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SNAP-21 PROGRAM, PHASE II

DEEP SEA RADIOISOTOPE-FUELED
THERMOELECTRIC GENERATOR
POWER SUPPLY SYSTEM

PRELIMINARY DESIGN DESCRIPTION
10-WATT SYSTEM
REVISION 1

Isotope Power Products

MINNESOTA MINING & MANUFACTURING CO.

2501 HUDSON ROAD, ST. PAUL, MINN. 55119 PH. 631-2500

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Report No. MMM 3691-5

Revision 1

AEC RESEARCH AND DEVELOPMENT REPORT

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SNAP-21 PROGRAM, PHASE II

**DEEP SEA RADIOISOTOPE-FUELED
THERMOELECTRIC GENERATOR
POWER SUPPLY SYSTEM**

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10-WATT SYSTEM**

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Prepared by
J. Wharam

Approved by
V. Yanisch, Manager
SNAP-21 Program

Issued by:
ISOTOPE POWER PROJECT
ELECTRICAL PRODUCTS GROUP
MINNESOTA MINING AND MANUFACTURING COMPANY
ST. PAUL, MINNESOTA 55119

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1.0 INTRODUCTION

1.1 SYSTEM FUNCTION

The SNAP-21 10-watt system will provide electrical power for use under the surface of the sea. It functions to convert the heat from a decaying radioisotope fuel into useful electrical energy. This heat energy is converted into electrical energy by a thermoelectric generator. Semiconductor-type thermoelectric materials, maintained in a temperature gradient, accomplish the conversion. The isotopic fuel supplies the heat applied to the thermoelectric materials and sea water acts as the heat sink to maintain the temperature gradient. Other components are employed to increase efficiency and condition the electrical output to the desired form. The components performing these functions will be enclosed in a vessel which will protect them from sea water pressure and exposure. No external inputs are required to maintain operation of the system. With this type of mechanically-static, unsupported operation, long life with no maintenance is achieved.

1.2 SUMMARY DESCRIPTION OF THE SYSTEM

1.2.1 ASSEMBLED SYSTEM DESCRIPTION

The radioisotopic fuel heat source is enclosed in a capsule which is surrounded by a two-piece shield. The shield in turn is surrounded by a vacuum thermal insulation system except in the area where the thermoelectric generator receives its heat. The thermoelectric generator which converts the heat to electricity is of the flat plate type.

The thermoelectric generator is attached to a mounting plate which also supports and locates the vacuum thermal insulation system in the pressure vessel body. An electric power conditioner mounted in the pressure vessel cover converts the thermoelectric generator electrical output to the desired voltage. The two-piece pressure vessel encloses all the components. A receptacle and plug mount on the pressure vessel cover for bringing electrical leads through the pressure vessel. Figure 1 shows the relative size, shape and location of these major components in the system.

Figure 1. SNAP-21 10-Watt System

1.2.2 SYSTEM OUTPUT

The system output is electrical power. During a five-year operating period the minimum outputs at the pins of the receptacle are:

Power	- 10 Watts
Voltage	- 24 ± 1 Volts DC
Nominal Load Current	- 0.417 Amp.

1.2.3 MECHANICAL AND PHYSICAL CHARACTERISTICS

The system, as designed, will have the following size and weights:

- Size: Length, small pressure vessel - 27.85 in.
Length, large pressure vessel - 35.55 in. (estimated)
Diameter - 15.836 in.
- Weight: Small pressure vessel (including receptacle) - 516 lbs.
Large pressure vessel (including receptacle) - 582 lbs. (estimated)

The system will be designed to withstand the following externally applied loads:

- Water Pressure - Sea level to 10,000 psi
- Vibration Loads - System subjected to vibration loads only
when in shipping container (reference
MIL-STD-810A dated June 23, 1964)

Acceleration Levels - 5 to 26 cps @ 3 g
26 to 40 cps @ 0.036 in. double amplitude
displacement to 50 cps @ 3.0 g peak

Duration - Frequency range traversed logarithmically
from 5 to 50 to 5 cps in 15 minutes

Total Cycling Time - Test cycle shall be performed
three times in each of the three orthogonal axes.

Total test time 135 minutes.

- Shock Loads - Reference MIL-STD-810A, dated June 23, 1964, Method 516.1, procedure I, except peak value shall be 3g and nominal duration 6 ms.

Shock Level - 3g peak value

Duration - 6 ms total nominal duration (sawtooth waveform)

Test Cycle - Three shocks in each direction applied along the three mutually perpendicular axes of the item for a total of 18 shocks.

1.2.4 MAJOR COMPONENT DESCRIPTION*

- Heat Source - The heat source is a radioisotope, Sr-90, fuel which is enclosed in a capsule. The capsule is designed to contain the fuel under all credible situations.
- Shield - The shield consists of two parts made of an alloy, uranium plus 8% Mo. The shield encloses the heat source to reduce the radiation level to an acceptable value.
- Insulation System - The insulation system is a vacuum container with the internal volume filled with heat reflective foil and quartz fiber spacers. It encloses the elevated temperature biological shield except in the area where the thermoelectric generator receives its heat input.
- Thermoelectric Generator - The thermoelectric generator contains thermoelectric legs assembled into couples connected into a series electrical circuit. The thermoelectric generator is the flat plate type with leg longitudinal axes parallel to each other and perpendicular to hot and cold frames. The legs are surrounded by powdered thermal insulation. The container is hermetically sealed and filled with special atmosphere. Fittings bring the electrical power out through the sealed container.

*Detailed component descriptions are provided in Section 2.0 and Appendix A.

- **Segmented Retaining Ring** - This component is an annular ring on which curved segments are mounted. These curved segments are spring loaded between the annular ring and interfacing components.
- **Power Conditioning Equipment** - This component contains electrical power converter and regulator. These internal components and circuitry are enclosed in a hermetically-sealed container.
- **Pressure Vessel** - The pressure vessel is two pieces, the body and the cover. When assembled, it encloses the system's internal components.
- **Receptacle** - Pins are mounted in an electrical insulation material in the body of the feed through receptacle.
- **Plug with Strain** - The plug with strain relief is a fitting on the end of an electrical cable. It mates with the feed-through receptacle with a mechanical lock and with sockets for mating with the feedthrough receptacle pins.

1.3 SYSTEM DESIGN REQUIREMENTS

The design requirements are presented in Appendix B, pages B-2 through B-4.

1.3.1 FUNCTIONING CONDITIONS

These are the conditions at which the system will normally function.

Surrounding Fluid - Sea Water

Fluid Pressure - Sea level to 10,000 psi

Fluid Temperature - 28 to 41° F

Moisture - 100 percent relative humidity in salt water

Maximum Fuel Temperature - 1463° F

Maximum Thermoelectric Leg Hot Junction Temperature - 1130° F

1.3.2 FUNCTIONAL REQUIREMENTS

During operation at functioning conditions, the system shall meet the following functional requirements:

Power Output - 10 watts minimum/5 year period

Voltage - 24 ± 1 volts; maximum ripple, peak to peak, 100 mv

Load Resistance - 57.6 ohms nominal

1.3.3 ENVIRONMENTAL REQUIREMENTS

The system will meet the following environmental requirements, which are of a transient nature other than functional conditions encountered during normal operation. After exposure to these conditions, the system will continue to operate in the prescribed manner.

Ambient Air Pressure - 10 to 32 inches of Hg

Humidity - 0 to 100 percent

Shock - As prescribed by MIL-STD-810A, dated June 23, 1964, by Procedure I, except that peak g level is 3g's and nominal duration is 6ms.

The system, when mounted on the shipping pallet, will be capable of withstanding the following environmental conditions and still function in the prescribed manner:

Ambient Air Temperature - 65° F to +130° F (6 months duration)

Vibration - As prescribed by MIL-STD-810A, dated June 23, 1964, for equipment transported by common carrier (max g level limited to 3.0 g peak).

1.3.4 SAFETY REQUIREMENTS

The system will be required to meet certain safety requirements concerning fuel containment and attenuation of isotopic radiation. The specific requirements are as follows:

Fuel Containment - Fuel containment capsule shall be capable of withstanding for 300 years pressures up to 10,000 psi and corrosive effects of salt water. The fuel capsule shall also be capable of containing the fuel when subjected to one-hour fire test, as set forth in code of the National Fire Protection Association.

Biological Shielding - Biological shielding shall surround the fuel capsule to effect an attenuation of nuclear radiation to 200 mr/hr at the surface of the system and 10 mr/hr at a distance of one meter from the system surface. The biological shield shall also be arranged so that the thermoelectric generator or power conditioner can be repaired or replaced without the use of hot cell facilities without exceeding the maximum permissible radiation exposure limits established by AEC.

2.0 DETAILED DESCRIPTION OF SYSTEM

2.1 SNAP-21 SYSTEM DESCRIPTION

2.1.1 SYSTEM CHARACTERISTICS

This system, as assembled from all the various components, has certain unique characteristics. These system characteristics affect or influence individual components of the system as well as the complete system.

The entire system is completely enclosed in a pressure vessel which seals the system against sea water pressure up to 10,000 psi. A fitting is attached to this pressure vessel providing a seal around pins which brings electrical and instrumentation leads out through the pressure enclosure.

The electrical power output leads to the fitting come from the power conditioner. The power conditioner converts the thermoelectric generator power output voltage to the required level. It also has a load voltage limiter, a no-load shunt, and provision to dissipate any excess power produced.

The internal components of the system are designed so that they do not restrict pressure vessel deflection in any area. This causes a problem in conducting the rejected heat from the generator to sea water. This problem is overcome by using a system of spring-loaded pressure contacts to form a flexible heat transfer path. This same system is also the thermoelectric generator mount and the vacuum insulation system positioner.

The thermoelectric generator converts the supplied heat to electrical power under mechanically static conditions. During operation it does not require maintenance, adjustment, or controls.

Only the heat which is transferred through the thermoelectric legs is effective in producing electrical power; the other extraneous heat loss is kept at minimum. The elevated-temperature biological shield is surrounded with a vacuum thermal insulation system except in the area where the thermoelectric generator receives its heat. In the area where the thermoelectric generator receives its heat, thermal insulation is used in all spaces around the thermoelectric legs to provide high thermal impedance.

The thermoelectric generator receives heat from the surface of the biological shield by thermal radiation. A mechanical load cannot be transferred from the shield to the generator for there is no physical connection between the generator and the shield.

The biological shield completely encloses the fuel capsule heat source to reduce radioisotopic radiation to the required level. It is also arranged so that the thermoelectric generator can be removed or installed without the need of hot cell facilities.

The heat source is a capsule containing Sr-90 radioisotopic fuel. This energy source generates heat at a fixed rate. A fixed amount of fuel is loaded into the system and no controls or regulation are required. The system components and the amount of fuel loaded into the system are designed to take into account the decay of heat output from the capsule during the five-year operating period. At all times the system operates at a nonfluctuating thermal heat balance.

Figure 1 shows the system and its major components; Table 1 tabulates the characteristics of the system.

2.1.2 SYSTEM TESTING

An assembled SNAP-21 system will be tested to verify the design and further define its characteristics, as well as for system acceptance. The tests to be conducted are as follows:

- a. System shock and vibration to determine the structural integrity of all components when assembled into a system.
- b. Operational performance tests at 10,000 psi salt water pressure.
- c. Performance tests in air to determine thermal response.
- d. Performance tests under transient electrical load conditions.
- e. Tests to determine electrical power output as a function of heat input as related to fuel capsule decay.
- f. Long-term tests for intermediate to long-term stability.
- g. System acceptance tests.

Table 1. System Characteristics

Design Life	5 years
Weight (Small Pressure Vessel)	516 pounds
Weight (Large Pressure Vessel)	582 pounds
Length (Small Pressure Vessel)	27.85 inches
Length (Large Pressure Vessel)	35.55 inches
Diameter	15.836 OD, Maximum
Volume (Small Pressure Vessel)	3339 cubic inches
Volume (Large Pressure Vessel)	4969 cubic inches
Electrical Output	11.7 watts BOL 10.1 watts EOL
Heat Input	203 watts BOL 179 watts EOL
Output Load Voltage	24 nominal
Fuel Temperature	1463°F Maximum
Fuel Capsule Surface	1450°F Maximum
Radiation Disk	1285°F
Thermoelectric Generator Hot Frame	1130°F
Thermoelectric Generator Hot Junction	1100°F Avg.
Thermoelectric Generator Cold Junction	179°F Avg.
Thermoelectric Generator Cold Frame	75 to 115°F
Segmented Retaining Ring	68 to 74°F
Pressure Vessel	43 to 62°F
Heat Balance BOL	
Heat to Thermoelectric Legs	132 watts
Heat Loss through T/E Insulation	8 watts
Insulation Envelope	32 watts
Other Losses	31 watts

2.2 SYSTEM COMPONENTS

2.2.1 HEAT SOURCE

The heat source provides the energy required for the operation of the system. Heat is emitted from the radioisotope decay of the fuel. In this system the heat source will operate at a maximum temperature of 1463° F. The heat source is located in the approximate

geometric center of the system and is immediately surrounded by the biological shield. Reference to Figure 1 will show the relative size and location of the heat source in the SNAP-21 system. Figure 2 is a sectioned drawing of the heat source assembly.

Fuel Form

The fuel for the heat source is Strontium-90 in the form of SrTiO_3 . The half life of the fuel is 27.7 years. For BOL conditions, the heat requirement is 203 watts minimum. The fuel has a specified power density of 0.7 to 0.8 watts/cm³ and a mass density of approximately 3.7g/cm³. While the fuel is referred to as Sr-90, it should be noted that the major portion of heat from radioactive decay, and the chief source of radiation from a shielding standpoint arise from the beta decay of its short lived daughter Yttrium-90. Most of this beta radiation, from both Sr-90 and Y-90 is converted into heat by inelastic collisions (electron-electron). A small quantity, as shown below, is converted to bremsstrahlung by radiative collision processes (coulomb field interactions).

Fuel Radiations

		<u>Sr-90</u>	<u>Y-90</u>
Beta Energy			
Maximum	Mev	0.545	0.27
Average		0.201	0.944
Bremsstrahlung Mev			
Conversion	Beta Particle	9.92×10^{-4}	2.08×10^{-2}

This bremsstrahlung is an electromagnetic radiation which requires shielding.

No gas is evolved due to the radioactive decay process. Thermal conductivity varies from 0.0132 to 0.0173 cal/sec-cm-c° at room temperature, depending on the density. The coefficient of thermal expansion is $1.12 \times 10^{-5} \text{ } ^\circ\text{C}^{-1}$. Melting temperature of the fuel is approximately 3450° F.

Enclosing Capsule

The fuel is enclosed in a single capsule. This capsule is designed to maintain encapsulation of the fuel under any credible conditions of accident. The fuel is enclosed in a double-walled container. It will be sized with a cavity to contain fuel producing 203 watts of heat with 0.8

NOTE:
 $\triangle 4$ 1- WELD ALL AROUND .10" WELD
 PENETRATION PER TPO-

Figure 2. Fuel Capsule Assembly

watts/cm power density. Figure 3 shows the fuel capsule components. The inner container, like the outer container, is cylindrical with flat ends. Table 2 gives the characteristics of the fuel capsule.

Material Compatibility

Because of the characteristics of the fuel, no materials' compatibility problems exist between the fuel and the capsule. Also, no material compatibility problems will exist where the exterior of the fuel capsule interfaces with the insulation system inner liner (Hastelloy X) and the shield plug enclosure (stainless steel).

Development

Additional development of the heat source is required. The size of the fuel cavity must be increased and the weld schedule must be re-established for the outer capsule container. The need for increasing the size of the fuel cavity is based on the need for 203 watts at BOL. This need will be confirmed after thermal heat balance and system operating tests have been evaluated. The need for weld schedule development is based on the penetration of welds obtained on those capsules previously fabricated. The re-establishment of the weld schedule will be in conjunction with Oak Ridge National Laboratories, who will do the actual welding. Weld evaluation will be in cooperation with Battelle Northwest Laboratory for ultrasonic testing of the weld penetration and by sectioning for metallurgical examination.

Figure 3. Fuel Capsule Components

Table 2. Capsule Characteristics

	Capsule	Capsule Liner
Material	Hastelloy Alloy C	316 SS
Outside Diameter, in.	3.20	2.690
Inside Diameter, in.	2.698	2.660
Outside Length, in.	3.337	2.736
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°F	2500°F
Linear Expansion Coefficient 10 ⁻⁶ /°F	8.2 @ 70-1600°F	12.8 @ 1900°F
Density, lb/in ³	0.323 @ 72°F	0.290 @ 72°F
Strength-H		
Strength-Tensile, psi	121,000 @ 72°F	75,000 @ 72°F
Strength-Shear, psi	30,000	N.A.
Yield, psi	81,000 @ 72°F	30,000 @ 72°F
Closure Method	Weld	Weld

Testing

Weld integrity of test capsules closed by the new weld schedule will be evaluated by both destructive and nondestructive means. Hydrostatic pressure tests will be performed and the welds sectioned and examined by metallographic techniques. In addition ultrasonic methods will be used to nondestructively evaluate weld penetration and soundness.

Testing will also be conducted at Naval Radiological Defense Lab to determine the salt water stability of the capsule.

Design Requirements and Performance Data

The SNAP-21 Technical Specifications require complete containment of the fuel in sea water at pressures up to 10,000 psi, at operating temperature, for 300 years, and under conditions of the one-hour fire test as set forth in the code of the National Fire Protection Association. However, a much broader design requirement was applied to the fuel capsule. The capsule was designed to contain the fuel under conditions of any credible accident.

Tests have been conducted to confirm the ability of the fuel capsule to contain the fuel. The details of these tests are in SNAP-21B Program, Deep Sea Radioisotope - Fueled Thermoelectric Generator Fuel Capsule Test Summary Report No. MMM 3321 - 16. The following tests were conducted:

1. Two capsules were subjected to fire tests.
2. Two capsules were subjected to thermal shock tests.
3. One capsule was subjected to vibration tests.
4. Four capsules were subjected to hydrostatic pressure tests.

After completion of the above tests, these capsules were examined for any failure modes; none were found. On this basis, the existing design is considered adequate to meet the requirements for which these capsules were tested.

The fuel capsule interfaces physically with two other components of the system. One end and the cylindrical diameter physically interface with the inner liner of the vacuum insulation system. Between the outside diameter of the fuel capsule and the inside diameter of the inner liner there is a clearance of 0.031 to 0.035 inches. This clearance is necessary for ease of assembly and for differential thermal expansion. The other end of the fuel capsule interfaces physically with the shield plug. The design details of the shield plug have not yet been completed, therefore physical interface conditions are not yet established.

The temperature drop between the fuel capsule and the inner liner of the insulation system will be between 10 and 15° F because heat flow across this interface is small. The temperature drop from the fuel capsule to shield plug cannot be predicted until the physical interface is defined.

Technical data summary of the heat source is as follows:

Size: 3.20 inches diameter, 3.34 inches long

Weight: 6 lbs.

Heat Available: 203 watts at BOL (existing design requirement)

Fuel: Sr-90

Fuel Form: Pressed pellets of SrTiO_3

Maximum Fuel Temperature: 1463° F

2.2.2 SHIELD

The function of the shield is to attenuate the bremsstrahlung radiation generated by the fuel decay. It accomplishes this because of the characteristics of the shield material and by completely surrounding the fuel. The nominal thickness of the shield is 2.6 inches. The material of the shield is an alloy of Uranium plus 8 percent molybdenum. The shield weighs 258 pounds.

The shield is made in two parts. The body is the larger portion and the plug is the smaller portion. Reference to Figure 1 shows the general size, shape and location of the shield in the SNAP-21 system. The body of the shield is completely enclosed within the high vacuum thermal insulation system. The shield plug will be enclosed in a hermetically-sealed container. One end of this container will be the thermal radiation disk which radiates the thermal heat across an air gap to the hot frame of the thermoelectric generator. The shield temperatures will be from 1300 to 1450° F during system operation.

Materials and Material Compatibility

Uranium plus 8 percent molybdenum is the shield material, selected on the basis of being the most efficient from the standpoint of both weight and size for attenuating the nuclear radiation. This material is dimensionally quite stable under conditions of changing temperature and is isotropic. Its melting point is also above operating temperatures.

As the shield is not insulated from the heat source it will operate at temperatures up to 1450° F. At this temperature there is a possibility that the shield material will form a low melting point eutectic alloy with one of the Group VIII metals. Of most concern is the iron and nickel in this group, common to high temperature alloys which are best suited for the inner liner of the insulation system. The solution for this problem is to separate

with a barrier the U-8 Mo. from any material with which it would form a eutectic alloy. Copper was selected as the best material for the barrier. Thickness of this copper barrier is determined by fabrication technique, strength, and material diffusion.

Safety and Hazard

The shield is the component which makes it safe, within limits, to handle the system. Once the shield has been sized such that it provides adequate shielding, the following considerations are taken into account:

1. The plug and body of the shield are attached to each other so that they surround the fuel capsule.
2. The material of the shield is protected from air so that oxidation of the U-8 Mo. does not occur.
3. The shield material is separated from other materials that would form low melting point eutectic alloys.

Development

Development of the shield will be required to make it compatible dimensionally with the system and to assure shielding integrity for system life. This development will be in the following areas:

1. Tolerance study for thermal growth for physically interfacing with mating system components.
2. Testing samples to determine materials compatibility and compatibility with the vacuum thermal insulation system.
3. Design of plug and development of means of encapsulation.
4. Configuration changes to provide adequate shielding or to reduce weight.

Testing

Testing will be conducted to determine the adequacy of the shield. This will be done by fabricating a shield, loading it with an isotopic fuel and measuring the radiation at the shield surface. When completed, this data will be used to analyze the need for a shield configuration change either to provide adequate shielding or to decrease weight.

Shield samples will be tested to demonstrate the following:

- 1) Operating temperature tests with coatings applied to samples of the shield or mating interfaces for diffusion rates and compatibility.
- 2) Coated shield samples tested by the Linde Division to determine off-gassing constituents and compatibility in the vacuum environment of the thermal insulation system.

Design Requirements

The Technical Specifications require that adequate shielding be provided to reduce radiation dose rates to the following levels:

Surface of the System	200 mr/hr
One Meter from Surface of System	10 mr/hr

No radiation measurement tests have been conducted with the shield.

Tests were conducted to verify the application method and material selected for the barrier between U-8 Mo. and system components. Supporting experimental data was obtained with 17 clad samples exposed to operating temperature and with the SNAP-23 Engineering Model system. The cylindrical samples of U-8 Mo., one-half inch in diameter and 2 inches in length, were electroplated with 0.020 inch copper followed by a 0.0005 inch chromium flash. These samples were sealed in separate quartz ampoules, six of which were under 10 microns vacuum and the remainder under an argon atmosphere (~1 atmosphere at exposed temperature). While variations in superficial appearance were noted, those samples tested for short times indicated basic compatibilities. Those samples exposed for longer times confirmed the conclusions from the short-term tests. The tests conducted with samples are shown in Table 3.

The detailed test procedures and results of these tests are included in Deep Sea Jan. - Feb. Bi-Monthly Report MMM 3321-13, March Monthly Report MMM 3321-14, April Monthly Report MMM 3321-15, and Final Summary Report MMM 3321-19.

Diffusion of the copper into the shield alloy was observed for the longer exposure periods as expected. Growth or continued diffusion is expected to continue until all of the copper is consumed. In the case of the SNAP-23, the barrier coating was applied to the shield

Table 3. Cladding Test Summary

Sample Number	Test Temperature	Test Duration
1a	1300°F	4 hours
2a	1300°F	4 hours
3a	1300°F	4 hours
4a	1300°F	4 hours
5a	1300°F	4 hours
6a	1300°F	4 hours
1b	1500°F	200 hours
2b	1500°F	200 hours
3b	1500°F	1887 hours
4b	1500°F	3015 hours
	1375°F	3438 hours
5b	1500°F	200 hours
6b	1500°F	200 hours
7	1500°F	247 hours
	1375°F	5347 hours
8	2100°F	48 hours
9	2100°F	48 hours
10	1375°F	575 hours
11	1375°F	5149 hours

liner. Approximately 0.0005-inch of molybdenum followed by 0.005-inch of copper was applied by flame spray technique.

Experimental work indicates that the flame sprayed copper, because of oxide inclusion, has a slower rate of diffusion. Further, the molybdenum substrate (necessary for flame spray application of copper) may also provide barrier properties. By applying this barrier to the enclosure shell the contact pressure is less, thereby reducing the intimacy of the diffusion interface. While interface conditions are not identical with SNAP-21, the satisfactory bench test performance for over a year substantiates this use of copper and molybdenum as a barrier material.

Recent modifications in the insulation envelope for supporting the shield indicate a change in cladding approach will be necessary. The shield being enclosed within the vacuum envelope requires that the cladding or barrier material also have a low vapor pressure. The refractory materials have this, and the necessary compatibility characteristics. Tantalum is one material proposed for this purpose. A metal can will be fabricated for surrounding the fuel capsule. A metal flange shroud will provide a compatible interface for mounting the shield to the inner liner flange. Other materials such as titanium and tungsten will be evaluated for this purpose.

2.2.3 INSULATION SYSTEM

The insulation system has the function of reducing the extraneous heat loss from the system. It surrounds the hot shield except in the area where the thermoelectric generator receives its heat. Figure 1 shows the general size, shape, and location of the insulation system in the SNAP-21 system.

The inner liner of the insulation system physically interfaces with the fuel capsule, the shield plug, and the shield body. The shield body is completely enclosed within the evacuated enclosure of the insulation system. The outer shell of the insulation system physically interfaces with the mounting plate - support ring and the body of the pressure vessel. There is very little heat flow through this outer shell of the insulation system and, subsequently, no consequential temperature drops.

Characteristics

The insulation system has the characteristic of being an excellent high temperature thermal insulator. Metallic foils provide high thermal resistance to radiant heat flow. Convective and conductive heat flow is reduced to a minimum by evacuating the system to less than ten microns of pressure and by separating the metallic foils with fibrous insulation. The requirement for a vacuum in turn requires that the insulation system surround the heat source with an inner and outer shell or liner which forms a hermetically-sealed container. For this insulation system the inner and outer shells are connected by a neck tube which must support the shield and fuel capsule. This neck tube must have structural strength to support the weight of the shield and fuel capsule when external loads are applied to the system. Figure 4 is a drawing of the unfueled insulation system. Table 4 summarizes the insulation system characteristics.

Figure 4. Advanced Mechanical Design of the SNAP-21B Insulation Envelope

Table 4. Vacuum Insulation System

Weight (less shield body)	50 pounds
Weight (with shield body)	292 pounds
Overall Length	15.004 inches
Diameter	12.390 inches
Nominal Insulation Thickness	1.72 inches
Coefficient of Heat Transfer (50 to 1300°F)	0.0008 $\frac{\text{Btu}}{\text{hrft}^2\text{°F}}$
Total Heat Flow (Insulation and Support) BOL	32 watts

Material Compatibility Considerations

Materials compatibility is a consideration where the insulation system physically interfaces with the shield and within the vacuum enclosure where all materials must be chemically and metallurgically compatible. The shield body will be separated from the inner liner of the insulation system by a duplex barrier coating with a substrate of molybdenum with a copper exterior layer on the inner liner. This barrier is to keep a low melting temperature eutectic alloy from forming between the U-8 Mo. and any Group VIII metals. The compatibility problems which may exist among the materials within the vacuum enclosure must be determined. Until it is determined if any unfavorable reactions will occur, corrective action cannot be designated.

Development

A considerable amount of development work is anticipated to arrive at an insulation system which will meet the requirements of the SNAP-21 system. This development effort will be conducted with individual components of the insulation system and with the assembled insulation system. The development which will be conducted on a component basis is as follows:

1. Determination of the outgassing characteristics of the components which will be exposed to the vacuum chamber. Outgassing rates and constituents of the gasses evolved will be determined. The insulating materials data obtained from Linde Division's Basic Insulation Technology contract AT(30-1)3632 with AEC will also be used in this portion of the testing and analysis.

2. Determination of getter effectivity for gettering the outgassing constituents.
3. Testing to determine the chemical and metallurgical compatibility of all the components exposed to the vacuum chamber.
4. Development and design of a seal-off fitting and sealing procedure. The objective is a fitting with high vacuum conductance for processing that will provide a reliable, leak-tight seal.
5. Development of a weld design and welding schedule. Particular attention will be devoted to the weld where the neck tube joins the top of the enclosure.
6. Analysis and development testing of the structural ability of neck tube design. Analytical investigation will be followed by load testing with the neck tubes to determine failure mode and failure load.
7. Development of a getter container to isolate the getter from the insulation after activation but retaining good vacuum conductance.

The development which will be conducted with assembled insulation systems is as follows:

1. Development by subjecting the system to external loading to determine the structural integrity. Negative results from these tests would require redesign in the area of failure.
2. Development testing to determine the vacuum integrity of the system. Negative results would require evaluation of outgassing rates, getter effectivity and quantity, and enclosure integrity.
3. Determination of thermal performance. Excessive heat loss would require determination of whether system was defective or if measured heat loss was indicative of true performance of system. If the true performance heat loss is greater than planned, the heat source for the Deep Sea System would have to be increased in size.
4. Development of an optimum conditioning cycle to reduce system component outgassing to a minimum prior to seal-off and getter activation.

5. Determination of insulation system dimensions that interface with other system components. These dimensions will be determined by system layout drawings and tolerance build-up determinations. Considerations will be fabrication and assembly capabilities, maximum thickness of insulation in space available, and restriction of movement of insulation system inside Deep Sea System.

Testing

Tests will be conducted with the insulation system in addition to those described in the development section.

1. Testing of the insulation system both in the SNAP-21 system and in a test stand to determine its ability to maintain required vacuum over long periods of time.
2. Determination of the ability of the insulation system to withstand the loads caused by external shock and vibration loads applied to the SNAP-21 system.

Design Requirements and Performance Data

The following design requirements apply to the insulation envelope:

1. The insulation envelope shall meet the physical interface requirements as designated by 3M Company drawing PD-37-1349B, Figure 5.
2. The system shall be designed to have minimum weight consistent with satisfactory performance but shall not exceed 50 pounds.
3. The structural components shall be designed to the minimum yield strength for their material (0.2 percent offset method) and with a safety factor of 1.5.
4. The system thermal heat loss shall not exceed a total of 30 watts with the heat source temperature of 1350° F at support end and 1450° F at opposite end with a cold side temperature of 50° F.

5. The system shall withstand, without failure which would degrade performance or change interface dimensions, the following externally applied loads:
 - a) Vibration - the unpackaged system shall withstand the vibration levels experienced during common carrier transportation as specified by MIL-STD-810A, Method 514.1, dated 23 June 1964, except that the maximum g level shall not exceed 3 g peak.
 - b) Shock - the unpackaged system shall withstand the shock levels defined in MIL-STD-810A, Method 516.1, Procedure 1, except that the peak value shall be 3g' s and the nominal duration shall be 6 ms.
 - c) Acceleration - the unpackaged system shall withstand a constant acceleration of 3g' s for 15 seconds minimum applied in any of three mutually perpendicular axes.
6. The system shall withstand temperature extremes of -65° F to +130° F during transportation, handling, and storage.
7. The system shall withstand an external gas pressure of 10-60 in.hg. The surrounding gas composition will be dry air and/or an inert gas.
8. The system operating life is five years preceded by a six-month storage period.
9. The system shall be capable of operating in any orientation. It shall also be designed for simplicity and ease of handling, transportation, and installation. Special handling and/or installation tools should be kept to a minimum.
10. Each system fabricated to the same design configuration shall be interchangeable with all others built to the same design configuration.

Performance tests were conducted on all three insulation systems fabricated during Phase I. These tests were to determine the heat loss through the system. The results of these tests are shown in Table 5.

Table 5. Performance Test Results

Mode of Heat Transfer	Heat Loss (Thermal Watts)		
	Unit I	Unit II	Unit III
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

The details of these tests are included in SNAP-21B Program, Phase I Final Summary Report No. MMM 3321-19.

2.2.4 THERMOELECTRIC GENERATOR

The thermoelectric generator converts the heat supplied by the heat source into electricity. Reference to Figure 1 shows its relative size, shape, and location in the system. It is physically mounted to the mounting plate - support ring with bolts. All the heat rejected from the cold side of the generator passes across this interface with a temperature drop of about 1° F. Heat is transferred to the generator hot frame from the thermal radiation disc. The hot frame of the generator does not come in contact with the radiation disc, but maintains a gap which varies from 0.048 to 0.153 inch. As this gap varies between these two values, the temperature drop across this interface will vary from 150 to 180° F. Powdered thermal insulation is packed in the annular space between the generator outer case and the neck tube of the insulation system.

Description of Characteristics

The thermoelectric generator converts heat to electricity under mechanically static conditions. As such, it needs no adjustments, controls, or maintenance. The thermoelectric materials which convert the heat to electricity must be in a special protective atmosphere. This requires that the generator enclosure be hermetically sealed. The portion of this enclosure which connects the hot and cold frame is an extraneous heat loss path. This case is fabricated with a wall 0.006 to 0.007 inch thick to keep the heat loss to a minimum. Figure 6 is a picture of the components which make up the generator enclosure (hot frame, cold frame, and two-piece outer case). Figure 7 is a cross-sectional illustrative drawing of the thermoelectric generator. Figure 8 shows the measured temperature profile of a thermoelectric generator in the No. 1 Deep Sea System at BOL conditions.

Figure 6. Generator Hot Frame, Case and Cold Frame

The thermoelectric generator characteristics summarized, are:

● Design Life	5 years
● Weight	18.8 pounds
● Diameter	7.84 and 4.45 inches
● Volume	89.3 in ³
● Electrical Output	13.3 watts BOL 11.4 watts EOL
● Efficiency	8.75% BOL 8.45% EOL
● Closed Circuit Voltage	5.067 + 0.727
● Number of Thermoelectric Couples	48
● Heat Input BOL	152 watts
● Couple Hot Junction Temperature	1100° F Avg.
● Couple Cold Junction Temperature	180° F Avg.
● Hot Junction Electrical Contact	150 psi pressure contact
● Cold Junction Electrical Contact	Bonded

Figure 7. 10-Watt Thermoelectric Generator

Figure 8. Typical Thermoelectric Generator BOL Operating Temperature Profile

Figure 7 shows the location of components in the generator and their general size and shape. Figure 9 is a drawing which shows the thermoelectric couples and their related hardware. The generator components are:

Hot Frame - The hot frame forms a part of the thermal radiation disc. It is made from 347 stainless steel. Structurally, it has sufficient strength to resist deformation from the force of the leg compression springs. The surface which faces the heat source has special surface treatment to reduce the temperature drop across this gap. The hot frame is at 1140° F temperature at BOL conditions.

Hot Side Electrical Insulation - This single piece of boron nitride electrical insulation at the hot side keeps the legs from shorting electrically to each other or to the generator case. It also contains recesses which form a part of the system and which position the ends of the legs at their hot end. The actual operating temperature has not been measured, but falls between the 1140° F of the hot frame and the 1100° F of the thermoelectric leg hot end at BOL.

Figure 9. Couple Isometric

Hot Junction Electrode - This coated copper part forms the electrical circuit between the hot junction button of P and N legs. One hot junction electrode is used for each thermoelectric couple, a total of 48 for the generator. It also makes up part of the hot side thermoelectric leg positioning system. Its operating temperature has not been measured, but falls in between 1100 and 1140° F.

Hot Junction Button - This low-carbon steel part forms the contact between the hot end of the thermoelectric legs and the hot junction electrode. It also forms a part of the hot side thermoelectric leg positioning system. One button is required for each thermoelectric leg, making a total of 96 for the generator. Its operating temperature is measured as the thermoelectric leg hot junction temperature and averages 1100° F.

N-Type Leg - This is one of the two types of thermoelectric legs used in the generator which converts the heat energy into electricity. At the cold end of these legs, the electrical polarity is negative. The material is powder pressed PbTe-PbTe. The generator contains 48 of these N-type legs. At BOL conditions, the hot junction temperature will average 1100° F and the cold junction temperature will average 180° F. Under these conditions the leg will absorb 1.355 watts of heat from the hot frame.

P-Type Leg - This is the other type of thermoelectric leg used in the generator to convert the heat energy into electricity. At the cold end of these legs, the electrical polarity is positive. The generator contains 48 of these P-type legs. The material is powder pressed $(\text{BiSb})_2\text{Te}_3$ -PbTe, SnTe. At BOL conditions the leg will absorb 1.395 watts of heat from the hot frame.

Cold Cap - The copper cold cap is soft soldered to the cold end of each thermoelectric leg. It forms a part of the cold end thermoelectric leg positioning system, heat transfer path, and cold end electrical circuit. A cold cap is required for each thermoelectric leg, for a total of 96 for the generator. The end opposite the one bonded to the thermoelectric leg has a spherical radius. This mates with the socket of the follower to form a flexible ball and socket joint at the cold end of the thermoelectric leg. Its temperature at BOL conditions averages 180° F.

Cold Junction Electrode - The cold junction electrode is bonded between cold caps of N- and P-type thermoelectric legs. One cold junction electrode is used with each pair or couple of thermoelectric legs, making 48 the total required for each generator. It forms a part of the electrical circuit at the leg cold end. At BOL operating conditions, the cold junction electrode temperature will average 180° F. No heat flows through this part. The cold junction electrode is made of copper wire.

Follower - The followers fit into the cold frame with one end extending out. This end has a spherical socket. The spherical socket mates with the spherical ball of the cold end cap. This forms a flexible interface across which heat is transmitted from the thermoelectric leg to the follower. Spring force is transmitted from follower to thermoelectric leg. The temperature drop across this interface is unknown. The force transmitted results in a compressive force equal to 150 psi in each thermoelectric leg. One follower is required for each thermoelectric leg, a total of 96 per generator. The aluminum follower is hard-coated to form the electrical insulation at the cold side of the thermopile. Force is exerted on the end opposite the spherical socket by a compression spring. The operating temperature of the followers ranges from about 85 to 180° F. The follower is 0.2495 inch in diameter and is 1.000 inch long.

Spring - Springs fit into the cold frame holes to exert pressure on the followers which is transmitted to the thermoelectric legs. This is done to maintain thermal contact at the cold end and both thermal and electrical contact at the hot end. One spring is required for each thermoelectric leg for a total of 96 for the generator. The springs for the N- and P-legs exert the same forces which result in a nominal leg contact pressure of 150 psi. The springs operate at temperatures of about 85 to 115° F. They are made from 302 stainless steel wire and have a diameter of 0.240 inch, free length of 1.94 inches and a spring rate of 6.2 lbs/in.

Cold Frame - The copper cold frame forms a part of the generator enclosure and structure. It contains the holes for the followers. It is also a part of the heat transfer path for the heat rejected from the cold ends of the thermoelectric legs. At BOL conditions, the cold frame operates at temperatures which vary from 115° F around the followers to 75° F where it bolts to the mounting plate-support ring (portion of the segmented retaining ring). The drop from 180° F leg end temperature to the 115° F temperature of the cold frame around the followers is the temperature drop across the cold end heat transfer system of cold cap, follower, to cold frame. The cold frame has a 7.860 inch diameter, 0.752 inch thick at the cold end and a 3.700 inch diameter, 2.000 inches long at the cold end.

Outer Case - The two-piece outer case is a thin-walled shell of 347 stainless steel that is a part of the generator hermetic enclosure. It also provides the restraint which keeps the hot and cold frames from separating due to leg spring force. However, as it also forms a path for extraneous heat loss, its thickness is kept to a minimum (0.006 to 0.007 in.) while maintaining structural integrity. At the generator hot end, the outer case is at 1125° F and 75° F at the cold end when at BOL conditions.

Thermal Insulation - Powdered MIN-K 1301 and microquartz pad insulation is packed in the generator and around the legs to reduce the heat loss through the generator. Approximately 8.7 watts of heat is transferred through this insulation at BOL conditions. It is exposed to generator surfaces ranging in temperature from 75 to 1125° F.

Fittings - To bring out the electrical leads, fittings are attached to the cold frame. Three of these fittings are required for each generator. They must provide electrical insulation between the feedthrough pin and the cold frame and also maintain a hermetic seal. They will operate at temperatures around 75° F. Each fitting has a single 446 stainless steel pin which is fused in glass into a mild steel body. The Phase I fittings were 0.291 inch in diameter and $1\frac{27}{64}$ inch long. The electrical feedthrough was $\frac{3}{32}$ inch in diameter.

Unique Design Considerations

The design of this thermoelectric generator involves some unique considerations. The following considerations apply to the thermoelectric generator for this system:

1. The outer case must withstand mechanical loads yet keep heat loss to a minimum. The design approach is to use a material which has a high strength-to-heat transfer ratio and to keep the material thickness to a minimum.
2. Thermoelectric materials and thermoelectric leg geometries must be selected which will provide maximum energy conversion efficiency and yet be compatible with physical and mechanical requirements of the system. The approach is to apply state-of-the-art knowledge for these determinations.
3. The outer case must be attached to the copper cold frame for mechanical strength and hermetic seal. The design approach is to silver braze a short section of the outer case to the cold frame prior to assembly, with the final closure being made by TIG-welding the two sections of the outer case together..
4. The cold end must be designed to transfer the heat from the cold end of the thermoelectric legs to the mounting plate-support ring. The design approach to keep temperature drop to a minimum is to select materials with a high coefficient of heat transfer, by good interface fits, and configuration of components.

5. Outer surface of the hot frame must be prepared for high thermal emissivity. The design approach is selection of hot frame material, surface preparation by vapor blasting, and oxidizing prior to thermoelectric generator assembly.

Development

Additional development will be conducted to improve or revise the generator design from the existing design in the following areas:

1. Thermoelectric generator leg and couple design. The data which has been accumulated since the existing leg and couple design was completed will be used as parameters in the computer code for re-evaluation of the leg and couple design.
2. An examination of the cold end heat transfer system for design and manufacturing changes to reduce leg cold junction temperature. The ball and socket of follower and cold cap will be closely examined using new information generated since existing design was prepared.
3. An evaluation of the strength of the outer case to withstand the mechanical loads. The results of this evaluation may result in a change in thermoelectric generator outer case configuration.
4. An evaluation of the fittings for electrical feedthrough. A different fitting may be used if a more suitable fitting than the one used can be procured.

Testing

Component testing for the thermoelectric generator will include temperature drop tests across the interface between the cold cap and follower ball and socket.

Assembled thermoelectric generators will be tested to establish and demonstrate the following:

1. Mechanical and structural integrity from shock and vibration testing.
2. Temperature drop across the follower - cold end cap interface.

3. Electrical performance characteristics under various electrical load conditions at normal operating and transient thermal conditions.
4. Long-term electrical performance characteristics.

Design Requirements and Performance Data

The following design requirements apply to the thermoelectric generator.

Design life	5 years	
Minimum power output	11.9 watts	
Closed circuit voltage	5.067 and 0.727 EOL	
Heat input required (watts)	BOL	EOL
Outer case	9	8
Insulation	11	9
Thermoelectric legs	132	118
Total	152	135
Maximum hot junction temperature	1100° F Avg. 1130° F Max.	

Physical configuration compatible with entire SNAP-21 System.

Mechanical strength to withstand specified external shock and vibration loads on SNAP-21 System.

During Phase I of the Deep Sea Program, five thermoelectric generators were operated with their performance measured. Thermoelectric generators numbers 3, 5, 6 and 7 were operated on the test bench. Thermoelectric Generator #4 was operated in the No. 1 SNAP-21B System. Table 6 is a summary of the generator electrical performance data.

2.2.5 SEGMENTED RETAINING RING

The size, shape, and location of the segmented retaining ring is shown in Figure 1. This component is multi-functional as follows:

Table 6. Generator Electrical Performance Data

Prototype No.	Power Output Watts	T-Hot	T-Cold	Total Oper. Hrs.	Date	Remarks
3	13.27	1100	118	96	2-25-65	T-hot based on average of two N-leg Seebeck voltages; BOL
	11.13	1093	164	9,716	4-14-66	End of one year from BOL; T-hot based on average of two N-leg Seebeck voltages
	10.91	1081	161	10,076	4-28-66	The start of the second year from BOL; T-hot based on average of two N-leg Seebeck voltages
	10.36	1091	172	13,847	10-3-66	BOL 2-25-65 to 10-3-66; T-hot based on average of two N-leg Seebeck voltages
5	11.42	1112	117	24	4-19-65	T-hot based on average of two N-leg Seebeck voltages; BOL
	11.34	1096	153	8,229	4-14-66	The end of one year from BOL; T-hot average of two N-leg Seebeck voltages
	11.17	1074	151	8,565	4-28-66	The start of the second year from BOL; T-hot based on average of two N-leg Seebeck voltages
	11.17	1077	165	12,329	10-3-66	BOL 4-19-65 to 10-3-66; T-hot based on average of two N-leg Seebeck voltages
6	14.03	1095	132	24	6-2-65	T-hot based on average of two hot electrode thermocouples; BOL
	11.34	1095	174	8,803	6-4-66	End of one year from BOL; T-hot based on hot frame thermocouple ref. to 6-2-65
	11.20	1075	168	9,089	6-16-66	T-hot based on hot frame thermocouple; ref. to 6-2-65. Start of second year

Table 6. Generator Electrical Performance Data (Continued)

Prototype No.	Power Output Watts	T-Hot	T-Cold	Total Oper. Hrs.	Date	Remarks
6	10.71	1075	186	11,700	10-3-66	BOL 6-2-65 to 10-3-66; base on thermocouple ref. 6-2-65
7	13.17	1099	127	168	6-8-65	T-hot based on average of two hot electrode thermocouples BOL
	11.03	1095	162	8,778	6-4-66	T-hot based on hot frame thermocouples; ref. to 6-30-65 end of one year from BOL
	10.69	1075	157	9,063	6-16-66	Start of the second year from BOL based on hot frame thermocouples; ref. 6-30-65
	10.35	1075	178	11,676	10-3-66	BOL 6-8-65 to 10-3-66; based on hot frame thermocouples 6-30-65
4	13.08	1100	179	1,176		BOL conditions from data 6-17-65, 6-18-65, 6-21-65 and 6-22-65
	12.66	1074	176			End of 1 year conditions from data 6-25-65 and 6-26-65
	12.40	1048	173			End of 2 years conditions from data 6-29-65, 6-30-65 and 7-1-65
	11.91	1022	172			End of 3 years conditions from data 7-6-65, 7-7-65 and 7-8-65
	11.71	1006	169			End of 4 years conditions from data 7-14-65, 7-16-65 and 7-19-65
	11.40	990	165			EOL conditions from data 7-28-65, 7-29-65 and 8-2-65
	12.32	1090	180	9,384		From data 5-26-66 (end of one year)
	12.09	1069	180	10,059		From data 6-23-66 (start of second year)
	11.85	1063	180	12,531		From data 10-1-66

1. It is a mounting plate for the thermoelectric generator.
2. It provides the heat transfer path from the thermoelectric generator to the pressure vessel and thus to the sea water.
3. It supports and locates the insulation system in the SNAP-21 System.

Characteristics

Figure 10 shows the segmented retaining ring as fabricated. Segments are assembled on the generator mounting plate section. These segments are spring loaded against protrusions on the mounting plate for heat transfer purposes. These segments are also spring loaded to provide support to the insulation envelope and force the segments against the pressure vessel for heat transfer. These segments are so dimensioned and spring loaded that when the pressure vessel deflects inward due to pressure, the segments move. This motion does not restrict pressure vessel deflection and exert excessive pressure on the insulation envelope outer shell.

The outside diameter of the segmented retaining ring is 12.445/12.440 inches and the thickness 2.900 inches. There are 12 aluminum segments retained on the mounting plate with bolts and compression springs. The spring rate is 420 lbs/in. per spring and under design conditions the spring force is from 125 lbs to 160 lbs/spring. This variation is due to tolerance variations with the interface components. Material compatibility is not considered to be a problem at the operating temperatures and environment.

Figure 10. Segmented Retaining Ring

Testing

Testing of the mounting plate-support ring will be incorporated in the SNAP-21 systems tests. During these systems tests, the performance of the mounting plate-support ring will be judged for its ability to:

1. Hold and support in position the thermoelectric generator and insulation system without amplify loads which are externally applied to the system.
2. Transfer the rejected heat from the thermoelectric generator to the pressure vessel with 15° F temperature drop or less.

Design Requirements and Performance Data

The design requirements of the mounting plate-support ring are as follows:

1. The configuration must be compatible with thermoelectric generator, pressure vessel, and insulation system when assembled together as the SNAP-21 System.
2. Transfer the rejected heat from the thermoelectric generator to the pressure vessel with 15° F temperature drop under conditions of BOL heat input.
3. Provide a mounting for the thermoelectric generator.
4. Support and locate insulation system.

One support system was included in the first SNAP-21B mockup system assembled and tested. The test conditions and procedures are described in the report, Preliminary Test Results of the SNAP-21B-1 System, dated June 7, 1965. During this test the mounting plate-support ring provided a suitable static mount for the generator and adequate static support and location for the insulation system. The measured temperature drop from the thermoelectric generator mounting point to the inside of the pressure vessel was 16° F at BOL heat input.

2.2.6 POWER CONDITIONER

Figure 1 shows the relative size, shape, and location of the power conditioner in the system. The power conditioner physically attaches to the inside of the pressure vessel cover pro-

trusion. This attachment not only serves as a mount for the power conditioner but also as a heat sink. The function of the power conditioner is to convert the output voltage of the generator from 5.1 volts to 24 volts. It also regulates the voltage output of the converter by shunting the excess power and by acting as a load when no external load is attached to the system.

Three wires connect the power conditioner to the thermoelectric generator and two wires connect it to the electrical feedthrough receptacle, attached to the pressure vessel cover.

Description of Characteristics

The power conditioner enclosure is shown by Figure 11. This enclosure houses a converter and a regulator circuit. It was sized so that it could hold two converters, two regulators, and an automatic selector switch. The enclosure is hermetically sealed and backfilled with an inert gas.

The electrical circuit of the power conditioner converts the electrical output of the thermoelectric generator to the proper voltage level and provides for a shunt load in case of a system load open circuit. The electrical circuit consists of two basic circuits, the converter and the regulator. The converter transforms the output load voltage of the thermoelectric generator to a higher value at the approximate ratio of 24 to 5. The regulator limits the output voltage of the converter to 24 ± 1 volts with maximum ripple of 0.1 volt peak to peak. The regulator also provides the shunt load for the system if the external load is removed. The power conditioner electrical circuit is shown in Figure 12.

The electrical circuits are designed to operate for 5 years in the system at ambient temperatures of $70 \pm 5^\circ \text{F}$. They also perform this power conditioning function at 88 percent efficiency at EOL conditions. Table 7 tabulates the characteristics of the power conditioner.

Development

Additional development work on the power conditioner will be a review of the existing design, including determination if any recent advances in the state-of-the-art can be applied to increase efficiency or reliability. Review will determine if circuit components used in the Phase I design are still available for procurement.

Figure 11. Power Conditioner Enclosure

*INDICATES PART OF T1

PARTS LIST

Q1-Q2	BENDIX	USA 2M1653
Q3-Q4	TEXAS INST.	2N3147
R1	DALE RH5	6.81Ω ± 1%
R2	DALE RH5	20Ω ± 1%
R3-R4	DALE RH5	1.0Ω ± 1%
R5	DALE MF 1/4	80KΩ - SELECT FOR 24.5V - NO LOAD
C1-C2	MALLORY TSS396K010P	10V-39 MFD TO LEVEL R OF TSS100
C3-C4-C5-C6	MALLORY TSS476K035PD	35V-47MFD TO LEVEL R OF TSS100
REGULATOR	TR10-LABS OR 3M DPD-37-1340A	75TE22
TI-TRANS	DWG DPD-37-1133A	3M-7-MP-I

Figure 12. Converter Circuit Diagram

Table 7. Power Conditioner Characteristics

Principal Components	Transistors, transformer, capacitor, resistors, zenor-diode
Weight	5 ±1/2 -lb
Length	4.4 inches
Diameter	10.2 inches
Efficiency	88 percent
Output Power	10.1 watts
Output Voltage	24 ±1
Input Power	13.8 watts BOL 11.7 watts EOL
Input Voltage	5.1 (with 0.7 tap)
Operating Temperature	70 ±5°F
Design Life	5 years

Testing

Power conditioners testing will be performed to demonstrate the following:

1. Effect on mechanical and structural integrity and electrical performance from externally-applied shock and vibration loads.
2. Electrical performance characteristics under various loads, transient, and normal operating ambient conditions.
3. Intermediate to long-term electrical stability characteristics.

Design Requirements and Performance Data

Table 8 itemizes the design requirements which apply to the power conditioner.

Tests were conducted with power conditioners during Phase I of the SNAP-21 Program. A summary of the results is given in Table 9. Detailed description of these tests and additional test data is contained in SNAP-21B Program, Phase I Final Summary Report, MMM 3321-19.

Table 8. Power Conditioner Design Requirements

Efficiency	85.0 % EOL
Power Output	10.1 watts
Output Voltage	24.0 volts
Voltage Ripple	100 mv (peak to peak)
Input Voltage	5.1 volts (0.7 volt bias tap) EOL
Input Power	11.9 watts EOL
Physical compatibility with space available within the SNAP-21 System.	
Mechanical structure adequate to provide support from specified externally-applied shock and vibration loads	

Table 9. Power Conditioner Long-Term Performance Data

Unit No.	Operating Hours	Power In	Voltage In	Voltage Out	Power Out	Eff. %
MP-B	172	12.054	4.837	24.00	10.70	88.76
MP-B	5011	12.040	4.838	24.00	10.70	88.9
MP-B	9919	12.046	4.840	24.00	10.70	88.85
MP-C	23	11.814	4.909	24.00	10.42	88.10
MP-C	5054	11.782	4.910	24.00	10.39	88.20
MP-C	9490	11.730	4.908	24.00	10.34	88.18

2.2.7 PRESSURE VESSEL

Figure 1 shows the size, shape, and location of the pressure vessel in the SNAP-21 System. The pressure vessel encloses the system, keeping out the sea water up to pressures of 10,000 psi. It is also a part of the heat transfer system for heat rejected from the thermoelectric generator and the power conditioner. The pressure vessel provides mounting location and restraining surfaces for other components of the system.

Description of Characteristics

Figure 13 shows the size and shape of the pressure vessel. The vessel is made up of two forged and machined parts, the body and the cover. These two parts are bolted together with an O-ring seal at the joint to form a pressure-tight enclosure for the system. A summary of data describing the pressure vessel is as follows:

Material	721 Titanium
Outer Diameter	15.836 inches
Height	27.850 inches
Weight	146 pounds
Joint Seal	Double Viton O-ring

Development

Additional development work will be done to arrive at final pressure vessel design.

Figure 13. SNAP-21 Pressure Vessel

A survey will be conducted to determine if 721 titanium is the most suitable material for the pressure vessel. If it is not, a different titanium alloy material may be selected. If this material has different mechanical properties, pressure vessel redesign would be required.

The cover for the large pressure vessel will be designed. Its dimensions will resemble those of the existing design of the pressure vessel body.

Testing

The following tests will be performed with the pressure vessel:

1. The new, larger cover will be tested with a pressure vessel body to demonstrate its ability to withstand 10,000 psi in sea water.
2. All pressure vessels will be qualified to 10,000 psi prior to use in system testing or acceptance.
3. All forging heats for material for pressure vessels will be qualified by cutting up vessel forgings and mechanically testing samples.
4. All vessel forgings will have test rings to be parted, cut up, and samples mechanically tested.

Design Requirements and Performance Data

The design requirements for the pressure vessel enclosure are as follows:

1. Must withstand 10,000 psi pressure without permanent deformation or leaking.
2. Must withstand the corrosive effects of sea water for five years so the ability of the pressure vessel enclosure to meet the first requirement is not affected.
3. Must be dimensioned, shaped, and sized to be physically compatible with the rest of the system.

Performance of the vessel was determined by testing a 1/4-scale model and a full-sized pressure vessel. The 1/4-scale model was tested to determine both deflection under pressure and failure pressure. The detailed results and procedures for these tests are

included in SNAP-21B Program, Phase I Final Summary Report, MMM 3321-19. Applied to the full-sized pressure vessel, the deflection tests on the 1/4-scale model showed the vessel would deflect as follows:

Diameter Decrease	0.046 inch Max.
Spherical Radius Decrease	0.020 inch
Body Length Decrease	0.023 inch
Total Length Decrease	0.043 inch

The 1/4-scale model failed at a pressure of 17,500 psi.

The full scale model was tested only to 10,000 psi. From the similarity of strain data recorded in this test and a comparison of material properties, a failure pressure of 15,500 psi was projected for the full-sized pressure vessel. Creep tests conducted with this full-sized vessel at 10,000 psi did not indicate that creep would contribute to premature failure.

2.2.8 ELECTRICAL FEEDTHROUGH RECEPTACLE

Figure 1 shows the relative size, shape, and location of the receptacle. The function of the receptacle is to provide a means of bringing the electrical power produced by the system out through the pressure vessel. It physically bolts to the cover of the pressure vessel and connects to electrical wires from the power conditioner. An O-ring provides the seal against sea water between the receptacle and the pressure vessel.

Description of Characteristics

Figure 14 is a photograph of a receptacle which has twelve feedthrough pins. The system power output could be brought out with two pins, but additional pins were included in the design for instrumenting the system. The pins of this receptacle are mounted in glass to electrically insulate the pins. The glass is fused to both the pins and the body of the receptacle to seal against the external water pressure. The pins are Niron gold and copper plated and the receptacle body is 721 titanium.

Development

Development will include determination of the number of pins required. This may result in the development of one receptacle with pins for both power and instrumentation for use on systems that will undergo development testing. Another receptacle with pins only for power output may be developed for systems for specific deep sea applications.

With the number of pins established, development of the procedure for fusing pins into the receptacle body will be required.

The material of the receptacle body would be changed if a material other than 721 titanium is selected for the pressure vessel.

Testing

Tests will be conducted on the fabricated receptacles as follows:

1. Vendor demonstration of ability to withstand 10,000 psi in salt water.
2. Retesting by 3M Company to check ability to withstand 10,000 psi salt water pressure.

Design Requirements and Performance Data

The receptacle will have the following design requirements:

No. of pins	To be determined
Operating pressure	10,000 psi sea water
Immersion period	5 years
Pin size	#16 AWG
Insulation Resistance	5,000 megohms min. at 500 VDC

Physically the receptacle must mate with the pressure vessel and plug for sealing against sea water pressure of 10,000 psi. Mechanically the receptacle must withstand deforming to cause leaks when mating with pressure vessel and plug.

The twelve-pin receptacle was tested at 10,000 psi. This pressure was applied from the exterior side of the receptacle and no leakage occurred around the pins.

2.2.9 PLUG WITH STRAIN RELIEF

The plug with strain relief attaches to the receptacle. Its purpose is to provide a means of carrying the electrical power generated by the system to an external load.

Description of Characteristics

Figure 15 illustrates the plug with strain relief. The plug with strain relief forms the transition from an undersea power transmitting cable to the receptacle. This transition is not only of electrical connectors but also for transmitting any tensile loads from the power cable to the receptacle. The strain relief is so designed that mechanical tensile loads are transmitted from the cable to the receptacle through a structure without causing tensile loads on the electrical leads. The plug with strain relief has a titanium alloy shell 3.5 inches in diameter, 14.5 inches long. The titanium alloy is the same one used for the pressure vessel and electrical receptacle to preclude galvanic corrosion problems. The plug is attached to the electrical receptacle by a threaded coupling ring which fits around a shoulder on the plug body and mates with the electrical receptacle. The cable armor sheathing is potted into the strain relief plug housing to transmit tensile loads from the sheath to the strain relief plug without putting a strain on the electrical leads.

Development

Development would be required on this component to achieve a water tight seal. The one unit fabricated leaked under pressure, allowing water into the pin area of the receptacle, which shorted the leads. This sealing problem appears to be one of bonding the seal material to the metal components of the plug or cable rather than a structural deficiency. Vendor testing and qualification must be established for this component.

Testing

The plug with strain relief will be tested by both the vendor and the contractor to demonstrate its ability to seal out sea water at 10,000 psi.

Design Requirements and Performance Data

The design requirements for the plug with strain relief are as follows:

Bottom View

Top View

Figure 14. Twelve-Pin Titanium Receptacle

Figure 15. Plug with Strain Relief

Maximum Operating Pressure	10,000 psi sea water
Number of Electrical Leads	Not determined (will match receptacle)

Physically, must mate with receptacle to form seal against 10,000 psi sea water pressure.

Mechanically, must not distort under sea water pressure to effect capability of seal.

Performance data on this component has been negative with sea water leakage into the area of plug-receptacle interface. The area of leakage is within the plug with strain relief and not at the interface between the plug and receptacle.

2.3 CONTROL AND PROTECTIVE DEVICES

System safety and operation is not dependent on controls or protective devices. The system, operating under balanced heat flow conditions, does not require any controls. The rate of energy generation by the heat source is a fixed value and cannot be increased or decreased by any influence except the decay of the fuel, which also cannot be changed by any influence. With the system under normal operation of steady state heat balance, control is intrinsic within the system itself. Tests with electrically heated SNAP-21 systems will demonstrate this characteristic.

The system is designed to operate unattended and will be unattended in actual operation. Protective devices, other than the protection designed into the system, will not be required. The fuel capsule as designed provides for containment of the fuel under all credible conditions. The biological shield provides for attenuation of the nuclear radiation. With these two objectives accomplished, no other type of protection is required.

An examination of various likely failure modes and their effects will verify that no controls as protective devices are required. The following modes of failure would cause the system to be unoperative or decrease power output but would not cause a hazard.

1. Generator open circuit would result in a power output drop to zero and the effect on the system would be the same as increasing system heat input by an amount equal to generator output. This would cause a temperature rise which will be determined by testing; the effect will be evaluated.
2. Generator short circuit would decrease generator output but should not have any other adverse effect on system.

3. Open external load circuit would have no effect on internal temperature as power would be dissipated in power conditioner.
4. Generator case leak would cause generator power output to degrade and cause slight increase in internal system temperature.
5. Loss of vacuum in insulation system would reduce all system internal temperatures and reduce system power output.
6. Sea water leakage through the enclosing pressure vessel would eventually cause the system to become inoperative. It would cause no hazard because internal temperatures would decrease and the fuel capsule is able to contain the fuel under these conditions.

Two failure modes which could cause a hazard are as follows:

1. External shock, vibration, or acceleration loads so great that the shield plug does not contain the fuel capsule within the shield body.
2. The fuel capsule being deformed by an external force so that it no longer contains the fuel.

However, neither of these types of failures could be prevented by the addition of a protective device. They will be guarded against by designing the system components to withstand all credible circumstances.

3.0 PRINCIPLES OF ASSEMBLY AND OPERATION

3.1 ASSEMBLY

The assembly of the system, with all major subcomponents previously assembled, will be as follows:

1. The insulation system will be mated into the body of the pressure vessel.
2. The fuel capsule will be installed into the inner liner of the insulation system. This step of the assembly operation must be done in a hot-cell facility. The body of the shield has previously become a part of the vacuum insulation system.
3. The mounting plate-support ring will be installed, which will position and locate the insulation system in the pressure vessel body.
4. The shield plug will be bolted into the inner liner of the insulation system. This operation must also be done in a hot cell facility. With this operation completed, the fuel capsule will be completely surrounded by shielding and hot cell facilities will no longer be required. At this same time, if the generator is not to be installed immediately, a heat sink will be attached to remove the heat from the system. The heat sink has not yet been designed.
5. The temporary heat sink will be removed and the thermoelectric generator installed in the system. A temporary shunt load will be attached to the generator to dissipate the heat from the power generated. With heat being rejected from the thermoelectric generator, a heat sink will be required for the pressure vessel body if there is any delay in the final assembly. The requirements for and design of this heat sink have not been accomplished.
6. The following assembly steps should be accomplished prior to the mating of the thermoelectric generator with the system:
 - Attach power conditioner to pressure vessel cover.
 - Make electrical connections between power conditioner and receptacle.
 - Attach receptacle to pressure vessel cover.

- Mate plug with strain relief to receptacle.
 - Attach dummy load to power output terminals of cable from plug with strain relief.
7. Make electrical connections between power conditioner and thermoelectric generator.
 8. Attach cover to pressure vessel.

This would complete the assembly of the system. Upon completion of assembly, the system would require heat sinking to remove rejected heat to maintain a pressure vessel exterior surface temperature of no more than 45°F. This heat sink will be constantly required, except for short periods, to keep the system from overheating causing damage to the functioning of the components. With all components assembled, the system begins functioning without any start-up activity and will operate normally when temperature equilibrium is reached. The shipping container design will be constrained by the fact that it will also serve as the heat sink.

3.2 NORMAL OPERATION

During normal operation of the system a steady-state heat balance condition is maintained. The rate at which heat is emitted from the heat source is determined by the characteristics of the fuel and the amount of fuel in the capsule. The system surrounding the heat source consists of various heat flow paths which have heat conductance based on material properties and configuration. With these fixed parameters, the system heat source temperature will increase until the temperature differential between the system heat source and the heat sink is such that the heat input will equal the heat transferred through the system. In equation form, it is

$$Q \text{ (heat input)} = U \text{ (total system thermal conductivity)} (T \text{ heat source} - T \text{ heat sink})$$

To keep the system operating at proper temperatures the heat sink must be sea water at a temperature of 28 to 41°F. Maintaining sea water temperature, is not a problem when the system is implanted. A means of providing these heat sink conditions will be required during storage and transportation.

3.3 DISASSEMBLY

The SNAP-21 system could be disassembled for repair of a component or as a shutdown procedure. The subject of disassembly for repair will be covered in Section 5.2. Complete shutdown of the system can only be accomplished by disassembly of the system. The disassembly of the unit for shutdown is very unlikely. This is based not only on the nature of the system but also on the nature of the application.

The need for a heat sink during disassembly would depend on how quickly the operation was completed. The limit of time the system could tolerate without a heat sink can be determined. If this time would be exceeded during disassembly, a heat sink would be required.

The steps of disassembly would be as follows:

1. Remove plug with strain relief from receptacle.
2. Remove pressure vessel cover and disconnect wires from thermoelectric generator to power conditioner.
3. Unbolt thermoelectric generator from mounting plate-support ring and remove from system.
4. Install heat sink to shield plug.

If further disassembly is required, a hot cell facility for protection against nuclear radiation would be required to complete the following:

5. Remove shield plug from inner liner of insulation system.
6. Withdraw the fuel capsule from the inner liner of the insulation system.

This would complete the disassembly of the system rendering it totally inactive.

4.0 HAZARDS AND SAFETY PRECAUTIONS

4.1 HAZARDS

The following hazards may occur:

1. During Assembly
 - a. Exposure to radiation from fuel capsule caused by mishandling during installation into the system or from fuel capsule removal from shielding.
 - b. Overexposure to radiation by too-long exposure by close proximity to the system prior to completion of assembly.
2. During Transportation
 - a. A catastrophic accident which would break the fuel capsule out of containment by the shield.
 - b. A catastrophic accident which would break open the fuel capsule, releasing the fuel.
 - c. Failure of the heat sink causing a temperature increase in the system to the extent that the fuel capsule melted and could not contain the fuel. A test will be conducted to determine the extent of temperature increase under conditions of heat sink failure.
3. During Storage
 - a. Failure of the heat sink causing a temperature increase in the system to the extent that the fuel capsule melted and could not contain the fuel.
 - b. Faulty fuel capsule which would fail to contain the fuel.
4. During Operation
 - a. Faulty fuel capsule which would fail to contain the fuel.

4.2 PRECAUTIONS

The following precautions must be taken to prevent any hazard from occurring.

- a. Establish and follow proper procedures for installing fuel capsule in system.
- b. Establish and follow exposure time restrictions when assembling the system.
- c. Design, with maximum practical safety factor, the shield plug bolts to maintain containment of fuel capsule in shield.
- d. Design transportation container and storage heat sink for system to provide maximum reliability.
- e. Use stringent quality control measures when fabricating the fuel capsule.

5.0 MAINTENANCE

5.1 PREVENTIVE MAINTENANCE

The system is a completely-enclosed, self-contained device. It operates mechanically static with no adjustments or controls. The system will operate in an unattended location undersea without preventive maintenance. It is an inherent characteristic of this system that it does not require preventive maintenance.

5.2 TROUBLE SHOOTING

Indication that the system is not functioning properly is a variation in electrical output. This could be a decrease in power output or a shift in voltage.

One of the following would cause a decrease in power output or shift in output voltage:

- a. Faulty power conditioner.
- b. Faulty thermoelectric generator.
- c. Increase in thermal conductivity through insulation system caused by loss of vacuum.

The following procedures would be followed to determine which component was faulty.

1. Remove pressure vessel cover and check power and voltage output from generator. If these values are within specifications, then the power conditioner would be the faulty component. Replace the power conditioner and reassemble the unit to complete the repair.
2. If the generator power output is low, but the open circuit voltage is at the correct level, then the generator is defective. Repair would be to remove the defective generator and replace it.
3. If the generator power output is low and open circuit voltage is low, the generator is defective if there is a potential between the output terminals and the generator frame. Repair would be to remove the defective generator and replace it.

4. If the generator power output is low, open circuit voltage is low, and there is no potential between power output terminals and the generator frame, the vacuum insulation system is defective. If this is the case, a hot cell facility would be required for repair. With the extensive effort required for replacing a defective insulation system, the generator and power conditioner should be bench checked for proper operation before reassembly of the system.

APPENDIX A

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

The SNAP-21 engineering design summary is based upon the Phase I design and experimental work completed on June 30, 1965. Adjustments have been made in those values which have changed due to the work on Phase II.

Contractor	Minnesota Mining and Manufacturing Co.
Contract No.	AT(30-1)-3691
Users and Missions	Not Available
Status	Phase II Development
Updated	October 10, 1966

SYSTEM AND GENERATOR DATA

System Concept	PbTe — thermoelectric, flat-plate type
Fuel	$\text{Sr}^{90} \text{TiO}_3$
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 (small pressure vessel)	516 ± 2 pounds	20 ± 1 pounds
(large pressure vessel)	582 (estimated)	
Length (inches, small pressure vessel)	27.85	4.12
(inches, large pressure vessel)	35.55	
Diameter (inches)	15.836 OD, maximum	7.84 and 4.45
Volume (cubic inches, small pressure vessel)	3339	89.3
(cubic inches, large pressure vessel)	4969	

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

	<u>Small</u>	<u>Large</u>
Total Pressure Vessel	151.27 lbs	217.27 lbs
Receptacle	5.0	5.0
Top Dome	40.0	106.0
Bottom Dome and Cylinder	106.0	106.0
All Bolts	0.27	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		

Radiation Disc (calc.) ----- 1.45 lbs

Segmented Retaining 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, Small Pressure Vessel -- 516 lbs

Less Plug with Strain Relief ----- Large Pressure Vessel -- 582 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 $\frac{\text{power output (watts e)}}{\text{heat input (watts th)}}$	5.8	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	1463° F
Fuel Capsule Surface	1412° F
Hot Junction, T_h	1100° F
Cold Junction, T_c	115° F (design objective)
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	3g peak value, 6 ms nominal duration
Vibration	5 to 26 cps at 1.3g 26 to 50 cps at 0.036 inch double amplitude displacement
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

SAFETY DATA

OPERATION, HANDLING, AND TRANSPORTATION – RADIATION DOSE RATES

	In Operation	At System Surface in Transport	One Meter From System Surface
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	1463
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

Physical Properties

Melting Point, °F	~ 3450
Boiling Point, °F	> 3450
Kindling Temperature, °F	> 3450
Maximum Continuous Operating Temperature, °F	1463
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 level

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
Linear Expansion Coefficient, 10 ⁻⁶ /°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)
Electrical Output	
Leg Thermal Input	
Energy Conversion Efficiency % (net, system)	5.6 (EOL)
Electrical Output	
System Heat Input	

* Electrical Resistance Losses Included.

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
Electrical Output		
Leg Thermal Input		

* Assumes No Electrical Resistance Losses.

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
<div style="display: flex; align-items: center; justify-content: center;"> <div style="margin-right: 10px;">Cold Seg.</div> <div style="text-align: center;"> <div style="margin-bottom: 10px;">↑</div> <div style="margin-bottom: 10px;">↓</div> <div style="margin-bottom: 10px;">↑</div> <div style="margin-bottom: 10px;">↓</div> <div style="margin-bottom: 10px;">↑</div> <div style="margin-bottom: 10px;">↓</div> <div style="margin-bottom: 10px;">↑</div> <div style="margin-bottom: 10px;">↓</div> <div style="margin-bottom: 10px;">↑</div> <div style="margin-bottom: 10px;">↓</div> </div> <div style="margin-left: 10px;">Hot Seg.</div> </div>	200	126	715	0.0274	1.46
	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
	1000	130	1730	0.0225	0.78
	1100	120	1850	0.0250	0.56

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

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

$$Z = 0.00159$$

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	122	1830	0.0224	0.65

Hot Junction Button

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

Cold Cap

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

Cold Junction Electrode

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 ± 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, % (Electrical Power Output/ Electrical Power Input)	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
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	

*3-wire input sealed in an aluminum enclosure.

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

<u>Material and Dimensions</u>	MIN-K 1301 insulation powder packed in all generator void spaces to a density of 13-14 lbs/ft ³ and xenon backfilled. The MIN-K 1301 is heat processed to 1300° F to remove water and residual organic binders. When packed into the generator it undergoes additional processing to remove moisture, contaminants and accomplish outgassing. The thermal conductivity of the xenon filled MIN-K 1301 insulation is estimated to be 0.0242 Btu/hr-ft-° F. Microquartz insulation in felt form is packed in the generator in strategic locations to prevent migration of the powdered MIN-K 1301.
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Electrical Insulation

Materials, Location	Boron nitride on generator hot frame, aluminum hardcoat on thermoelectric leg spring-loaded follower
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Housing (Pressure Vessel)

Material	Not determined
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	Viton	3.234	0.139	Seal between vessel and receptacle
O-ring	1	Viton	14.359	0.275	Outer seal between sections of pressure vessel
O-ring	1	Viton	13.309	0.275	Inner seal between sections of pressure vessel

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.

APPENDIX B

U. S. ATOMIC ENERGY COMMISSION
NEW YORK OPERATIONS OFFICE

TECHNICAL PROVISIONS
THERMOELECTRIC RADIOISOTOPE-FUELED
POWER SUPPLY SYSTEM FOR DEEP-SEA
AND OCEAN BOTTOM APPLICATIONS

REVISION 1

MARCH 1, 1964

INTRODUCTION

- A. These Technical Provisions establish the technical requirements and objectives for development, design, fabrication, and testing of a thermoelectric radioisotope-fueled power supply system capable of operation in deep-sea and ocean bottom.
- B. "System" as used in these Technical Provisions shall be deemed to include a thermoelectric radioisotope-fueled generator, thermal insulation, an electrical power conditioner and regulator, shielding, a pressure vessel, and all other items required for operation of the system as described in these Technical Provisions.

1.1 Design Requirements

- 1.1.1 The system shall have a minimum electrical output of 10 watts, direct current, at 24 volts.
- 1.1.2 The system shall provide the specified power continuously for a minimum period of five years under the operational environmental conditions specified herein.
- 1.1.3 The system shall be capable of unattended operation requiring no maintenance.
- 1.1.4 The system shall have the following steady state voltage characteristics:
 - Upon initiation of operation and for a minimum of five (5) years thereafter - 24 ± 1 volt with an external load of 57.6 ohms (rated load)
- 1.1.5 The system shall be designed so that the radiation level shall not exceed 200 mr/hr at the surface of the system and 10 mr/hr at one meter from the surface.
- 1.1.6 The system shielding shall be designed to permit ease of repair, removal and replacement of the thermoelectric subsystem without exceeding the maximum permissible radiation exposure limits established by the AEC.
- 1.1.7 The system shall be completely contained within the pressure vessel.
- 1.1.8 The electrical power conditioner and regulator, and the thermoelectric subsystem shall be capable of being repaired, removed and replaced without the use or need for hot cell facilities.
- 1.1.9 The system shall not exceed a cylindrical envelope of eighteen (18) inches in diameter and twenty-six (26) inches in length, and shall not exceed a weight of five hundred and fifty (550) pounds.
- 1.1.10 For a period of at least five years, the overall system efficiency shall not be less than 6.75 percent, and the efficiency of the thermoelectric leg subsystem shall not be less than 10.0 percent.

- 1.1.11 The thermal conductivity of the thermal insulation shall not be greater than 0.0005 Btu/hr-ft-°F during operation.
- 1.1.12 Instrumentation shall be incorporated to monitor the following parameters of the system:
 - a. Hot Junction Temperature
 - b. Cold Junction Temperature
 - c. Open circuit voltage
 - d. Short circuit voltage
 - e. Short circuit current
 - f. System voltage under load conditions
 - g. System current under load conditions
 - h. Internal gas pressure
 - i. Internal humidity
 - j. Pressure vessel leakage
- 1.1.13 Instrumentation lead connections shall be provided external to the pressure vessel to permit the monitoring and automatic recording, if required, of the parameters specified in 1.1.12 above, and to permit short-circuiting of the system output, wherever appropriate.
- 1.1.14 The system shall be designed such that the instrument lead penetrations can be permanently sealed, wherever required.
- 1.1.15 The pressure vessel shall be designed so that no leakage shall occur during the installation of the system, and during operation of the system under environmental conditions for its design life, but in no event less than five years.
- 1.1.16 The pressure vessel shall be designed to withstand the corrosive conditions associated with the operational environment for the design life of the system, but in any event not less than five years.
- 1.1.17 The system shall incorporate provisions designed to facilitate handling, transportation and installation.
- 1.1.18 The system shall be designed so that handling, transportation and installation can be accomplished safely requiring a minimum of special equipment.

- 1.1.19 Any special equipment or tools required for the system shall be kept to a minimum.
- 1.1.20 The fuel capsule shall be capable of complete containment of the fuel under all conditions of intended use, credible accidents, and for a minimum period of 300 years. The fuel capsule shall be designed to withstand, at operating temperature:
 - a. Standard one hour fire tests as set forth in the code of the National Fire Protection Association.
 - b. Environmental Corrosion for 300 years before release of the fuel.
 - c. Hydrostatic pressures from sea level to 10,000 psi.
 - d. One hour vibration test with a maximum loading of 16 g's and with varying frequency from 10 - 10,000 cps.
- 1.1.21 The system shall be designed, fabricated, and tested in accordance with the latest applicable codes, standards, and practices.
- 1.1.22 The system shall be capable of operation when emplaced in any attitude.
- 1.1.23 The radioisotope fuel employed in the system shall be strontium-90 of the Titanate form as described in section 3.0 of these Technical Provisions.
- 1.1.24 The system shall be capable of being stored under fueled or unfueled conditions for extended periods of time without any adverse effects to the system.
- 1.1.25 The fuel capsule shall be designed such that the encapsulation can be readily accomplished by personnel at a Government facility.
- 1.1.26 The system design should be capable of being upgraded to power outputs of 20, 60, and 100 watts(e).

2.0 Environmental Data

The system described in these Technical Provisions shall be capable of providing its required performance under all of the environmental conditions specified below. One exception to be noted is that the steady state voltage characteristic requirement need not apply when the system is operated in air or ambient water temperature conditions outside the 28° F to 41° F range.

a. Ambient air temperature	-65° F to +130° F
b. Ambient air pressure	10 to 32 in of Hg
c. Ambient water temperature	28° F to 41° F
d. Moisture	100% relative humidity in a salt atmosphere.
e. Mechanical Vibration	5 to 32 cycles per second having an excursion within .054 to .066 inches or an excursion producing 3 g's.
f. Ambient water pressure (seawater)	Sea level to 10,000 psi

3.0 Isotopic Power Data – Strontium-90

	Sr^{90}
Source Material	SrTiO_3
Half-Life	27.7 years (Y^{90} -- 64.2 hours)
Radiation Emitted	$\text{Sr}^{90} \rightarrow \text{Y}^{90}$ 100% beta - 0.54 Mev $\text{Y}^{90} \rightarrow \text{Zr}^{90}$ ~ 100% beta - 2.26 Mev
Activity Concentration	33 curies/g of fission product SrTiO_3
Radiochemical Purity	The most likely radiochemical impurity, Ce^{144} , does not exceed 150 mc per gram of Sr^{90} isotope. Sr^{89} is present in concentrations dependent on length of time since discharge from the reactor and is usually < 25% of the Sr^{90} activity at time of fabrication of source pellets.
Chemical Purity	> 75% Sr. The major cation impurity in Ca with smaller quantities of Ba and Fe. Current products contain ~ 95% Sr and the weight ratio of Sr^{90} to total Sr is ~ 0.5.
Specific Power	0.21 watts per gram of SrTiO_3 .
Density	~ 3.7 g/cm ³ . The theoretical density is 5.11 g/cm ³ . Production values vary from 3.2 to 4.2 g/cm ³ , averaging about 3.7 g/cm ³ .

Power Density	0.7 - 0.8 watts/cm ³ . Sr ⁸⁹ will contribute in proportion to its concentration at a rate of 3.4 watts/1000 curies of Sr ⁸⁹ .
Thermal Conductivity	Values reported for inactive SrTiO ₃ vary from 0.0132 to 0.0173 cal/sec · cm · °C at room temperature, depending on the density
Coefficient of Expansion	$1.12 \times 10^{-5} \text{ }^{\circ}\text{C}^{-1}$
Melting Point	~1900°C
Mechanical Strength	Fair
Thermal and Radiation Stability	The thermal stability is good. The radiation stability is good as exhibited in two-year old samples.
Decay Product	Zirconium
Radiation Attenuation	The tenth value layer for the high energy component of Sr ⁹⁰ - Y ⁹⁰ bremsstrahlung is 1.6 in. of lead.
Gas Evolution Due to Radioactive Decay Processes	None
Leach Rate	Inactive SrTiO ₃ leaches at a rate of 1 µg/day · cm ² in sea water. Tests on 18-month old pellets of F.P. SrTiO ₃ indicate a leach rate of ~1 mg/day · cm ² .
Vapor Pressure	No data available.
Resistance to Thermal Shock	No data available.
Burnup Characteristics	Dispersibility poor.
Capsule Compatibility	Good.

APPENDIX C

U. S. ATOMIC ENERGY COMMISSION
NEW YORK OPERATIONS OFFICE

TECHNICAL SPECIFICATIONS FOR
RADIOISOTOPE-FUELED THERMOELECTRIC
POWER SUPPLY SYSTEMS (10 WATT(E) AND 20 WATT(E)) FOR
DEEP-SEA AND OCEAN BOTTOM APPLICATIONS

JUNE 24, 1966

a. System Performance Specifications and Physical Characteristics

Nominal Size, watts(e)	10	20
Minimum power out, EOL, watts(e)	10	20
Minimum design operating life, yrs.	5	5
Maximum power in, BOL, watts(th)	203	372
Voltage, DC volts	24 ± 1	24 ± 1
Load Resistance, ohms	57.6	28.8
Maximum ripple, peak to peak, mv	100	100
Maximum weight in air, pounds	507 ^{1/}	595 ^{2/} 775 ^{1/} 890 ^{2/}
Maximum diameter, inches	16	16 18 18
Maximum length, inches	28	35 32 44

1/ for system with minimum sized pressure vessel dome

2/ for system with pressure vessel dome equal to lower pressure vessel body.

b. System Environmental Specifications

The system shall operate in accordance with the above performance specifications under the following environmental conditions:

Water Temperature	28° F - 41° F range
Ambient water pressure	Sea level to 10,000 psi
Moisture (Humidity)	100% relative humidity in a salt atmosphere

c. System Handling and Specifications

The system shall be capable of operation in accordance with the above performance specifications and environmental conditions after exposure to the following:

Temperature in ambient air (6 months duration)	-65° F to +130° F
Ambient air pressure	10 to 32 in. of Hg
Humidity	0 to 100%
Vibration (w/shipping pallet)	Perform vibration tests required for equipment transported by common carrier according to MIL-STD-810A, dated June 23, 1964 except that the maximum g level shall be limited to 3.0 g peak.
Shock	Perform shock tests in accordance with MIL-STD-810A, Method 516.1. Procedure I except that the peak value shall be 3 gs and the nominal duration shall be 6 ms.

d. System Safety Specifications

The system shall be capable of complete containment of the radioisotope fuel and shall provide adequate biological shielding in accordance with the following specifications:

Biological Shielding

Dose rate at surface of system, mr/hr	200
Dose rate at 1 meter from surface, mr/hr	10

Fuel Containment

Lifetime of capsule at pressures up to 10,000 psi at operating temperatures in a sea water environment, yrs.	300
Temperature capability of fuel capsule.	Survive one hour fire tests as set forth in code of the National Fire Protection Association

e. General Requirements

The system shall permit, without the use or need for hot cell facilities, removal, repair and replacement of the thermoelectric converters, power conditioners and regulators without exceeding the maximum permissible radiation exposure limits established by the AEC.

The system shall be completely contained within the pressure vessel. The system shall incorporate provision for safe handling, transportation and installation utilizing a minimum of special equipment and tools. The radioisotope fuel employed in the system shall be strontium-90 of the titanate form as described in Section E. of the Technical Specification.

f. SrTiO₃ Fuel Specifications

Isotopic Power Data - Strontium-90

	Sr ⁹⁰
Source Material	SrTiO ₃
Half-Life	27.7 years (Y ⁹⁰ -- 64.2 hrs.)
Radiation Emitted	Sr ⁹⁰ → Y ⁹⁰ 100% beta - 0.54 Mev Y ⁹⁰ → Zr ⁹⁰ ~100% beta - 2.26 Mev
Activity Concentration	33 curies/g of fission product SrTiO ₃
Radiochemical Purity	The most likely radiochemical impurity, Ce ¹⁴⁴ , does not exceed 150 mc per gram of Sr ⁹⁰ isotope. Sr ⁸⁹ is present in concentrations dependent on length of time since discharge from the reactor and is usually <25% of the Sr ⁹⁰ activity at time of fabrication of source pellets.
Chemical Purity	> 75% Sr. The major cation impurity in Ca with smaller quantities of Ba and Fe. Current product contain ~95% Sr and the weight ratio of Sr ⁹⁰ to total Sr is ~0.5.

Specific Power	0.21 watts per gram of SrTiO_3 .
Density	$\sim 3.7 \text{ g/cm}^3$. The theoretical density is 5.11 g/cm^3 . Production values vary from 3.2 to 4.2 g/cm^3 , averaging about 3.7 g/cm^3 .
Power Density	$0.7 - 0.8 \text{ watts/cm}^3$. Sr^{89} will contribute in proportion to its concentration at a rate of $3.4 \text{ watts/1000 curies of Sr}^{89}$.
Thermal Conductivity	Values reported for inactive SrTiO_3 vary from 0.0132 to $0.0173 \text{ cal/sec-cm-}^\circ\text{C}$ at room temperature, depending on the density.
Coefficient of Expansion	$1.12 \times 10^{-5} \text{ }^\circ\text{C}^{-1}$
Melting Point	$\sim 1900^\circ\text{C}$
Mechanical Strength	Fair
Thermal and Radiation Stability	The thermal stability is good. The radiation stability is good as exhibited in two-year old samples.
Decay Product	Zirconium
Radiation Attenuation	The tenth value layer for the high energy component of $\text{Sr}^{90} - \text{Y}^{90}$ bremsstrahlung is 1.6 in. of lead
Gas Evolution Due to Radioactive Decay Processes	None
Leach Rate	Inactive SrTiO_3 leaches at a rate of $1 \text{ } \mu\text{g/day} \cdot \text{cm}^2$ in sea water. Tests on 18-month old pellets of F.P. SrTiO_3 indicate a leach rate of $\sim 1 \text{ mg/day} \cdot \text{cm}^2$.
Vapor Pressure	No data available.
Resistance to Thermal Shock	No data available.

Burnup Characteristics

Dispersibility poor.

Capsule Compatibility

Good.

g. System Acceptance Test Specification and Requirements

All systems designated for operational use shall be tested in accordance with the System Acceptance Test Specifications and Requirements to be furnished by the contractor and approved by the Contracting Officer.