$

$$U_i = \frac{A_i}{L_i}$$

$$\text{Mean Temp} = 708^{\circ}\text{F}$$

$$635^{\circ}\text{F}$$

$$K = 11.6 \text{ Btu/hr ft}^{\circ}\text{F}$$

$$11.2 \text{ Btu/hr ft}^{\circ}\text{F}$$

$$U_i = \frac{4.760(\pi)(.035)}{.320(12)} = .132$$

$$U_2 = \frac{4.760(\pi)(.0095)}{2.00(12)} = .00590$$

$$U_3 = \frac{4.760(\pi)(.085)}{.57(12)} = .1885$$

$$U = \frac{1}{1/.132 + 1/.0059 + 1/.1885} = .00548$$

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$$Q_{\text{BOL}} = 11.6(.00548)(1271-145) = 71.6 \text{ Btu/hr} = 21.0 \text{ watts}$$

$$Q_{\text{EOL}} = 11.2(.00548)(1138-132) = 61.7 \text{ Btu/hr} = 18.1 \text{ watts}$$

II. Generator Structure and Insulation

<u>Summary of Results:</u>	Heat Flux (Watts)	
	<u>B.O.L.</u>	<u>E.O.L.</u>
A. Min K 1301 around legs	5.77	5.20
B. Min K 1301 annular ring	2.20	1.98
C. Micro Quartz Annular ring	.68	.60
D. T/E Legs	136.8	119.90
E. Outer Case	<u>9.93</u>	<u>8.84</u>
	155.4	136.5

Calculations:

A. Min K 1301 Around Legs

$$A_{\text{legs}} = 96(.1875)^2(.785) = 2.65 \text{ in}^2$$

Area of Min K 1301, .818 in. thickness

$$A_{\text{MK}} = (3.70)^2(.785) - 2.65 = 8.10 \text{ in}^2$$

$$K = .0242 \text{ Btu/hr ft}^{\circ}\text{F (Min K 1301 Xenon gas filled)}$$

$$L = .818 \text{ in.} \quad Q = \frac{KA\Delta T}{L}$$

$$Q_{\text{BOL}} = \frac{.0242(8.1)(1100-115)}{.818(12)} = 19.65 \text{ Btu/hr} = 5.77 \text{ watts}$$

$$Q_{\text{EOL}} = \frac{.0242(8.1)(887)}{.818(12)} = 17.7 \text{ Btu/hr} = 5.20 \text{ watts}$$

B. Annular Ring Min K 1301

$$\text{O.D.} = 4.394 \text{ in.} \quad \text{I.D.} = 3.700$$

$$L = 1.165 \text{ in.} \quad A = .785(4.394^2 - 3.700^2) = 4.41 \text{ in}^2$$

$$Q_{\text{BOL}} = \frac{.0242(4.41)(985)}{(1.165)(12)} = 7.5 = 2.2 \text{ watts}$$

$$Q_{\text{EOL}} + \frac{.0242(4.41)(887)}{1.165(12)} = 1.98 \text{ watts}$$

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C. Annular Ring - Micro Quartz

BOL Temperature Conditions:

$$T_h = 1100^{\circ}\text{F}$$

$$T_c = 75^{\circ}\text{F}$$

$$\Delta T = 1025^{\circ}\text{F}$$

$$\frac{1.165}{1.750} (1025) = 682^{\circ}\text{F}$$

$$\text{Temp} = 1025 - 682 = 343^{\circ}\text{F}$$

$$\text{Mean Case Temp} = \frac{343 + 75}{2} = 209^{\circ}\text{F}$$

$$\text{Cold Side Temp} = 95^{\circ}\text{F}$$

$$L = 1.750 - 1.165 = .585 \text{ in.}$$

$$Q = \frac{KL\Delta T}{\ln r_2/r_i}$$

$$r_2 = 2.197$$

$$r_2/r_i = 1.188$$

$$r_i = 1.850$$

$$\ln r_2/r_i = .174$$

$$K = .40 \text{ Btu/hr ft}^{\circ}\text{F}$$

$$Q_{\text{BOL}} = \frac{.40(.585)(343-95)}{(.174)(144)} = 2.52 \text{ Btu/hr} = .68 \text{ watts}$$

EOL Temperature Conditions:

$$T_h = 990^{\circ}\text{F}$$

$$T_c = 72^{\circ}\text{F}$$

$$\Delta T = 918^{\circ}\text{F}$$

$$\frac{1.165}{1.750} (918) = 611^{\circ}\text{F}$$

$$\text{Temp} = 918 - 611 = 307^{\circ}\text{F}$$

$$\text{Mean Case Temp} = \frac{307 + 72}{2} = 190^{\circ}\text{F}$$

$$\text{Cold Side Temp} = 88^{\circ}\text{F}$$

$$Q_{\text{EOL}} = \frac{.40(.585)(307-88)}{.174(144)} = 2.04 \text{ Btu/hr} = .598 \text{ watts}$$

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D. Thermoelectric Legs

The heat fluxes through the thermoelectric legs were determined using computer program #1190 dated 9/24/65.

	<u>BOL</u>	<u>EOL</u>
T_h	1100°F	990°F
T_c	179°F	165°F
$Q_{BOL} = 136.8$ watts		$Q_{EOL} = 119.90$ watts

	<u>BOL</u>	<u>EOL</u>
E. <u>Outer Case</u> (347 Stainless Steel)		
$A = (4.389)(\pi)(.006) = .0829$ in ²	$T_h = 1124^\circ\text{F}$	1023°F
$L = 2.383$ in. (for effective thickness .006)	$T_c = 95^\circ\text{F}$	88°F
	Mean Temp = 610°F	556°F
	$K = 11.3$	11.1 Btu/hr
		Btu/ft hr°F ft°F

$$Q = \frac{KA(T_h - T_c)}{L}$$

$$Q_{BOL} = \frac{11.3(.0829)(1124-95)}{(2.383)(12)} = 33.9 \text{ Btu/hr} = 9.93 \text{ watts}$$

$$Q_{EOL} = \frac{11.1(.0829)(1023-88)}{2.383 (12)} = 30.2 \text{ Btu/hr} = 8.84 \text{ watts}$$

III. Insulation Between Generator Case and Insulation System Support Tube
(Min K 1301)

	<u>BOL</u>	<u>EOL</u>
I.D. = 4.425 in.	$T_h = 1124^\circ\text{F}$	1023°F
O.D. = 4.760 in .	$T_c = 75^\circ\text{F}$	72°F
$A = (4.760^2 - 4.425^2)(.785)$	Mean	
$= 2.43$ in. ²	Temp = 600°F	500°F
	$K = .23$ Btu/hr ft°F	$.22$ Btu/hr ft°F
	$L = 3.016$ in.	

$$Q = \frac{KA\Delta T}{L}$$

$$Q_{BOL} = \frac{.23(2.43)(1124-75)}{3.016} = 1.355 \text{ Btu/hr} = 0.4 \text{ watts}$$

$$Q_{EOL} = \frac{.22(2.43)(1023-72)}{3.016(144)} = 1.172 \text{ Btu/hr} = .342 \text{ watts}$$

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IV. Instrumentation

	Heat Flux (Watts)	
	<u>BOL</u>	<u>EOL</u>
Heat loss by conduction in thermocouple and heater lead wires	3.11	2.33
I ² R heating in heater leads	0.35	0.26
Current coil of watt meter	0.23	0.17
Miscellaneous	<u>0.31</u>	<u>0.24</u>
	4.00	3.00

V. Summary Heat Balance

Heat Losses Accounted For:

I. Linde Insulation System	48.8	42.4
II. Generator Structure & Insulation	155.4	136.5
III. Insulation Between Generator Case and Insulation System		
Support Tube	.4	.3
IV. Instrumentation	<u>4.0</u>	<u>3.0</u>
TOTAL	208.6	182.2

APPENDIX D**PROGRAM DOCUMENTS**Quarterly Reports

*Quarterly Report No. 1, 9 March to 30 June 1964. Report No. NY00(3321)-3 (August 1964).

*---No. 2, 1 July to 30 September 1964. ---MMM(3321)-7 (October 1964).

*---No. 3, 1 October to 31 December 1964. ---MMM(3321)-11 (January 1964).

Bimonthly Report

*Bimonthly Report, 1 January to 28 February 1965. ---MMM(3321)-13 (March 1965).

Monthly Reports

Monthly Progress Letter No. 1, April 1964. (15 May 1964).

---No. 2, May 1964 (15 June 1964).

---No. 3, July 1964. Report No. NY00(3321)-4 (10 August 1964).

---No. 4, August 1964. ---MMM(3321)-5 (10 September 1964).

---No. 5, October 1964. ---MMM(3321)-8 (15 November 1964).

*C-92a distribution. Other program documents had limited distribution.

---No. 6, November 1964. ---MMM(3321)-9 (15 December 1964).

---No. 7, January 1965. ---MMM(3321)-12 (15 February 1965).

Monthly Report No. 8, March 1965. ---MMM(3321)-14 (April 1965).

Monthly Report (No. 9), April 1965. ---MMM(3321)-15 (May 1965).

Test Reports

Fuel Capsule Test Summary. Report No. MMM(3321)-16 (May 1965).

Preliminary Test Results of the SNAP-21B-1 System. ---MMM(3321)-17 (June 1965).

SNAP-21B Test Summary Letter No. 1 (7 July 1965).

---No. 2 (12 July 1965).

---No. 3 (26 July 1965).

---No. 4 (2 August 1965).

---No. 5 (30 August 1965).

---No. 6 (7 September 1965).

---No. 7 (13 September 1965).

---No. 8 (22 September 1965).

---No. 9 (7 October 1965).

---No. 10 (13 October 1965).

---No. 11 (20 October 1965).

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- No. 12 (28 October 1965).
- No. 13 (8 November 1965).
- No. 14 (1 December 1965).
- No. 15 (6 January 1966).
- No. 16 (7 February 1966).
- No. 17 (8 March 1966).
- No. 18 (8 April 1966).
- No. 19 (9 May 1966).
- No. 20 (9 June 1966).
- No. 21 (8 July 1966).