SNAP-21 PROGRAM, PHASE II

DEEP SEA RADIOISOTOPE - FUELED THERMOELECTRIC GENERATOR POWER SUPPLY SYSTEM

FINAL DESIGN DESCRIPTION 10-WATT SYSTEM

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1.0 INTRODUCTION

1.1 SYSTEM FUNCTION

The SNAP-21 10-watt system provides electrical power for use under the surface of the sea. It functions by converting 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 heat 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 are enclosed in a pressure vessel which protects 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 electrical output of the thermoelectric generator to the desired voltage. A two-piece pressure vessel encloses all the components. There are two pressure vessel models, one with a long cover and one with a short cover. A receptacle and plug mounted on the pressure vessel cover bring electrical leads through the pressure vessel. Figure 1-1 shows the relative size, shape and location of these major components in the system.

The system is normally supplied in a reusable handling, storage, and shipping container. The container provides thermal and dynamic protection during transportation and storage. Information on the shipping container will be included in this document where applicable.

A complete design summary of the system is included in Appendix A for ready reference.

1.2.2 Nominal System Output

Performance data is based on operation in 28-41°F sea water.

● Power Output, watts (e)	10
● Design Life, years*	5
● Output Voltage, vdc	24 ± 1
● Load Resistance, ohms	57.6
● Maximum Output Voltage Ripple, mv (peak-to-peak)	100
● Current at Rated Load, amps	0.417

*Note: Design life commences on date of system assembly.

Figure 1-1. SNAP-21 10-Watt System (Short Cover Configuration)

1.2.3 Physical Characteristics

(a) System Only

	<u>Short Cover</u>	<u>Long Cover</u>
● Weight (in air), pounds	645	750
● Length, inches	25	34
● Diameter, inches	16	16

(b) System in Shipping Container

	<u>Short Cover</u>	<u>Long Cover</u>
● Weight, pounds	1740	1920
● Height, inches	68	68
● Diameter, inches	58	58

1.2.4 Environmental Capability

During handling, shipping, and storage the SNAP-21 system is normally installed in a shipping container which provides thermal and dynamic protection for the system. The environmental capability of the system is therefore listed with and without the shipping container.

Environmental Capability While Installed in Shipping Container

● Air temperature extremes during a one-month shipping cycle	-65° to +130°F
● Humidity (salt atmosphere)	0 to 100 percent
● Air temperatures extremes during five-month storage	-65° to +95°F
● Vibration	Normal vibration encountered during truck, rail, ship and air transport.

- Shock Shock incurred by a 3-inch flat drop or a 6-inch corner drop of the shipping container.
- Air Pressure Atmospheric pressure varying from sea level to 30,000 feet.

Environmental Capability Without Shipping Container

- Sea water temperature, °F 28 to 41
- Sea water pressure, psi 0 to 10,000
- Moisture (relative humidity) 0 to 100 percent in a salt atmosphere
- Vibration MIL-STD-810A dated 23 June 1964
Method 514.1, Equipment Class 6,
Figure 514-6, except the frequency shall be limited to 50 cps and the acceleration limited to 3g.
- Shock MIL-STD-810A dated 23 June 1964
Method 516.1, Procedure I
except the peak acceleration shall be 6g's and the normal duration shall be 6 ms.

1.2.5 Nuclear Safety

The radioisotope fuel is completely shielded so that the radiation is attenuated to less than 200 mr/hr at the surface of the system and less than 10 mr/hr at 1 meter from the surface.

The fuel is contained in a capsule which is capable of complete containment under all credible accident conditions including immersion in sea water for 300 years at 10,000 psi and a one-hour fire test as set forth in the code of the National Fire Protection Association.

1.2.6 Major Component Identification

The major system components are identified below. A complete description of each will be presented in Section 2.0.

- Heat Source – The heat source is a radioisotope fuel, SrTiO_3 , 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 uranium-8 w/o Molybdenum alloy. The shield encloses the heat source to reduce the radiation level to a safe level.
- Insulation System – The insulation system is a vacuum container with heat reflective foils and quartz fiber spacers wrapped around the biological shield. It insulates 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 in a series electrical circuit. The thermoelectric generator is the flat-plate type with leg longitudinal axes parallel to each other and perpendicular to the hot and cold frames. The legs are surrounded by powdered thermal insulation. The container is hermetically sealed and filled with a special atmosphere. The electrical power is brought out through hermetically sealed fittings.
- Mounting Plate Support Ring – This component is an annular ring on which curved segments are mounted. These curved segments are spring loaded and serve to position and restrain the insulation system within the pressure vessel.
- Power Conditioner – This component is a solid-state dc-dc converter and voltage regulator. The electronic components and circuitry are enclosed in a hermetically-sealed container mounted to the pressure vessel cover.
- Pressure Vessel – The pressure vessel is two pieces, body and cover. When assembled, it encloses the system's internal components. There are two cover sizes, long and short.
- Electrical Receptacle – This component is bolted to a boss in the pressure vessel cover and contains electrical contact pins mounted in an electrical insulation.
- Cable Connecting Plug – The plug is a fitting for the end of an electrical cable. It mates with the electrical receptacle with a mechanical lock and with sockets for mating with the electrical receptacle contact pins.

1.3 SYSTEM DESIGN REQUIREMENTS

1.3.1 Design Basis

Previous background, basic engineering principles and an extensive component development program provided the design basis for this system.

Previous background is particularly important with regard to thermoelectricity since the state-of-the-art is changing rapidly. The following engineering principles are notable with regard to the SNAP-21 System.

- a. Ability of thermoelectric materials to convert heat into electricity.
- b. Characteristic of radioisotope fuel to evolve heat during the decay process.
- c. Ability of biological shielding material to attenuate radioisotope radiation.
- d. Ability of a high vacuum thermal insulation to cause a high thermal impedance.
- e. Ability of electrical components in the proper circuit to condition electrical power.
- f. Ability of supporting components to provide heat transfer, structural support, protection against sea water pressure and corrosion, and a method of making electrical power available at the required voltage level.

The majority of the specific technical requirements for the SNAP-21 System are contained in the Technical Specification which was the governing document for system design. The requirements contained in the Technical Specification are summarized below. The complete Technical Specification is included in this report as Appendix B.

1.3.2 Operational Conditions

These are the normal operating conditions for the system:

- Surrounding Fluid — Sea water
- Fluid Pressure — Sea level to 10,000 psi
- Fluid Temperature — 28 to 41°F

1.3.3 Performance Requirements

Under operating conditions, the system shall meet the following performance requirements after five years continuous operation:

- Power Output — 10 watts minimum
- Voltage — 24 ± 1 volts; maximum ripple, peak-to-peak, 100 mv
- Load Resistance — 57.6 ohms nominal

1.3.4 Environmental Requirements

The system shall be capable of operation in accordance with the above performance specifications after the system, within the shipping container, has been exposed to the following conditions:

- a) Shipment — The system, in its shipping container, shall be capable of withstanding a one-month shipping cycle. During this month, the system must be capable of withstanding the normal shock and vibration environment encountered during truck, rail, ship and air transport. In addition, the system in its shipping container, shall be capable of withstanding an accidental shock load corresponding to a 3-inch flat drop and a 6-inch corner drop.

Hot temperature extremes during the shipping cycle shall consist of a 24-hour cycle of temperature starting with 10 hours at +90°F, followed by 5 hours of steady increase to +130°F, 4 hours at +130°F, and 5 hours of steady decrease to 90°F. Wind speed negligible.

Cold temperature extremes during the shipping cycle shall consist of -65°F continuous. Wind speed negligible.

The system shall be capable of air shipment in an unpressurized compartment at altitudes up to 30,000 feet. Temperature during this mode of shipment shall be in accordance with MIL-STD-210A, Figure I, "Hot and Cold Atmospheres - Temperature vs Altitude".

- b) Storage – The system in its shipping container shall be capable of withstanding storage in air for 5 months at air temperature ranging from -65°F to +95°F.
- c) During all phases of shipping and storage the system, in its shipping container, will be shielded from direct solar radiation. Relative humidity may range from 0 to 100 percent.

1.3.5 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

The SNAP-21 System 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 watertight electrical receptacle is attached to this pressure vessel providing a means by which electrical and instrumentation leads are brought 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 the excess power produced at the beginning of life.

The internal components of the system are arranged so that they are not subjected to loads during pressure vessel deflection caused by external hydrostatic pressure. This causes a problem in conducting the rejected heat from the generator to the sea water since space between components must be provided to allow for pressure vessel deflection. This problem is overcome by using a system of spring-loaded pressure contacts to form a flexible heat transfer path. The components of this system also form a mounting surface for the thermoelectric generator and position and restrain the vacuum insulation system.

The thermoelectric generator converts the radioisotope decay 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. Extraneous heat losses directly reduce system efficiency and are therefore kept to a minimum. To minimize these losses, the fuel capsule and biological shield are surrounded with a vacuum thermal insulation system except in the area where the thermoelectric generator receives its heat.

The thermoelectric generator receives heat from the surface of the biological shield by thermal radiation and gas conduction. Mechanical loads cannot be transferred from the shield to the generator as there is no physical connection between the generator and the shield.

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 decrease in heat output from the capsule during the five-year operating period. The temperature profile of the system decreases uniformly with time as the heat input of the fuel decreases; consequently, there are no rapid fluctuations in temperature.

The biological shield completely encloses the radioisotope heat source to reduce nuclear radiation to a safe level. It is also designed so that the thermoelectric generator can be removed or installed without hot cell facilities.

The system and its major components has already been shown in Figure 1-1. Table 2-1 tabulates the major characteristics of the system and Table 2-2 is a tabulation of the measured performance of the first four fueled systems and the predicted performance of systems fueled with the maximum and minimum amounts of fuel, 209 and 219 watts (t), respectively. A parametric presentation of system thermal and electrical performance as a function of time, sea water temperature and system electrical load resistance is presented in Appendix C. It is important to note that the system performance data presented in Table 2-2 and Appendix C is based on an extrapolation of actual system performance data

and will therefore vary slightly from some of the calculated performance data presented later in this report.

Table 2-1. 10-Watt System Characteristics

●	Performance (based on operation in +41°F water)		
	Design Operating Life		5 years
	Minimum Power Output (EOL) (Based on Load Resistance of 57.6 Ω)		10 watts (e)
	Output Voltage		24 ± 1 vdc
	Output Voltage Ripple (maximum)		100 mv
	Fuel Loading (BOL), Minimum		209 watts (t)
	Maximum		219 watts (t)
●	Physical Characteristics		
		<u>Short Cover</u>	<u>Long Cover</u>
	Weight in Air, pounds	640	750
	Length, inches ⁽¹⁾	25.1	33.7
	Diameter, inches	15.85	15.85
	Volume, cubic inches	3120	4540

⁽¹⁾Overall length of pressure vessel – electrical receptacle adds 2.75 inch.

Table 2-2. Summary of System Performance

(All data based on operation in 40°F water and fixed load resistance of 57.6Ω)

System Designation System Characteristics	System S10P1		System S10P2		System S10P3		System S10P4		System with Minimum Fuel (3)		System with Maximum Fuel (3)	
	BOL	EOL	BOL	EOL	BOL	EOL	BOL	EOL	BOL	EOL	BOL	EOL
Thermal												
• Fuel Loading, watts (t)	210.4	185.5	207.7	183.1	213.5	188.3	210.4	186.0	209	184	219	193
• Insulation System Heat Loss, watts (t) ⁽¹⁾	52.3	48.4	56.7	52.0	55.4	50.9	57.3	52.5	53.6	49.2	55.5	50.9
• Insulation System Thermal Efficiency, %	74.9	73.9	72.8	71.6	74.1	73.0	72.8	71.7	74.3	72.7	74.7	71.0
Temperature Profile												
Pressure Vessel, °F	45	44	43	42	44	43	42	42	43	42	43	42
Cold Frame, °F	63	56	60	56	64	58	63	61	59	57	60	58
Cold Junction (avg), °F	92	83	88	79	92	81	91	86	87	82	89	83
Hot Junction (avg), °F	985	893	958	867	992	894	984	999	960	877	1015	900
Hot Frame (avg), °F	1040	940	1040	917	1054	947	1052	945	1032	930	1075	970
Emitter Plate, °F	1255	1155	1227	1130	1267	1170	1255	1158	1235	1140	1280	1180
Electrical												
• Total Thermoelectric Generator Power Output, watts (e) (before conditioning)	14.64	11.79	14.24	11.33	14.75	12.13	14.58	11.90	14.5	11.8	15.2	12.8
• System Power Output, watts (e) (2) (conditioned to maintain 24 ± 1 vdc)	10.40	10.31	10.38	10.15	10.45	10.33	10.35	10.35	10.4	10.4	10.4	10.4
• Conditioned Output Voltage Ripple, mv	68	68	65	65	60	60	60	60	60	60	60	60
• System Efficiency, % (before power conditioning)	6.96	6.35	6.86	6.19	6.91	6.44	6.93	6.39	6.95	6.41	6.95	6.65

(1) Insulation system heat loss corrected for actual system temperature profile.

(2) Power conditioner limits system power output to 10.4 watts (e) at fixed system load resistance of 57.6Ω. Excess power is dissipated in power conditioner.

(3) Predicted performance based on extrapolation of average fueled system performance.

2.2 SYSTEM COMPONENTS

2.2.1 Heat Source

The heat source provides the thermal energy input to the system. Heat is obtained from the radioisotope decay of a pellet of Strontium-90. In the SNAP-21 System the heat source operates at a maximum temperature of 1600°F. This maximum temperature occurs during shipment at maximum ambient conditions. The heat source is located in the approximate geometric center of the system and is immediately surrounded by the biological shield. Reference to Figure 1-1 will show the relative size and location of the heat source in the SNAP-21 System. Figure 2-1 is a section drawing of the heat source assembly.

Fuel Form

The fuel for the heat source is Strontium-90 in the form of a SrTiO_3 pellet. It is prepared by hot pressing in a platinum foil liner. The half life of the fuel is 27.7 years. For BOL conditions, the system heat requirement is 209 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 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	2.27
Average	0.201	0.944
Bremsstrahlung Mev/Beta Particle Conversion	9.92×10^{-4}	2.08×10^{-2}

Figure 2-1. Heat Source Assembly

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 $1.12 \times 10^{-5}/^{\circ}\text{C}$. Melting temperature of the fuel is approximately 3450°F.

Enclosing Capsule

The fuel is enclosed in a single capsule. This capsule is designed to completely contain the fuel under any credible accident. The fuel capsule is a double-walled container. It is sized to contain fuel producing 209-219 watts of heat with 0.8 watts/cm³ power density. Figure 2-1 shows the fuel capsule components. The inner container, like the outer container, is cylindrical with flat ends. Table 2-3 gives the characteristics of the fuel capsule.

Enclosing Method

The fuel capsule is a container within a container. The platinum jacketed Sr-90 pellet is first enclosed in a 304L stainless steel container known as the liner. The liner consists of a cylinder with two end plates. The end plates are TIG welded to the cylinder to enclose the capsule. No filler wire is used.

The SR-90 pellet, in the liner, is then enclosed in an outer container made from Hastelloy C-276. This outer container provides structural and corrosion protection for the fuel. The outer container is also a cylinder with two end plates. The outer container is closed by electron beam (EB) welding.

This weld technique provides full penetration (0.205 inch) with a minimum of distortion.

Material Compatibility

Because of the nonreactive nature of the fuel, no materials' compatibility problems exist between the fuel and the capsule. Also, no material compatibility

Table 2-3. Summary of Major Dimensions and Material Properties for Fuel Capsule and Liner

Dimension/or Property	Capsule	Capsule Liner
Material	Hastelloy Alloy C-276	304L, Stainless Steel
Inside Diameter, inch	2.797	2.735
Inside Length, inch	2.939	2.759
Wall Thickness, Sides, inch	0.200	0.020
Wall Thickness, Ends, inch	0.200	0.075
Total Weight, pounds	3.8	0.1
Melting Point, °F	2350	2500
Thermal Conductivity Btu/hr-ft/°F	10.0 at 1150°F	12.4 at 932°F
Linear Expansion Coefficient, 10 ⁻⁶ /°F	8.2 at 70-1600°F	12.8 at 1900°F
Density, lb/in ³	0.323 at 72°F	0.290 at 72°F
Strength-Tensile, psi	121,000 at 72°F	75,000 at 72°F
Strength-Yield, psi	81,000 at 72°F	30,000 at 72°F
Closure Method	Weld (electron beam)	Weld (TIG)
Minimum Weld Penetration, inch	0.205	0.020
Shear Strength, psi	30,000	Not applicable

problems exist where the exterior of the fuel capsule interfaces with the insulation system inner liner (Hastelloy-X) and the shield plug enclosure (stainless steel).

Testing

Inspection of the final electron beam closure weld must be a remote operation because of the nuclear radiation. The weld is inspected by two non-destructive test techniques:

- a) Ultrasonic inspection, and
- b) Immersion leak test.'

These tests verify that the minimum weld penetration of 0.205 inch has been achieved and that the weld is sound with a leak rate less than 10^{-5} STD cc/sec of air.

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.

A summary of the heat source characteristics is as follows:

Size:	3.20 inches diameter, 3.34 inches long
Weight:	6 lbs (including fuel)
Heat Available:	209 watts minimum at BOL
Fuel:	Sr-90 (SrTiO_3)
Fuel Form:	Pressed pellet of SrTiO_3
Maximum Fuel Capsule Temperature:	~1600°F

2.2.2 Biological Shield and Plug

The function of the shield is to attenuate the Bremsstrahlung radiation generated by the fuel decay. It accomplishes this by completely surrounding the fuel with 2.6 inches of an alloy of uranium plus 8 percent molybdenum. The shield (with plug) weighs 265 pounds.

The shield is made in two parts. The body is the larger portion and the plug is the smaller portion. Reference to Figure 1-1 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 is encapsulated in a hermetically-sealed enclosure to prevent oxidation. One end of this enclosure is the thermal radiation disk which radiates the thermal energy from the fuel across an air gap to the hot frame of the thermoelectric generator. The shield temperature varies from 1300 to 1450°F during system operation and shipment at BOL. The shield assembly and shield plug are shown in Figures 2-2 and 2-3, respectively.

Materials and Material Compatibility

The shield material, uranium plus 8 percent molybdenum, was 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 stable after temperature cycling and is isotropic.

Figure 2-2. Biological Shield with Support Components Assembled

Figure 2-3. Shield Plug Assembly

The shield alloy is considered a reactive metal and has a melting point of approximately 2190°F. If exposed to oxidizing agents the shield will be rapidly attacked; exposure of the shield to air at temperatures of above 500°F will also cause rapid oxidation. The oxide (U_3O_8) formed is nonadherent and at 800°F in free air the oxidation proceeds initially on massive uranium metal at a rate of 0.080 inch per hour. In addition, the alloy forms eutectics with Group VIII metals (iron 1325°F, nickel 1375°F, chromium 1400°F). The mechanical and physical properties of the shield material are presented in Table 2-4.

Table 2-4. Mechanical and Physical Properties of Uranium-8 Percent Molybdenum

Property	Ambient Temperature	800°C
Tensile Strength	120,000 - 145,000 psi	9100 psi
Yield Strength	115,000 - 140,000 psi	--
Elongation	8 - 15 percent	69 percent
Reduction in Area	20 - 50 percent	--
Modulus of Elasticity	12×10^6 psi	5.6×10^6 psi
Impact Strength (Charpy)	4-8 at -40°F	--
Hardness (Rockwell)	C-28	32 DP
Electrical Resistivity	70 microhms - cm	--
Density	0.629 lbs/cu in	--
Coefficient of Thermal Conductivity	8.23 Btu/hr-ft ² /°F	--

The thermal expansion coefficients, as given by the Handbook of Thermophysical Properties of Solid Materials, are (refer to Figure 20):

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

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

The shield and plug operate at temperatures as high as 1460°F, which is high enough to form a lower melting point eutectic alloy with the Group VIII metals.

Since these metals are present in the high temperature alloys that make up the shield support system and the shield plug enclosure, some measures must be taken to prevent eutectic formation at the interfaces of these components.

The method used to prevent this eutectic formation is to separate the components with a material that is compatible with both the U-8 w/o Mo and the Group VIII metals.

The compatibility barrier that is used between the shield and the inner liner and spider is aluminum oxide, Al_2O_3 . The Al_2O_3 is plasma sprayed on the contact surfaces of the inner liner and spider and then ground to final dimensions. Minimum thickness of the coating is 0.008 inches. The compatibility barrier between the U-8 w/o Mo shield plug and its 347 stainless steel enclosure is provided by 0.01-inch thick sheets of tantalum.

Safety and Hazard

The shield and plug are the components that provide personnel safety from nuclear radiation so that it is safe to assemble, handle and transport the system.

The shield thickness has been sized to provide this protection; however, the following conditions must be maintained in order to insure its effectiveness:

1. The shield plug must be securely attached to the shield body after the fuel capsule is inserted. This attachment is accomplished with six high temperature stainless steel bolts that attach the radiation disk portion of the shield plug enclosure to the inner liner. The inner liner is in turn bolted to the shield (see Figure 2-2).
2. The shield material, U-8 w/o Mo, must be protected from air at its operating temperature to prevent oxidation. The shield body is protected from oxidation because it is enclosed in the vacuum enclosure of the insulation system. The shield plug is protected by hermetically sealing it in a welded stainless steel enclosure.
3. The U-8 w/o Mo shielding material must be physically isolated from any of the Group VIII metals (or their alloys) to prevent eutectic

formations at operating temperature. This isolation is provided by separating the shield from the support system components by a layer of aluminum oxide plasma sprayed on the support system components, inner liner and spider. The shield plug is separated from its stainless steel enclosure by thin sheets of tantalum.

It should also be noted that the U-8 w/o Mo shield material, and its oxide, are toxic if ingested or inhaled. Care must therefore be taken to prevent any ingestion or inhalation of dust, filings, machining chips, etc., when handling these components during fabrication and assembly. A flash coat of copper is electrolytically deposited on these components after the final machining operation as a personnel safety measure during component handling.

Testing

During the SNAP-21 development program, tests were conducted to demonstrate that the shield is capable of providing personnel protection from nuclear radiation under normal operating conditions. The development tests that demonstrated shield integrity consisted of the following:

- A total of four systems were fueled and assembled. Radiation measurements on these systems confirmed the design calculations and demonstrated that the radiation level was within the specified dose rate. (See Design Requirements in following paragraph.)
- The integrity of the attachment joint between the shield plug and the shield was demonstrated during the shock and vibration testing of four fueled systems. These tests were conducted at operating temperature at the maximum dynamic levels required by the technical specification.
- The effectiveness of the aluminum oxide compatibility barrier to prevent eutectic formations between the shield and the support system components has been demonstrated by the assembly of 12 insulation systems. Four of these systems were disassembled following thermal processing at elevated temperatures up to 1550°F and thermal testing at normal operating temperatures. The Al_2O_3 coating was intact in all four disassembled systems and there was no evidence of degradation.
- The ability of the hermetic enclosures to provide an air tight environment for the shield and plug has been demonstrated by the assembly of 12 insulation systems and five plug assemblies. Since the shield is located inside the vacuum envelope of the

insulation system, it is adequately protected from oxidation. If this vacuum envelope is breached, the thermal impedance of the insulation system is decreased so drastically that the shield temperature will quickly drop below 800°F and oxidation will not be a problem. The plug is enclosed in a welded stainless steel enclosure. The weld joints are leak tested by immersion in a liquid. One plug was disassembled following a test in a fueled system. There was no evidence of leakage or plug oxidation.

Design Requirements

The design requirements of the shield and plug are as follows:

- Nuclear Radiation Shielding – The shield and plug assembly must reduce the radiation dose rate from a 32,000 curie SrTiO₃ fuel source to the following levels:

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

- Size – The shield-plug assembly shall have the following maximum external dimensions:

Diameter	8.8 inches
Length	9.0 inches

- Weight – The shield and plug assembly shall not be greater than 275 pounds.
- Interface Requirements – The shield interfaces with two components of the shield support system, the inner liner and support spider. The interface between these components requires very close dimensional control. In order to insure that the shield dimensions at operating temperature can be accurately predicted, the shield must be in the gamma stabilized condition when machined.
- Vacuum Stability – The shield must be capable of operating continuously for five years in a hard vacuum at temperatures up to 1450°F without outgassing.
- The shield plug enclosure must provide a circular, high emissivity surface to serve as a heat source for the thermoelectric generator.

A summary of the shield characteristics is as follows:

Size	8.75 inches diameter x 8.96 inches long
Minimum Shield Thickness	2.6 inches

Weight (Shield with Plug)	265 pounds
Material	U-8 w/o Mo Alloy
Measured Radiation Level	
Surface of System	<200 mr/hr
One Meter from Surface of System	< 10 mr/hr

2.2.3 Insulation System

The HTVIS (high temperature vacuum insulation system) is one of the major components in the SNAP-21 System. A sectional view of the HTVIS with all components and materials identified is shown in Figure 2-4.

Functional and performance requirements of the HTVIS are as follows:

- It must provide structural support for the directly shielded 32,000 curie Sr-90 fuel source. The shield-fuel source assembly weighs 280 pounds and operates continuously at approximately 1300°F with temperature excursions up to 1450°F. Dynamic loads that the system must withstand are 6g shock in 0.006 second, and vibration in accordance with MIL-STD-810A, except that the maximum g level is limited to 3g.
- The extraneous heat losses from the shielded fuel source must be minimized, except in the area where heat is transferred from the shield to the thermoelectric generator. To meet the overall efficiency requirements of the SNAP-21 system, the HTVIS thermal efficiency must be 75-80 percent.
- The insulation system must be compact and lightweight, with a maximum allowable insulation thickness of 1.5 inches and a maximum weight of 60 pounds, excluding the shield assembly.
- The system must operate unattended in an air environment for a minimum of five years.

Functional Description

The major components of the HTVIS are an inner liner, spider, three tension tie-rods, multilayer thermal insulation, and an outer enclosure. The biological shield which becomes a part of the insulation system, has been described in the previous paragraph.

Figure 2-4. SNAP-21 High Temperature Vacuum Insulation System

The required low overall thermal conductivity is achieved by the use of a high-vacuum multilayer insulation developed by the Linde Division of Union Carbide Corporation and commonly referred to as "Super Insulation". The insulation system consists of many layers of thin metal foil wrapped around the shield. Each foil is separated by a layer of quartz or glass cloth. The metal foils act as thermal radiation barriers and the glass and quartz separators minimize thermal conduction. The entire system is evacuated to a pressure less than 10 microns and then sealed off. The vacuum is maintained by means of a gettering system which chemically combines with or otherwise physically adsorbs any gasses which are generated by offgassing. The vacuum prevents shunt heat loss due to gas conduction.

When used in the SNAP-21 System, the encapsulated isotope fuel source is placed in the small diameter cavity in the inner liner and retained in place by an encapsulated plug of U-8 w/o Mo which is bolted to the inner liner and becomes part of the biological shield. The top of this plug is in close proximity to a heat collector on the thermoelectric generator. Thus, the heat from the isotope heats the entire biological shield and is then transferred from the plug portion of the shield to the thermoelectric generator.

Materials of Construction

The material selected for each component in the HTVIS was based on the applicability of its properties to its specific requirements. A brief summary of the rationale for each material in the shield support system is shown below.

- Biological Shield – Uranium-8 weight-percent molybdenum (U-8 w/o Mo) was selected on the basis of fabricability and efficiency (from the standpoint of both size and weight) for attenuating the nuclear radiation. It is susceptible, however, to formation of a eutectic alloy with some of the Group VIII metals (notably iron and nickel) at the operating temperature. Since the high temperature alloys best suited for the support system contain both of these metals, a compatibility barrier must be provided between them to prevent the eutectic formation. The barrier used is aluminum oxide (Al_2O_3) plasma sprayed on the contacting components (inner liner and spider). See Figure 2-4. (Note: A more detailed description of the shield is presented in paragraph 2.2.2.)
- Inner Liner – Hastelloy-X was selected for this application because of a combination of: its excellent resistance to oxidation at operating temperatures; a coefficient of thermal expansion that is slightly

greater than that of the U-8 w/o Mo shield material; good high temperature mechanical properties; and excellent welding characteristics.

- Shield Support Spider – Hastelloy-X was selected for this application also, primarily because of its coefficient of expansion and good high temperature mechanical properties.
- Thermal Radiation Barriers (Foil) – The metal foils used in the high temperature zone (1450°F to 900°F) are copper. The remaining foils are aluminum. The metal selection is based on vapor pressure and thermal radiation properties. The spacers used between foils are quartz in the high temperature zone and glass in the remainder.
- Tension Tie-Rod - Male Portion – Inconel 625 was selected for the hot end of the tie-rod because of a combination of good high temperature strength and creep properties and low thermal conductivity.
- Tension Tie-Rod - Female Portion – Inconel 718 was selected because of its high strength at temperatures up to 1200°F and its low thermal conductivity.
- Outer Enclosure – The outer enclosure is made from 304 stainless steel. It serves as a vacuum enclosure and is structurally massive in comparison to the primary shield support system.

Shield Support System

The shield is supported within the outer enclosure by the thin cylindrical neck tube at one end and by three tension tie-rods at the other end.

The thin cylindrical neck tube (0.012-0.013 inch thick) is the critical member in the support structure, since it has the lowest factor of safety. The mode of failure of the neck tube is shear buckling. Failure by buckling can occur at stresses below the yield stress; consequently, it is necessary to support the shield at both ends to keep the shield deflection to a minimum under dynamic loads, since it is excessive deflection that will cause buckling of the neck tube. The tie-rods provide this support at the other end of the shield. As shown in Figure 2-4, the tie-rods are located at an angle with respect to the shield center line. This angle has been selected so that the thermal expansion of the neck tube-shield-spider assembly is equal to the tie-rod expansion. This is necessary to prevent overstressing or looseness of the tie-rod in the hot operating condition.

When the shield undergoes the temperature change from room temperature to operating temperature, the spider end of the shield moves with respect to the

outer enclosure. Since the tension tie-rods are connected to both the spider and the enclosure, some means of allowing this movement without binding or bending must be provided. This freedom of movement is provided by a ball-and-socket joint at each end of the rod. The joints are lubricated by burnishing with molybdenum disulfide to prevent sticking or welding in the high temperature – high vacuum environment.

In the course of its normal life cycle, the HTVIS will be subjected to dynamic loads at two temperature conditions: cold (ambient) during handling and shipment of the HTVIS as a separate component, and hot (operating temperature) when it is part of an operating system. As mentioned previously, the primary failure mode is buckling of the neck tube caused by deflection of the shield. It is obvious, then, that the shield support system must prevent excessive deflection in both the hot and cold conditions. Simply stated, this means that all components in the support system must be "tight" at both temperature conditions. To provide a tight system in both the hot and cold conditions, it was necessary to devise a shield support system that would allow the necessary clearances between mating parts to permit easy assembly and to compensate for the difference in thermal expansion between components of different materials. Some complicating factors in the design of this system were:

- The U-8 w/o Mo alloy loses much of its tensile strength at operating temperature and, therefore, cannot be used in a tensile application at high temperature because of excessive creep,
- Penetrations into the shield must be filled with U-8 w/o Mo or kept to a bare minimum to prevent radiation streaming,
- The problem of eutectic alloy formations with Group VIII metals, and
- The high coefficient of thermal expansion of U-8 w/o Mo compared to that of the common refractories which are compatible with it (molybdenum or tungsten).

The shield support system devised to meet these requirements utilizes the differences in thermal expansion of Hastelloy-X and U-8 w/o Mo, plus another material (molybdenum) which has a coefficient of thermal expansion approximately a third of that of U-8 w/o Mo and is compatible with it. By the proper combination of these materials, it is possible to provide a tight system in both the hot and cold conditions.

The method used to support the biological shield is shown in detail in Figure 2-4 and in a more descriptive manner in Figure 2-5. The key fit diameters and bearing surfaces identified in Figure 2-5 are defined as follows:

- Diameter "A" — Interface diameter between shield and inner liner.
- Surface "A" — Bearing surface between shield and inner liner.
- Diameter "B" — Interface diameter between shield and spider.
- Surface "B" — Bearing surface between shield and spider.

As shown in Figure 2-6, the method of support is different in the hot and cold conditions. In the cold condition, the shield support bolts and spider support bolt are torqued to a specified value which results in a compressive load at surfaces A and B. This creates a radial friction force which prevents radial movement of the shield with respect to the neck tube and support spider. In this condition, there is clearance at diameters A and B. Thus, in the cold condition, the shield is supported axially by the shield support bolts and the three tension tie-rods and positioned radially by friction at surfaces A and B.

The clearances at diameters A and B and the thickness of the molybdenum expansion washers under the shield and spider support bolts are such that there will be an interference fit at diameters A and B and the bolts will be loose when the shield temperature is increased to its operating temperature. Thus, the shield will be positioned radially by the diametral interference and will be supported in the axial direction by the combined axial friction force at diameter A and the tension tie-rods. The tabulation in Figure 2-5 summarizes the hot and cold condition of the support. The problem of high creep rates in the U-8 w/o Mo bolts at operating temperature is eliminated in this concept, since the low coefficient of expansion of the molybdenum expansion washers prevents tensile loads at elevated temperature. The molybdenum expansion washer also serves as a compatibility barrier between the U-8 w/o Mo bolts and the inner liner or spider.

Design Requirements and Performance Data

Design requirements of the HTVIS are contained in 3M Company Specification No. 3M-37-IPL-33 dated 23 February 1967, "Technical Specification For a High

Condition of Component or Interface	Shield Temperature	
	Cold	Hot
Shield Support Bolts	Tension due to assembly torque	Loose due to difference in expansion of bolt and washer
Surface A	Compression due to support bolt tension creates radial friction force	Loose
Diameter A	Clearance	Interference creating an axial friction force
Spider Support Bolt	Tension due to assembly torque	Loose due to difference in expansion of bolt and washer
Surface B	Compression due to support bolt tension creates radial friction force	Loose
Diameter B	Clearance	Interference

Figure 2-5. Functional Description of 10-Watt Shield Support System

NOTES

Temperature Vacuum Insulation System – Model A". A summary of the technical requirements contained in this specification are presented below.

1. The insulation envelope shall meet the physical interface requirements as designated by 3M Company drawing PD-37-1349B, Figure 2-6.
2. The system shall be designed to have minimum weight consistent with satisfactory performance but shall not exceed 60 pounds.
(Does not include the biological shield and spider.)
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 45 watts when the system is operating in the following thermal gradient:

Emitter Plate Temperature	1285°F
Support Spider Temperature	1435°F
Outer Enclosure Temperature	50°F

5. The system shall withstand without performance degradation or change in 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 3g 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 6g's and the nominal duration shall be 6 ms.

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.
10. Each system fabricated to the same design configuration shall be interchangeable with all others built to the same design configuration.
11. The system shall be capable of withstanding a continuous radiation level of 500 mr/hr.

A summary of the insulation system characteristics is as follows:

● Envelope Configuration	— Meets requirements shown in Figure 2-6
● Weight (excluding Shield and Spider)	— 60 pounds
● Heat Leak	— 52 watts (t)*
● Dynamic Capability	— Meets vibration and shock requirements of 3M-37-IPL-33 as demonstrated by 4 development tests.

2.2.4 Thermoelectric Generator

The thermoelectric generator converts the heat supplied by the heat source into electricity. Reference to Figure 1-1 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

*Average heat leak of six systems of the final configuration.

generator hot frame from the thermal radiation disk. The hot frame of the generator does not come in contact with the radiation disk, 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 180 to 200°F. Powdered thermal insulation is packed in the annular space between the generator outer case and the neck tube of the insulation system.

Functional Description

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 2-7 is a picture of the components which make up the generator enclosure (hot frame, cold frame, and two-piece outer case). Figure 2-8 is a cross-sectional illustrative drawing of the thermoelectric generator. Figure 2-9 shows the calculated temperature profile of a thermoelectric generator at BOL operating conditions. A summary of the thermoelectric generator characteristics is shown in Table 2-5.

Figure 2-7. Generator Hot Frame, Case and Cold Frame

Figure 2-8. 10-Watt Thermoelectric Generator

Figure 2-9. Typical Thermoelectric Generator BOL Operating Temperature Profile (Calculated)

Table 2-5. Thermoelectric Generator Characteristics

• Design Life	5 years
• Weight	18.8 pounds
• Diameter	7.9 and 4.3 inches
• Volume	89.3 in ³
• Electrical Output	13.4 watts BOL 11.4 watts EOL
• Generator Efficiency	8.3 percent BOL 8.2 percent EOL
• Generator Load Voltage	4.73
• Number of Thermoelectric Couples	48
• Heat Input (BOL)	161 watts
• Couple Hot Junction Temperature (BOL)	1000°F avg.
• Couple Cold Junction Temperature (BOL)	90°F avg.
• Hot Junction Electrical Contact	150 psi pressure contact
• Cold Junction Electrical Contact	Bonded

Figure 2-8 shows the location of components in the generator and their general size and shape. Figure 2-10 is a drawing which shows the thermoelectric couples and their related hardware. The generator components are:

Cold Frame – The cold frame is made from copper and forms the main structural component of the generator. One side is drilled with holes to receive the followers while the other side has a mounting flange for supporting the generator in the system. Reject heat from the thermoelectric legs flows from the followers through the cold frame to the generator mounting plate which is part of the segmented retaining ring.

Outer Case – The outer case is made from 347 stainless steel. It serves as part of the generator enclosure and as a load carrying member to support the hot frame assembly and to resist the spring force of the

Figure 2-10. Thermoelectric Couple Isometric

thermoelectric legs. Since the outer case connects the hot frame directly to the cold frame, it is a direct path for shunt heat losses. It must be made as thin as possible to minimize the shunt heat losses. The thickness of the outer case is 0.006-0.007 inch. This thickness is governed by the stress rupture strength of the material.

Hot Frame – The hot frame is a flat circular disk made from 347 stainless steel. It serves as a heat accumulator to receive heat from the radiation disk on the biological shield. It has sufficient structural strength to resist deformation from the force of the thermoelectric leg compression springs. The surface of the hot frame that faces the heat source is specially treated to increase its absorptivity, thereby improving its heat transfer capability.

Hot Side Electrical Insulator – This component is a flat disk of boron nitride that electrically isolates the hot junctions of the thermoelectric couples from the hot frame. Boron nitride is used because it has good thermal conductivity and is a good electrical insulator. The insulator also has shallow recesses on one side to receive the hot junction electrodes and therefore maintains alignment of the hot end of the thermoelectric legs.

N-Type Leg – This is one of the two types of thermoelectric legs used in the generator which convert 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.

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.

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.

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. No heat flows through this part. The cold junction electrode is made of copper wire and is soldered to the cold caps.

Hot Junction Button – This 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 considered as the thermoelectric leg hot junction temperature and averages 1000°F at BOL. It is made from low-carbon steel.

Hot Junction Electrode – This part forms the electrical circuit between the hot junction button of P and N legs from adjacent thermoelectric couples. 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. Each hot junction electrode is positioned in a recess in the hot side electrical insulator.

Follower – The followers fit into holes in 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 by a compression spring between the follower and the cold frame. The force results in a compressive stress of 150 psi in each thermoelectric leg. One follower is required for each thermoelectric

leg, a total of 96 per generator. The follower is made from beryllium oxide. This material provides positive electrical insulation between the thermopile and the cold frame and its thermal conductivity is as good as aluminum.

Compression Spring – The compression springs are located between the follower and the bottom of the follower hole in the cold frame. They exert a compressive force on the followers which is transmitted to the thermoelectric legs. This force results in a contact pressure of 150 psi at the hot end of the thermoelectric legs. This contact pressure is required to achieve good thermal and electrical contact at the hot junction. One spring is required for each thermoelectric leg, or a total of 96. The springs are made from 302 stainless steel.

Cold Frame – The cold frame is the primary structural component of the thermoelectric generator. It contains holes for the followers and forms the heat transfer path for the heat rejected from the thermopile to the generator mounting plate. It is made from copper to achieve maximum thermal conductivity.

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, since it is a path for direct shunt heat loss, its thickness is kept to the minimum required for structural integrity (0.006 to 0.007 inch).

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.

Electrical Feedthroughs – Special fittings are used to bring electrical leads through the generator enclosure. A total of three leads are required, a positive and negative lead from the thermopile and a bias voltage tap from the thermopile which is required for operation of the dc-dc power conditioner. The headers consist of a ceramic

cylinder with a KOVAR tube passing through the center. The tube is bonded to the ceramic cylinder by a ceramic-to-metal sealing process and the copper conductor is in turn brazed to the KOVAR tube. The header is sealed in the cold frame with a solder joint. A cross-section view of a header is shown in Figure 2-11.

Unique Design Requirements

During the design and development of the thermoelectric generator, a number of unique requirements had to be considered. These requirements had a significant influence on the final configuration of the generator.

A summary of the primary requirements are listed below:

1. The system design life of five years requires that the thermoelectric materials used in the generator be very stable with regard to thermoelectric degradation. To meet this requirement only materials with proven compatibility and stability were employed. This includes not only the thermoelectric elements but all materials in contact with them and the methods of mounting and thermal and electrical contacting.
2. The thermoelectric generator must be designed to provide maximum efficiency at EOL (end-of-life) when the heat input from the radioisotope fuel is at a minimum. From an efficiency standpoint, it is advantageous to operate the thermoelectric legs at as high a hot end temperature as possible; however, the design temperature must be selected such that the legs are not overheated at BOL (beginning-of-life) when the heat input is approximately 12 percent greater. A further consideration in establishing the hot end operating temperature is that the temperature increase due to system shipment in an air environment at BOL must be within acceptable limits. The hot junction temperature limit established for this extreme condition is 1100°F.
3. A basic requirement for long-term stability of the thermoelectric elements is that they must be maintained in a protective gaseous atmosphere. This atmosphere is provided by backfilling the generator during assembly. In

Figure 2-11. Electrical Feedthrough Header

order to maintain this atmosphere, the generator enclosure must be hermetically sealed. These seals are provided by metal-to-metal and ceramic-to-metal seals at the various enclosure joints.

4. In order to obtain maximum thermoelectric efficiency, the thermal impedance through the thermoelectric legs must be kept to a minimum. This requirement is usually not compatible with the additional requirements of electrical isolation of the thermoelectric legs from the generator enclosure and flexibility in the leg mounting system. In order to obtain a solution that is compatible with all of these requirements, a unique combination of materials and mounting method must be used.
5. The design of the generator outer case must be a compromise between structural integrity and minimized shunt heat leak. Structurally it must be stiff enough to withstand dynamic loads with a minimum of deflection and have adequate high temperature strength to prevent failure due to creep rupture. From a thermal loss standpoint, it must be kept as thin as possible to minimize shunt heat loss from the hot frame to the cold frame.

Thermopile Design Summary

A summary of the thermopile design is shown in Table 2-6 while design details of each thermoelectric leg are shown in Table 2-7. Note that emphasis is placed on performance values at EOL since this is the design point for the generator.

The thermoelectric design parameters that were used to design the thermopile are presented in Appendix D. Complete information on the generator design and analysis can be found in Report No. MMM 3691-34, "Thermoelectric Generator Performance Evaluation and Design Description".

Table 2-6. SNAP-21 10-Watt Generator Thermopile Design Summary

Number of Couples	48
Type of Circuit	Series
Hot Junction	Pressure Contact, 150 psi
Cold Junction	Bonded
Load Voltage at Maximum Efficiency, vdc (EOL)	4.73
Current at Maximum Efficiency (EOL), amps	2.41
Power at Maximum Efficiency, P_o (EOL), watts (e)	11.4
Heat Absorbed by Legs, Q_l (EOL), watts (t)	119.4
Open Circuit Voltage at EOL, vdc	7.99
Circuit Resistance at EOL, ohms	1.35
Thermoelectric Efficiency at EOL, $\frac{P_o}{Q_l} \times 100\%$	9.55
Shunt Heat Loss at EOL, Q_s , watts (t)	20.0
Generator Efficiency at EOL, $\frac{P_o}{Q_l + Q_s} \times 100\%$	8.2 percent

Table 2-7. SNAP-21 10-Watt Generator Thermoelectric Leg Design Summary

Thermoelectric Material:	Hot Segment	PbSnTe (ES-1110 with "Soft Nose" ES-1111)	PbTe (ES-1103)
	Cold Segment	BiSbTe (ES-1116)	PbTe (ES-1104)
Fabrication Method:		Hot segment pressed and sintered. Cold segment pressed and sinter-bonded to hot segment.	Both segments separately pressed, then sinter-bonded to form.
Hot Segment Length, inch		0.326	0.329
Cold Segment Length, inch		0.187	0.184
Total Leg Length, inch		0.513	0.513
Diameter, inch		0.188	0.188
Length to Area Ratio L/A, inch		18.48	18.48
Hot Junction Temperature, °F EOL		900	900
BOL		1005	1005
Max. (during shipment) (a)		1020	1020
Cold Junction Temperature, °F EOL		105	105
BOL		115	115
Max. (during shipment) (a)		204	204
Segment Temperature, °F EOL		404	402
BOL		454	452
Max. (during shipment) (a)		560	560
*Open Circuit Voltage, mv		73.9	93.0
*Load Voltage, mv		43.8	54.7
*Average Resistivity, $\mu\Omega$ -inch		783	757
*Current, amps		2.41	2.41
*Power, watts (e)		0.091	0.150
*Rate of Heat Absorption, watts (t)		1.08	1.37
*Rate of Heat Rejection, watts (t)		0.99	1.22
*Thermoelectric Material Efficiency, %		8.44	10.92

(a) Short Circuit Condition.

*These parameters apply to maximum efficiency conditions at EOL.

Design Requirements and Performance Data

The design requirements of the thermoelectric generator are as follows:

- Design Life 5 years
- Minimum Power Output (EOL) 11.4 watts
- Load Voltage (EOL) 4.73 vdc
- Bias Voltage Tap (EOL) 0.7 vdc
- Hot Junction Temperature
 - BOL Maximum 1100°F
 - Operating 1000°F
 - EOL Maximum 1100°F
 - Operating 900°F
- Cold Junction Temperature
 - BOL Maximum 225°F
 - Operating 115°F
 - EOL Maximum 225°F
 - Operating 105°F
- Physical Configuration Compatible with SNAP-21 System (see Figure 1-1).
- Dynamic Capability - Must be capable of withstanding same shock and vibration environment as system - see Section 1.3.
- Overall Efficiency (EOL) 7.79 percent minimum

The actual performance of each generator is checked by subjecting it to an ingradient acceptance test. This test consists of testing the generator in a temperature gradient that simulates the EOL conditions. The power output of the generator is then measured and compared to the theoretical power it should produce for the actual test temperatures. The comparison is made as a ratio of the experimental power divided by the theoretical (calculated) power. The minimum acceptable value of this ratio, $\frac{P_x}{P_c}$, is 0.95.

A summary of the acceptance test data for four (4) generators of the final design is shown in Table 2-8.

Table 2-8. Acceptance Test Results: SNAP-21 Thermoelectric Generators

Parameter	A10P2	A10P3	A10P4	A10P5	Design Values
Hot Junction Temperature, T_h (°F)	904	897	897	900	900
Cold Junction Temperature, T_c (°F)	106	104	105	105	105
Open Circuit Voltage, E_o (vdc)	8.26	8.16	8.17	8.15	7.99
Load Voltage, V_L (vdc)	4.73	4.73	4.73	4.73	4.73
Thermopile Resistance, R_1 (ohms)	1.44	1.41	1.45	1.43	1.35
Power Output, P_o (watts)	11.54	11.49	11.18	11.35	11.4
Power Output Ratio, P_x/P_c	1.02	1.02	0.99	0.993	*
*Design requirements for P_x/P_c ratio is a minimum of 0.95.					

2.2.5 Segmented Retaining Ring

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

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 2-12 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

Figure 2-12. Segmented Retaining Ring

not restrict pressure vessel deflection and isolates the insulation envelope outer shell from hydrostatic forces.

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 640 lbs/in per spring, and under design conditions the spring force is 250 lbs/spring. Material compatibility is not considered to be a problem at the operating temperatures and environment.

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 so that there is no relative motion between the insulation system and pressure vessel when the system is subjected to the dynamic environment specified in 1.3.

The performance of the segmented retaining ring has been verified by a separate component dynamic test in which a segmented retaining ring was tested in a pressure vessel with a dummy insulation system and in the dynamic testing of six (6) actual SNAP-21 systems. On all of these tests, there was no evidence of insulation system movement within the pressure vessel and the temperature drop across the ring has been less than 15°F.

2.2.6 Power Conditioner

Figure 1-1 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 boss. 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 4.73 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. This excess power is dissipated as heat which is conducted to the pressure vessel cover through the attachment ring.

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 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 4.73 vdc output load voltage of the thermoelectric generator to 24 vdc. 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 2-13. Note that an auxiliary bias voltage tap from the thermopile is used in the circuit. This tap is used to provide a starting and operating bias.

The electrical circuits are designed to operate for five years in the system at ambient temperatures of $70 \pm 10^\circ\text{F}$. They also perform this power conditioning function at a minimum of 88 percent efficiency at EOL conditions.

The electrical circuits are enclosed in an aluminum enclosure in the form of a right circular cylinder. The enclosure is hermetically sealed by welding. Prior to final closure the interior of the power conditioner is filled with a flexible silicone foam. The foam serves as a watertight cushion around the circuit components and it will prevent movement of any loose particles which could cause shorting. A sectioned view of the power conditioner assembly is shown in Figure 2-14.

Design Requirements and Performance Data

The design requirements of the power conditioner are summarized below:

●	Design Life		5 years
●	Voltage Requirements	Input	4.73 vdc
		Output	24.0 vdc
		Bias (optional)	0.7 vdc
●	Output Voltage Regulation
(when load is varied from 57.6Ω to ∞)		24 ± 1 vdc

3. REFERENCE DRAWINGS - PD 37 4217 ASSEMBLY BASE PLATE POWER CONDITIONER
PD-37-4218 POWER CONDITIONER ASSEMBLY
2. RESISTOR, R12 SELECTED AT ASSEMBLY FOR 24.5 VOLTS AT 0.4 AMP OUTPUT
1. NUMBERS APPEARING ON THE ELEMENTARY DIAGRAM INDICATE POINTS AT COMMON
POTENTIAL NUMBERS WITHIN CIRCLES INDICATE COMPONENT TERMINAL IDENTIFICATIONS
- NOTES

DEVICE DESIGN	3M DWG NUMBER	MANUFACTURER		APPLICABLE MILITARY SPEC.	
		NAME	NUMBER	MIL SPEC NO	MIL DESIGNATION
Q1 Q2	20 2017	BENDIX CORP	JAN 2N1653	MIL S 19800/219A	
Q3 Q4	20 2065	SOLITEON DEVICES	ES 291(SDT 1872)		
Q11	20 2021	FAIRCHILD SEMI CONDUCTORS	2N 2484		
Q2	20 2019	MOTOROLA	JAN 2N2907A	MIL S 19500/251A	
Q13	20 2020	SOLITEON DEVICES	2N 2695 (SDT 4599)		
Q14	20 2016	SOLITEON DEVICES	2N 2914 (SDT 1156)		
VR1	20 2022	FAIRCHILD SEMI CONDUCTORS	USN 1N753A	MIL S 19500/127D	
VR2, VR3	20 2023	FAIRCHILD SEMI CONDUCTORS	1N4611A (MCR 2222)		
R1	20 2009P6	DALE ELECT INC	ABH 10 10W 6.81Ω	MIL R 39009	RER 65F6251P
R3	20 2009P5	DALE ELECT INC	ABH 10 10W 5.0Ω	MIL R 39009	RER 65F3800P
R20	20 2009P7	DALE ELECT INC	ABH 50 50W 30.9Ω	MIL R 39009	RER 75F30R9S
R1	20 2010P1	IRC INC	GEM 60 1/8W 14.5Ω	MIL R 55182	RNR 60E1432FP
R12	20-2010P2	IRC INC	GEM 60 1/8W 39.2K TO 130.3K	MIL R 55182	RNR 60E3925FP
R13	20 2008P4	DALE ELECT INC	ABH 2 3090Ω 2W	MIL R 39007A	RWR 71G30915FS
R14	20 2008P3	DALE ELECT INC	ABH 3 2220Ω 2.25W	MIL R 39007A	RWR 20G22215FS
R5 R18 R19	20 2008P2	DALE ELECT INC	ABH 3 1500Ω 2.25W	MIL R 39007A	RWR 20G15015FS
R16	20 2008P5	DALE ELECT INC	ABH 2 5110Ω 2W	MIL R 39007A	RWR 71G51115FS
R17	20 2008P1	DALE ELECT INC	ABH 3 511Ω 2.25W	MIL R 39007A	RWR 20G51105FS
C1 C4	20 2015P2	MALLORY CO	T55476K055PD 47μF 35V	MIL-C 39003A	CSR 13F476KP
C5	20 2015P3	MALLORY CO	T55476K055PD 10μF 35V	MIL-C 39003A	CSR 13C276KP
C11	20 2081P1	CORNING ELECT	CYF810101J	MIL-C 25269A	CYR 10C101JR
C12	20 2081P2	CORNING ELECT	CYF820202J	MIL-C 25269A	CYR 20C202JR
C13	20 2082P1	SPRAGUE ELECT	135P045222	MIL-C 14157C	CPV08A1KC104R
T1 L1 L2	E PD-37 355	ADC CORP	3MT MP K XX	MIL T 39015	TFR 5R0322R

Figure 2-13. Elementary Diagram of Power Conditioner

- 5 PERFORM FINAL ACCEPTANCE TEST AS REQUIRED BY ES 1601
- 12 IDENTIFY (AS SHOWN) WITH APPLICABLE REVISION LEVEL PER AM12800A PAR 9.2
- 11 REMOVE WIRE CONNECTIONS TO TERMINAL AND CLEAN TERMINALS OF EXCESS SOLDER ALSO CLEAN EXTERIOR OF CASE
- 10 AFTER WELDING REMOVE TERMINAL TO CASE CONNECTION AND ATTACHMENT RING AGAIN PERFORM THE DIELECTRIC TEST AS SPECIFIED IN NOTE 9
- 9 INITIAL THE LID ASSEMBLY (ITEM 3) ORIENTATED AS SHOWN SHORT THE FIVE ELECTRICAL TERMINALS TOGETHER AND PERFORM A DIELECTRIC TEST IN ACCORDANCE WITH MIL-STD-202C METHOD 301 APPLY 500 VDC ACROSS FIVE SHORTED TERMINALS TO CASE THE LEAKAGE CURRENT SHOULD NOT EXCEED 5 MICROAMPS AFTER THE DIELECTRIC TEST CONNECT THE TERMINALS TO THE CONTAINER BASE BY SOLDERING OR BOLTING PINS AND JUMPERS TO THE TERMINALS AND TO THE POWER CONDITIONER ATTACHMENT USING (FIG. C PD 37 4216) WELD THE LID ASSEMBLY TO THE CONTAINER BY MEANS OF INERT GAS SHIELDED ARC WELDING THE MAXIMUM PERMITTED BASE TEMPERATURE IS 150°F THE MAXIMUM LID TERMINAL TEMPERATURE PERMITTED IS 250°F
- 8 CLEAN MOUNTING SURFACES OF LID ASSEMBLY (ITEM 3) AND CONNECT LEADS FROM ASSEMBLY BASE PLATE (ITEM 4) TO LID ASSEMBLY TERMINALS CUT OUT FOAM AS REQUIRED TO CAPTIVATE LEADS BY COVER USE SOLDER (ITEM 7) AND A SOLDERING IRON WHICH HAS A MEANS OF AUTOMATICALLY CONTROLLING THE TIP TEMPERATURE TO 300±20°F
- 7 AFTER CURING, REMOVE DUMMY LID AND ALLOW FOAM SURFACE TO BE EXPOSED TO AMBIENT AIR FOR 96 HOURS TO ALLOW ENTRAPPED FOAMING GAS TO DIFFUSE
- 6 THOROUGHLY CLEAN INTERIOR OF ASSEMBLY AND PREPARE UNIT FOR INSULATING FOAM (ITEM 8) BY HEATING ASSEMBLY TO 150°F APPLY FOAM (ITEM 8) IN ACCORDANCE WITH MANUFACTURERS INSTRUCTIONS CONFINE FOAM TO DESIRED VOLUME BY DUMMY LID COATED WITH A PARTING AGENT USE DUMMY LID TO HOLD LEADS FROM ASSEMBLY BASE PLATE (ITEM 4) IN PLACE CURE FOAM FOR 3 HOURS AT 150°F.
- 5 ARRANGE LEADS FROM ASSEMBLY BASE PLATE (ITEM 4) FOR MINIMUM LENGTH CONSISTANT WITH CONNECTION TO TERMINALS OF ASSEMBLY LID CONTAINER (ITEM 3).
- 4 REMOVE (A) HOLDING SCREWS OF PRINTED CIRCUIT BOARD ASSEMBLY AND MOVE IT BACK TO PERMIT INSTALLATION OF BASE PLATE SCREWS & WASHERS (ITEMS 8 & 9) TIGHTEN ALL BASE PLATE SCREWS TO 10 LB IN-LBS REINSTALL PRINTED CIRCUIT BOARD ASSEMBLY & REINSTALL HOLDING SCREWS TO 5-6 IN-LBS
- 3 APPLY A THIN FILM OF HEAT SINK COMPOUND (ITEM 5) TO THE MOUNTING SURFACE OF THE ASSY BASE PLATE (ITEM 4)
- 2 THOROUGHLY CLEAN ALL PARTS OF ALL FOREIGN MATTER, ESPECIALLY SMALL METAL PARTICLES & FILINGS INSIDE OF HOLES, BY BLOWING COMPRESSED AIR OR SELECTIVE AREA SOLVENT APPLICATION
- 1 WELD THE CYLINDER (ITEM 2) TO THE BASE (ITEM 1) BY MEANS OF INERT GAS SHIELDED ARC WELDING VERIFY HERMETIC SEAL - MAXIMUM ACTUAL LEAK RATE SHOULD NOT EXCEED 5.2×10^{-6} CC HELIUM PER SEC AT 25±5°C

NOTES:

PART LIST			
QTY	LOC	QTY	DESCRIPTION
1	1	PD-37 4218	ASSY, POWER CONDITIONER
1	1	PD-37 4211	BASE, CONTAINER, POWER CONDITIONER
2	1	PD-37-1212	CYLINDER, CONTAINER, POWER CONDITIONER
3	1	PD-37 4219	ASSY LID, CONTAINER, POWER CONDITIONER
4	1	PD-37 4217	ASSY-BASE PLATE, POWER CONDITIONER
5	A/R	20 2078	HEAT SINK COMPOUND
6	A/R	20 219	ELECTRICAL INSULATING FOAM 3M XR 507
7	A/R	20 2050	SOLDER, 60-40 RESIN CORE
8	6	MS 16990 15	6-32 UNC-2A x 5/8 LB
9	6	MS 35333 71	WASHER LOCK, INTERNAL TOOTH #6
10	1	PD 37 4228	INSULATION DISK, MICA

Figure 2-14. Power Conditioner Assembly

●	Filtering		Output ripple less than 0.1 volt peak-to-peak.
●	Power Input		Varies from 13.4 watts at BOL to 11.4 watts at EOL.
●	Overload Capability		Must be capable of continuous operation with open output circuit and maximum input power.
●	Starting Characteristics		Must be capable of starting under a 40 Ω output load after any combination of output circuit conditions of short or open circuit.
●	Efficiency (EOL)		88 percent minimum at 24.0 volts output.
●	Temperature Extremes	Operating Non-Operating	+50 to +80°F -65 to +150°F
●	Humidity		0 to 100 percent relative humidity
●	Dynamic Environment		Must be capable of withstanding system dynamic environment.
●	Size and Weight		Must be compatible with existing SNAP-21 System - see Figure 1-1. Maximum weight 6 pounds.

A summary of the power conditioner characteristics is shown in Table 2-9. All power conditioners are acceptance tested in accordance with ES-1601. A summary of the performance data for four (4) power conditioners of the final design is shown in Table 2-10.

2.2.7 Pressure Vessel

The primary function of the pressure vessel is to provide a watertight environment for the SNAP-21 System components for five years in sea water with external pressures of up to 10,000 psi. It must also serve as an attachment surface for various internal components and must provide an efficient and stable heat transfer path for heat rejected to the sea water.

Table 2-9. Power Conditioner Characteristics

Characteristic	Value
● Design Life	5 years
● Weight	5.5 pounds
● Length	3.5 inches
● Diameter	6.5 inches
● Efficiency	88 percent (min)
● Output Power	10.1 watts
● Output Voltage at Rated Load	24 ± 1 vdc
● Input Power	13.4 watts (BOL) 11.4 watts (EOL)
● Input Voltage	4.73 vdc 0.7 vdc (bias)
● Operating Temperature	+50 to +80°F
● Enclosure Material	Aluminum
● Hermetic Sealing Method	Welding
● Dynamic Capability	Demonstrated by component and system tests.

Table 2-10. Performance Summary for Prototype Power Conditioners

		H10P1	H10P2	H10P3	H10P4	Acceptance Criteria
Starting Characteristics		20.6 ohm	32.8 ohm	34.9 ohm	33.7 ohm	Must begin to operate with load of 50 ohm/max
Ratio Accuracy	V_{out}	24.00 v	24.00 v	24.00 v	24.00 v	Input voltage shall be 4.73 ± 0.17 v and load voltage be 24.00 ± 0.02 v at rated load (57.6 ohm)
	V_{in}	4.80 v	4.80 v	4.798 v	4.804 v	
	R_{load}	57.2 ohm	58.0 ohm	57.2 ohm	57.4 ohm	
Output Filtering		0.068 v at 1.10 x rated load	0.065 v at 1.10 x rated load	0.060 v at 1.10 x rated load	0.065 v at 1.10 x rated load	Output ripple less than 0.10 v peak-to-peak
Voltage Regulation	V_{open}	24.50 v	24.45 v	24.51 v	24.52 v	Output voltage shall be 24 ± 0.6 v from open circuit to rated load. At open circuit, voltage shall be 24.6 ± 0.1 v
	$V_{rated\ load}$	24.11 v	24.11 v	24.12 v	24.08 v	
Voltage Drift		No drift noted	No drift noted	No drift noted	No drift noted	The drift after rated load to no load shall be 0.1 v from its initial no load over two 1-minute periods
Efficiency		90.66 percent	90.24 percent	90.42 percent	90.10 percent	Efficiency must be greater than 88 percent
Overload		Recovered within one second	Recovered within one second	Recovered within one second	Recovered within one second	Return to normal operation within one second after operating under short circuit

Description of Characteristics

- Material

The pressure vessel is made from Berylco 165 (Cu, 1.8 Be, 0.2 Co) forgings that are heat treated to produce tension yield strengths (0.2 percent offset) of 130 to 160 Ksi. Since the pressure vessel is subjected to external pressure, the compressive properties of the material are required for design. The compressive properties of Berylco 165 were measured and are shown in Figures 2-15 and 2-16.

- Dimensions

There are two pressure vessel configurations; one with a long and one with a short cover. The body is common to both configurations. The overall dimensions of both configurations are shown in Figure 2-17. The dimensions shown are all nominal values.

- Pressures

The values for working, design and proof pressure are as follows:

Working Pressure = 10,000 psi

Design Pressure = 16,500 psi

Proof Pressure = 11,000 psi

The design pressure was established as follows:

Design Pressure = working pressure x 1.5 safety factor + 10 percent factor for variations in materials and heat treatment

The 16,500 psi external pressure was used to determine wall thicknesses such that material yield stress would not be exceeded, and failure by buckling instability would not occur.

- Stress and Safety Factor

The maximum calculated stress at 11,000 psi proof pressure is as follows:

For cylindrical portion 77,850 psi

For hemispheres 91,200 psi

For hemisphere penetration boss through the cover 94,950 psi

Minimum safety factor based on yield strength is, therefore:

$$\frac{140,000}{94,950} = 1.48$$

- Dimensional Change Under Hydrostatic Pressure

The maximum dimensional changes occur at the proof pressure of 11,000 psi. The calculated deflections are as follows:

For the hemispheres in the radial direction 0.022 inch

Figure 2-15. Berylco-165 (AT) Stress vs. Strain in Compression
Minimum Design Properties for SNAP-21 Pressure Vessel

Figure 2-16. Berylco-165 (AT) in Compression. Tangent Modulus and Secant Modulus vs. Stress Level Based on Design Compression Curve

NOTE (1) DIMENSION MAY VARY $\pm 1'$ DEPENDING ON CABLE USED

Figure 2-17. SNAP-21 Pressure Vessel Configurations

For the cylindrical portions
in the radial direction

0.024 inch

For the cylindrical portions
in the longitudinal direction

0.0089 inch

- Sealing Method

The pressure vessel joints (body-to-cover and cover-to-electrical receptacle) are achieved by double O-ring seals. The O-ring material is ethylene propylene which was selected for its excellent stability in a sea water environment.

- Corrosion and Marine Fouling

In order to survive for five years in a sea water environment and to maintain a good heat transfer path, the pressure vessel material must be highly resistant to corrosion and fouling. Berylco 165 has demonstrated that it meets both of these requirements by its successful use as the material for underwater telephone repeater housings that have been in service for well over five years.

- Assembly

Attachment of the pressure vessel cover to the body and the receptacle to the cover is accomplished by bolts made from Berylco 25. The chemical composition of these bolts is virtually identical to Berylco 165; consequently, there will be no galvanic corrosion.

Design Requirements and Performance Data

- Design Life 5 years
- Operating Pressure 0 to 10,000 psi
- Proof Pressure 11,000 psi
- Operating Medium Sea water
- Temperature +28 to +41°F
- Size Must be compatible with SNAP-21 specification - see Appendix B
- Marine Fouling and Corrosion Must have inherent resistance to marine fouling and corrosion
- Leakage No evidence of leakage after 4 hours at 11,000 psi

• Weight (maximum)	Body	185 pounds
	Long Cover	190 pounds
	Short Cover	75 pounds

The ability of the pressure vessel to withstand the working pressure of 10,000 psi has been demonstrated by the proof test of six (6) pressure vessels to the proof test pressure of 11,000 psi. There was no leakage or permanent deformation in any of the vessels.

2.2.8 Electrical Receptacle

The function of the electrical receptacle is to provide a means of bringing electric power and instrumentation leads out of the pressure vessel. The relative size, shape, and location of the receptacle is shown in Figure 1-1. Further details of the receptacle are shown in Figure 2-18.

Description of Characteristics

As shown in Figure 2-18, the electrical receptacle consists of two basic parts, a housing and a pin insert. Some of the features of the design are as follows:

- The housing, which is exposed to the sea water environment, is made from Berylco 165, the same material as the pressure vessel, to preclude any possibility of galvanic corrosion.
- The receptacle-to-pressure vessel interface incorporates a double O-ring seal. This seal is redundant, as is the seal between the pressure vessel cover and body, for maximum reliability.
- The receptacle has 22 electrical pins mounted in a removable insert. This permits replacement of the insert in the event of damage during assembly or test.
- The receptacle design is identical to a proven commercially available design currently in production except for the material. It also mates with a cable connecting plug of proven design.
- The cable connecting plug that mates with the receptacle can be terminated in a standard sheathed cable or a double armored cable without changing its functional design. Thus a standard rubber sheathed cable can be used for test purposes when minimum size and maximum flexibility are required. No further development effort will be necessary to attach an armored cable to the units to be implanted.
- The pin insert is capable of withstanding full hydrostatic proof pressure (11,000 psi); consequently, a leak in the seal between the receptacle and the mating cable connecting plug will not destroy the system.

Figure 2-18. Electrical Receptacle

Design Requirements and Performance Data

Complete design requirements are contained in a procurement specification, 3M-IPP-100, Ref. A. A summary of the basic requirement is presented below:

- Physical:
 - a) Must mate with SNAP-21 pressure vessel cover.
 - b) Must mate with a cable connecting plug of proven design.
 - c) The mating cable connecting plug must have a positive indexing feature.
- Electrical Interface:
 - a) A minimum of twenty-two 16-gauge pins.
 - b) Pins must be fused in a removable pin insert.
 - c) The pins shall have solder cups.
- Weight: 6.5 pounds maximum
- Material: The receptacle housing must be made from the same material as the pressure vessel, Berylco 165 (Berylco 25 is an acceptable alternate because of its chemical similarity).
- Electrical Resistance: Minimum resistance from pin-to-pin or pin-to-housing shall be 2,000 megohms at 300 vdc.
- Seal Integrity: Receptacle-to-pressure vessel and pin insert-to-receptacle must withstand 11,000 psi hydrostatic pressure.

A total of six receptacles have been fabricated and subjected to the 11,000 psi external hydrotest proof pressure with no failures. A summary of the receptacle characteristics is as follows:

- Physical Interface: Mates with SNAP-21 pressure vessel – see Figure 2-19.
- Materials:
 - Receptacle Housing – Berylco 165
 - Pin Insert – Inconel 718
 - Pins – Copper Cored KOVAR – Gold Plated
- Electrical Pins:
 - Number – 22
 - Size – 16 gauge
- Weight: 4.4 pounds

Figure 2-19. Electrical Receptacle Interface Requirements

- Approved Vendor: Marsh and Marine Division of Vector Cable Company
Houston, Texas
- Mating Connector Marsh and Marine Model No. MS (2) 0-22-CCR (Berylco 165)

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 have demonstrated these characteristics.

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 have verified that no controls or 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 of approximately 60°F in the thermoelectric generator and biological shield. This temperature rise does not create any safety hazard.

2. Generator short circuit would decrease generator output but should not have any other adverse effect on system.
3. Open external load circuit will have no effect on internal temperature since the generator output power is dissipated in the power conditioner.
4. Generator case leak would cause generator power output to degrade and cause slight increase in internal system temperature (less than 50°F).
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 by rupture of the thermoelectric generator and the HTVIS. It would cause no hazard because internal temperatures would decrease. 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, based on a safety analysis of the system, these failure modes were considered incredible.

3.0 PRINCIPLES OF ASSEMBLY AND OPERATION

3.1 ASSEMBLY

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

1. The insulation system is mated into the body of the pressure vessel.
2. The mounting plate-support ring is then installed, which positions and locates the insulation system in the pressure vessel body.
3. The fuel capsule is then 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.
4. The shield plug is then installed and 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 (within 2-3 hours), a heat sink must be attached to remove the heat from the system.
5. If used, the temporary heat sink will be removed and the thermoelectric generator installed in the system. With heat being directed from the thermoelectric generator to the generator mounting plate, a heat sink will be required on the mounting plate if there is any unusual delay in the final assembly.

6. Make electrical connections between the thermoelectric generator and the electrical connectors mounted on the generator mounting plate.
7. Attach cover assembly to pressure vessel. The pressure vessel assembly consists of the cover, power conditioner and electrical receptacle all pre-wired to electrical connectors that mate with the connectors on the lower half of the system.

This completes assembly of the system. The system now requires heat sinking to remove rejected heat to maintain a pressure vessel exterior surface temperature of no more than 140°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 serves as the heat sink by using temporary heat transfer fins. Complete instructions for the installation of these fins is contained in the "Shipping and Handling Manual" No. MMM 3691-42.

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 conductances 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

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

The normal system operating temperatures are sea water at a temperature of 28 to 41°F. Maintaining system temperatures within acceptable limits is not a problem when the system is implanted since the sea water is an efficient heat sink.

Heat rejection to the atmosphere during storage and transportation is less efficient than to sea water; consequently, some means must be employed to increase heat transfer efficiency to air. This is accomplished by the heat rejection fins which are attached to the pressure vessel during all shipping and handling operations.

3.3 DISASSEMBLY

The SNAP-21 System can 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 steps of disassembly would be as follows:

1. Remove cable connecting plug from receptacle.
2. Remove pressure vessel cover.
3. Unbolt thermoelectric generator from mounting plate-support ring and remove from system.
4. Install heat sink to shield plug. Cool shield assembly to 300°F or less.

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. A fire resulting in a temperature increase in the system to the extent that the fuel capsule melted and could not contain the fuel.

3. During Storage:

- a. A fire resulting in 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. Follow proper procedures for installing fuel capsule in system.
- b. Follow exposure time restrictions when assembling the system.
- c. Use stringent quality control measures when fabricating the fuel capsule.
- d. Establish and follow procedures that contain adequate safety measures during handling, shipment and storage.

5.0 MAINTENANCE

5.1 PREVENTIVE MAINTENANCE

The system is a completely-enclosed, self-contained device. Its operation is completely 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 TROUBLESHOOTING

If the system is in-service powering an underwater device, the first indication of trouble will be a variation in electrical output. This variation could be in the form of a drop in power or shift in voltage.

Any of the following could be the cause:

- a. Faulty power conditioner.
- b. Faulty thermoelectric generator.
- c. Increase in thermal conductivity through insulation system caused by loss of vacuum.
- d. Pressure vessel leak.
- e. Inability of the system to reject heat causing overheating.
- f. Leak in external power cable which could short power leads thus giving a false indication of system failure.
- g. Faulty wiring inside the system.

The following procedures should be followed to determine which component is faulty, assuming that the system is accessible.

- a) Place the system in a water tank, or provide other means of dissipating the reject heat such as the cooling fins. Check the power output in this condition.
- b) If system is still not operating satisfactorily, remove the electrical cable and check system output voltage and power with a new cable or directly from the receptacle pins.
- c) If the system output is still not as required, a number of diagnostic electrical tests can be conducted through the electrical receptacle. First, the system temperature profile can be measured and compared with the predicted profile. Temperatures grossly lower than predicted would indicate an insulation system failure.
- d) If the system temperature profile is normal, the problem is then an internal electrical problem. A number of electrical tests can be performed to isolate the cause; however, 3M Company should be contacted to assist in this portion of the investigation since the system can be damaged internally if these tests are not properly conducted.
- e) Whether or not the problem can be isolated by external electrical tests, it is virtually certain that the system must be disassembled to effect a repair. The system should never be disassembled without first contacting 3M Company and preparing a detailed repair procedure that is tailored to the specific system and its problem. It is possible to replace certain defective parts; however, it must be done in a controlled manner and must be supervised by someone who is familiar with both the operational and nuclear safety aspects 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 and II design and experimental work.

Contractor	3M Company
Contract No.	AT(30-1)3691
Users and Missions	Not Available
Status	Operational Prototype

SYSTEM AND GENERATOR DATA

System Concept	Radioisotope Fueled Thermoelectric Generator - Directly Shielded	
Generator Concept	PbTe - thermoelectric, flat-plate type	
Fuel	Sr-90 TiO_3	
Major System Assemblies	Pressure vessel, single-module generator, insulation envelope, fuel capsule and shield, and power conditioning equipment.	

	<u>Total System</u>	<u>Generator</u>
Design Life (years)	5	5
Weight (small pressure vessel)	640 ± 10 pounds	19 ± 1 pounds
(large pressure vessel)	750 ± 10 pounds	

	<u>Total System</u>	<u>Generator</u>
Length (inches, small pressure vessel)	25.1	4.12
(inches, large pressure vessel)	33.7	
Diameter (inches)	15.85 OD, max	7.9 and 4.3
Volume (cubic inches, small pressure vessel)	3120	86
(cubic inches, large pressure vessel)	4540	

SNAP-21 10-WATT SYSTEM WEIGHT SUMMARY

<u>Component</u>	<u>System Configuration</u>	
	<u>Small Cover</u>	<u>Long Cover</u>
1. Fuel	2.2	2.2
2. Fuel Capsule	4.3	4.3
3. Insulation System		
a. Spider	7.5	
b. Inner Liner	3.5	
c. Shield	247.0	
d. Enclosure, Bolts, Rods, Foils	51.0	
	<u>309.0</u>	<u>309.0</u>
4. Radiation Plug	17.5	17.5
5. Thermoelectric Generator	18.0	18.0
6. Segmented Retaining Ring	24.0	24.0
7. Power Conditioner	5.5	5.5
8. Pressure Vessel Body	182.0	182.0
9. Pressure Vessel Cover	70.0	183.0
10. Electrical Receptacle	4.4	4.4
11. Miscellaneous (Bolts, O-Rings, Wire, etc.)	10.0	10.0
	<u>646.9</u>	<u>759.9</u>
Total	646.9	759.9

Note: All weights are actuals based on components from a prototype system.

ELECTRICAL CHARACTERISTICS OF THE SNAP-21 SYSTEM

	Total System		Generator	
	BOL	EOL	BOL	EOL
Electric Output, watts (e) ⁽¹⁾	10.4	10.1	13.3	11.4
Thermal Input, watts (th) (nominal) ⁽²⁾	215	189	161.0	139
Efficiency, % $\frac{\text{power output (watts e)}}{\text{heat input (watts th)}}$	4.8	5.3	8.25	8.2
Specific Power, watts (e)/pound ⁽³⁾	0.16	0.155	0.74	0.63
Closed Circuit Voltage, volts ⁽¹⁾	24.4	24.0	4.82 0.7	4.73 0.7
Design Voltage, volts	24	24	same	same
Design Current, amps	0.42	0.42	N/A	N/A
(1) Based on rated load of 57.6 Ω				
(2) Required fuel loading is 209 watts. Allowable range is 209-219 watts.				
(3) Based on short cover configuration.				

SNAP-21 SYSTEM FINAL HEAT BALANCE, WATTS(t)

Component	BOL	EOL
Generator		
Legs	139	119
Insulation	9	8
Outer Case	13	12
Insulation System		
Neck Tube	20	18
Tie-Rods	14	13
Foils	12	11
Other		
Insulation System Neck Tube to Generator Case	8	8
Nominal Fuel Loading – watts (t)	215	189

SYSTEM ENVIRONMENTAL CAPABILITIES

OPERATIONAL ENVIRONMENT (INCLUDING TRANSPORTATION)

Temperature	+28 to +41°F (operating) -65 to 130°F (shipping and storage)
Pressure	10, 000 psi (22, 500 feet ocean depth)
Humidity	Minimum – 0 percent Maximum – 100 percent in salt atmosphere
Shock	6g peak value, 6 ms nominal duration
Vibration	5 to 26 Hz at 1.3g 26 to 40.5 Hz at 0.036-inch double amplitude displacement 40.5 to 50 Hz at 3g maximum
Acceleration	As incurred in vibration and shock as stated above

STORAGE

Storage Life	6 months
Temperature	-65 to +130°F
Pressure	10 to 32 inches Hg
Humidity	100 percent relative humidity
Other	None

SAFETY DATA

OPERATION, HANDLING, AND TRANSPORTATION – RADIATION DOSE RATES

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

SYSTEM DESIGN TO MAINTAIN FUEL CAPSULE INTEGRITY

Accident	Rupture of pressure vessel
Maximum Temperature, °F	1463
Maximum External Pressure, psi	10,000
Impact Velocity (capsule intact)	Not applicable
Re-entry 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
<u>Physical Properties</u>	
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	27.7	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)	209 to 219
EOL, watt (T_h)	183 to 193
Capsules per Generator	1
Isotope and Chemical Form	Sr-90TiO ₃

Capsule

Overall Length, inch	3.34
Overall Diameter, inch	3.20
Length/Area, in ⁻¹	0.415
Fuel Loading per Capsule, BOL	209-219 watt (T_h) 995 to 1040 gm 32,000 curies
Internal Volume per Capsule	
Total, in ³	18.1
Fuel, in ³	18.1
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-276	SS 304L
Inside diameter, inch	2.797	2.735
Inside Length, inch	2.939	2.759
Wall Thickness, Sides, inch	0.200	0.020
Wall Thickness, Ends, inch	0.200	0.075
Total Weight, pound	3.8	0.1
Melting Point, °F	2350	2500
Thermal Conductivity, Btu/hr-ft/°F	10.0 at 1150°F	12.4 at 932°F
Linear Expansion Coefficient, 10 ⁻⁶ /°F	8.2 at 70-1600°F	12.8 at 1900°F
Density, lb/in ³	0.323 at 72°F	0.290 at 72°F
Strength-Tensile, psi	121,000 at 72°F	75,000 at 72°F

	<u>Capsule</u>	<u>Capsule Liner</u>
Yield, psi	81,000 at 72°F	30,000 at 72°F
Closure Method	Weld (electron beam)	Weld (TIG)
Minimum Penetration, inch	0.205	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	1.4 ohms (EOL)
Module	N/A ohms
Couple	N/A ohms
Type of Circuit	Series
Thermoelectric Efficiency, %*	9.55 (EOL)
Electrical Output	11.4 watts (e)
Leg Thermal Input	119.4 watts (t)
Energy Conversion Efficiency, %	8.2 (EOL)
Electrical Output	11.4 watts (e)
Generator Heat Input	139 watts (t)

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 (0.53 long x 0.23 wide x 0.040 thick)

Cold Cap

Material	Copper
Thickness (Length), inch	0.235
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, Beryllium oxide follower to the generator cold frame

POWER CONDITIONER

Circuit Type	Modified Royer	
Converters/System	1	
Principal Components	Transistors, transformer, capacitors, resistors, zener diode	
Weight, pound	5.5	
Length, inch	3.5	
Impedance, ohms	N/A	
Diameter, inch	6.5	
Transistor Material	Germanium Silicon	
Transformer Core Material	50 percent Ni-Fe	
	<u>BOL</u>	<u>EOL</u>
Efficiency, % (Electrical Power Output/ Electrical Power Input)	N/A	88.0 minimum
Output Power, watt (e)	10.3	10.0
Output Voltage, volts (s)	24.4	24.0
Output Current, amps (s)	0.415	0.416
Input Power, watt (e)	13.4	11.4
Input Voltage, volts (s)	4.82, 0.7*	4.73, 0.7*
Input Current, amps (s)	N/A	2.41
Oscillating Frequency, cps	250	
Operating Temperature	+50 to +80°F	
Voltage Regulation	+2.5 percent	
Transistor Losses, watt (e)	0.621 maximum	
Ripple, mv (peak-to-peak)	100	
Transformer Losses, watt (e)	0.379 maximum	
Line Losses	0.200	

NOTE: All performance data based on rated output load of 57.6 .

*Three-wire input sealed in an aluminum enclosure.

OTHER COMPONENTS

Fill Gas or Vacuum – Vacuum Insulation System

Composition, Percent, and Purpose	Vacuum in space occupied by thermal insulation between shield and pressure vessel.
Pressure	1 to 10 microns
Temperature Range	50° to 1350°F
Thermal Conductivity (apparent)	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 Beryllium oxide follower.
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Housing (Pressure Vessel)

Material	Beryllium Copper
Coating	None
Outer Diameter, inches	14.490
Height, inches	25.1 and 33.7
Typical Thickness, inches	0.975
Flange: OD, inches	15.85
ID, inches	12.54
Typical Thickness, inches	1.65

Seals

<u>Type</u>	<u>No. Per System</u>	<u>Material</u>	<u>ID (in.)</u>	<u>Actual Thickness (dia)</u>	<u>Remarks</u>
O-ring	1	Ethylene Propylene	2.984	0.139	Seal between vessel and receptacle
O-ring	1	Ethylene Propylene	2.234	0.139	Seal between vessel and receptacle
O-ring	1	Ethylene Propylene	14.359	0.275	Outer seal between sections of pressure vessel
O-ring	1	Ethylene Propylene	13.309	0.275	Inner seal between sections of pressure vessel

Electrical Feedthroughs

Type, Number, Material

Electrical pins located in Inconel 718 pin insert in electrical receptacle. Total of 22 16-gauge KOVAR pins, gold-plated.

APPENDIX B

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

Revision 1, April 29, 1968

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)	209	372
Voltage, dc volts	24±1	24±1
Maximum ripple, peak to peak, mv	100	100
Maximum weight in air, pounds	507 ^{1/}	595 ^{2/}
Maximum diameter, inches	16	16
Maximum length, inches	28	35

^{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 (with shipping pallet)	Perform vibration tests required for equipment transported by common carrier according to MIL-STD-810A, dated June 23, 1964.
Shock	Perform shock tests in accordance with MIL-STD-810A, Method 516.1, procedure I, except that the peak value shall be 6 g's 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 g of the Technical Specification.

f. 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.

g. SrTiO₃ Fuel Specifications

Isotopic power data – Strontium 90	Sr ⁹⁰
Source material	SrTiO ₃
Half-life	27.0 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 contains ~95% Sr and the weight ratio of Sr ⁹⁰ to total Sr is ~0.5.
Specific power	0.21 watt 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 1μg/day.cm ² in sea water. Tests on 18-month old pellets of FP 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

h. 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.

APPENDIX C

SYSTEM PERFORMANCE CURVES FOR MINIMUM AND MAXIMUM FUEL LOADING

These performance curves are based on extrapolations of average data obtained from the first four fueled SNAP-21 10-Watt Systems. Performance of an individual system can be expected to deviate from these curves because of inherent manufacturing variations of individual components.

MINIMUM FUEL LOADING
209 WATTS (t)

Figure C-1. System Performance – 209 Watts
Power vs. Load Resistance in 40°F Water

Figure C-2. System Performance – 209 Watts
Voltage vs. Load Resistance in 40°F Water

Figure C-3. System Performance – 209 Watts
Current vs. Load Resistance in 40°F Water

Figure C-4. System Performance – 209 Watts
Power vs. Load Resistance in 60°F Water

Figure C-5. System Performance – 209 Watts
Voltage vs. Load Resistance in 60°F Water

Figure C-6. System Performance – 209 Watts
Current vs. Load Resistance in 60°F Water

Figure C-7. System Performance – 209 Watts
Power vs. Load Resistance in 80°F Water

Figure C-8. System Performance – 209 Watts
Voltage vs. Load Resistance in 80°F Water

Figure C-9. System Performance – 209 Watts
Current vs. Load Resistance in 80°F Water

Figure C-10. System Performance – 209 Watts
System Power, Voltage and Current
vs. Water Temperature

Figure C-11. System Performance – 209 Watts TEG Power, Voltage and Current vs. Water Temperature

Figure C-12. System Performance – 209 Watts System Temperature vs. Water Temperature

Figure C-13. System Performance – 209 Watts System
Temperature vs. Water Temperatures

Figure C-14. System Performance – 209 Watts System
Temperature vs. Water Temperatures

MAXIMUM FUEL LOADING
219 WATTS (t)

Figure C-15. System Performance – 219 Watts
Power vs. Load Resistance in 40°F Water

Figure C-16. System Performance — 219 Watts
Voltage vs. Load Resistance in 40°F Water

Figure C-17. System Performance – 219 Watts
Current vs. Load Resistance in 40°F Water

Figure C-18. System Performance – 219 Watts
Power vs. Load Resistance in 60°F Water

Figure C-19. System Performance – 219 Watts
Voltage vs. Load Resistance in
60°F Water

Figure C-20. System Performance – 219 Watts
Current vs. Load Resistance in 60°F Water

Figure C-21. System Performance – 219 Watts
Power vs. Load Resistance in 80°F Water

Figure C-22. System Performance – 219 Watts
Voltage vs. Load Resistance in 80°F Water

Figure C-23. System Performance – 219 Watts
Current vs. Load Resistance in 80°F Water

Figure C-24. System Performance – 219 Watts System
Power, Voltage and Current vs. Water
Temperature

Figure C-25. System Performance – 219 Watts TEG Power, Voltage and Current vs. Water Temperature

Figure C-26. System Performance – 219 Watts System Temperature vs. Water Temperatures

Figure C-27. System Performance – 219 Watts System Temperatures vs. Water Temperatures

Figure C-28. System Performance – 219 Watts System Temperatures vs. Water Temperatures

APPENDIX D

THERMOELECTRIC DESIGN PARAMETERS

To design a thermopile that will meet the system requirements, it is necessary to have thermoelectric design parameters that accurately predict generator performance. Prior to designing the SNAP-21 Phase II Design 3 thermopile, a set of parameters was established from the Phase II development test data and from data generated in the SNAP-27 and SNAP-23 programs.

The following procedures were used to establish the SNAP-21 thermoelectric design parameters:

- a) The basic thermoelectric materials were recharacterized using the TELPS equipment. The material characterization curves are shown in Figures D-1 through D-16.
- b) A scale-up factor was established to compensate for the difference between the thermoelectric materials properties as determined by the TELPS equipment and their performance in an actual generator. This was done by determining the ratio of experimental to calculated values for Seebeck voltage, E_x/E_c , and electrical resistance, R_x/R_c , using actual generator performance for experimental values and the material characterization (TELPS) data for calculated values.
- c) To compensate for the change in Seebeck voltage and resistance at the end of five years, a performance/time factor was established. This factor was based on data from the SNAP-27 10-couple modules. These modules employed the same thermoelectric materials as the hot segments of the SNAP-21 legs and the same internal conditions of gas pressure, contact pressure and thermal insulation. Since there is no available data on the change in performance of the cold segment material as a function of time, it was assumed that these materials would not experience a performance change over the five-year life. It is felt that this is a reasonable assumption since the

Figure D-1. Seebeck Coefficient (S)
(N Leg Hot Segment -
ES-1103)

Figure D-2. Resistivity (ρ)
(N Leg Hot Segment -
ES-1103)

Figure D-3. Thermal Conductivity (K)
(N Leg Hot Segment -
ES-1103)

Figure D-4. Dimensionless Figure of Merit (Z T)
(N Leg Hot Segment -
ES-1103)

Figure D-5. Seebeck Coefficient (S)
(N Leg Cold Segment -
ES-1104)

Figure D-6. Resistivity (ρ)
(N Leg Cold Segment -
ES-1104)

Figure D-7. Thermal Conductivity (K)
(N Leg Cold Segment -
ES-1104)

Figure D-8. Dimensionless Figure of Merit (Z T)
(N Leg Cold Segment -
ES-1104)

Figure D-9. Seebeck Coefficient (S)
(P Leg Cold Segment -
ES-1116)

Figure D-10. Resistivity (ρ)
(P Leg Cold Segment -
ES-1116)

Figure D-11. Thermal Conductivity (K)
(P Leg Cold Segment -
ES-1116)

Figure D-12. Dimensionless Figure of Merit (Z T)
(P Leg Cold Segment -
ES-1116)

Figure D-13. Seebeck Coefficient (S) (P Leg Hot Segment - ES-1110)

Figure D-14. Resistivity (ρ) (P Leg Hot Segment - ES-1110)

Figure D-15. Thermal Conductivity (K) (P Leg Hot Segment for Separately Pressed and Bonded PbSnTe - ES-1110)

Figure D-16. Dimensionless Figure of Merit (Z T) (P Leg Hot Segment Pressed and Bonded PbSnTe - ES-1110)

change is a strong function of maximum operating temperature, and the cold segments of the legs operate well below their maximum allowable (560°F maximum vs 700°F allowable).

- d) The scale-up and performance/time factors were then combined to establish a design factor that is applied to the basic material characterization data. Thus, the material data times its design factor can be used in the thermoelectric design computer program to design a thermopile for five-year life.

A summary of the design factors used for Design 3 is presented in Table D-1.

Table D-1. Thermoelectric Material Design Factors

Factor		P Leg	N Leg
<u>Scale-up Factor</u>			
Obtained by comparing average generator data from generators 10D5, 10D6, and 10D7 with calculated data.	E_x/E_c	0.98	0.98
	R_x/R_c	1.04	0.91
<u>Performance/Time Factor</u>			
Factors based on data from SNAP-27 10-couple modules for hot segment materials only. Cold segments were assumed not to change.	E_x/E_c	0.95	1.02
	R_x/R_c	0.87	1.09
<u>Combined Design Factor</u>			
Obtained by multiplying scale-up factor by performance/time factor.	E_x/E_c	0.93	1.00
	R_x/R_c	0.90	1.00
$\frac{E_x}{E_c} = \frac{\text{Experimental Seebeck Voltage}}{\text{Calculated Seebeck Voltage}}$ $\frac{R_x}{R_c} = \frac{\text{Experimental Thermopile Resistance}}{\text{Calculated Thermopile Resistance}}$			