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SNAP 21-B PROGRAM DEEP SEA RADIOISOTOPE-FUELED THERMOELECTRIC GENERATOR POWER SUPPLY SYSTEM QUARTERLY REPORT NO. 3 1 October 1964 to 31 December 1964

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1 October 1964 to 31 December 1964

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

By
T. J. Antolak
V. Yanisch, Jr.

ABSTRACT

The deep sea power supply system will use segmented semiconductor PbTe thermoelectric alloys which, when operated between 1100° F and 100° F, will perform at 10% materials efficiency. Generator design modifications have resulted in attainment of thermoelectric performance at 94% of theoretical prediction.

A high temperature vacuum thermal insulation envelope is being developed for this system. Alternate insulation designs are being investigated to ensure minimum heat loss with resultant increase in system efficiency.

To prevent potential formation of high temperature eutectic solutions, a chromium-plated copper liner has been selected to separate the fuel capsule and the biological shield. This same method has been selected for the exterior of the shield in order to provide oxidation and eutectic protection.

Fabrication and procurement of system components are in progress.

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DEEP SEA RADIOISOTOPE-FUELED
THERMOELECTRIC GENERATOR
POWER SUPPLY SYSTEM

SUMMARY

A preliminary engineering design summary is presented in Appendix A. Details of each component and subassembly show the current design status of the SNAP 21-B system.

System instrumentation has been established. Theoretical system thermal analysis has been completed and components have been fabricated for system thermal testing and integration.

An analysis was conducted to determine the effect of an alternate thermal insulation subsystem on the total system design.

A prototype thermoelectric generator was fabricated utilizing electron-beam welding to provide structural joining and hermetic sealing.

Approximately 400 P and N-legs have been fabricated for assembly into three full-scale prototype thermoelectric generators.

An additional 6-couple test module utilizing a revised thermoelectric leg design was placed on test. Approximately 16% more power output is exhibited by this unit compared to previous modules. Earlier module tests are still in operation, showing steady power output with time (3,768 hours maximum) at a hot junction temperature of 1100⁰ F.

A stainless steel vessel was fabricated for use in system thermal testing and system integration. Pressure vessel accessories have been specified.

Fuel capsule components were fabricated and welded. Weld specimens proved satisfactory by visual and metallographic examination.

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The shield-fuel capsule and shield-insulation envelope interfaces have been defined. The shield is currently being fabricated.

An enclosure for the dc-dc converter was designed and is being fabricated. Converter analysis was directed to selection of a reliable voltage regulator.

An insulation envelope was designed and analyzed. Alternate designs are being considered for potential efficiency gain. The initial insulation envelope is being fabricated.

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1.0 SNAP 21-B DEEP SEA RADIOISOTOPE-FUELED THERMOELECTRIC POWER SUPPLY SYSTEM

1.1 PLANNED OBJECTIVES

The planned program objectives are as follows:

- To design and fabricate a power supply system to operate in seawater at 10,000 psi external pressure for five years with a minimum continuous power output of 10-watts (e) at 24 volts.
- To design and fabricate the system with an overall efficiency of 6.75 percent and a maximum weight of five hundred fifty (550) pounds.
- To design the system and sub-systems to withstand the environmental conditions as outlined in the contract Technical Provisions and Scope of Work.
- To design the system for unattended operation, complete containment within a pressure vessel, and easy replacement or repair of the thermoelectric generator and electric power conditioner.
- To design the system for upgrading to output power levels of 20, 60 and 200 watts (e).

1.2 PROGRAM EFFORT AND ACCOMPLISHMENT THIS PERIOD

- System instrumentation has been established.
- Computerized system thermal analysis has been completed. This computer program provides print-out of a system configuration facsimile with its associated temperature profile.
- Components have been fabricated for system thermal testing and preliminary system assembly.
- An analysis was conducted to determine the effect of an alternate thermal insulation subsystem on the system design.
- Preliminary systems specifications were drafted (Appendix A). Figure 1-1 shows the current system design.

1.3 TECHNICAL DISCUSSION AND RESULTS

1.3.1 SYSTEM INSTRUMENTATION

The technical provisions of the SNAP 21-B program require that instrumentation be provided to monitor the following parameters of the system:

1. Hot junction temperature
2. Cold junction temperature
3. Open circuit voltage
4. Short circuit voltage
5. Short circuit current
6. System voltage under load conditions
7. System current under load conditions
8. Internal gas pressure
9. Internal humidity
10. Pressure vessel leakage

Hot junction temperature will be referenced to thermocouples externally attached to the generator hot frame. Prototype thermoelectric generators will include internal thermocouples attached directly to the hot electrode to provide the reference data. Direct hot junction temperature measurement would require heavy gauge (long life) thermocouple leads inside the generator. Hot junction electrode size and complete generator close-pack design prevent the use of heavy gauge thermocouples.

Cold junction temperature will be measured directly at the cold end electrode by using a thermocouple. The lower operating temperature of the cold end allows the use of small diameter thermocouple leads with little probability of failure.

System electrical performance will be monitored with standard equipment. Open circuit voltage and short circuit current will be measured at the thermoelectric generator. System parameters will be measured at the electrical feed-through receptacle. All system instrumentation lead connections will be external to the pressure vessel. Actual measurements will be affected by instrumentation lead and connection losses. System performance parameters will be directly measured to calibrate the external monitors.

Internal gas pressure and humidity will be measured within the cover of the pressure vessel. A pressure sensing transducer with a range of over three atmospheres absolute pressure has been selected. The transducer is of the bridge type with relative insensitivity to vibration and shock environments. Pressure transducer voltage will be supplied

by a stabilized power supply. Output voltage from the transducer can be converted to pounds of pressure by reference to calibration curves.

Various modes of humidity sensing of the internal vessel were reviewed with a resistance element selected as a sensor. This wide range sensor will also serve as the vessel leakage detector. An absorbent media will reduce the humidity to a reference level within the range of the resistance sensor. Any excursion above this reference level will determine the degree of leakage. Investigation will be conducted to determine the amount of absorbent material required. Absorbent material placement will be determined contingent upon the amount required.

A meter read-out instrument will provide stabilized voltage to the humidity-leakage sensor. The value indicated on the meter, after temperature correction by calibration curve, will indicate the humidity condition. Humidity and pressure values can be recorded continually by the use of a non-current-drawing chart recorder.

In addition to required instrumentation, provisions have been made to monitor the insulation envelope pressure, dc-dc converter component temperatures, and the internal system space temperature.

1.3.2 SYSTEM THERMAL ANALYSIS

A general purpose thermal analysis computer program was completed. The program (Quarterly Report No. 2, p. 2-33) provides for thermal analysis of any cylindrical system configuration. The computer analysis was refined to include a data-checking program and direct graphical output of the cylindrical configuration with its corresponding temperature distribution.

The cross-section of the current system design was reduced to an equivalent set of rectangles. From these, input data was prepared for the thermal analysis program. The program determined the temperatures of various points throughout the generator, and a plot (Figure 1-2) of the equivalent rectangles and temperatures was generated. This plot represents the current theoretical temperature distribution of the SNAP 21-B power supply operating in 41° F sea water.

Since the program output consists of equivalent rectangles with no supporting nomenclature, the temperatures were manually transferred to the actual system profile (Figure 1-2) to establish the relationship. Further duplication of this transformation will be unnecessary.

The graphical print-out of the computer analysis will be directly used for this system final design, analysis, test and specification. Upgraded system designs will also be accomplished with this analysis tool.

1.3.3 THERMAL TEST ASSEMBLY

A pressure vessel thermal test will be conducted to correlate predicted and actual thermal performance of the system components to provide a means to evaluate prototype components in an integrated system prior to their receipt or procurement.

Figure 1-3 shows the stainless steel vessel body (See Section 3.3.1) which internally conforms to the prototype vessel while the external surfaces are primarily as-cast.

Figure 1-4 illustrates the test apparatus substitute for the insulation envelope. The circular concave surface and flat integral top ring are dimensionally identical to the matching part of the prototype insulation envelope. The purpose of the column is to position this substitute within the pressure vessel at the same overall length as the prototype envelope. The disc provides separation from the bottom of the vessel body to avoid filling that volume with insulation during thermal testing. The upper volume will contain an electrical heater to simulate the heat source and will be otherwise completely insulated.

The insulation envelope fits into the vessel as shown in Figure 1-5. Note the clearance between the vessel and insulation envelope walls. This clearance allows the prototype pressure vessel to deflect as a free body under pressure with no direct effect on the insulation envelope. This provision in the SNAP 21-B design allows removal or replacement of all sub-systems within the pressure vessel. The insulation envelope is positioned and held in the vessel by the generator mounting plate-segmented centering ring assembly (Figure 1-6).

Figures 1-7 and 1-8 illustrate the thermal test assembly without the generator and with the generator in place on the mounting plate.

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Figure 1-3. Stainless Steel Vessel Body

Figure 1-4. Insulation Envelope Substitute

Figure 1-5. Vessel-Insulation Assembly

Figure 1-6. Generator Mounting Plate with Segmented Centering Ring

Figure 1-7. Vessel, Insulation, Mounting Plate - Centering Ring Assembly

Figure 1-8. Lower System Assembly with Thermoelectric Generator in Place

1.3.4 SYSTEM ANALYSIS WITH ALTERNATE THERMAL INSULATION

Performance of the currently designed SNAP 21-B power supply system is dependent on development of a low heat loss, high vacuum thermal insulation envelope (See Section 7.0). Since primary technology with this type of insulation has been directed to cryogenic applications, exacting thermal performance at high temperatures is a state-of-the-art requiring specific application development effort.

Development of the high vacuum insulation envelope is in progress. Theoretical heat loss analysis indicates a low loss; however, analysis is predicated on the validity of extrapolated curves obtained in controlled laboratory experiments. In the event that high temperature performance and life would be ineffectual for long-term use in the SNAP 21-B system, a study was conducted on an alternate insulation subsystem.

High molecular weight (xenon) gas-filled "MIN-K 1301" was selected as the alternate insulation as it had previously been used in the thermoelectric generator void space and it provided the lowest extraneous heat loss. Since actual thermal performance data is unavailable for this insulation combination at the shield operating temperature, a conservative thermal conductivity of 0.02 BTU/hr-ft-°F was used.

A computer program was devised to determine system weight, size, and efficiency as a function of fuel loading. A maximum radiation dose rate of 200 mr/hr. at the surface of the pressure vessel was imposed on the program. The current system component design parameters were incorporated into the analysis so the program output would indicate the degree of redesign or new design required. The details of the computer program and method of analysis are presented in Appendix B.

1.3.4.1 ALTERNATE INSULATION ANALYSIS RESULTS

Two conclusions were drawn from the analysis.

- (1) The current SNAP 21-B system design and technology can be extended to provide a system of acceptable weight with a minimum 4% efficiency.
- (2) A new design concept and an insulation investigation would be required to develop a system of acceptable weight with an efficiency approaching that of the present design.

Two factors of primary concern in the design of a deep sea power supply system are weight and efficiency. Weight affects ease of handling and efficiency determines cost of operation.

Two components, the biological radiation shield and the pressure vessel, are the major contributors to total system weight. The results of the alternate insulation system analysis shows that vessel weight increases sharply (Figure 1-9) with efficiency increase beyond 4%. Efficiency gain relative to increased insulation thickness is negligible beyond 4% efficiency.

Figure 1-9. Alternate Vessel Weight Versus Net System Efficiency

The shield weight decreases almost linearly (Figure 1-10) with increasing efficiency. Shield size is decreased as the vessel size increases since the system surface radiation dose rate is the governing factor.

Figure 1-11 shows total system weight as a function of net system efficiency. It is apparent that the present design efficiency of the SNAP 21-B system cannot be obtained utilizing the current system design with "MIN-K 1301" as an alternate thermal insulation. A system can be readily developed with current technology to perform at 4% efficiency.

Details of weight, dimensions, fuel load and efficiency of any specific alternate system are presented as tables in Appendix B.

Figure 1-10. Alternate Shield Weight versus Net System Efficiency

Figure 1-11. Alternate Total System Weight Versus Net System Efficiency

2.0 SNAP 21-B THERMOELECTRIC GENERATOR

2.1 PLANNED OBJECTIVES

The planned objectives are as follows:

- To design, develop, and fabricate a thermoelectric generator which shall provide a net system power output of 10 watts, direct current, at 24 volts.
- To design, develop, and fabricate the thermoelectric generator to provide the specified output continuously for a minimum period of 5 years.
- To design, develop, and fabricate the thermoelectric generator with a thermoelectric leg subsystem efficiency of 10.0 percent.
- To design and fabricate the thermoelectric generator for removal and replacement in the system without a hot cell facility and with minimum special equipment.
- To design, develop, and fabricate the thermoelectric generator to withstand the environmental conditions as specified in the contract Technical Provisions.

2.2 PROGRAM EFFORT AND ACCOMPLISHMENT THIS PERIOD

- Three non-operating test generators without thermoelectric couples and associated hardware were fabricated, tested and evaluated utilizing electron beam welding.
- The preliminary prototype thermoelectric generator design was revised to utilize electron beam welding.
- A prototype thermoelectric generator utilizing electron beam welding was fabricated and tested.
- The generator mounting plate and segmented centering ring received minor design alterations and a plate and ring were fabricated.
- Essentially all components have been fabricated for assembly into three prototype thermoelectric generators.
- An assembly and welding fixture was designed and built to aid in the fabrication of the thermoelectric generator.

- Approximately 500 P-type thermoelectric legs and 400 N-type thermoelectric legs have been fabricated for evaluation purposes. These legs will be assembled into the three full scale prototype generators to be built next quarter.
- A six-couple module was put on test (designated A-4) utilizing a new thermoelectric leg design. This module exhibits approximately 16% more power output than 6-couple modules A-1, A-2, and A-3.
- Six-couple modules A-1 and A-3 have operated, at steady power output, for 3,768 hours and 2,520 hours respectively, at a hot junction temperature of 1100°F.

2.3 TECHNICAL DISCUSSION AND RESULTS

2.3.1 THERMOELECTRIC GENERATOR DESIGN AND FABRICATION

The preliminary design of the first thermoelectric generator uses an O-ring to form a seal between the generator case and the cold frame of the generator. The case material is 347 stainless steel and the cold frame material is copper. This generator is shown in Figure 2.23 of the SNAP 21-B Program Quarterly report No. 2. The generator hot frame material is 347 stainless steel. The hot side electrical insulation is boron nitride. Internal thermal insulation is powdered "MIN-K 1301". The generator is to be back-filled with xenon gas. The generator uses 48 thermoelectric couples, series connected through hot junction electrodes and ball-type copper cold end electrodes with 20-gauge silver leads between couples. A spring-follower arrangement between the cold electrode and the cold frame provides force to maintain pressure contacts at the hot frame and at the hot junction of the thermoelectric legs.

An investigation was conducted to determine other methods of fastening the generator case to the cold frame to eliminate the use of O-ring seals. Electron-beam welding appeared to be a good method of attaching the copper cold frame to the 347 stainless steel case. A design of a non-operating thermoelectric generator (without thermoelectric couples) was made to test the practicality of the weld. Three electron-beam welded, non-operating generators were built. The first non-operating generator had a small leak. However, the welding experience proved valuable since the second and third units were welded successfully with no difficulty. These three non-operating generators were also electron-beam welded between the case and the hot frame with complete success. These weld tests showed that hermetic seals can be obtained by using electron-beam welding between the hot and cold frames and the generator case. Welding times and rates of feed were established.

The original design of the first prototype generator was revised to utilize electron-beam welding instead of an O-ring seal.

A prototype generator was built utilizing the established welding technique. Examination showed that a pinhole leak developed during welding. This occurred because of the closeness of the weld to an edge of the cold frame and also because a piece of insulation had been drawn between the mating parts during assembly. The generator was then sealed by the use of an auxiliary O-ring seal installed over the leak. (See section 2.3.5)

Surfaces to be welded must be free of foreign material. To assure that insulation is not introduced at the weld joint, the cold frame of the generator was redesigned to provide an insulation barrier. The barrier provides for the internal insulation to be mechanically restricted during final device assembly, specifically when shrinking the case on the cold frame. (See section 2.3.2.2)

The mechanical design of the prototype thermoelectric generator has been completed (Figure 2-1). The changes from the preliminary generator design are based on information gained during fabrication of the first prototype generator.

Figure 2-1. Thermoelectric Generator Assembly

Three prototype generators are being built. All parts except the thermoelectric couples are completed and are undergoing inspection prior to assembly.

2.3.2 THERMOELECTRIC GENERATOR ASSEMBLY

A single fixture was designed for use in assembly of the generator and to hold the unit while the case is welded to the hot and cold frames. Two other fixtures were designed and fabricated to aid in generator assembly. These fixtures were used to assemble the three non-operating generators so that electron-beam welding evaluation could be performed. No fixture difficulty was encountered in generator assembly or in establishing the welding procedure.

2.3.2.1 ASSEMBLY FIXTURES

Three fixtures were made for use in assembling the generators. These include an assembly and welding fixture, a compression yoke and a generator case sleeve.

The assembly and welding fixture (Figure 2-2) was designed to be used in the assembly of the generator and to hold and orient the generator during welding of the case to the hot and cold frames. During assembly, the fixture maintains the relative position of the hot and cold frames while the thermoelectric legs are being installed. It is then used to compress the thermoelectric leg subassembly. After compression, it holds the partially assembled generator while electrical connections are completed, thermal insulation is packed into place, and the generator case is fitted into position. During welding, the fixture (Figure 2-3) is connected to an external drive system which rotates the generator under the welding beam.

The compression yoke (Figure 2-4) is installed on the generator while the generator is in the assembly fixture. It holds the generator in compression for handling and shipping prior to welding.

The case sleeve (Figure 2-5) fits over the exterior of the generator case. Its functions are to restrain the case and prevent inward buckling during evacuation and final processing of the generator; it also acts as a heat sink for the generator case during welding.

2.3.2.2 GENERATOR ASSEMBLY PROCEDURE

The thermoelectric generator is assembled with the use of the assembly and welding fixture. The hot and cold frames are attached to the fixture, and the fixture is adjusted

Figure 2-2. Thermoelectric Generator Assembly and Welding Fixture

Figure 2-3. Assembly Fixture with Welded Generator in Place

Figure 2-4. Thermoelectric Generator with Compression Yoke

Figure 2-5. Case Sleeve Assembly

so the hot and cold frames are separated at a prescribed distance (Figures 2-6 and 2-7). At this distance, the leg compression springs exert just enough pressure to hold the thermoelectric couples and related hardware in position. The generator is then assembled by installing one thermoelectric couple at a time starting from the center of the generator and working out to the periphery.

When all thermoelectric couples are in place, the subassembly is compressed by moving the hot and cold frames closer together. Electrical connections are then made to feed-

Figure 2-6. Thermoelectric Generator Subassembly

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

through terminals in the cold frame. Thermal insulation is packed around the thermoelectric legs and surrounding void space. The generator case (designed for an interference fit at both ends) is heated and slipped into position over the hot and cold frames. At this point, preliminary assembly is complete, and the compression yoke is attached to the assembled generator so that the unit may be removed from the assembly fixture.

For welding, the assembly fixture is mounted in a controlled atmosphere electron-beam welder. The generator assembly (with yoke) is replaced in the fixture and the compression yoke is removed. The case sleeve (Figure 2-5) is fitted over the generator case. The case is then joined to the hot and cold frames while being rotated under an electron beam.

The welded generator is removed from the fixture and leak-checked to determine if the hermetic seal is established. The generator is then evacuated, back-filled with xenon, and sealed.

2.3.3 THERMOELECTRIC COUPLE DESIGN

2.3.3.1 THERMOELECTRIC DESIGN WITH PROVISION FOR CONVERTER BIAS

The current leg design may be used in a single generator circuit as well as in a generator with a third terminal (tap) for dc-dc converter bias. A very small fraction (1 %) of the available power is required to operate the converter bias circuit. However, this tap provides considerable efficiency gain in the converter.

The actual increase in required power in the tapped portion of the generator is about 7%. The load mismatch in the tapped portion causes a very slight drop in voltage output to the converter (0.727 volts instead of 0.728 volts bias, and 5.067 instead of 5.1 volts for the power circuit), but does not affect the voltage applied to the load.

Table 2-1 indicates the beginning and end-of-life power and voltage relationships that exist in the present system:

2.3.3.2 EFFECT OF TOLERANCES ON SEVERAL THERMOELECTRIC PARAMETERS

The variation in several parameters due to the given tolerances on the leg geometry, temperature, segmenting ratio, Thomson effect, etc. are summarized in Table 2-2 for a constant temperature gradient except where temperature was selected as the variable parameter.

Table 2-1. Thermoelectric Generator Power, Voltage, and Heat Predictions

	Beginning of Life	End of Life
V_1	0.868 volts	0.727 volts
V_2	5.95 volts	5.067 volts
P_1	0.0981 watts	0.0815 watts
P_2	13.8 watts	11.7 watts
V	24.0 volts	24.0 volts
P	10.1 watts	10.1 watts
Q_{IN}	138.6 watts	124.2 watts
Q_{OUT}	124.8 watts	112.5 watts

- V_1 = bias voltage
 V_2 = power circuit voltage
 P_1 = power into bias circuit
 P_2 = power into main line of converter
 V = system voltage
 P = system power output
 Q_{IN} = heat required by thermoelectric subassembly
 Q_{OUT} = heat rejected by thermoelectric subassembly

Effect of Leg Geometry Tolerances

A given percent change in diameter (Table 2-2) has a greater effect on power output than the same percent change in leg length because power is a function of the length-to-area rather than the length-to-diameter ratio. This geometry factor would be even more pronounced if contact area at the segment point or ends of the legs were reduced for any reason. In practice, junction temperatures usually change to compensate for variations in geometry, thereby reducing changes in output power. However, since each junction temperature cannot be measured or controlled, it is imperative the leg dimensions be accurate for scientific prediction of thermoelectric performance.

Table 2-2 also shows that a relatively large variation in the ratio of L_c/L does not affect output power and has a very small effect on efficiency.

Table 2-2. Variation of Thermoelectric Performance with Parameter Tolerances

Design Specifications ($T - ^\circ F$):

$$T_{hEOL} = 950 \quad T_{cEOL} = 100 \quad T_{hBOL} = 1100 \quad T_{cBOL} = 120 \quad (L_C/L)_P = 0.455 \quad (L_C/L)_N = 0.383$$

Parameter	% Δ	Δ % T_s	Δ % Q_s	Δ % P_o	$\Delta \eta_{TE}$
L_P - Length of P Leg	2.24	-	2.24	2.24	-
D - Diameter of Leg	2.67	-	5.6	5.6	-
$(L/A)_P$ - Length/Area	7.9	-	7.9	7.9	-
L_N - Length of N Leg	1.8	-	1.8	1.8	-
$(L/A)_N$ - Length/Area	7.5	-	7.5	7.5	-
$(L_C/L)_P$ - $\frac{\text{Length Cold Seg.}}{\text{Length of P Leg}}$	2.5	1.61	-	-	0.002 (0.00175)
T_{hPEOL} - Hot Junction Temp.	5	5.1	8.4	8.4	0.019
T_{cPEOL} - Cold Junction Temp.	5	0.38	1.3	1.3	0.001
$(L_C/L)_N$ - $\frac{\text{Length Cold Seg.}}{\text{Length of N Leg}}$	2.5	1.88	-	-	0.0026
T_{hNEOL} - Hot Junction Temp.	5	3.59	7.2	7.2	0.0302
T_{cNEOL} - Cold Junction Temp.	5	1.05	1.6	1.6	0.0064
R - Resistance of Leg	5	-	5	5	-
τ_P - Thomson Correction	-	+7.3	-7.9	-2.4	+0.056
τ_N - Thomson Correction	-	+3	-7.7	-0.81	+0.055

Subscript Nomenclature:

P	= P-Leg	η	= Efficiency
N	= N-Leg	τ	= Thomson Coeff.
EOL	= End of Life	Δ	= Change
BOL	= Beginning of Life	T_s	= Segment Temperature
C	= Cold end		
Q_s	= Heat Supplied		
P_o	= Power Out		

2.3.3.3 EXPECTED CHANGES IN PERFORMANCE DUE TO THOMSON EFFECT

The heat liberated or absorbed by a current in a conductor in which there is a temperature gradient depends on the direction of the current with respect to the direction of the temperature gradient. The Thomson coefficient of the material, defined as $\tau = T dS/dT$, may be described as the product of the absolute temperature and the temperature dependent Seebeck coefficient, $S = dE/dT$. Thus, the Thomson Coefficient is proportional to the second derivative of the Seebeck voltage with respect to temperature. This means that within a single thermoelectric leg, heat can be evolved in one portion and liberated in another.

The most significant effect caused by the Thomson heat term as shown in Table 2-2 is the upward shift in temperature at the segment point. This increase is about 7% in the given P-leg and is sufficient to cause operating temperatures to go higher than what would be desired because of strength considerations of the cold segment material. Also of importance is the drop in predicted power even though it is realized at a slight increase in efficiency for a given leg geometry operating under static conditions. This drop in power occurs because the actual resistance of the leg is greater than predicted, and the increase in resistance is greater than the effective increase in Seebeck voltage without considering the Thomson effect which has not been included in leg design calculations.

2.3.3.4 THERMOELECTRIC LEG ANALYSIS

The characteristics of the materials used in the N and P-legs of the thermoelectric couples used in this generator under optimum efficiency conditions are presented in Quarterly Report 2, Section 2.0. This combination of materials usually utilized under maximum efficiency conditions in the segmented thermoelectric legs is selected on the basis of their being chemically, thermally and mechanically compatible. The Figure of Merit of each segment material exhibits an optimum within the temperature range over which it is used. Also, to minimize internal Joulean heat losses, the segments are closely matched in terms of the optimum current for maximum efficiency per watt of conducted heat.

A comparative analysis (Table 2-3) was conducted with the current leg design (designated "A") and with a design which accounts for the Thomson heat term (designated "B"). The "B" design allows for a 10% extraneous electrical loss in the generator instead of 5%, and selects a lower segmenting temperature for the P-leg. Although it is not indicated because the designs are based on different analytic methods, the actual power developed in the "B" design legs is theoretically greater than that of the current "A" design legs.

Table 2-3. Comparison of 10 Watt-24 Volt Thermoelectric Generators

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

Also, a higher thermoelectric efficiency is predicted by including the Thomson effect. This new design is presently theoretical and requires development testing and evaluation prior to use in the SNAP-21 system. Further investigation will be conducted during upgraded systems development.

2.3.4 THERMOELECTRIC COUPLE TESTING

2.3.4.1 SIX-COUPLE MODULE TESTS

During the previous quarter the three six-couple modules described in Quarterly Report No. 2 (modules A-1, A-2 and A-3) were periodically monitored to determine the long-term performance characteristics of the associated thermoelectric legs. In addition, a fourth module (designated A-4) was put on test. Module A-4 was identical to modules A-1, A-2 and A-3 in every detail except leg geometry. The legs used in module A-4 were the result of a thermoelectric leg redesign presented in Quarterly Report No. 2.

Modules A-1, and A-2 contain 0.578 inch long, 0.188 inch diameter, segmented, simultaneously pressed, N and P-legs. Module A-3 contains the same type of N-legs, but the P-legs are composed of individually pressed segments bonded to intrasegment discs. Table 2-4 shows a summary of the geometrical characteristics of the legs contained in modules A-1, A-2 and A-3. Module A-4 contains 0.600 inch long, 0.188 inch diameter, segmented, simultaneously pressed N-legs, and 0.446 inch long, 0.188 inch diameter, segmented, individually pressed and bonded P-legs. Table 2-5 is a summary of the geometrical characteristics of the legs contained in module A-4.

Tables 2-6 through 2-10 show typical performance data for the four modules. In these tables the following nomenclature is used:

T_h ($^{\circ}\text{F}$)	- average hot electrode temperature
T_c ($^{\circ}\text{F}$)	- average cold electrode temperature
E_o (volt)	- open circuit voltage
E_L (volt)	- closed circuit voltage
I_L (amp)	- load current
P_o (watt)	- power delivered to load
R (m-ohm)	- internal electrical resistance

Table 2-4. Thermoelectric Leg Data

Modules A-1, A-2 and A-3

	Segment	Material	L	D	A	$\frac{L_c}{L}$	$\frac{L}{A}$
"N"	Cold	M-13	0.222	0.188	0.0276	-	-
	Hot	M-10	0.356	0.188	0.0276	-	-
	Total	M-10/M-13	0.578	0.188	0.0276	0.383	20.9
"P"	Cold	M-29	0.381	0.188	0.0276	-	-
	Hot	M-15	0.197	0.188	0.0276	-	-
	Total	M-15/M-29	0.578	0.188	0.0276	0.660	20.9

L - total length (inch)
 D - diameter (inch)
 A - cross sectional area (inch²)
 L_c - cold segment length (inch)

Table 2-5. Thermoelectric Leg Data

Module A-4

	Segment	Material	L	D	A	$\frac{L_c}{L}$	$\frac{L}{A}$
"N"	Cold	M-13	0.232	0.188	0.0276	0.386	-
	Hot	M-10	0.368	0.188	0.0276	-	-
	Total	M-10/M-13	0.600	0.188	0.0276	-	21.7
"P"	Cold	M-29	0.203	0.188	0.0276	0.455	-
	Hot	M-15	0.243	0.188	0.0276	-	-
	Total	M-15/M-29	0.446	0.188	0.0276	-	16.2

L - total length (inch)
 D - diameter (inch)
 A - cross sectional area (inch²)
 L_c - cold segment length (inch)

Table 2-6. Typical Performance Data, Module A-1*

Date	T _h (°F)	T _c (°F)	E _o (volt)	E _L (volt)	I _L (amp)	P _o (watt)	R (m ohm)
8-4-64	1097	116	1.31	0.66	1.96	1.29	342
8-24-64	1100	115	1.35	0.68	1.93	1.31	347
9-21-64	-	117	1.33	0.68	1.99	1.37	324
10-23-64	-	118	1.33	0.69	2.00	1.38	320
11-25-64	-	116	1.34	0.68	2.08	1.41	318
12-30-64	-	112	1.33	0.68	2.09	1.42	311

* begin test 7-28-64 (3768 hours as of 12-31-64)

Table 2-7. Typical Performance Data, Module A-2*

Date	T _h (°F)	T _c (°F)	E _o (volt)	E _L (volt)	I _L (amp)	P _o (watt)	R (m ohm)
8-19-64	1103	116	1.33	0.67	1.93	1.29	345
9-21-64	-	116	1.33	0.68	1.89	1.29	342
10-28-64	-	111	1.34	0.67	1.98	1.33	336
11-30-64	-	114	1.34	0.68	1.98	1.35	332
12-31-64	-	107	1.34	0.67	1.78	1.19	376

* begin test 8-11-64 (3432 hours as of 12-31-64)

Table 2-8. Typical Performance Data, Module A-3*

Date	T _n (°F)	T _c (°F)	E _o (volt)	E _L (volt)	I _L (amp)	P _o (watt)	R (m ohm)
9-17-64	1106	114	1.35	0.65	1.93	1.26	360
10-1-64	1103	110	1.36	0.67	1.99	1.34	344
10-14-64	1100	117	1.35	0.68	2.00	1.35	331
10-30-64	1100	115	1.35	0.67	2.14	1.44	317
12-15-64	-	115	1.35	0.69	2.13	1.47	311
12-28-64	-	117	1.35	0.69	2.13	1.46	314

* begin test 9-15-64 (2520 hours as of 12-28-64)

Table 2-9. Typical Performance Data, Module A-4*

Date	T _h (°F)	T _c (°F)	E _o (volts)	E _L (volt)	I _L (amp)	P _o (watt)	R (m ohm)
10-22-64	1097	116	1.37	0.68	2.36	1.59	297
10-30-64	1101	115	1.39	0.69	2.21	1.53	318
11-25-64	-	115	1.39	0.71	2.26	1.61	300
12-30-64	-	113	1.40	0.72	2.30	1.67	294

* begin test 10-20-64 (1728 hours as of 12-30-64)

Table 2-10. Predicted and Current Module Performance Data

	Modules A-1, A-2, and A-3				Module A-4	
	Computer Prediction	Experimental			Computer Prediction	Experimental A-4****
		A-1*	A-2**	A-3***		
T_h ($^{\circ}\text{F}$)	1100	1100 (est)	1100 (est)	1100 (est)	1100	1100 (est)
T_c ($^{\circ}\text{F}$)	115	112	107	117	115	113
E_o (volt)	1.37	1.33	1.34	1.35	1.39	1.40
E_L (volt)	0.69	0.68	0.67	0.69	0.70	0.72
R (m-ohm)	298	311	376	314	268	294
I_L (amp)	2.30	2.09	1.78	2.13	2.61	2.30
P_o (watt)	1.57	1.42	1.19	1.46	1.82	1.67

* Based on data of 12-30-64

** Based on data of 12-31-64

*** Based on data of 12-28-64

**** Based on data of 12-30-64

Portions of the data from these tables are displayed graphically in Figures 2-8 through 2-11.

As indicated in the graphs there is a gradual increase in power output with time for all four modules. This increase in power is theoretically caused by leg assimilation to the couple hardware and by in-temperature-gradient annealing of the thermoelectric legs.

The output power level in module A-2 increased from 1.29 watts on 8-19-64 to 1.35 watts on 11-30-64, then decreased to 1.19 watts on 12-31-64. Although the exact cause of the power loss after 11-30-64 is as yet unknown, it is suspected that an external

Figure 2-8. Module A-1 Performance

Figure 2-9. Module A-2 Performance

Figure 2-10. Module A-3 Performance

Figure 2-11. Module A-4 Performance

temperature perturbation is responsible rather than a direct degradation of the legs. On 12-15-64 a change of watt meters was made, resulting in an over-heating (estimated 1250°F) and an under-cooling (estimated 600-800°F) of the module. Prolonged exposure to high temperature is known to result in a decrease in performance.

An alternate probability for module A-2 power reduction is that the temperature cycle induced a leak in the module. This assumption is supported by the increase in the N-leg open circuit voltage noted in Tables 2-11 and 2-12 (the presence of oxygen causes the type of Seebeck change observed in these tables). It is also possible, however, that the N-leg open circuit voltage increase has been caused by an increase in the hot junction temperature. The heater block thermocouple of module A-2 is inoperative, but watt-meter readings indicate an increase in power input. Careful monitoring of the input power required to maintain the desired six-couple open circuit voltage should indicate the status of the module. If an increase in input is necessary to maintain the desired open circuit voltage, there is a strong possibility that the thermoelectric legs are failing. Prior to the change in performance, the input power and the N-leg open circuit voltage both indicated a constant hot electrode temperature with increasing power output with time.

The power output of module A-3 has increased from 1.26 watts on 9-17-64 to 1.46 watts on 12-28-64. This power output (1.46 watts) is within approximately 7% of predicted power output. Again, as with module A-1, the heater block temperature, power input, and N-leg open circuit voltage all indicate a constant hot electrode temperature. The behavior of the couples in this module appears to be about the same as those in modules A-1 and A-2.

The power output of module A-4 has increased from 1.59 watts on 10-22-64 to 1.67 watts on 12-30-64. Although there is no question as to the validity of the power increase indication for this module, the magnitude of the increase is somewhat questionable since both the input power and the N-leg open circuit voltage indicate a slight increase in the hot electrode temperature. Valid assessment of the power increase will be made when temperatures are adjusted and the module stabilizes. It is apparent that the thermoelectric couple redesign was a definite improvement since module A-4 is producing about 16 percent more power than modules A-1 and A-3 (based on the current performance data of these modules as shown in Table 2-10). This performance increase in module A-4 is not masked by an increase in input power since modules A-1, A-3 and A-4 are all using about the same power for operation.

Table 2-11. Predicted and Previous Leg Performance Data
Modules A-1, A-2 and A-3

	Computer Prediction			Experimental								
				A-1			A-2			A-3		
	N	P	Couple	N	P	Couple	N	P	Couple	N	P	Couple
T_h ($^{\circ}\text{F}$)	1100	1100	1100	1100	1100	1100	1100	1100	1100	1105	1105	1105
T_c ($^{\circ}\text{F}$)	115	115	115	119	117	118	120	112	116	111	117	114
E_o (volt)	0.127	0.102	0.229	0.123	0.097	0.220	0.124	0.098	0.220	0.126	0.097	0.223
R (m-ohm)	23.2	25.0	48.2	23.4	31.1	54.5	22.8	37.2	60.0	19.0	32.0	51.0

Table 2-12. Predicted and Current* Leg Performance Data
Modules A-1, A-2 and A-3

	Computer Prediction			Experimental								
				A-1			A-2			A-3		
	N	P	Couple	N	P	Couple	N	P	Couple	N	P	Couple
T_h ($^{\circ}\text{F}$)	1100	1100	1100	1100 (est)	1100 (est)	1100 (est)	1100 (est)	1100 (est)	1100 (est)	1100 (est)	1100 (est)	1100 (est)
T_c ($^{\circ}\text{F}$)	115	115	115	120	117	118	115	110	113	109	115	112
E_o (volt)	0.127	0.102	0.229	0.125	0.099	0.223	0.142	0.071	0.214	0.127	0.097	0.225
R (m-ohm)	23.2	25.0	48.2	25.1	30.0	54.6	45.0	17.8	63.3	24.2	27.5	52.1

*Based on data of 1-5-65

2.3.4.2 SINGLE COUPLE TEST

During the past quarter, single-couple tests were conducted to evaluate the effect of replacing the iron hot end electrode with a copper electrode. The copper electrode is separated from the thermoelectric legs by an iron disc. Copper has about 1/20 the electrical resistivity of iron at 1100°F.

Figure 2-12 shows the module used for these tests. The components of the module include the following: an aluminum cold frame, a stainless steel heater block and support structure, mica hot electrode insulation, aluminum spring followers, and copper cold electrodes. The hot electrodes are composed of copper straps and cold-rolled steel discs. Although the module contains two thermoelectric couples, these couples are not connected in series. The performance of each of the couples is monitored separately. Figure 2-13 shows the entire test apparatus.

Figure 2-12. Single-Couple Module Components

The thermoelectric legs used in the single-couple test (designated X-2) are of the same type contained in six-couple modules A-1 and A-2; namely, segmented, simultaneously pressed N and P-legs. The geometrical characteristics of these legs are shown in Table 2-4. The results of test X-2 are shown in Figure 2-14 using the following nomenclature:

- Ex - experimental open circuit voltage
- Ec - computer predicted open circuit voltage
- Rx - experimental internal resistance
- Rc - computer predicted leg resistance

Px - experimental power output
Pc - computer predicted power output

Figure 2-13. Single-Couple Test Apparatus

The theoretically predicted R_c and P_c values do not account for extraneous resistances, whereas these resistances are necessarily included in the R_x and P_x measurements. Therefore, the minimum attainable internal resistance ratio will be approximately 1.01 to 1.03 rather than 1.00. There will obviously be a corresponding reduction in maximum attainable power output ratio.

Figure 2-14. Single-Couple Module Performance

Examination of the data shows that the average internal resistance ratio is 1.05 for couple number one and is 1.06 for couple number two. Since the minimum attainable ratio is about 1.02, this indicates that these couples incur only about 3 or 4 percent excessive resistance. This is considerably less than the initial 11 to 20 percent experienced by the four 6-couple modules.

The combination of the resistance and corresponding open circuit voltage results in an average power output ratio of 0.94 for couple number one and 0.89 for couple number two. This indicates output of all but 2 to 9 percent of the predicted power.

2.3.4.3 PROTOTYPE GENERATOR TEST

During the previous quarter the first 48-couple prototype generator was assembled and put on test. A photograph of this generator is shown in Figure 2-15. This generator

Figure 2-15. Initial Prototype Generator

contained sufficient thermocouple instrumentation to accurately determine quadrangular radial temperature profiles for both the hot and cold electrodes. Eight hot electrode thermocouples and sixteen cold electrode thermocouples were used. With the thermocouple distribution chosen, it would have been possible to monitor the electrical performance of four of the 48 couples (both the total couple and the individual N and P-legs). In addition, a single cold frame thermocouple was provided to determine the temperature drop from the cold electrodes to the cold frame.

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Because of the weld leak and subsequent seal modifications, the thermocouples were damaged making their respective temperature and electrical performance indications questionable. The generator was processed and brought up to temperature on November 18, 1964.

Sufficient thermocouple instrumentation remained to indicate that the hot electrodes and cold caps were at the desired temperatures (1100°F and 115°F). Single couples were generating about the expected voltages, but the generator was producing only 91 percent of its rated voltage and 65 percent of its rated power. Generation of rated voltage by the couples, but not by the entire generator, indicated an internal short circuit. This was verified by a voltage probe from the generator circuit to the generator case. Since there had been a loss of continuity for many of the thermocouples, it was suspected that one or more of these free wires may have been causing the electrical short.

Since this generator was inoperative, thermocouples were attached to the collector and emitter plates and the thin stainless steel case to obtain temperature measurements. The temperature drop across the radiation air gap and the temperature distribution of generator case is to be determined experimentally.

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3.0 SNAP 21-B PRESSURE VESSEL

3.1 PLANNED OBJECTIVES

The planned objectives are as follows:

- To design and fabricate a pressure vessel which will completely contain the system under operating conditions for a minimum five-year period.
- To design and fabricate a pressure vessel which will withstand environmental corrosive conditions and will incur no leakage during placement and design-life operation.
- To design and fabricate a pressure vessel with provision for external instrumentation and power leads.
- To design and fabricate a pressure vessel which will withstand all remaining environmental conditions as specified in the contract Technical Provisions.

3.2 PROGRAM EFFORT AND ACCOMPLISHMENT THIS PERIOD

- Procurement of the prototype pressure vessel was initiated.
- A stainless steel vessel was fabricated for use in system integration and thermal analysis.
- A stainless steel electrical feed-through receptable was procured.
- Design and specifications were completed for the prototype titanium receptacles. Two units are on order.
- Design and specification of a strain-relief plug are in progress.
- O-ring seals have been procured.

3.3 TECHNICAL DISCUSSION AND RESULTS

3.3.1 STAINLESS STEEL VESSEL

A stainless steel vessel was procured for use in system thermal analysis (see Quarterly Report No. 2, page 2-33) and in system integration. The unit was cast, welded, and machined from CF-8C (AISI type 347) stainless steel. All machining conforms to the design specifications of the prototype pressure vessel with the following exceptions:

1. The outside of the lower hemispherical surface (body) and the outside of the upper hemispherical surface (cover) was left in an as-cast condition to eliminate the necessity of a time-consuming and costly contour machining operation.
2. The outside of the cylindrical surface (body) was only partially turned to dimensions since insufficient material remained after casting shrinkage.
3. The inside hemispherical surfaces of the body and cover were only rough-machined (125 finish) to meet minimum thermal test requirements.

Figure 3-1. Stainless Steel Vessel - Exterior

Figure 3-2. Stainless Steel Vessel - Interior

Figures 3-1 and 3-2 illustrate the exterior and interior of the thermal test vessel after machining. Upon completion of heat transfer testing, the unmachined surface of the cover and body will be turned to prototype dimensions for use in system integration.

3.3.2 PRESSURE VESSEL ACCESSORIES

Examination of the stainless steel electrical feed-through receptacle (Figures 3-3, 3-4) resulted in the following design and specification changes in the prototype titanium receptacles:

1. Bolt clearance holes were increased in size so that fabrication and assembly could be easily accomplished without using extensive tools and fixtures.
2. The locator key (Figure 3-3) will be attached to the inside wall of the receptacle with an interference fit rather than by brazing or bonding.
3. O-ring groove machining will conform to standard groove dimensions with edge and corner radius tolerances.

Figure 3-3. Stainless Receptacle - Top View

Figure 3-4. Stainless Receptacle - Bottom View

4. Surface contamination of the titanium caused by glass fusing and plating processes will be removed during final machining.
5. To prevent radial seal leakage, only concentric finish irregularities will be permitted.

Experimental glass fusing to titanium (Figure 3-5) indicates excellent bonding which will withstand design pressure. Surface contamination of the titanium is induced by the high temperature glass sealing operation. However, contamination (hydrogen) is non-detrimental to the metal-to-glass bond.

O-ring seals for use in the prototype pressure vessel, the stainless steel vessel, and the electrical feed-through receptacles have been procured. Seal material is 90-durometer Viton. Dimensions of the vessel O-rings were established as follows:

	<u>Inside Diameter (inch)</u>	<u>Nominal Crossectional Diameter (inch)</u>
Outside Vessel Seal	14.325 $\pm$ 0.030	0.25
Inside Vessel Seal	13.309 $\pm$ 0.030	0.25
Receptacle Seal	3.234 $\pm$ 0.031	0.125

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Figure 3-5. Samples of Glass Fusing to Titanium

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

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4.0 SNAP 21-B FUEL CAPSULE

4.1 PLANNED OBJECTIVES

The planned objectives are as follows:

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

4.2 PROGRAM EFFORT AND ACCOMPLISHMENT THIS PERIOD

- Fuel capsule components were fabricated, and 15 matched sets of capsule components were forwarded to Oak Ridge National Laboratory.
- Preliminary weld specimens proved satisfactory by visual and metallographic examination.
- Simulated fuel pellets of "Al Si Mag 614" were procured from American Lava Corporation. These pellets will be inserted into the test capsules during the welding operation.
- A prototype fuel capsule with electrical heaters was designed.
- Potential formation of high temperature eutectic solutions between various components was studied. A chromium-plated copper liner has been selected to separate the fuel capsule and biological shield.

4.3 TECHNICAL DISCUSSION AND RESULTS

4.3.1 FUEL CAPSULE FABRICATION

Fuel capsule components were fabricated (Figure 4-1) using Hastelloy Alloy C material for the outer capsule and 316 stainless steel for the inner capsule. Each component was measured with a micrometer and/or calipers, and the measured dimension was compared to the design dimension. Components were dimensionally matched for each capsule assembly, and 15 sets were forwarded to Oak Ridge National Laboratory for fabrication. Four assemblies, quality-rejected for dimensional and appearance anomalies, were used to develop the capsule welding procedure.

Figure 4-1. Fuel Capsule Components

Preliminary weld specimens (Figures 4-2, 4-3) were metallographically acceptable with respect to weld integrity. In order to inspect weld penetration, the outer capsule was sectioned and polished. The specified minimum weld penetration of 0.100 inch was achieved. Figures 4-4 and 4-5 illustrate the degree of weld penetration and homogeneity.

To substantiate the fuel capsule design during testing, simulated fuel pellets will be inserted into the test capsules prior to the welding operation. Preferable mock fuel material is non-radioactive strontium titanate. However, investigations of availability

Figure 4-2. Completed Inner Capsule (SS316)

Figure 4-3. Section of Completed Outer Capsule (Hastelloy Alloy C)

Figure 4-4. Top Weld Structure (7.5x)

Figure 4-5. Bottom Weld Structure (7.5x)

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and cost of strontium titanate resulted in the selection of "Al Si Mag 614", an alumina (Al_2O_3) base mixture, as the simulated fuel pellet material. This material has a density (3.7 grams/cm^3) equal to that of strontium titanate; the properties of thermal expansion are very nearly equal, and the cost is 15% of that of strontium titanate. Simulated fuel pellets (Figure 4-6) were procured and forwarded to Oak Ridge National Laboratory for encapsulation in the SNAP 21-B fuel capsules.

Figure 4-6. Simulated Fuel Pellet

4.3.2 PROTOTYPE FUEL CAPSULE DESIGN

An electrically heated fuel capsule will be utilized in the SNAP 21-B system testing to evaluate operational parameters and component compatibility.

Preliminary design of the electrically heated fuel capsule is complete. A copper block of simulated fuel pellet size will be inserted into the fuel capsule assembly. The block (Figure 4-7) will have three holes for heater cartridges. Chromalox cartridge heaters will be inserted into the holes and connected to allow simultaneous operation of the three heaters in a parallel circuit. Present heater selection is as follows:

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Figure 4-7. Electrically Heated Fuel Capsule Concept

Manufacture	Chromalox "Redhead"
Dimensions	0.375 inch OD by 2.5 inches long
Power	165 watts
Voltage	115-230 volts ac
Sheath Material	Incoloy
Lead Material	Nickel Alloy
Lead Sheathing	High Temperature Fiberglas

The prototype heated fuel capsule is designed to operate at design generator power with 40% of the cartridge heater capability.

4.3.2.1 EUTECTIC PROTECTION

The fuel capsule average operating temperature has been determined to be approximately 1380° F (750° C). This temperature requires absolute separation of the Hastelloy Alloy C capsule from the U-8 molybdenum alloy biological shield in order to prevent eutectic formation. Investigation indicates that the group VIII metals (including iron, nickel, and cobalt - all present in Hastelloy Alloy C) of the periodic table are susceptible to eutectic formation with U-8 molybdenum alloy at temperatures of 1290° F to 1650° F (700° to 900° C).

To provide absolute separation, a double-cup liner was devised to completely enclose the fuel capsule. Selection of material for this component was reduced to copper, silver, gold, chromium, titanium, tantalum, and ceramics.

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Thin section ceramics, when subjected to high stresses produced by thermal test cycling and vibration loading, would be susceptible to potential failure.

Copper, silver, gold, and titanium are subject to long-term diffusion into Hastelloy Alloy C.

Chromium is susceptible to diffusion into Uranium-8 molybdenum.

A possible combination of these materials was studied as an alternate solution to the use of tantalum and tungsten which are difficult to fabricate and are susceptible to oxidation. Oxidation is a consideration since the interface between the biological shield and insulation envelope must also be similarly protected, but must also be oxidation resistant.

Chromium-plated copper was selected as the protective liner material. Copper will provide the diffusion barrier to U-8 molybdenum and chromium will provide the diffusion barrier to Hastelloy Alloy C. The composite will physically separate the fuel capsule from the shield to prevent eutectic formation.

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5.0 SNAP 21-B BIOLOGICAL RADIATION SHIELD

5.1 PLANNED OBJECTIVES

The planned objectives are as follows:

- To design and fabricate a biological radiation shield to limit the nuclear radiation level to 200 mr/hr at the system surface and 10 mr/hr at one meter from the system surface.
- To design the radiation shield to permit easy thermoelectric subsystem repair or replacement without requiring hot cell facilities and without exceeding the maximum permissible radiation exposure limits as established by the AEC.

5.2 PROGRAM EFFORT AND ACCOMPLISHMENT THIS PERIOD

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

5.3 TECHNICAL DISCUSSION AND RESULTS

A critical interface exists between the biological radiation shield and the surrounding vacuum insulation envelope. At this interface shield mechanical support, shield oxidation protection, and high vacuum maintenance of the insulation envelope must all be provided. Satisfactory interface definition is primarily dependent upon compatibility of the materials used.

Immobilization of the shield to prohibit excessive movement during transportation, implantation, or operation is particularly important to prevent damage to the thermoelectric generator and insulation envelope. In order to work independently on the shield and insulation envelope, firm external shield dimensions were defined. Allowance was provided for protection of the uranium-molybdenum alloy (shield) by a mutually-compatible material which would provide the necessary separation from the Inconel-X alloy used for the vacuum insulation envelope. The final protected shield dimensions provide for 0.032 inch of cladding over the shield.

The high oxidation rate of the uranium-molybdenum shield alloy indicated that some protective cladding would be necessary. Since at operating temperature the Inconel-X inner shell of the insulation envelope was susceptible to eutectic formation with the uranium-molybdenum, the cladding must also provide separation between the shield and insulation envelope while itself being free from similar eutectic behavior. Limited information is available on the compatibility of various metals with the shield alloy at the SNAP 21-B shield operating temperature. A similar separation is required at the shield-fuel capsule interface, and the protective coating material selection of chromium-plated copper is discussed in section 4.3.2.1 of this report.

An alternate protective material for the biological shield is a titanium shell since diffusion is not experienced at this interface temperature. This protection could be provided in the form of a fabricated sheet metal shell or by the direct casting of the shield alloy into a titanium mold liner. By using metal spinning techniques, a titanium sheet metal shell can be fabricated to enclose the machined shield. Spinning tolerances would require final profile machining and shimming to maintain the interface fit with the insulation envelope. This in turn would produce irregular heat flux and temperature distribution. Casting the shield into the cladding directly, using a titanium mold liner, appears attractive since precision machining of the entire shield would be unnecessary. However, such a procedure has not been attempted before and would require research and development effort.

It is expected that direct casting, if developed, would provide the preferred oxidation-eutectic protection for the shield at reduced unit cost; although in this case, a single SNAP 21-B shield does not warrant development time and expense. This method should, however, be further investigated for multiple unit development and potential production of a SNAP 21 system.

Quotations for the fabrication of the shield from depleted uranium-8% molybdenum alloy were received from two suppliers. An order has been placed with the Nuclear Metals Division of National Lead Company on the basis of both lower cost and superior delivery schedule. The order includes one complete radiation shield including assembly bolts, and one additional plug which will be used with the prototype electrical heater. The uranium was supplied to the vendor in the form of Davidson-derby material and was procured from Argonne National Laboratory. Fabrication has proceeded through the alloying and casting processes as illustrated in Figures 5-1 and 5-2.

Figure 5-1. Shield Casting with Sprue Attached

Figure 5-2. Shield Casting Showing Capsule Cavity

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6.0 SNAP 21-B DC-DC CONVERTER

6.1 PLANNED OBJECTIVES

The planned objectives are as follows:

- To develop a regulated power conditioner (dc-dc converter) to provide 10 watts minimum power output at 24 volts with an external rated load of 57.6 ohms.
- To develop a dc-dc converter with a minimum efficiency of 85% and a five-year life.

6.2 PROGRAM EFFORT AND ACCOMPLISHMENT THIS PERIOD

- Investigation of zener diode capability is being conducted with several zener diode manufacturers.
- Four prototype "Super Zener Diode" regulators have been placed on long-term electrical test.
- The converter enclosure has been designed and several units are being fabricated.

6.3 TECHNICAL DISCUSSION AND RESULTS

6.3.1 ZENER DIODE REGULATOR

The Zener diode regulator limits the output voltage of the thermoelectric generator and dc-dc converter. This device provides protection to the load, rejects output power when no load is connected, and rejects the resultant surplus power produced by the generator at beginning of life. The major criterion for diode selection is reliability.

Preliminary reliability information on zener diodes indicates a failure rate of 0.29% per 1000 hours for a standard zener diode. Since two of these zener diodes would be required in the SNAP 21-B regulator, about 25% of the regulators will have failed over a five-year life. The electrical degradation criteria for this failure rate is much wider than the electrical tolerance permitted for the regulator, so a failure rate in excess of 25% over a five-year life would be expected. Also, standard zener diodes will not provide adequate regulation to meet the $\pm 3\%$ voltage regulation requirement.

Standard zener diodes being unacceptable, a formal inquiry has been placed with five zener diode manufacturers. No replies have been received to date, but it is expected that these manufacturers will be unable to provide either the reliability or the electrical specifications. Because of the expected high failure rate, other approaches were investigated.

A new type regulator has recently become available. This regulator has an outer package which is similar to that of a zener diode and is called a "Super Zener Diode" regulator. The electrical characteristics are similar, but superior to those of the zener diode. Four of these units have been placed on long term electrical test.

The reliability of a special version of this "Super Zener Diode" regulator is expected to be perhaps five times the reliability of the standard zener diode. Even with five times the reliability of the zener diode, about 5% of the regulators can be expected to fail in five years. While this reliability level is considered adequate for a development device, actual system application may require a higher degree of reliability.

Recent availability of a high reliability reference diode and the availability of other high reliability components indicate that a regulator exhibiting much higher reliability could be built. This regulator would consist of discrete components and will require specific development effort oriented to meet actual user requirements.

6.3.2 DC-DC CONVERTER ENCLOSURE

The enclosure for the dc-dc converter serves three functions:

1. It provides the mount and operating atmosphere for the dc-dc converter circuit.
2. It transfers heat from the converter components to the pressure vessel.
3. It positions and retains the converter within the pressure vessel.

The converter enclosure design (Figure 6-1) has been completed. The SNAP 21-B prototype power supply will contain one dc-dc converter and regulator commensurate with system requirements. However, modular space has been provided within the enclosure to accommodate an automatic selector switch and additional converter for potential power regulation redundancy.

The enclosure was designed to provide the shortest heat flow path from converter components while maintaining maximum utilization of space in the top hemisphere of the pressure vessel. During final assembly, the unit will be sealed and back-filled with a

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Figure 6-1. Converter Enclosure Design

dry atmosphere to provide a suitable operating environment. The converter enclosure parts (Figures 6-2, 6-3) consist of spun 12-gauge 6061 aluminum walls heliarc welded to a 6061 aluminum base plate. The enclosure is to be sealed by a 12-gauge 6061 aluminum cover (Figure 6-3). The cover will be heliarc welded in place.

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Figure 6-2. DC-DC Converter Enclosure Subassembly

Figure 6-3. DC-DC Converter Final Closure

7.0 SNAP 21-B INSULATION ENVELOPE

7.1 PLANNED OBJECTIVES

The planned objectives are as follows:

- To develop an insulation envelope with the thermal conductivity of the insulation to be not greater than 0.0005 BTU/hr-ft-⁰F during operation.
- To develop an insulation envelope with a five-year life to withstand the environmental conditions of the system as outlined in the Technical Provisions.

7.2 PROGRAM EFFORT AND ACCOMPLISHMENT THIS PERIOD

- Thermal and mechanical analyses have been completed for the initial insulation envelope. Expected heat loss is 28.0 watts (th).
- An alternate mechanical design is being investigated for potential reduction in thermal losses.
- Simulated shields have been fabricated of stainless steel for the two preliminary insulation envelopes. Electrical heater blocks were also designed and fabricated.
- Fabrication and assembly of the initial insulation envelope was started.
- Thermal test procedure has been established.

7.3 TECHNICAL DISCUSSION AND RESULTS

Three insulation envelopes for operation at boundary temperatures of 1325⁰F to 50⁰F will be constructed for the SNAP 21-B program. The first two units will be assembled on stainless steel simulated shields. The mechanical and thermal properties of the insulation envelopes will be evaluated. The third unit will be assembled on the prototype shield and will incorporate any design changes indicated from tests of the preceding two units. The insulation envelopes will be of the same size and general configuration, and processing will be in accordance with a five-year design-life objective.

Insulation envelope thermal performance is attained by using reflective shields, fibrous spacers, a high vacuum, and a getter to maintain the vacuum over a given time period.

A series of reflective shields are used to reduce thermal radiation transfer. These shields are constructed from metal foil of aluminum for lower temperature applications and copper, stainless steel or nickel for higher temperatures. The shields are thin to permit minimum weight and flexible contour fitting of the insulation. The material of the fibrous mats that separate the shields is glass for lower temperature use and quartz or ceramic for higher temperature use. A suitable vacuum level is maintained in the insulation envelope through the use of a high capacity getter material.

The mode of heat transfer and properties of the constituent insulating materials are temperature-dependent. At higher temperatures, thermal radiation becomes increasingly important as compared to solid conduction transfer through the fibrous spacer materials. The vapor pressure of the materials increases at higher temperatures, tending to increase gaseous conduction by encroachment on the vacuum. The preparation of the insulation envelope involves processing procedures at high temperatures to sufficiently outgas the materials while simultaneously improving the emissivity of the radiation shields. A getter is included in the sealed system to take up residual outgassing and to maintain the vacuum at a proper level for the design life. The extent of processing and quantity of getter used is dependent on the design life objective. At higher temperature applications, a vacuum approaching 10^{-3} mm Hg is maintained to keep gaseous conduction at low level. Above 10^{-2} mm Hg, gaseous conduction will appreciably increase the total heat transfer through the insulation envelope.

The insulation envelope will consist of a vacuum enclosure, heat source support structure, insulation layers, and a vacuum maintenance getter.

7.3.1 MECHANICAL DESIGN AND ANALYSIS

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

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

The initial design (Figure 7-1) was established to meet the interface requirements of the pressure vessel, shield thermoelectric generator, and segmented centering-ring

Figure 7-1. Initial Insulation Envelope Design

of the SNAP 21-B system. Components and structure internal to the insulation envelope or not affecting interface fits are subject to optimization and redesign to satisfy the design objectives.

The major fixed-design enclosure components (Figure 7-1) include:

- (1) Inner shell - upper and lower heads
- (2) Outer shell - upper and lower heads
- (3) Outer shell - cylindrical section
- (4) Top ring

Inner Shell

The inner shell serves two functions:

- (1) It forms a leak-tight internal pressure housing.
- (2) It provides a point of attachment between the heat source (shield) and the support mechanism.

Inconel-X was selected for the inner-shell material on the basis of high temperature creep strength and available welding technology. A creep strength value of 16,000 psi to produce 2% total elongation in 40,000 hours at operating temperature was used in the design analysis.

Since the shield will be held primarily by the support structure, the forces acting on the inner shell are basically the internal vacuum and the external system atmosphere. Calculations indicate that a shell thickness of 0.0048 inches is satisfactory. The design, however, requires a weld adjacent to the heat source unit which involves consideration of the difference in coefficients of thermal expansion of the various metals being used, and material weldability. The inner shell will be 0.050 inches thick and each head will weigh about 1.6 pounds. This thickness represents a factor of safety of about 10 in the region away from the weld and may be reduced as welding experience is gained.

Outer Shell - Upper Head

The upper head of the outer shell serves as part of the enclosure and as the contact member to the segmented centering-ring.

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

The upper head has a concave circular surface which mates with the segmented centering-ring. This component must withstand the mounting force (2,400 lbs) of the ring and the vacuum of the insulation envelope. Two methods of analysis were used to determine the structural integrity of the upper head.

The first method of analysis was to assume that the upper head was a flat, ring-shaped plate, clamped at its outermost edge (Figure 7-2). The loading assumed to exist was that which would be present if the true load were projected down on the flat ring. This analysis indicated that an upper head thickness of 0.220 inch would provide a 2.3 factor of safety using 316 stainless steel.

The second method of analysis was to assume a beam of rectangular cross-section and unit width which was cantilevered at one end and loaded with applicable forces on a per-unit length of circumference (Figure 7-3). This analysis indicated that a 1.7 factor of safety is realized with an upper head thickness of 0.220 inch. Calculations also show a large bending moment at the point of attachment to the cylindrical section of the outer shell. Since analysis of this design configuration was necessarily restricted to mechanical approximations, the upper head was specified to be 0.220 inch thick, and the wall was extended into the cylindrical section to compensate for high bending moments.

Outer Shell - Lower Head

The lower head is a partial hemisphere potentially subject to small area contact due to pressure vessel deflection at operating pressure. Mechanical analysis (Figure 7-4) indicated a 2.3 factor of safety with a wall thickness of 0.240 inch. This component weighs approximately 11.4 pounds in the design configuration illustrated in Figure 7-1.

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

7.3.1.1 SUPPORT DESIGN

A survey was conducted on available materials on the basis of a strength-to-thermal conductivity ratio. This survey indicated that a material manufactured by sintering small particles of silica, obtained by grinding a piece of fused silica, has advantages over other materials. The strength used in the comparison for this material was the modulus of rupture, a value used to denote the ultimate strength of a brittle material when subjected to forces producing bending. The compressive strength of this material

$p = 14.7 \text{ psi}$
 $a = 6.2 \text{ inches}$
 $b = 3.7 \text{ inches}$
 $c = 2.45 \text{ inches}$

$$(1) W = P \pi (b^2 - c^2) = 358 \text{ lbs}$$

$$(2) P'' = P + P'$$

To find P' : The bearing pressure of the 2,400 pound load is determined and then applied to the entire surface of the ring.

$$(3) P' = \frac{\text{Load}}{\text{Area}} = \frac{2400}{\pi [(6.2)^2 - (4.6)^2]} = 44.3 \text{ psi}$$

$$(2a) P'' = 44.3 + 14.7 = 59 \text{ psi}$$

The stress at the outside diameter of the ring is given by:

$$(4) \sigma_a = \frac{3P''}{4t^2} \left[(a^2 - 3b^2) + \frac{4b^4}{a^2 - b^2} \left(\ln \frac{a}{b} \right) \right] + \frac{3W}{2\pi t^2} \left[1 - \frac{2b^2}{a^2 - b^2} \left(\ln \frac{a}{b} \right) \right]$$

$$(4a) \sigma_a = 13,100 \text{ psi}$$

The stress at the inside diameter of the ring is given by:

$$(5) \sigma_b = \frac{3P''}{4t^2} \left[\frac{4a^2b^2}{a^2 - b^2} \left(\ln \frac{a}{b} \right) - (a^2 - b^2) \right] + \frac{3W}{2\pi t^2} \left[1 - \frac{2a^2}{a^2 - b^2} \left(\ln \frac{a}{b} \right) \right]$$

$$\sigma_b = -9350 \text{ psi}$$

$$\text{Factor of Safety} = \frac{30,000}{13,100} = 2.3$$

* Roark, R.J., "Formulas for Stress and Strain", McGraw-Hill Book Company, New York, 1954

Figure 7-2. Upper Head Analysis - Ring Method

a = 2.45 inches
b = 3.7 inches
c = 6.2 inches
d = 4.6 inches

The mean diameter (D_m) on which the 2,400 pound load is carried is 5.4 inches. The mean load per unit length is given by:

$$(1) \quad \text{Mean Load} = L' = \frac{\text{Load}}{\pi D_m} = 70.7 \text{ lb/in}$$

The mean load distributed over the length of application results in a pressure of:

$$(2) \quad P' = \frac{L'}{c-d} = 44.2 \text{ psi}$$

There is a vacuum load (P) of 14.7 psi (Figure 7-2).

There is a vacuum load (W) of 358 pounds (Figure 7-2); this load is distributed around the circumference as given by:

$$(3) \quad L'' = \frac{W}{2\pi b} = 15.4 \text{ lb/in}$$

The resulting loading pattern is shown below:

X = 0.9 inch
Y = 1.6 inches
Z = 2.5 inches

$$(4) \quad M = L''Z + PX \left(Y + \frac{X}{2}\right) + (P + P') \frac{Y^2}{2} = 141 \text{ in-lb}$$

if the beam thickness (t) = 0.220 inch, $j = 0.11$

$$(5) \quad \sigma = \frac{Mj}{I} = \frac{3M}{2j^2} = 17,500 \text{ psi}$$

$$\text{Factor of Safety} = \frac{30,000}{17,500} = 1.7$$

* Roark, R.J., "Formulas for Stress and Strain", McGraw-Hill Book Company, New York, 1954

Figure 7-3. Upper Head Analysis - Beam Method

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Assume a loading situation of:

$P = 2400$ pounds (from ring)

$M = 350$ in-lb (from ring position)

$r = 1.25$ inches

$R = 6.5$ inches

$t = 0.240$ inch

from reference*: $(1) S = 1.82 \frac{r}{R} \sqrt{\frac{R}{t}} = 1.92$

from reference* charts: using S:

$$\text{Radial membrane force from } P = N_{XP} = -0.065 \frac{P}{t} = -650 \frac{\text{lbs}}{\text{in}}$$

$$\text{Radial moment from } P = M_{XP} = 0.032 P = 77 \frac{\text{in-lb}}{\text{in}}$$

$$\text{Tangential membrane force from } P = N_{YP} = 0.020 \frac{P}{t} = -200 \frac{\text{lb}}{\text{in}}$$

$$\text{Tangential moment from } P = M_{YP} = 0.010 P = 24 \frac{\text{in-lb}}{\text{in}}$$

$$\text{Radial membrane force from } M = N_{YM} = -0.075 \left(\frac{M}{Rt} \sqrt{\frac{R}{t}} \cos \theta \right) = \pm 87.5 \frac{\text{lb}}{\text{in}}$$

$$\text{Radial moment from } M = M_{YM} = 0.070 \left(\frac{M}{R} \sqrt{\frac{R}{t}} \cos \theta \right) = \pm 19.2 \frac{\text{in-lb}}{\text{in}}$$

$$\text{Tangential membrane force from } M = N_{YM} = -0.023 \left(\frac{M}{Rt} \sqrt{\frac{R}{t}} \cos \theta \right) = \pm 26.8 \frac{\text{lb}}{\text{in}}$$

$$\text{Tangential moment from } M = M_{YM} = 0.023 \left(\frac{M}{R} \sqrt{\frac{R}{t}} \cos \theta \right) = \pm 6.5 \frac{\text{in-lb}}{\text{in}}$$

$$(2) \text{ Radial stress} = \sigma_x = \frac{N_{XP}}{t} + \frac{N_{XM}}{t} \pm \frac{6M_{XP}}{t^2} \pm \frac{6M_{XM}}{t^2}$$

$$\text{Maximum } \sigma_x = -13,075 \text{ psi}$$

$$\text{likewise, maximum } \sigma_y = -8,575 \text{ psi}$$

$$(3) \text{ Factor of Safety} = \frac{30,000}{13,075} = 2.3$$

* Bijlaard, P.P., "Computation of the Stresses from Local Loads in Spherical Pressure Vessel or Pressure Vessel Heads", The Welding Research Council Bulletin No. 34, March, 1957.

Figure 7-4. Lower Head Analysis

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is much higher than the modulus of rupture. Mounting the material in a manner which will not create an intolerable stress concentration necessitates its use as a compression-type support. A compression-type support system has been designed (Figure 7-1).

Accurate determination of the component dimensions at an elevated temperature, and actually accomplishing alignment of the supports, is necessary to avoid an excessive bending moment on the supports during the various possible types of loading.

Further investigation of fused silica supports indicated that this type of support would be unsatisfactory since strength values were obtained on heavy cross-section samples. The tube size (0.125 inch wall) required for the insulation envelope would not allow development of a suitable moment of inertia. To obtain the required mechanical performance, a much larger cross-sectional area is necessary which will proportionately increase the heat loss.

A study of alternate support methods was conducted. Three immediate methods were evaluated. First, a series of truncated cones (telescoping tubes) was considered since a long conduction path can be obtained. The confined space between the enclosure walls limits the number of tube cycles, resulting in a total insulation envelope heat loss of approximately 34 watts. Second, long wire supports were evaluated. Because of the elevated temperature, the high strength normally developed in cold drawn wire cannot be realized, so this method was rejected.

The support structure selected for use in the first insulation envelope is a single thin wall tube located at the bottom of the enclosure. The tube is welded to the enclosure at both ends to allow function as a cantilevered beam. Figure 7-5 shows the revised insulation vacuum enclosure design with the thin-wall tube support.

Stress analysis of the thin-wall tube support resulted in the following:

Buckling

Realistic design stress for local buckling of a thin-wall tube under uniform longitudinal compression is 40% to 60% of theoretical value. Using 40% of theoretical value, the design buckling stresses at temperature were determined as:

$$\sigma_{1325^{\circ}\text{F}} = 21,600 \text{ psi}$$

$$\sigma_{50^{\circ}\text{F}} = 31,900 \text{ psi}$$

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Figure 7-5. Insulation Enclosure - First Unit

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The maximum compressive stress will be applied to the tube in operation and under a vibration condition producing 3 g's. This maximum stress was calculated to be 9580 psi, providing a 2.2 factor of safety.

Bending

The maximum transverse bending moment which may be applied to a thin-wall tube without exceeding the elastic instability stress was reduced to an equivalent critical stress and determined as:

$$\sigma_{B,Cr} 1325^{\circ} F = 35,400 \text{ psi}$$

$$\sigma_{B,Cr} 50^{\circ} F = 52,300 \text{ psi}$$

The maximum bending of the support tube occurs perpendicular to the tube center-line under 3 g vibration loading. The actual stress values for this condition were calculated as:

$$\sigma_B 1325^{\circ} F = 32,440 \text{ psi}$$

$$\sigma_B 50^{\circ} F = 49,240 \text{ psi}$$

The stress analysis was based on no support being provided by either the thermal insulation or the bellows. The minimum 1.06 factor of safety under a 3 g load situation will be magnified to some degree by subsidiary support from the bellows and insulation.

7.3.1.2 ALTERNATE MECHANICAL DESIGN

To further reduce heat losses and to provide a greater factor of safety in the support member, thermal and mechanical analyses are being conducted on replacement of the bellows with a tube. The bellows was initially selected for containment of the vacuum while minimizing neck heat loss with a long conduction path. Since the thin-wall tube is currently required as the most feasible support, use of a stronger tube in place of the bellows may result in a more efficient insulation envelope. Results of these analyses are expected prior to fabrication of the second insulation envelope.

7.3.2 HEAT LOSS ANALYSIS

The insulation envelope design criteria provide for a unit with a maximum heat loss of 25 watts (th) and a five-year life. Results of thermal analysis of the insulation envelope designs are shown in Table 7-1.

Table 7-1. Insulation Heat Losses - Watts (Th)

Heat Loss Component	Bellows and Fused Silica Design	Bellows* and Thin-Wall Support Design	Thin-Wall** Neck Tube Design
Insulation Layers	7.2	7.2	7.2
Bellows	6.6	6.6	} 17.6
Support	8.4	14.2	
Total (watts)	22.2	28.0	24.8
<p>*Current Design - The first unit will be fabricated to this design.</p> <p>**Preliminary Values - The second unit will be fabricated to this design if final design analysis indicates it to be superior.</p>			

The calculated heat losses are based on two experimentally determined curves showing thermal performance of the insulation layers. The thermal conductivity as a function of hot side temperature is shown in Figure 7-6.

The dimensionless thermal conductivity as a function of vacuum is shown in Figure 7-7. As indicated, the thermal design objectives will require maintenance of vacuum at less than 15 microns of mercury over the five-year design life.

Thermal Energy Loss Calculations

Insulation Layers

Total mean surface area of insulation = $A_I = 3.44 \text{ ft}^2$

$$T_1 = 1325^\circ \text{ F}, \quad T_2 = 50^\circ \text{ F}$$

$$\text{Insulation thickness} = \Delta X_I = 1.716 \text{ inches}$$

Figure 7-6. Mean Apparent Thermal Conductivity of High Temperature Insulation versus Hot Side Temperature

Figure 7-7. Thermal Conductivity Ratio versus Vacuum

Temperature difference = $\Delta T = T_1 - T_2 = 1275^\circ \text{F}$

Mean apparent thermal conductivity between 1325°F and 50°F

$K_m = 0.0008 \text{ BTU/hr-ft-}^\circ\text{F}$ (from Figure 7-6)

Heat loss = $q_I = K_m A_I \frac{\Delta T}{\Delta x_I} = 24.5 \text{ BTU/hr.} = 7.2 \text{ watts (th)}$

Bellows-Conduction

Bellows outside diameter = OD = 5.9 inches

Bellows inside diameter = ID = 4.9 inches

Number of convolutions = N = 11

Thickness = t = 0.008 inch

$$\text{Mean bellows diameter} = D_m = \frac{OD + ID}{2} = 5.4 \text{ inches}$$

$$\text{Mean cross-sectional area} = A = \pi D_m t = 0.137 \text{ inch}^2$$

$$\text{Approximate bellows length} = \Delta X = N(OD-ID) = 11 \text{ inches}$$

$$\text{Mean thermal conductivity of Inconel X} = K_x = 115 \frac{\text{BTU-in}}{\text{Hr-Ft}^2-\text{°F}}$$

$$q_{B1} = K_x A \frac{T}{\Delta X}$$

$$q_{B1} = 12.7 \text{ BTU/hr} = 3.7 \text{ watts}$$

Bellows Radiation

$$\text{Radiation area} = A_R = \frac{\pi}{4}(OD^2 - ID^2) = 0.059 \text{ Ft}^2$$

$$\text{Reflective surfaces} = N_R = 2N = 22$$

$$\text{Stefan-Boltzman Constant} = \sigma = \frac{173}{\text{°R-Ft}^2\text{-Hr}}$$

$$\text{Emissivity} = \epsilon = 0.35$$

$$q_{B2} = \frac{\sigma \epsilon A_R (T_1^4 - T_2^4)}{(2 - \epsilon)(N_R + 1)} = 9.9 \text{ BTU/hr.} = 2.9 \text{ watts}$$

$$\text{Total heat loss through bellows} = q_{B1} + q_{B2} = 3.7 + 2.9 = 6.6 \text{ watts}$$

Bottom Support

$$X = 2.75 \text{ inches}$$

$$D = 1.25 \text{ inches}$$

$$A = \frac{\pi}{4}(D^2 - d^2) = 0.244 \text{ inch}^2$$

$$d = 1.00 \text{ inch}$$

Mean thermal conductivity of Corning No. 794 Glass = $K_c = 0.63 \frac{\text{BTU}}{\text{Hr-Ft-}^\circ\text{F}}$

$$q_{BS} = K_c A \frac{\Delta T}{\Delta X} = 5.95 \frac{\text{BTU}}{\text{Hr}} = 1.75 \text{ watts}$$

Top Supports

$$D = 1.00 \text{ inch}$$

$$d = 0.88 \text{ inch}$$

$$X = 1.56 \text{ inches}$$

$$\text{Area} = \frac{\pi}{4} (D^2 - d^2) = 0.177 \text{ inch}^2$$

$$\text{Area of three supports} = A_T = 0.53 \text{ inch}^2$$

$$q_{TS} = K_c A_T \frac{\Delta T}{\Delta X} = 22.7 \frac{\text{BTU}}{\text{Hr}} = 6.65 \text{ watts}$$

$$\text{Total heat loss of supports} = q_{BS} + q_{TS} = 8.4 \text{ watts}$$

$$\text{Total insulation envelope heat loss} = 22.2 \text{ watts}$$

7.3.3 INSULATION ENVELOPE FABRICATION

Two simulated biological shields (Figure 7-8) have been fabricated of stainless steel. Two mating electrical heater blocks (Figure 7-8) were also fabricated. These units will be used in assembly and processing of the first and second insulation envelopes.

Each simulated shield and heater block is thermocouple instrumented (Figure 7-9) so temperatures may be monitored during insulation processing and testing.

In assembly of the insulation envelope, the instrumented, simulated shield is placed in the lower head of the inner shell (Figure 7-10). Instrumentation is then drawn over the heater block cavity of the simulated shield and the inner shell-upper head assembly is fitted over the simulated shield (Figure 7-11). The inner shell-upper head assembly consists of the top-ring, bellows, and upper head.

Figure 7-8. Simulated Biological Shield with Electrical Heater Block

Figure 7-9. Instrumented, Simulated Shield

Figure 7-10. Instrumented, Simulated Shield in Inner Shell - Lower Head

Figure 7-11. Enclosed Shield Subassembly

Succeeding units may have a straight tube support in place of the bellows. The upper and lower heads are then joined by a circumferential edge weld and the bottom support is welded to the lower head.

After welding, the subassembly is mounted on a wrapping mandrel (Figure 7-12) fitted with a block fixture which conforms to the heater block cavity and bolt arrangement of the simulated and prototype shields.

The subassembly is then wrapped with alternate layers of thin metallic foil and fibrous spacer material which forms the insulation.

Details of assembly for placement of the getter material and attachment of the outer shell are being developed during construction of the initial unit.

7.3.4 THERMAL PERFORMANCE TEST PROCEDURE

It is necessary to determine the actual heat loss of the insulation envelope for correlation of design analysis and for system specification.

Steady state energy losses will be measured while minimizing extraneous heat losses to provide accurate evaluation of the insulation envelope thermal performance.

The heater block will be inserted into the simulated shield as shown in Figure 7-13. An electrical resistance heater cartridge in the heater block will be the thermal energy source during the test. The large metallic areas available for solid conduction within the shield, as opposed to the high quality insulation surrounding it, will ensure a uniform temperature on the outer surface of the shield. Thermocouples will be used to measure the temperature of the outer surface of the shield, bellows-ends, and outer shell.

Insulation will be installed over the heater block and within the bellows region. An O-ring and flat plate will seal this volume during the evacuation necessary to ensure proper performance of the insulation.

Instrumentation and power leads will be brought out of this evacuated volume through a vacuum sealant gland.

The test will be started, after assembly of the equipment, by evacuating the bellows volume. Power will be supplied to the heater cartridge and the shield surface temperature monitored. The temperature of the outer shell surface will be controlled by the

Figure 7-12. Insulation Wrapping Mandrel

circulation of fluids. The steady state energy loss is then obtained by measuring the electrical input to the heater cartridge. Thermal energy losses not attributable to the insulation system, such as through the insulation in the bellows region, lead wires and wire sheathing, may be accurately calculated. The input power to the system may then be corrected to yield an accurate evaluation of the thermal energy losses.

Figure 7-13. Thermal Performance Test Assembly

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APPENDIX A

SNAP 21-B RADIOISOTOPE POWER SUPPLY PRELIMINARY ENGINEERING DESIGN SUMMARY

This preliminary design summary was prepared in accordance with the standard RIPS form. A complete design summary will be drafted upon completion of the system. The final summary will include drawings, diagrams and performance characteristics which are currently presented in appropriate sections of Quarterly Reports.

ENGINEERING DESIGN SUMMARY of: SNAP 21-B Deep Sea Radioisotope-Fueled Thermoelectric Power Supply System

Contractor: Minnesota Mining and Manufacturing Company

Contract No. AT (30-1) 3321

User(s) and Mission: N/A

Status: Conceptual Design Complete 12-1-64

Date Prepared: 1/11/65

SYSTEM AND GENERATOR DATA

System Concept: PbTe - T/E - 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	pounds	507 $\pm$ 10 pounds	19 $\pm$ 2 pounds
Length	inches	27.85	4.15
Diameter	inches	15.836 OD maximum	7.84 and 4.45
Volume	cubic inches	3339	89.3

		<u>Total System</u>		<u>Generator</u>	
		Start of Life	End of Life	Start of Life	End of Life
Electric output	watt (e)	10.1	10.1	13.8	11.7
Thermal input*	watt (th)	185.6	163.8	138.6	124.2
Efficiency	percent	5.44	6.16	10.0	9.39
Specific power	watt (e)/pound	0.20	0.20	0.73	0.62
Open circuit voltage	volts	24	24	5.95 + 0.868	5.067 + 0.727
Design voltage	volts	24	24	Same	Same
Design current	amps	0.421	0.421	N/A	N/A

Temperature Profile

Design Basis: Start of Life

Fuel maximum	1422°F	
Fuel capsule surface	1412°F	
Hot junction or T _h	1100°F	
Cold junction or T _c	103°F	
Thermionic T _v	N/A	
Generator housing	1108 by 86°F	
Tip of fins	N/A	
Converter housing	N/A	
Ambient	41°F	
Total thermal input*	185.6 watt	100%
Heat to T/E	138.6 watt	74.7%
Heat dumped for power flattening**	2.32 (e) watt	1.2%
Heat loss through T/E insulation	6.3 watt	3.4%
Other system heat losses	37.0 watt	19.9%
DC-DC converter loss	1.38 watt	0.8%
Heat from housing	60.8 watt	32.8%
Dump from generator	124.8 watt	67.2%

*Thermal input has been revised as follows:

Heat Requirement Area	Previous Analysis (watts)	Current Analysis (watts)
Thermoelectric legs	144.0	138.6
Insulation envelope	24.0	28.0
Other	19.0	19.0
Total	187.0	185.6

**Power flattening heat dump is by zener diode regulator (2.32 watts (e) at start of life, approaching zero with decay of the radioisotope)

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SYSTEM ENVIRONMENTAL CAPABILITIES

Operational Environment (including transportation)

Temperature: $34.5^{\circ}\text{F} \pm 6.5^{\circ}\text{F}$ (nominal)
-65 $^{\circ}\text{F}$ to +130 $^{\circ}\text{F}$ (extreme range)

Pressure: 10,000 psi; 22,500 feet (ocean depth)

Humidity: Minimum - N/A
Maximum - 100% in salt atmosphere

Shock: As incurred in vibration

Vibration: 5 to 32 cycles per second having an excursion within 0.054 to 0.066 inch or an excursion producing 3 g's

Acceleration: As incurred in vibration

Storage

Storage life: 5 years

Temperature: $42.5^{\circ}\text{F} \pm 97.5^{\circ}\text{F}$

Pressure: 10 to 32 inches of Hg

Humidity: 100% relative humidity +

Other: None

SAFETY DATA

Operation, Handling and Transportation

Radiation Dose Rates

	In Operation	At System Surface	Unshielded at 1 Meter from Center of System, Maximum
Total gamma mrad/hr:	200	200	10
Total neutron mrad/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: 1425 $^{\circ}\text{F}$

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Maximum pressure	10, 000 psi
Impact velocity (capsule intact)	N/A ft/sec
Re-entry Burnup:	N/A
Long-term Corrosion:	Exposed to Sea Water at 10, 000 psi
Design Life:	300 years

FUEL SPECIFICATIONS USED IN DESIGN AND SAFETY ANALYSIS

Fuel supplied by	ORNL
Isotopic composition	SR-90
Chemical form	SrTiO ₃

Physical Properties

Melting point	1900° F
Boiling point	N/A° F
Kindling temperature	N/A° F
Maximum continuous operating temperature	1425° F
Limiting factor	Capsule integrity
Density	3.7 gm/cc at 70° F
Specific activity	33 curies/gm
Specific power	0.21 watt/gm
Power density	0.8 watt/cc
Specific heat	0.143 BTU/gm° F
Thermal conductivity	0.0132 cal/sec-cm ° C

Nuclear Radiation

Type	t 1/2 (yrs)	Energy (mev)	%	Remarks
gamma (bremsstrahlung)	30	2.18 max.	100	Primary Beta absorbed in fuel, secondary gamma by bremsstrahlung radiation

Determined Dose Rates

Type of radiation	Dose rate (mrad/hr.)	Remarks
gamma	200	At surface of Pressure Vessel

Chemical Properties

Chemical reactions	None applicable
Corrosion effects	None

Health Data

Half-lives:

Radiological	28 years
Biological	50 years
Effective	18 years
Maximum permissible body burden	20 μc
MPC air	$3 \times 10^{-10}^* \mu\text{c/cc}$
MPC water	$4 \times 10^{-6}^* \mu\text{c/cc}$

Toxicity: N/A

*168-hour week

HEAT SOURCE

System

Thermal Input:

Start of life	185.6 watt (th)
End of life	163.8 watt (th)
Capsules per generator	1
Isotope(s) and chemical form	Sr-90 SrTiO ₃

Capsule

Overall length	3.337 inches
Overall diameter	3.198 inches
Length/Area	0.416 inch^{-1}
Fuel Loading per capsule (start of life)	187 watt (th) 890 gms 30,000 curies

Internal volume per capsule

Total	14.3 inches ³
Fuel	14.3 inches ³
Void	0 inch ³
Internal Pressure	60 maximum psi @ 1400° F after 1 year

		Capsule	Capsule Liner
<u>Material</u>		Hastelloy Alloy C	SS 316
Inside diameter	inches	2.698	2.660
Inside length	inches	2.737	2.680
Wall thickness, sides	inches	0.250	0.020
Wall thickness, ends	inches	0.250	0.030
Total weight	pounds	3.8	0.1
Melting point	° F	2400	2500
Thermal Conductivity	BTU/hr-ft-° F	10.0 @ 1150° F	12.4 @ 932° F
Linear expansion coefficient	10 ⁻⁶ /° F	8.2	12.8 @ 1900° F
Density	pounds/inch ³	0.323 @ 72° F	0.290 @ 72° F
Strength-Tensile	psi	121,000 @ 72° F	75,000 @ 72° F
Yield	psi	81,000 @ 72° F	30,000 @ 72° F
Closure-Method		weld	weld
Material		Hastelloy Alloy C	SS 316
Penetration	inches	0.100	0.020
Shear strength		100%	100%

THERMOELECTRIC CONVERSION ASSEMBLY

Couples/generator	48
Modules/generator	1
Couples/module	N/A
Electrical resistance:	
Generator	1.32 ohms (end of life)
Module	N/A ohms
Couple	N/A ohms
Type of circuit: series	
Thermoelectric efficiency	10.0% (start of life)
Energy conversion efficiency (net, system)	6.16% (end of life)

Thermoelements

		<u>P</u>	<u>N</u>
Thermoelectric material (segmented)		(BiSb) ₂ Te ₃ -PbTe, SnTe	PbTe-PbTe
Fabrication method		powder-pressed	powder-pressed
Length	in.	0.446	0.600
Diameter	in.	0.188	0.188
Length/Area	in.	16.15	21.73
Average operating temp.	° F	N/A	N/A
Hot junction temp.	° F	1100	1100
Cold junction temp.	° F	103	103
Thermoelement efficiency	%	8.87	11.04

		SEGMENT		SEGMENT	
		COLD	HOT	COLD	HOT
Seebeck coefficient (millivolt/° F)	T ° F				
	S @ 200	84	42	128	75
	S @ 600	96	92	165	116
	S @ 1000	N/A	126	126	126
Electrical resistivity (μohm-in.)	ρ @ 200	260	480	730	200
	ρ @ 600	630	900	~2500	650
	ρ @ 1000	N/A	1800	~3000	~1800
Thermal conductivity (watt/in. -° F)	K @ 200	0.021	0.023	0.027	0.039
	K @ 600	0.022	0.019	0.021	0.023
	K @ 1000	N/A	0.022	0.029	0.022
Figure of Merit (10 ⁻⁴ - ° R ⁻¹)	Z @ 200	0.00127	0.00018	0.00082	0.00070
	Z @ 600	0.00064	0.00054	0.00057	0.00079
	Z @ 1000	N/A	0.00041	0.00020	0.00045

Hot Shoe

Material	Iron
Thickness	0.020 inch
Diameter	0.228 inch
Bond (material, thickness and method)	N/A
Diffusion barrier (material and thickness)	Hot shoe serves this function

Note: Connected in series by copper electrode
(0.544L x 0.248W x 0.040 Thick)

Cold Shoe

Material	Copper
Thickness	0.176 and 0.326 inch
Diameter	0.188 inch
Bond (material, thickness and method)	Tin Solder
Diffusion barrier (material and thickness)	N/A

Electrical Leads Between Couples

Material	Silver
Thickness	N/A inch
Diameter	0.033 inch
Method of attachment to cold junction	Solder

Thermal Contact

Method of assuring thermal contact	Spring pressure
Materials and dimensions	From generator 347 S. S. hot frame through boron nitride electric insulation, copper hot strap, iron hot shoe, thermoelectric leg, copper cold shoe, aluminum follower to the generator cold frame (See Quarterly Report No. 2 -- Figure 2.1)

DC-DC CONVERTERS

Circuit type:	Modified Royer
Converters/system:	1
Principal components:	Transistors, transformer, capacitors, resistors, zener diode
Weight	6 ± 2 pounds
Length	4.4 inches
Impedance	N/A ohms
Diameter	10.2 inches
Transistor material	Germanium/silicon
Transformer core material	50% Ni-Fe

		<u>Start of life</u>	<u>End of life</u>
Efficiency	%	N/A	87.5 Min.
Output power	watt(e)	10.1	10.1
Output voltage(s)	volts	24.0	24.0
Output current(s)	amps	0.421	0.421
Input power	watt(e)	13.8	11.7
Input voltage	volts	N/A	5.1, 0.7*
Input current	amps	N/A	2.22, 0.150*
Oscillating frequency		250 cps	
Operating temperature		70° F ± 5° F	
Voltage regulation		± 3.0%	
Transistor losses		1.104 watt(e) Maximum	
Ripple (peak to peak)		100 mv	
Transformer losses		0.326 watt(e) Maximum	
*3-wire input			
sealed in an aluminum enclosure			

OTHER COMPONENTSFill Gas or Vacuum

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

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

Material and Dimensions	"MIN-K 1301" insulation powder-packed and xenon back-filled in all generator void space
Estimated Thermal Conductivity	0.0192 BTU/hr-ft-° F

Electrical Insulation

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

Material	721 Titanium
Coating	None
Outer diameter	14.675 inches
Height	27.850 inches
Typical thickness	1.090 inches
Flange: O.D.	15.831 inches
I. D.	10.500 inches
Typical thickness	2.665 inches

Seals

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

Electrical Lead Throughs

Type, number material:	Through pressure vessel; 28 "Niron" gold and cooper plated pins; Titanium 721; to be bolt attached to pressure vessel penetration
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APPENDIX B

SNAP 21-B SYSTEM ANALYSIS WITH ALTERNATE THERMAL INSULATION

The SNAP 21-B system design provides an insulation envelope surrounding the biological radiation shield and fuel capsule. This insulation is intended to direct maximum heat transfer to the thermoelectric generator and to minimize extraneous heat loss. In the event that the current insulation envelope proves ineffectual for long-term use in the system, an alternate insulation must be selected and an appropriate system designed.

This study was conducted to determine if the existing system design could be modified to provide an efficient system of acceptable size, or if an entirely new concept would be required.

METHOD OF ANALYSIS

The existing system configuration (Figure B-1) was reduced to basic design components. Each of the components was assigned reference dimensions from the generator-shield baseline and from the centerline.

Each pertinent system parameter such as fuel loading, heat loss, and component size was quantitatively reduced to a function of the fuel radius (R_1). A computer program was written in Fortran to perform the following calculation procedure.

1. Set the radius of the fuel (R_1).
2. Calculate the fuel length = $2R_1$.
3. Calculate WATTS = $f(\text{fuel volume})$
4. Since the thermoelectric generator assembly required 171 watts, subtract 171 from WATTS to get heat loss through the insulation.
5. Calculate R_3 , R_4 , and R_5 to allow for the proper heat loss and a dose rate of 200 mr/hr at the surface of the vessel.
6. Calculate total weight of the system consisting of:
 - a. Constant weight of thermoelectric generator
 - b. Heat sink
 - c. Fuel

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Figure B-1. SNAP 21-B System Configuration

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- d. Fuel capsule
 - e. Shield
 - f. Insulation
 - g. Pressure vessel
7. Calculate efficiency = 10 watts/WATTS.
8. Increment the radius of the fuel and repeat from step 2.

Use of 171 watts in step 3 was established as the total thermal requirement of the thermoelectric generator leg subassembly, internal generator heat loss, and shield support losses.

Step 5 is an iterative computer calculation which operates as shown in Figure B-2. The thermal conductivity of "Min-K 1301" used in this analysis is: $K = 0.02 \text{ BTU/Hr-Ft-}^{\circ}\text{F}$. Program result was a print-out of pertinent information from an efficiency of 1.54% to an efficiency of 4.65%. Sample results are presented in Table B-1.

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Figure B-2. Determination of Shield and Insulation Thicknesses

Table B-1. Alternate Thermal Insulation Analysis Sample Results

Item	Program Increment								
	1	2	3	5	7	10	21	27	37
Fuel	2	2	2	3	3	3	4	5	7
Fuel Capsule	4	4	4	4	4	5	6	6	7
Shield	140	168	195	233	257	291	385	432	492
Insulation	571	273	166	79	48	32	15	13	10
Pressure Vessel	3668	1754	1076	529	340	241	154	146	140
Heat Sink	278	185	145	105	88	77	67	65	64
<u>System</u>	4662	2386	1588	951	740	648	630	667	720
L ₁	1.97	2.17	2.34	2.54	2.65	2.78	3.04	3.13	3.19
L ₂	2.22	2.42	2.59	2.79	2.90	3.03	3.29	3.38	3.44
L ₃	4.97	5.21	5.41	5.68	5.86	6.09	6.72	7.02	7.42
L ₄	5.27	5.51	5.71	5.98	6.16	6.39	7.02	7.32	7.72
L ₅	7.25	7.68	8.06	8.53	8.82	9.18	10.06	10.45	10.91
L ₆	30.12	24.28	21.21	17.62	15.84	14.74	13.81	13.90	14.12
R ₁	1.37	1.39	1.41	1.44	1.47	1.53	1.71	1.81	1.98
R ₂	1.67	1.69	1.71	1.74	1.77	1.83	2.01	2.11	2.28
R ₃	3.65	3.86	4.05	4.29	4.43	4.61	5.05	5.25	5.48
R ₄	24.18	18.33	15.19	11.47	9.59	8.31	6.81	6.61	6.44
R ₅	28.05	21.27	17.62	13.31	11.13	9.64	7.90	7.67	7.47
R ₆	32.06	25.74	22.43	18.54	16.61	15.40	14.35	14.43	14.63
<u>Heat Input (Watts)</u>	215	223	231	248	266	295	417	495	648
<u>Efficiency (%)</u>	4.65	4.48	4.32	4.03	3.76	3.39	2.40	2.02	1.54

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