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AEC RESEARCH AND DEVELOPMENT REPORT

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SNAP 21-B PROGRAM
DEEP SEA RADIOISOTOPE-FUELED
THERMOELECTRIC GENERATOR
POWER SUPPLY SYSTEM
BIMONTHLY REPORT
1 January 1965 to 28 February 1965

Published March 1965

Prepared by:

D. A. Benson

Approved by:

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Program Manager

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Bimonthly Report
1 January 1965 to 28 February 1965
SNAP 21-B PROGRAM
DEEP SEA RADIOISOTOPE-FUELED
THERMOELECTRIC GENERATOR
POWER SUPPLY SYSTEM

By

D. A. Benson

V. Yanisch, Jr.

ABSTRACT

The deep sea power supply system will use segmented semiconductor PbTe thermoelectric alloys which, when operated between 1100° F and 103° F, will perform at 10% materials efficiency. Generator design modifications have resulted in attainment of thermoelectric performance at 94% of theoretical prediction.

A fuel capsule and radiation shield have been developed that not only provides adequate fuel containment but has been proved to be completely safe in all environmental hazards and credible accidents.

The high temperature thermal insulation envelope has been redesigned to provide additional strength and improve structural characteristics.

Fabrication and procurement of system components are in progress.

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Report No. MMM(3321)-13

Bimonthly Report
1 January 1965 to 28 February 1965
SNAP 21-B PROGRAM
DEEP SEA RADIOISOTOPE-FUELED
THERMOELECTRIC GENERATOR
POWER SUPPLY SYSTEM
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BIMONTHLY REPORT

SUMMARY

An 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.

The first system integration test was conducted and all special instrumentation devices requiring long lead time have been received.

The fabrication of thermoelectric couples was completed and three prototype generators were assembled. Two of these prototype generators were processed, sealed and placed on test at simulated thermal conditions to measure power output.

Fuel capsule tests were performed to simulate the various possible environmental hazards.

Fabrication of the biological radiation shield was completed.

Three DC-DC converters were constructed, sealed in their cases and leak tested.

Fabrication and assembly of the initial insulation envelope was completed. Processing and thermal heat loss tests were conducted on this first system.

The pressure vessel material, alloy 721 Titanium has been received, tested, and approved by the forging vendor. Initial work has been started on forging tools and dies.

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Report No. MMM (3321)-13

Bimonthly Report
1 January 1965 to 28 February 1965

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

Contract AT(30-1)3321

INTRODUCTION

This contract work is being conducted by the 3M Company, Isotope Power Laboratory, Electrical Products Division. The main objectives of this program are to design, develop, fabricate, and test components leading to the manufacture of a 10-watt, 24-volt power supply for deep sea application at 10,000 psi.

The main system design requirements areas follows:

- 10-watt 24-volt continuous output
- 5-year life
- High efficiency
- Minimum weight
- High reliability
- Resist salt water corrosion at 10,000 psi
- Sr-90 titanate fuel
- Fully shielded device
- Removable thermoelectric generator

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Figure 1-1. SNAP 21-B Radioisotope-Fueled Thermoelectric Generator Power Supply System

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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 subsystems 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 ACCOMPLISHMENTS

- System instrumentation has been established and all special instrumentation devices requiring long lead time have been received.
- System humidity reduction calculations have been made.
- The first system integration test was conducted.

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:

- Hot junction temperature
- Cold junction temperature
- Open circuit voltage
- Short circuit voltage
- Short circuit current
- System voltage under load conditions
- System current under load conditions
- Internal gas pressure
- Internal humidity
- Pressure vessel leakage

All special instrumentation requiring possible long lead time has been received.

A description of how most of the instrumentation will be measured was given in the third quarter report. Instrumentation not received by the third quarter or covered in the SNAP 21-B third quarterly report is described as follows:

A Consolidated Electrodynamics Corp. Type 4-312, 0 to 50 psi absolute pressure range transducer will be used to sense the pressure within the vessel cover. A Kepco, Inc. Model ABC 10 power supply will furnish a regulated DC voltage to the transducer. The millivolt output of the transducer can be recorded on any non-current drawing millivolt meter or recorder. The system has been checked at atmospheric pressure in the 3M laboratory for stability. A view of this test setup is shown in Figure 1-2.

A Hydrodynamics, Inc. wide range sensing element Model #15-2001 and read-out indicator Model #15-3001 will be used to measure the relative humidity in the vessel cover. The indicator unit also provides the power needed to supply the sensor unit and a voltage output tap for recording instrumentation. The system will provide readout of the relative humidity in the sensor area and the temperature for correction of the indicated relative humidity during temperature excursions. When sealing the vessel in high humidity conditions, a desiccant is provided to reduce the humidity to within the range of the sensor. The sensor is capable of a 33 to 94% humidity range at 40°F to a 21 to 83% humidity range at 120°F. A view of this test setup is shown in Figure 1-3.

Preliminary calculations indicate a quantity of 120 grams of silica gel desiccant will reduce the humidity from 100% to 45% at a temperature of 100°F. A laboratory test, using simulated conditions, will be initiated to substantiate the calculations.

Figure 1-2. Pressure Transducer with Power Supply

Figure 1-3. Humidity Sensor Test Apparatus

1.3.2 SYSTEMS INTEGRATION TESTS

The first system integration test was conducted during this period.

Although this was a systems test, it has been designated a "simulated thermal test" since several of the system components were simulated rather than of prototype design. The primary purpose of this test was to obtain a first indication of the feasibility of the proposed system as a whole. Although the thermal response of the system was of primary concern, the test also provided for a shakedown of the various mechanical components.

Concerning thermal response, the greatest value of this test was to provide experimental data for correlation with "design" or predicted heat transfer and temperature distributions.

1.3.2.1 System Integration Test Hardware

The hardware used for this test is shown in Figure 1-4 and is listed as follows for reference and identification:

- 1) Pressure Vessel: A cast, type CF8C (AISI-347) stainless steel pressure vessel was used. This vessel was machined in two parts, the body and the cover. The resulting vessel was per design except for excess material on the exterior hemispherical surfaces of the cover and body. This excess material resulted in hemispherical wall thicknesses of about one inch rather than the prescribed 1/2 inch.
- 2) Insulation Envelope Substitute: A stainless steel and aluminum structure was used to provide the necessary axial support for the segmented centering ring. This envelope substitute was designed to simulate the load bearing capabilities of the Linde super insulation system. See Figure 1-5.
- 3) Insulation: The area below the horizontal plate of the envelope substitute was packed with Johns-Manville Micro-Quartz® and the area above the plate (around the thermoelectric generator) was packed with Johns-Manville MIN-K 1301®.
- 4) Thermoelectric Generator: The 3M-37-P1 thermoelectric generator was used in this test. This device was electrically shorted and contained no internal thermocouple instrumentation. Because of the short circuit, it was necessary to operate in an open circuit condition throughout the test. See Figure 1-6.

- 5) Mounting Plate: The generator mounting plate was fabricated as shown in Figure 1-7.
- 6) Centering Ring: The segmented centering ring components are shown in Figure 1-8.

1.3.2.2 System Integration Test Instrumentation

The location of the thermocouple instrumentation for this test is shown in Figure 1-4. Three types of thermocouples were used to cover the expected temperature spectrum. These were as follows:

<u>Thermocouple No.</u>	<u>Calibration</u>
1 - 24	TYPE T (copper-constantan)
25 - 29	TYPE K (chromel-alumel)
31	TYPE J (iron-constantan)

All internally-located thermocouples were enveloped in a Fullers Earth-sodium silicate adhesive. All surface thermocouples were spot welded except for #22 which was bonded using Technical "G" copper cement.

1.3.2.3 System Integration Test Results

The results of the various phases of this test are shown in Table 1-1. It is important to note several facts shown in the experimental data:

- 1) The critical temperature drop across the 0.128 inch radiation gap (thermocouples 25 and 26) was about 200⁰ F. This is very close to the predicted or expected value.
- 2) The temperature at the base of the cold plate (thermocouple #1) was near the expected value of 90⁰ F.
- 3) Comparison of the data in columns C and D shows that a true steady-state temperature condition was achieved and that there is little change of these thermal conditions over a period of four days. It should be recognized, however, that the water temperature for this thermal condition was 49⁰ F rather than 40⁰ F.

With successful completion of this system integration test, the proposed prototype system will meet design thermal conditions.

Figure 1-4. System Integration Test - Hardware and Instrumentation

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Table 1-1. System Integration Test Data

	A	B	C	D
Date	2/9/65	2/11/65	2/11/65	2/15/65
Time	4:35 p.m.	9:30 a.m.	9:05 p.m.	9:00 a.m.
Input Power	230	220	192	220
<u>Thermocouple</u>	<u>Temperature (° F)</u>			
1	89	95	89	96
2	83	89	84	90
3	82	90	84	90
4	75	82	76	82
5 *	72	79	74	79
6 **	68	75	71	75
7	73	80	76	81
8	68	74	70	74
9	56	62	59	62
10	48	53	52	53
11	52	58	56	58
12	46	50	48	50
13	42	46	46	47
14	49	55	51	54
15	229	277	243	274
16	581	613	520	596
17	269	300	266	300
18	66	72	68	74
19	53	59	57	60
20	47	54	52	54
21	47	53	52	53
22	52	58	56	58
23	45	52	50	52
24	43	49	48	49
25	1324	1325	1207	1318
26	1125	1127	998	1124
27	Not Functioning			
28	1151	1164	1025	1147
29	1134	1142	1012	1133
30	Not Located			
31	106	116	106	114
*In mounting plate				
**In segment				

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1.3.3 THERMOELECTRIC PROTOTYPE DESIGNATIONS

To better identify thermoelectric prototypes under investigation each prototype has been given a designation as shown in Table 1-2.

Table 1-2. Thermoelectric Prototype Generator Designation

Designation	Status
3M-37-P1	Developed short circuit, disassembled
3M-37-P2	Assembled, not electron beam welded, disassembled
3M-37-P3	Electron beam welded; system leaked; O-ring seal on test
3M-37-P4	(Same as 3M-37-P3)
3M-37-P5	Rebuild, new case fabrication, use thermoelectric couples from 3M-37-P 2

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Figure 1-5. Insulation Envelope Substitute

Figure 1-6. Thermoelectric Generator

Figure 1-7. Mounting Plate

Figure 1-8. Segmented Centering Ring

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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

- The fabrication of thermoelectric couples was completed.
- Three prototype generators were assembled. Two of these three generators were electron beam welded to attach and seal the case to the generator.
- An O-ring seal, dimensionally compatible with the rest of the system, was designed and applied to the two prototype generators which leaked at the electron beam weld.
- These two prototype generators were processed, sealed, and placed on test to measure power output at simulated thermal conditions.
- Development was initiated on a new generator case design that would permit final closure by means other than electron beam welding.

- The three 6-couple modules (described in SNAP 21-B quarterly No. 3) were monitored to determine long term performance. Experimental data collected from the modules were reviewed and analyzed.
- The design of the final generator has initiated with completion pending the outcome of generator case development.
- Two hundred P and N-legs of the latest design have been fabricated for building the final two generators.
- An experimental generator case was revised with a silver brazed joint utilized between the copper cold frame and the stainless steel generator case, and with a heliarc weld between the generator case segments and the hot frame. Prototype generator 37-37-P5 will utilize these principles. Two more prototype generators, (3M-37-P6 and 7) will be built shortly utilizing the revised case design and new fabrication techniques.
- Three cases (simulating the weld areas of the proposed generator cases) were fabricated and welded. One case was sectioned and analyzed.
- Three experimental generator cases were fabricated and generators will be assembled without thermoelectric couples, but will contain springs and thermal insulation.
- Thermoelectric generator terminals were studied, and special terminals were ordered for evaluation.

2.3 TECHNICAL DISCUSSION AND RESULTS

2.3.1 THERMOELECTRIC GENERATOR DESIGN AND FABRICATION

The assembly of three generators was begun after completion of thermoelectric couple fabrication. These generators differed from the original design in the following ways:

- 1) Generator case design detail was changed to provide a better electron beam weld at the cold frame.
- 2) The hot junction electrode design was modified to reduce circuit electrical resistance.
- 3) Simultaneously pressed P-legs were used in one generator to obtain performance data.

2.3.1.1 Generator Case-to-Cold Frame Weld Procedure

When assembly of the three generators was complete, electron beam welding was used to attach the generator cases to the copper cold ends on two of the generators. However, it became apparent because of leaks that this procedure was inadequate. For this reason, the third generator was not welded.

The O-ring seal was installed into the two generators which had been welded (See Figure 2-1). With a hermetic seal temporarily assured, the generators were processed, sealed and placed on test to measure electrical power output (See Figure 2-2).

A program was initiated to develop a different generator case design which would permit closure by means other than electron beam welding. Several designs utilizing a TIG welding procedure were evaluated. TIG welding can not be used to attach the case to the copper cold frame directly. Therefore, a short section of the case would need to be silver brazed to the cold frame prior to making the final closure weld.

Several designs were studied to evaluate the effect of their parameters upon the weld of the two generator case sections. Parts were fabricated incorporating various thicknesses of the generator case. Preliminary components were TIG welded with welding parameters (welding speeds, feeds, current, and gas flow) being varied during the procedure. These welds were examined by macroetching cross sections of the weld area, see Figures 2-3, 2-4. On the basis of these examinations, further weld development and testing will be conducted.

2.3.1.2 Thermoelectric Leg Configuration

The design of the final generator has been initiated and incorporates a thermoelectric leg configuration different from the previous generator design. This leg configuration is a result of the most recent thermoelectric leg analysis. The N and P-leg length is a parameter of this revised design and will affect the generator structure. The length of the generator case will be modified to accommodate this new leg length. The completion of this final generator design is contingent upon completion of the case development.

Two hundred N and P-legs of the latest design have been fabricated. These legs will be used in the two final thermoelectric generators, prototypes, 3M-37-P6 and 7.

2.3.2 THERMOELECTRIC GENERATOR ASSEMBLY

The same fixture was used for assembly of the three generators as described in SNAP 21-B Quarterly Report No. 3. No problem was encountered with this fixture or with

Figure 2-1. Generator O-Ring Installation

Figure 2-2. Thermoelectric Generator Prototype 3M37-P3 and 4 on Test

Figure 2-3. Hot Side Edge Weld of Mock-Up Generator Case

(a)

(b)

Figure 2-4. Cold Side Side Weld of Mock-Up Generator Case

(a)

(b)

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the assembly procedure. Whereas no changes were made in the fixture, it is ascertained that free movement of the rotating shafts is important for obtaining good electron beam welds. For this reason, when the generator was assembled in position, extreme care was taken to align the two shafts at each end of the fixture so that free rotation could be assured.

2.3.2.1 Thermoelectric Legs

The thermoelectric legs were revised as shown in Figure 2-5. Lengths of the P type segmented legs were changed from 0.451" nominal to 0.411" and N-type elements were changed from 0.600" to 0.571". This was done to allow for a lower segmenting temperature in the P-leg to allow for the Thomson effect. (See Section 2.3.3.3 Expected Changes in Performance Due to Thomson Effect, SNAP 21-B Program Quarterly Report No. 3). Because of the Thomson effect there is an upward temperature shift at the segment point. Therefore, a higher extraneous electrical loss was allowed in the generator and a lower segmenting temperature was chosen for the P-leg. As a result, the actual power developed in thermoelectric legs (while allowing for the Thomson effect) is theoretically higher (See table 2-3, SNAP 21-B Quarterly Report No. 3). The overall length of the thermoelectric-legs with cap was changed from 0.776" to 0.746" nominal. These legs will be used in generators 3M-37-P6 and 7.

2.3.2.2 Electrical Output Terminals

Electrical output terminals will be counterbored into the bottom of the copper cold frame for additional mechanical protection. The terminals will also be repositioned slightly to make generator assembly easier. Special glass-to-steel hermetically sealed terminals with extra-long tubular feed-throughs for thermocouples are under investigation. These long feed-throughs will allow the thermocouples to be fastened and hermetically sealed with less danger of thermally shocking the glass headers. This can be done by heat-sinking the tubes between the glass seal and soldering area.

2.3.3 SIX-COUPLE ELEMENT TESTS

To accurately appraise the performance of the different thermoelectric modules, it is necessary to be aware of the physical differences in the thermoelectric legs used in each. A description of the geometrical characteristics of these legs is detailed in SNAP 21-B Quarterly Report No. 3. During the months of January and February, 1965, the three 6-couple thermoelectric modules described in that report were periodically monitored to determine the long-term performance characteristics of the associated thermoelectric legs. In addition, all experimental data collected from the modules were reviewed and thoroughly analyzed to more accurately determine the true level of module performance.

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Figure 2-5. P and N-Type Thermoelectric Legs

Figure 2-6. Thermoelectric Generator
Electrical Output Terminal

Tables 2-1 to 2-3 show performance data for modules A-1, A-3 and A-4. The test of module A-2 was terminated February 16, 1965, as will be described below. In Tables 2-1 to 2-3 the following nomenclature is used:

T_h ($^{\circ}$ F)	- Average hot electrode temperature
T_c ($^{\circ}$ 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

Comparison of the data in these tables with that presented in Tables 2-6 to 2-9 of the third Quarterly SNAP 21-B Report reveals only small performance differences in any of the given modules. These differences are presented after thorough data analysis as mentioned above. Portions of the data from Tables 2-1 to 2-3 are shown graphically in Figures 2-7 to 2-9.

As seen in Figures 2-7 to 2-9, and as discussed in the last quarterly report, there has been a gradual increase in power output with time for all three modules. The power output for each of the modules has asymptotically approached a maximum value and is remaining constant at the respective level.

Examination of the data in Figures 2-7 and 2-8 shows that module A-1 and A-3 are performing almost identically. Both exhibit Seebeck voltage deviations of about 1 percent (within the experimental error tolerances) and have approached a 10 percent deviation power level. It is important to note that although these modules are delivering about 10 percent less than the expected output power, performance is stable after nearly 5000 hours of continuous operation. It should be noticed that these modules contain legs with identical geometrical characteristics; however, A-1 has simultaneously pressed P-legs and A-3 has individually pressed and bonded P-legs.

Examination of the data in Figure 2-9 substantiates the apparent output power increase for module A-4 as indicated in the last quarterly report. This module has exhibited a constant Seebeck voltage of 1.39 volts, exactly as predicted, and has approached a steady 6 percent power deviation level. The steady performance after nearly 3000 hours of continuous operation is of greater significance than the exact power level. Based on performance (Table 2-4), this module is delivering about 21 percent more power than modules A-1 and A-3. The legs in module A-4 have different geometrical characteristics than those contained in modules A-1 and A-3. The P-legs in module A-4 are of the individually pressed and bonded variety.

Table 2-1. Performance Data Thermoelectric 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	1098	115	1.31	0.66	1.96	1.29	342
8-24-64	1100	115	1.35	0.68	1.93	1.31	347
9-17-64	1090 Est	119	1.34	0.69	2.00	1.34	326
10-27-64	1100 Est	117	1.35	0.68	2.07	1.40	325
11-30-64	1100 Est	115	1.35	0.68	2.09	1.42	320
2-25-65	1100 Est	114	1.35	0.68	2.09	1.41	323

*Begin test 7-28-64 (5,112 hours as of 2-25-65)

Table 2-2. Performance Data Thermoelectric Module A-3*

Date	T _h (°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
10-14-64	1100	117	1.35	0.68	2.00	1.35	331
10-26-64	1097	114	1.35	0.67	2.13	1.42	320
1-21-65	1100 Est	111	1.35	0.69	2.10	1.44	316
2-16-65	1100 Est	113	1.35	0.68	2.11	1.42	320
2-26-65	1100 Est	113	1.35	0.68	2.09	1.41	323

*Begin test 9-15-64 (3,960 hours as of 2-26-65)

Table 2-3. Performance Data Thermoelectric Module A-4*

Date	T_h (°F)	T_c (°F)	E_o (Volt)	E_L (Volt)	I_L (Amp)	P_o (Watt)	R (M-Ohm)
10-29-64	1099	115	1.39	0.70	2.22	1.54	312
11-25-64	1102	115	1.39	0.71	2.26	1.61	300
1-5-65	1100 Est	114	1.39	0.72	2.30	1.66	291
1-21-65	1100 Est	112	1.39	0.73	2.33	1.71	282
2-19-65	1100 Est	117	1.39	0.70	2.46	1.71	283

*Begin test 10-20-64 (2,952 hours as of 2-19-65)

Table 2-4. Thermoelectric Module Performance Data

	Modules A-1 and A-3		Module A-4
	A-1*	A-3**	A-4***
T_h (°F)	1100 Est	1100 Est	1100 Est
T_c (°F)	114	113	117
E_o (Volt)	1.35	1.35	1.39
E_L (Volt)	0.68	0.68	0.70
R (M-Ohm)	323	323	283
I_L (Amp)	2.09	2.09	2.46
P_o (Watt)	1.41	1.41	1.71

*Based on data of 2-25-65

**Based on data of 2-26-65

***Based on data of 2-19-65

Figure 2-7. Electrical Performance Data Module A-1

Figure 2-8. Electrical Performance Data Module A-3

Figure 2-9. Electrical Performance Data Module A-4

2.3.4 PROTOTYPE GENERATOR TESTS

During the previous two months, two 48-couple prototype generators were assembled and put on test. These generators were designated prototypes 3M-37-P3 and 4.

In order to fully evaluate and compare the performance characteristics of these two generators, differences in the thermoelectric legs used in each assembly should be noted. Both generators contain legs of identical geometrical characteristics and both contain segmented, simultaneously pressed N-legs. Prototype 3M-37P3 contains segmented, simultaneously pressed P-legs; however, prototype 3M-37P4 contains segmented, individually pressed and bonded P-legs. The physical characteristics of the legs contained in both these generators are shown in Table 2-5.

Typical performance data for prototypes 3M-37-P3 and 4 are shown in Tables 2-6 and 2-7. In these tables, the same nomenclature is used as was defined for Tables 2-1 to 2-3. Prototype 3M-37-P3 was put on test February 21, 1965, and prototype 3M-37-P4 on February 22, 1965; hence only a small amount of data had been compiled prior to this report. When comparing the data in Tables 2-6 and 2-7, the ΔT differences imposed upon each of these generators should be noted. It appears upon cursory reading that prototype 3M-37-P3 is performing much better than 3M-37-P4; however, it should be noted that prototype 3M-37-P3 is operating with a ΔT of about 973, whereas prototype 3M-37-P4 is operating with a ΔT of about 962. Although this difference is relatively small, the total effect when imposed upon 48 couples in series can be quite significant.

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Table 2-5. Thermoelectric Leg Data Prototypes 3M-37-P 3 and 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. Performance Data Prototype 3M-37-P 3

Date	T _h (°F)	T _c (°F)	E _o (Volt)	E _L (Volt)	I _L (Amp)	P _o (Watt)	R (Ohm)
2-25-65	1091	118	10.70	5.35	2.48	13.27	2.15

Table 2-7. Performance Data Prototype 3M-37-P 4

Date	T _h (°F)	T _c (°F)	E _o (Volt)	E _L (Volt)	I _L (Amp)	P _o (Watt)	R (Ohm)
2-24-65	1098	136	10.98	5.49	2.30	12.62	2.38

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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

- The pressure vessel material alloy 721 titanium, was received by the forging vendor.
- Acceptance tests were made on the pressure vessel material.
- Material acceptance was confirmed.
- Initial forgings were made from billet ends of the 721 titanium heat to be used for the pressure vessel.
- Titanium blocks were machined in preparation for fusing glass around the electrical feed-through pins.
- An order was placed for an electrical plug which will provide strain relief and coupling to the pressure vessel.
- Design of this plug has been completed and fabrication has been started. Titanium is being used as the structural material.

3.3 TECHNICAL DISCUSSION AND RESULTS

The pressure vessel material was received at Taylor Forge and Pipe Works and acceptance tests were run by both Taylor Forge and Titanium Metals Corporation of America. The acceptance tests were tabulated and found to vary slightly. Discussions

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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

- The fuel capsule tests were performed to simulate the various possible environmental hazards.
- The fuel capsule material was verified analytically.
- The electric heater design was completed.

4.3 TECHNICAL DISCUSSION AND RESULTS

During the proposed operation of the generator, it is possible that the fuel capsule may be subjected to various environmental hazards. These hazards were simulated with a fire test, a thermal shock test, a vibration test and a hydrostatic pressure test conducted on sample capsules. Each capsule tested contained a pellet of AISiMg-614, a material intended to closely simulate the physical properties of strontium titanate. Results indicate satisfactory maintenance of integrity, other than the formation of a slight greenish oxide coat during exposure to fire temperatures, no damage occurred to any of the test specimens.

A sample of the fuel capsule material was verified analytically to be Hastelloy-C by 3M laboratory personnel.

Two capsules (Nos. 9 and 10) were fire tested. They were placed in a furnace and heated as shown in Table 4-1. A thermocouple placed adjacent to a capsule was used to register temperature. Figure 4-1 shows capsule No. 9 after being fire tested.

4.3.1 FIRE TEST

Two capsules (Nos. 9 and 10) were fire-tested. They were placed in a hot furnace and heated as shown in Table 4-1. A thermocouple placed adjacent to a capsule was used to register temperature. Figure 4-1 shows capsule No. 9 after being fire-tested.

Figure 4-1. Capsule After Fire Test

Table 4-1. SNAP 21-B Fuel Capsule Fire Test

Time (minutes)	Temperature (°F)	Time (minutes)	Temperature (°F)
0	968	65	1760
1	1040	73	1837
3	1065	74	1850
8	1130	83	1850
13	1184	103	1850
18	1249	134	1852*
23	1308	138	1832
28	1368	303	1276
33	1418	444	1053**
38	1479		
43	1535		
48	1609		
53	1641		
59	1700		

*Power turned off; capsules remain in furnace

**Capsules removed from furnace

Upon removal from the furnace and with subsequent cooling, it was noted that the once shiny surfaces of the capsules were oxidized black. To verify the apparent integrity maintenance, the capsules were hydrostatically pressurized to 10,000 psi. Accurate weighings on a triple beam balance before and after the pressure application revealed no fluid intrusion. Dye penetrant applied to the surfaces and a helium leak check of each capsule verified the soundness of the capsule.

4.3.2 THERMAL SHOCK TEST

A capsule (No. 12) was allowed to equilibrate at 1850° F in a furnace. It was removed from the furnace and immediately plunged into 50° F water. The action was repeated on another capsule (No. 18). The surfaces of these capsules oxidized and were noted to have a slight greenish cast upon removal from the water. Hydrostatic pressure tests to 10,000 psi with accurate weighings before and after showed no loss of capsule integrity. Dye penetrant applied to each capsule revealed no surface cracks and helium leak checks indicated that the capsule's integrity had not been breached.

4.3.3 HYDROSTATIC PRESSURE TEST

Four capsules (Nos. 6, 7, 8 and 14) were pressurized to 29,500 psi in an isostatic press. The pressure was increased manually at a 1000 psi per minute rate. Any deformation which occurred was relatively minor and not immediately apparent. A micrometer revealed a 0.020 to 0.030 inch depression radially and a similar depression lengthwise. Accurate weighings with a triple beam balance before and after pressure application showed no fluid inclusion. Dye penetrant revealed no surface cracks, and a helium leak check on each capsule verified that no breeches were incurred.

4.3.4 VIBRATION TEST

A vibration test was performed on one of the capsules (No. 13) at Environ Laboratories in Minneapolis, Minnesota. A 3M representative witnessed the test. Equipment involved included an M-B model C-50 shaker, a M-B model T-88 control console, an M-B model T-665 amplifier, an Endevco model 2226 accelerometer and Endevco model 2641B amplifier. All vibration was applied parallel to the longitudinal axes of both the test unit and the dummy unit.

The initial run was made with the dummy unit to determine what resonance, if any, occurs. No resonances were noted during this run. This was completed in eight (8) minutes, fifty (50) seconds.

For the next run, the dummy unit was replaced with the test unit and a cycling test was accomplished. This run consisted of making three complete cycles from 5 cps to 3000 cps to 5 cps and from 65 cps to 1080 cps. During this run, the phenomena of Table 4-2 was noted.

Table 4-2. SNAP-21B Fuel Capsule Vibration Test

Cycle	Started Resonance Build-Up	Peaked Resonance	Completed Resonance
1st up	280 cps	830 cps	
1st down	1000 cps	800 cps	
2nd up		620 cps	
2nd down	1140 cps	780 cps	300 cps
3rd up	600 cps	809 cps	1000 cps
3rd down	1013 cps	780 cps	320 cps
4th up	160 cps	814 cps	1059 cps

These frequencies are approximate. This run was completed in 62 minutes, 10 seconds.

The third run was a resonance dwell on a test unit. This dwell was performed entirely at 16 g's peak acceleration. The dwell was started at 820 cps. After 1.5 minutes, the resonance was again peaked; this time at 820 cps. After four minutes of dwell, the resonance was again peaked; this time at 833 cps. After five minutes of dwell, the resonance was again peaked; this time at 831 cps. After six minutes of dwell, the resonance was again peaked; this time at 827 cps. After six and one-half minutes of dwell, the resonance was again peaked; this time at 783 cps. After ten and one-half minutes of dwell, the resonance was again peaked; this time at 884 cps, and it was dwelled at this frequency for 13 minutes. The shifting of the resonant dwell was due to the mock fuel and/or its container moving within limits in the test unit.

In place of the dwell, a cycling test between the frequencies of 600 cps and 1000 cps at a level of 16 g's peak acceleration for a period of ten minutes, three seconds was substituted.

A hydrostatic pressure test to 10,000 psi, a dye penetrant check and a helium leak check indicated that integrity of the capsule had been maintained.

4.3.5 ELECTRIC HEATER

The electric heater for SNAP-21B is designed to closely simulate the heating characteristics of a fuel capsule loaded with the radioisotope fuel.

Three cartridge heaters connected in a parallel circuit are inserted into a cylindrical copper block. The dimensions of the copper block correspond to the outside dimensions of the stainless steel inner fuel liner. The copper block is then inserted into a prototype fuel capsule. Three holes on a triangular pitch are drilled into the upper fuel capsule and plate to accommodate the leads from the cartridge heaters. The entire assembly is then enclosed inside of a chromium-plated copper jacket. The purpose of the copper jacket is to prevent contact between the U-8% Mo shield and the Hastelloy-C fuel capsule. The leads from the heater are brought out of the shield through holes drilled in the shield plug. The parallel connection is made on the outside of the shield. The cartridge leads are insulated with the American Lava fishbone (alumina) ceramic beads as the lead insulation material. Figures 4-2 and 4-3 are photographs showing the components of the heater element and an assembly of the electric heater.

Two versions of the heater have been made. One uses a heater made by the Ogden Manufacturing Company (No. 0-62 2-5) of 120 volts and 100 watts. The other, Chromalox C-12038 cy XX 120 volt and 165 watts.

Figure 4-2. Electrical Heater Components

Figure 4-3. Electrical Heater Assembly

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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

- Fabrication of the radiation shield was completed.
- Materials and methods for maintaining subsystem compatibility were determined.

5.3 TECHNICAL DISCUSSION AND RESULTS

5.3.1 RADIATION SHIELD FABRICATION

Fabrication of the radiation shield was completed in January. Radiography, however, revealed a void in the bottom of the shield. The void was located and drilled and plugged with bar stock. The plug was secured by welding subsequent radiograph indicated a sound shield resulted. The shield with the plug and bolts was weighed prior to cladding. The shield weighed 255 pounds.

Pure depleted uranium metal is the best low weight shielding material. Pure uranium, however, has an undesirable phase change at the operating temperature of the shield. The uranium-8% molybdenum alloy selected for the biological shield exhibits a gamma stabilized structure with little loss in density. It offers high strength, ductility and excellent corrosion resistance. It machines well and hot forms by most forging processes. It is highly susceptible to oxidation and forms eutectics with many of the common engineering materials (Group VIII metals, Fe, Ni, Co, etc.). It must therefore be protected from oxidation and contact with incompatible materials.

An extensive literature survey revealed a scarcity of information on the compatibility of the shield alloy with contacting materials. However, the general consensus is that Hastelloy-C and U-8% molybdenum can form an eutectic solution at temperatures near

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the operating temperature of the SNAP-21 B fuel capsule and shield. Also, U-8% Mo can similarly react with Inconel and Inconel alloys. Therefore, the problem is to physically separate the radiation shield (U-8% Mo) from the fuel capsule (Hastelloy-C) and the insulation system (Inconel X).

A compatible material well suited as a separating layer is copper. Copper, however, is subject to rapid oxidation at the operating temperatures.

The design procedure is to use 0.025" of electroplated copper as the basic separating material and to plate the copper with a thin (0.0005 inch) flashing of chromium. An investigation was made by the Nuclear Metals Division of National Lead Company in order to determine the best method of plating the copper onto the uranium alloy. They prepared twelve small cylindrical specimens of clad U-8% Mo using several different plating techniques. (A detailed description of the various platings will be included in the report next month.) After plating, a sample of each method was subjected to an exposure of one hour at 1400° F in an argon atmosphere. The samples were then sectioned and examined.

This study indicated that the shield should be directly plated with copper from a sulfate solution for the electrolyte. The plating time was estimated at 36 hours. Considerable difficulty ensued when following this laboratory scheme in the production plating baths.

Treering and non-uniform deposits proved especially troublesome. These characteristics had shown up in the laboratory specimens but were thought to have been overcome in the last attempts. The addition of a brightener helped some, but it was still necessary to remove the shield and plug periodically to dress it to a uniform thickness. It was then necessary to reactivate the surface of the copper such that plating could continue. The use of a 5% sulfuric acid solution was called for but was misread as 0.5% and the subsequent plate was non-adherent and complete stripping of the plate was necessary. Future platings are expected to be thinner to avoid some of these problems.

The fuel capsule cannot be plated because of its "hot" (radioactive) nature when loaded with the fuel pellets. Neither is it convenient to electroplate the inside of the radiation shield. Therefore, the barrier between the fuel capsule and the radiation shield has been formed by fabricating a copper cylinder to fit between the capsule and the shield.

Arrangements are being made for National Lead Company to ship the shield to the Linde Division of Union Carbide Company. It is expected that the shield will be shipped via RR express, Armed surveillance.

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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

- Three converters were constructed, sealed into their cases and leak tested. All converters met the electrical specifications but one converter case had a leak.
- Parts for the converter test fixture were fabricated and construction of the test fixture was started.
- The maximum permissible leak rate for the converter case was determined.
- The backfilling procedure for the converter case was defined, and a preliminary specification was generated.
- The possibility of gas evolution from the converter transformer (due to nuclear radiation) was investigated and found to be no problem with respect to pressure build up in the converter case.
- A specification has been prepared which is suitable for ordering a high reliability transformer for the converter. Due to delivery time problems, it will not be possible to obtain this transformer before the end of Phase I of the SNAP 21-B program.
- Data concerning the reliability of the main converter transistors has been received from the manufacturer and evaluated for application to this program.
- The resistance of the 28-pin external connector was measured. This resistance will absorb about 1.5 percent of the generator power. This loss is a direct result of the requirement for measuring generator open circuit voltage and will not be included in system efficiency calculations.
- The converter component mounting assembly was redesigned to provide better heat transfer and to simplify assembly.

6.3 TECHNICAL DISCUSSION AND RESULTS

6.3.1 TRANSFORMER DESIGN

Three transformers for the prototype converters were constructed in the 3M laboratory. Figure 6-1 shows the specification for the transformer electrical parameters. Although this transformer is considered to be of high quality, its reliability is not expected to be as high as that of a transformer which is purchased from an experienced and qualified transformer manufacturer.

Several months ago a letter outlining the electrical specifications, mechanical specifications, and reliability requirements for the transformer was sent to twelve transformer manufacturers. At that time the replies to this inquiry indicated that a failure rate of about 0.05 percent per 1000 hours could be expected. A failure rate of 0.05 percent per 1000 hours would result in failure of 2.2 percent of the transformers during the five year operating life of 44,000 hours.

Of the twelve manufacturers contacted, six issued quotations based on the specifications. Of these six manufacturers, only two were considered capable of meeting the requirements at this time. These two were Raytheon Company Magnetics Operation and United Transformer Company.

It is considered desirable to order sample quantities of this transformer from each manufacturer. Evaluation of the sample production transformers, would provide a basis for final selection of a transformer supplier.

A specification detailing the work to be performed on this transformer was prepared and sent to the transformer manufacturers as part of an order for the prototype transformers. Long delivery time of this transformer (8 to 10 weeks) and the lack of electrical design information on the final thermoelectric generator makes it impossible to receive these transformers and to evaluate them in time to be incorporated into the final prototype system.

6.3.2 CONVERTER DESIGN

Three prototype converters were constructed in the month of January. These were tested for compliance to electrical specifications prior to connection to the regulators and placement in their cases. All converters exceeded the minimum efficiency requirement of 85 percent as shown in Table 6-1. This table also shows the converter parameters at other stages of construction.

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Table 6-1. Converter Performance

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

6.3.2.1 Converter Case

The three converters were sealed into their cases during the month of February. Figures 6-2 through 6-6 show the various stages of construction.

The converter enclosures, less the cover, were leak checked to 10^{-6} mm Hg pressure by a saturated helium bath. Two enclosures passed this test successfully while one unit was rejected. The reject unit was subsequently rewelded and passed the leak check specification.

The enclosure covers were nickel plated to facilitate soldering of the electrical terminations and thermocouple wire feed through fitting. The tabulation fitting was heliarc-welded in place. This fitting served as the processing port for the enclosure.

Prior to placing the converters into their cases, the entire converter plate was cleaned carefully and coated with 1/16" of Scotchcast No. 8 resin. This coating reduces the possibility of a short.

After testing and evaluation with the converter-regulator mounted in the enclosure, the thermocouple wires and electrical connections were made to the cover. The cover was then fitted in place and the converter-regulator re-tested. The heat developed during the heliarc welding of the cover to the enclosure required special handling to prevent damage to the converter components. The enclosure was partially submerged in a water bath as a heat sink. The inner and outer perimeter interfaces of the enclosure were welded in segments while the heat transfer members were monitored to indicate the heat build up. Aluminum filler rod was used to effect the weld.

The converter-regulator units were once again tested for proper operation and found to be satisfactory prior to environmental processing. Two converter-regulator units were enclosed at this time. After the leaky enclosure was satisfactorily repaired, the converter-regulator was mounted, tested, and enclosed using the same procedure.

The temperature rise of the regulator with respect to the converter mounting flange is 18.3°C (33°F). The estimated temperature of the converter mounting flange with the converter mounted into the generator is 15.6°C (60°F). The operating temperature of the regulator is therefore about 33.9°C (93°F). The operating temperature of the transformer will be nearly equal to the temperature of the main power transistor. The temperature rise of the main power transistor with respect to the mounting flange is 4.4°C (8°F). The temperature of the main power transistor is 20°C (68°F). These operating temperatures are considerably below the temperatures which were assumed in the initial calculations.

Figure 6-2. Converter Removed from Case

Figure 6-3. Converter Installed in Case

Figure 6-4. Converter Installed "Super/Reg" Diode Showing

Figure 6-7. Bell Jar with Leak Detector Attached

Figure 6-8. Converter Test Fixture

Figure 6-9. Converter Test Fixture

6.3.2.2 Converter Mounting Assembly Redesign

The converter component mounting assembly was redesigned to include a component panel of 3/32" thick #6061 aluminum plate. See Figure 6-2. This plate was designed to conform to the periphery of the doughnut shaped enclosure. The component panel is pie shaped covering a 120° arc of the annulus area. Two standards of 1/4" aluminum are welded to the bottom of the container. The standards provide a rigid mount for the component panel. The converter transformer, a comparatively heavy component, is mounted on the panel so that the weight is supported rigidly between both standards. The standards provide an efficient path for heat flow from the transistor and regulator components to the base container interface.

6.3.2.3 Converter Backfilling Operation

The converter case was alternately evacuated to 5 psia and backfilled with dry inert gas five times. During four backfills, the pressure was increased to 30 psia by backfilling with nitrogen. The third backfill was helium. The case was not fully evacuated to limit the stress on the converter case and converter components. The moisture content after backfilling is expected to be low enough to eliminate moisture condensation at -65° F. The 2.77 percent helium remaining in the case after the fifth backfill provides for leak detection. The final backfill pressure was adjusted for a pressure of 30 psia at 70° C (158° F).

Leak Rate -- If the minimum pressure in the converter case at -55° C (-67° F) is to be 0 psig, then the maximum internal pressure at 70° C (158° F) will be 23.6 psia. The maximum leak rate must not result in a pressure lower than 23.6 psia at 70° C if the converter case is held at 70° C over a five year period. If the initial pressure at 70° C is 30 psia, the maximum leak rate will be 7.22×10^{-6} cc/second.

Allowing a 5:1 safety factor and considering the helium ratio, the maximum leak rate on a helium mass spectrometer leak detector would be 10^{-8} cc/second. The sensitivity of the leak detector is 10^{-9} cc/second.

Figure 6-7 shows the bell jar with the leak detector attached. Table 6-2 shows the observed leak rates of the converters. Converter D did not pass the leak rate test.

Radiation Pressure Buildup -- Potting compounds have a tendency to decompose into gasses in the presence of gamma radiation. Since potting compounds are used in the construction of the SNAP 21-B converter, the gas evolution was investigated. Since

Table 6-2. Leak Rates of Converter Cases

Converter	Leak Rate*
MP-C	10^{-9} cc/sec
MP-D	4×10^{-6} cc/sec
MP-E	3×10^{-9} cc/sec

*As indicated on a helium-mass spectrometer leak detector.
The maximum permitted leak rate is 10^{-8} cc/sec.

no gas evolution data were available on the potting compounds which were used, a preliminary calculation was based on the outgassing of natural rubber. Natural rubber has one of the higher outgassing rates, and is assumed to be a sufficiently accurate standard. Calculations indicate that a pressure increase of only 0.0002 psi in 30 psia will occur after five years of exposure to the beginning-of-life radiation dose of 200 mr/hr. Since this is over three orders of magnitude below what could be tolerated, no problem is expected.

6.3.2.4 Converter Test Fixture

Figures 6-8 and 6-9 show the partially completed test fixture for two converters. One converter is complete with sealed case. The other converter is a breadboard version to permit observation of internal parameters.

The test fixture contains a regulated power supply which simulates two separate thermoelectric generators, including simulation of the characteristics of the bias tap. All measurement points are brought out to terminals on the front panel. Three types of measurements are to be made: voltage, current and temperature. The voltage and current are read out on a Fluke differential voltmeter with an accuracy of 0.05 percent of input from 0.1 volt to 500 volt or ± 0.1 percent of input, or ± 0.05 MV below 0.1 volt. The current reading is obtained through the use of a special 0.25 percent precision shunt. The temperature readings are obtained with iron-constantan thermocouples and a potentiometer accurate to $\pm 1^\circ$ F. Parameters to be measured are input current, output current, input voltage, output voltage, bias voltage, temperature of converter mounting base, and temperature of ambient air inside of cabinet. A running time meter is provided to keep an accurate check of actual operating hours.

6.3.3 TRANSISTOR RELIABILITY

Reliability data and drift analysis data supplied by Bendix¹ on the main power transistors indicates a failure rate of 1 percent per 1000 hours at 110°C. The design temperature for the converter was 70°C maximum. Using the failure rate extrapolation supplied by Bendix (double every 10°C increase in temperature), the failure rate at 70°C is 0.055 percent per 1000 hours. A failure rate of 0.055 percent per 1000 hours would result in the failure of 2.4 percent of the transistors over a five year operating life of 44,000 hours.

As mentioned in section 6.3.2.1 the actual transistor operating temperature will be about 20°C. The failure rate at 20°C is expected to be about 0.0015 percent per 1000 hours. A failure rate of 0.0015 percent per 1000 hours would result in the failure of 0.06 percent of the transistors over a five year operating life of 44,000 hours.

6.3.4 OUTPUT CONNECTOR POWER LOSS

In order to meet the systems requirement of providing facilities to measure generator open circuit voltage, it will be necessary to bring the high current generator terminals out through the 28-pin connector. The contact resistance of this connector is repeatable at about 0.003 ohm. The present plug for the connector uses #18 wire. The two feet of #18 connecting wire has a resistance of 0.013 ohm. The total resistance per connector is therefore 0.016 ohm. Since the generator current of about 2.3 amps at about 5 volts flows through two of these connectors, a net power loss of about 1.5 percent will occur in the connector. Since this loss is part of the instrumentation and would not occur in a final system, it will not be included in calculating the system efficiency.

¹Reliability of 25 amp DAP Transistors Covering 2N 1651, 2, 3; 2N1751; 2N2285, 6, 7; 2N2636, 7, 8; (Covering the Period January 1962 to August 1962) The Bendix Corporation; Holmdel, New Jersey.

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-° F 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

- Fabrication and assembly of the initial insulation envelope was completed. See Figure 7-1.
- Processing was completed and thermal heat loss tests were conducted on this first system.
- Evaluation was completed of the use of a neck tube to replace bellows and support tube as a structural member for the second and third envelope.
- Fabrication and assembly were initiated and completed on the second insulation envelope.
- Processing of the second insulation envelope was initiated.

7.3 TECHNICAL DISCUSSION AND RESULTS

7.3.1 INSULATION ENVELOPE DESIGN AND ANALYSIS

The analysis of the alternate mechanical design for the second and third insulation envelopes has been completed. This alternate design substitutes a single neck tube for the bellows and lower support tube (See Figure 7-2). This design change was made to reduce heat loss through the mechanical structure, yet maintain proper mechanical support. Stress analysis was performed on a basis of a 3g load imposed on the system. The details of this computation are included in Appendix B with a summary of the neck tube stresses included in the following table:

Figure 7-1. Insulation Envelope - First Design

Figure 7-2. Second and Third Insulation Envelope Design

Table 7-1. Neck Tube Stresses

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

The thermal analysis of this alternate neck tube support design in comparison to the former system showed a reduction in heat loss of 3.2 watts. This 3.2 watts reduction was caused by changes in the support structure; loss though the super insulation remained unchanged.

7.3.2 INSULATION ENVELOPE ASSEMBLY AND FABRICATION

Fabrication of the first insulation envelope was completed during this period with the welding of the upper and lower shell center seam. The bellows had previously been welded to the upper, inner shell. This inner shell was leak-checked after the welding and had no leaks. The support tube was welded in place on the lower inner shell, and then wrapping of the insulation was started. After the wrapping was completed, the outer shells were fitted into place and welded to complete the enclosure of the super insulation. With this enclosure complete and leak-checked, the electric heater was bolted into position. The system was heated and vacuum pumping was also started as part of the processing procedure. As processing continued, the temperature on the hot side was increased to 1550° F to aid in increasing the outgassing rate of the insulation material. With processing complete (as indicated by the dynamic pressure, and by the pressure rise with the pumps sealed off), a heat balance test was conducted.

This heat balance test was conducted with a hot side temperature of 1180° F and cold side temperature of 90° F. Under these conditions the heat input was 38 watts with a calculated extraneous loss of 7.1 watts through electrical leads, top plug insulation,

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thermocouple wires, and radiation windows in top plug. This results in a heat loss through the insulation envelope of 29.1 watts. With these results extrapolated to the condition of hot side temperature of 1325° F and cold side temperature of 50° F, the heat loss through the insulation envelope would be 40.1 watts.

After testing, the system was cooled in preparation for final sealing. During this cooling a leak was discovered in the bellows. Examination showed that this leak was caused by an arc from the electric heater lead wires. Because of the leak, the test was not completely successful, although the heat balance test data was still valid.

Fabrication and assembly was initiated on the second insulation envelope from piece parts previously acquired. This envelope differed from the first envelope in that a neck tube replaced the bellows and the lower support tube was eliminated. The center seam of the inner shell was welded and leak checked. Insulation wrapping was completed and the outer shell was fitted and welded into place. Processing was started after leak checking the outer shell by applying heat and pumping the system. This processing will continue until the envelope pressure has been reduced to the proper level, and the outgassing rate is low enough to be compatible with the amount of getter for five year life.

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APPENDICES

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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: Prototype Design Being Prepared

Date Prepared: 3-1-65

SYSTEM AND GENERATOR DATA

System Concept: PbTe - T/E - Flat Plate Type

Fuel: Sr-90 TiO₃

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 ± 10 pounds	19 ± 2 pounds
Length	inches	27.85	4.12
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)	191.0	168.2	142.0	125.0
Efficiency	percent	5.28	6.00	9.72	9.37
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, Sea Water	41°F

HEAT DISTRIBUTION

Total thermal input	191.0 watts	100%
Heat to T/E	142.0 watts	74.4%
Heat loss through T/E insulation	6.4 watts	3.3%
Other system heat losses	42.6 watts	22.3%
Heat rejected from housing	49 watts	32.8%
Heat rejected T/E couples	128.2 watts	67.2%

Heat requirement area

Thermoelectric legs	142.0 watts
Insulation envelope	30.3 watts
Other	<u>18.7 watts</u>
Total	191.0 watts

SYSTEM ENVIRONMENTAL CAPABILITIES

Operational Environment (including transportation)

Temperature:	34.5° F $\pm$ 6.5° F (nominal) -65° F to + 130° 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° F $\pm$ 97.5° F
Pressure:	10 to 32 inches of Hg
Humidity:	100% relative humidity
Other:	None

SAFETY DATA

Operation, Handling and Transportation

Radiation Dose Rates

	<u>In Operation</u>	<u>At System Surface</u>	<u>Unshielded at 1 Meter from Center of System, Maximum</u>
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 ⁰ F
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 ⁰ F
Boiling point	N/A ⁰ F
Kindling temperature	N/A ⁰ F
Maximum continuous operating temperature	1425 ⁰ F
Limiting factor	Capsule integrity
Density	3.7 gm/cc at 70 ⁰ F
Specific activity	33 curies/gm
Specific power	0.21 watt/gm
Power density	0.8 watt/cc
Specific heat	0.143 BTU/gm ⁰ F
Thermal conductivity	0.0132 cal/sec-cm ⁰ 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 μ c
MPC air	3 x 10 ^{-10*} μ c/cc
MPC water	4 x 10 ^{-6*} μ c/cc

Toxicity: N/A
 *168-hour week

HEAT SOURCE

System

Thermal Input:

Start of life	191.0 watt (th)
End of life	168.2 (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

		<u>Capsule</u>	<u>Capsule Liner</u>
<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

		<u>Capsule</u>	<u>Capsule Liner</u>
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	9.72% (start of life)
Energy conversion efficiency (net, system)	6.00% (end of life)

<u>THERMOELECTRIC LEGS</u>	<u>P</u>	<u>N</u>
Thermoelectric Material (Segmented)	(BiSb) ₂ Te ₃ -PbTe, SnTe	PbTe-PbTe
Fabrication Method	Powder Pressed	Powder Pressed
Hot segment length	inch 0.267	0.371

Cold segment length	inch	0.144	0.200
Total Leg length	inch	0.411	0.571
Diameter	inch	0.188	0.188
Length/area	inch ⁻¹	14.9	20.7
Hot Junction Temperature	°F	1100	1100
Cold Junction Temperature	°F	103	103
Segment Temperature @ Max. Eff.	°F	548	425
Open Circuit Voltage	mv	105.8	125.8
Load Voltage @ Max. Eff.	mv	62.8	72.8
Average Resistivity	μΩ in.	1149	1042
Current @ Max. Eff.	Amps	2.5	2.5
Power @ Max. Eff.	Watts	0.16	0.18
Rate of Heat Rejection	Watts	1.34	1.35
Rate of Heat Absorption	Watts	1.50	1.53
Material Efficiency	Percent	10.5	11.7

N-leg

Operating Temperature °F	T °F	S μV/°F	ρ μΩ in.	K watts/in. °F	Z °C ⁻¹ x 10 ³ *
103	100	115	460	0.0325	1.59
↑	200	126	715	0.0274	1.46
cold	300	138	1050	0.0240	1.36
seg.	400	149	1450	0.0219	1.26
425	500	105	540	0.0258	1.42
↑	600	115	720	0.0233	1.42
hot	700	125	950	0.0213	1.39
seg.	800	133	1200	0.0203	1.31
↓	900	134	1470	0.0205	1.07
1100	1000	130	1730	0.0225	0.78
↓	1100	120	1850	0.0250	0.56

P-leg

103	↑	100	88.5	359	0.0140	2.80
		200	94.5	505	0.0130	2.44
	cold	300	102.5	657	0.0129	2.22
	seg.	400	106.9	843	0.0140	1.74
548	↓	500	105.3	1021	0.0161	1.22
		600	93.0	890	0.0180	0.97
		700	102.0	1070	0.0181	0.97
	hot	800	111.0	1290	0.0190	0.90
	seg.	900	118.0	1520	0.0203	0.81
		1000	123	1750	0.0212	0.73
1100	↓	1100	122	1830	0.0224	0.65

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

$$Z = 1.59 \times 10^{-3}$$

$$Z = 0.00159$$

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 (0.544 L x 0.248 W x 0.040 Thick)

Cold Shoe

Material	Copper
Thickness	0.175 and 0.334 inch

Diameter 0.188 inch

Bond (material, thickness and method) Tin Solder

Diffusion barrier (material and thickness) N/A

Electrical Leads Between Couples

Material Copper

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 $5 \pm 1/2$ pound

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	85.0 minimum
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 ^o F ± 5 ^o 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 COMPONENTS

Fill 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

Temperature 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. Micro quartz insulation in felt form located strategic locations to prevent powder shifting.

Estimated Thermal Conductivity 0.0192 BTU/hr-ft-°F

Electrical Insulation

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

Housing (Pressure Vessel)

Material 721 Titanium

Coating None

Outer diameter 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

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Electrical Lead Throughs

Type, number material:

Through pressure vessel; 28 "Nitron" gold
and copper plated pins; Titanium 721; to be
bolt attached to pressure vessel penetration

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Appendix B
SNAP 21-B INSULATION ENVELOPE
STRUCTURAL AND THERMAL CALCULATIONS

1.0 SPECIFIED ENVIRONMENTAL CONDITIONS

Mechanical vibration 5 to 32 cps, sinusoidal waveform, having an excursion (double amplitude) of 0.054 to 0.066 inch and maximum acceleration of 3 g. The vibration characteristics may be translated into equivalent acceleration loads by the following curves:

Figure B-1. Acceleration vs Vibration Curves for Support Tube

2.0 DESIGN BASIS

- 1) Acceleration is constant 3 g for the 5 to 32 cps frequency band.
- 2) Axial and lateral acceleration conditions are imposed on the support at separate time intervals. Acceleration is limited to three mutually perpendicular axial directions. Torsional cage is shown merely to demonstrate structural integrity for this condition.

- 3) Support constraint at outer casing is a fixed end condition.
- 4) Support tube consists of inconel X-750 with the following 1350° F operating temperature properties.

Tensile strength $\approx 101,000$ psi (reference 1)

Yield strength $\approx 90,000$ psi (reference 1)

Proportional limit $\approx 80,000$ psi (reference 2)

Dynamic modulus of elasticity $\approx 244 \times 10^6$ psi (reference 1)

Poisson's ratio, $\nu \approx 0.29$ (reference 1)

- 5) Support tube dimensions are as follows:

Over-all length, $\ell \approx 2.385$ in.

Mean diameter, $d \approx 4.920$ in.

Minimum thickness, $t \approx 0.011$ in.

3.0 FORCES IMPOSED ON THE SUPPORT TUBE BY VARIOUS POSSIBLE ACCELERATION

Deceleration modes may be approximated as follows:

Figure B-2. Support Tube Forces

Axial Compression of Support Tube

$$\begin{aligned}\text{Compressive Stress } \sigma_c &= 470/\pi/4 (4.932^2 - 4.910^2) \\ \sigma_c &= 2770 \text{ psi}\end{aligned}$$

Axial Tension of Support Tube

$$\begin{aligned}\text{Tensile Stress } \sigma_t &= 1150/\pi/4 (4.932^2 - 4.910^2) \\ \sigma_t &= 6780 \text{ psi}\end{aligned}$$

Transverse Bending of Support Tube

$$\text{Bending Stress } \sigma_b = P/A + Mc/I$$

Assume the force equivalent to 3 g (810#) acting at the center of the inner shell or approximately 675 inches from the most distant thin wall section σ vacuum load $\simeq 340/\pi/4 (4.932^2 - 4.910^2)$:

$$\sigma_b = \frac{810d}{\pi r^3 t} = 2000 + \frac{810 (6.75)(4.920)}{2\pi (2.46)^3 (0.011)} = 28,100 \text{ psi}$$

Torsion of Support Tube

Assume torque forces result from 3 g (810 lb.) rotational deceleration of the inner vessel. Radius of gyration may be determined by considering the inner vessel as a thick wall cylinder with inside diameter $\simeq 3.25$ in. and outer diameter $\simeq 8.625$ in.

$$\begin{aligned}\text{Radius of Gyration, } r &\simeq \frac{\sqrt{d_i^2 + d_o^2}}{4} \\ r &\simeq 2.31 \text{ in.}\end{aligned}$$

Torque resulting from 3 g rotation deceleration $\simeq 2.31 (810)$.

Torque $\simeq 1870$ in-lb.

Torsional stress, $\sigma_\tau = Tc/J$ where $c = d/2 = 2.46$ in. and J , polar moment of inertia = $2\pi r^2 t = 1.029$ in.

$$\sigma_\tau = 1870 (2.46) \div 1.03 = 4470 \text{ psi}$$

$$\sigma_{\tau} + \sigma_{\text{vac load}} = 4470 + 2000 = 6470 \text{ psi.}$$

Combined Transverse Bending and Axial Compression

$$\sigma_{b+c_{\text{max}}} = P/A + Mc/I = 2770 + 26,100 = 28,870 \text{ psi}$$

Combined Transverse Bending and Axial Tension

$$\sigma_{b+t_{\text{max}}} = P/A + Mc/I = 6780 + 26,100 = 32,880 \text{ psi}$$

4.0 ALLOWABLE STRESS LEVELS FOR ABOVE LOADINGS

Axial Compression

Using the same calculation included in progress report No. 2, the theoretical buckling stress, σ_{cr} , is as follows (reference 3):

$$\sigma_{\text{cr}} = \frac{Et}{r \sqrt{3(1-\nu^2)}} = \frac{24.4 \times 10^6 (0.011)}{2.46 \sqrt{3(1-(0.29))^2}} = 65,800 \text{ psi}$$

Assuming a practical design limit of 40 to 60% of the above value as indicated previously, σ_{cr} under uniform axial compression or $\sigma_{\text{cr}} \simeq 0.3 Et/r \simeq 32,700 \text{ psi}$.

Safety factor of the present design based on the above assumptions $\simeq 32,700/2770 \simeq 11.5$.

The preceding calculation does not consider the effects of 17.9 psi internal pressurization conditions. Various elasticity analysis for axial compression with internal pressure indicates improvement in critical buckling stress from recommended minimum design levels ($\sigma_{\text{cr}} \simeq 0.3 Et/r$ (reference 3)) toward the theoretical value of $\sigma_{\text{cr}} \simeq 0.6 Et/r$ (references 4 and 5). Lo, Crate, and Schwartz (reference 4) have tested thin walled cylinders under axial loading through a range of internal pressure and found that the theoretical increase in load with pressure was substantiated although the actual buckling stress obtained experimentally at zero pressure was of the order of half the theoretical value. The maximum pressure applied to the cylinder produced an axial tension stress in the wall equal to roughly half the compression stress at which buckling occurs with no internal pressure. The buckling stress was twice the unpressurized buckling stress. Later investigations (reference 6), however, indicate limited reproducibility of test data. The following curve

included in reference 6 indicates conservative design values for compressive buckling stress as a function of internal pressure. Critical compressive stress for the present case is approximated as follows:

$$0.007 pr/Et \approx 1.14 \times 10^{-6} \text{ from which the value of}$$

$$\frac{\sigma_{c_{cr}}}{E} \frac{R}{t} \approx 0.23$$

Figure B-3. Theoretical Buckling Stress Under Uniform Axial Compression vs Internal Pressure Critical Compression Stress for the Support Tube

$$\sigma_{c_{cr}} \approx 0.22 Et/r \approx 0.23 (24.4 \times 10^6) 0.011/2.46 \approx 25,000 \text{ psi}$$

The above approximation indicates no appreciable change for the present case of axial compression with internal pressure apparently due to the low magnitude of pressurization. Therefore, design safety factor ≈ 9 .

Axial Tension

Safety factor using yield stress of $\sim 80,000$ psi is equal to $80,000/6780 \approx 11.5$.

Transverse Bending

The buckling behavior of cylinders under bending loads corresponds to that of axially compressed cylinders in two respects: theoretical formulations predict buckling stresses of the same order of magnitude for both cases, and secondly, test data are below theoretical predictions by approximately the same amount. Roark (reference 3) predicts local buckling by a relationship analogous to the case of axial compression as follows:

$$\text{Critical Moment, } M_{cr} = \frac{K E r t^2}{1 - \nu^2}$$

where

K is a constant = 1.14.

Since critical stress can be considered $\sigma_{cr} = M_{cr} c / I$ where $c = r$ and $I = \pi r^3 t$, bending

$$\sigma_{cr} = \frac{K E t}{\pi (1 - \nu^2) r}$$

$$\text{Bending } \sigma_{cr} = \frac{1.14(24.4 \times 10^6)(0.011)}{3.14 (1 - 0.29^2)(2.46)} \simeq 43,200 \text{ psi}$$

The above value corresponds to approximately 30% increase over the value calculated for buckling under axial compression.

$$\text{Safety Factor} \simeq 43,200 / 28,100 \simeq 1.54$$

Limited testing has been conducted for the condition of cylinders under bending and internal pressure. No reliable test data exists for r/t configurations < 3000 (reference 6). Hence, any calculation including internal pressure effects may be as misleading as the above calculation for axial compressive loading.

Torsion

For a thin wall cylinder loaded in torsion in the elastic range, buckling is not accompanied by immediate collapse as in the cases of axial compression or bending of thin wall cylinders. From experimental results, initial material or shape imperfections do not appear to affect buckling strengths to any appreciable extent (reference 7). Again, due to the lack of

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extensive test data (reference 6), internal pressure effects are not considered. Timoshenko (reference 7) recommends the following equation for torsional buckling stress:

$$\text{Torsional } \sigma_{cr} = \frac{Et^2}{(1 - \nu^2) \ell^2} \left[4.6 + \sqrt{7.8 + 1.67 \left(\sqrt{1 - \nu^2} \frac{\ell^2}{2tr} \right)^2} \right]^{3/2}$$

$$\text{Torsional } \sigma_{cr} \simeq 565 [45.6] \simeq 26,300 \text{ psi}$$

$$\text{Safety factor} \simeq 26,300/6470 \simeq 4$$

Combined Transverse Bending and Axial Tension or Axial Compression

It is assumed these conditions do not exist during operation of the system. The above calculations are included to indicate the high stress levels imposed on the support tube by simultaneous multidirectional acceleration forces.

5.0 SUPPORT DEFLECTIONS

Total deflection of support system under specified environmental conditions can be approximated from the individual deflections of flange and support tube members as follows.

Flange Deflections (Static 3 g Levels)

Steady-state vacuum deflection of the flange may be determined as a function of distributed surface vacuum loading and concentrated vacuum load (340 lbs) at the inner edge by the following relationship (reference 3).

$$\begin{aligned} \text{Maximum } y &= \frac{-3w(m^2 - 1)}{16m^2 Et^3} \left[a^4 + 3b^4 - 4a^2b^2 - 4a^2b^2 \text{LN} \frac{a}{b} + \frac{16a^2b^4}{a^2 - b^2} \left(\text{LN} \frac{a}{b} \right)^2 \right] \\ &\quad - \frac{3W(m^2 - 1)}{4\pi m^2 Et^3} \left[a^2 - b^2 - \frac{4a^2b^2}{a^2 - b^2} \left(\text{LN} \frac{a}{b} \right)^2 \right] \end{aligned}$$

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where

- w = unit applied load (147 psi)
- m = reciprocal of Poisson's ratio (~ 3.45)
- E = modulus of elasticity (30×10^6 psi)
- W = concentrated edge load (~ 340 lbs)
- a = outer flange radius (~ 3.75 in.)
- b = inner flange radius (~ 2.45 in.)
- t = flange thickness (~ 0.1875 in.)

Maximum steady-state flange deflection $\simeq 0.00043$ in.

Using the same method maximum flange deflection is calculated for steady 3 g upward and downward acceleration forces with resulting respective values of 0.000296 and 0.00116 in.

Calculated torsional deflection of the flange under torque loading of 1870 in-lb is 0.000147 in. Displacement associated with 3 g transverse acceleration forces is considered of the same magnitude due to flange rigidity and high natural frequency. Magnification of the above displacements under vibratory conditions is considered as unity.

Support Tube Deflections (Static 3 g Levels)

Deflections of the support to be under various 3 g directional vibrations can be considered from stress-strain diagrams (reference 2) for the above stress levels.

Compressive deflection $\simeq 0.0002$ (2.385) $\simeq 0.000477$ in.

Extensional deflection $\simeq 0.0003$ (2.385) $\simeq 0.000715$ in.

Bending deflection may be determined by considering the support tube as a cantilever beam with superposed transverse forces imposed at the shield-tube connection instead of the shield midpoint as indicated previously.

Maximum y, deflection at tube-shield interface may be defined as follows:

$$\text{Max } y = -\frac{1}{3} \frac{W L^3}{E I}$$

$$\text{Max } y = -\frac{1}{3} \frac{(2290)(2.385)^3}{(24.4 \times 10^6)(0.5146)}$$

$$\text{Max } y = 0.000808 \text{ in.}$$

Torsional deflection of the support tube under 3 g (1870 in-lb) torsional forces may be approximated as follows:

$\theta = TL/KG$ where θ = angle of deflection, radians; T = torque (1870 in-lb);
 L = tube length (2.385 in.); K = polar moment of inertia (1.029 in.^4);
 G = modulus of rigidity ($\sim 7.5 \times 10^6 \text{ psi}$).

$$\theta = 1870 (2.385) / (7.5 \times 10^6)(1.029) \simeq 0.578 \times 10^{-3} \text{ radians}$$

$$\text{Linear deflection} \simeq 0.0014 \text{ in.}$$

In order to determine displacement magnification effects under vibratory conditions, consider the solid curve as representative of these conditions (See Figure B-4).

Amplitudes at frequency values greater than 21 cps are considered to be controlled by 3 g acceleration limit. Amplitude between 5 to 29 cps is assumed constant at the greater of the two given amplitude values. Use of constant 3 g input acceleration values thereby determines the higher support stress levels.

Support Tube Deflections (Vibratory 3 g Levels)

Displacements under vibration are calculated by determining the natural frequency of the support tube and the magnification effects associated with the input frequencies:

1. Extensional Natural Frequency (rigid mass and massless support)

$$f_n = \frac{1}{2\pi} \sqrt{K/M} \quad \text{cps}$$

Figure B-4. Graph Showing Effect of Vibration on Displacement Amplitude for Support Tube

where

$$K \simeq 1.25 \times 10^7 \text{ lb-in}^{-1}$$

$$M \simeq 270/386 \simeq 0.7 \text{ lb-sec}^2\text{-in}^{-1}$$

$$f_n \simeq 675 \text{ cps}$$

2. Transverse Cantilever Bending (massless beam-concentrated mass load)

$$f_n = \frac{1}{2\pi} \sqrt{\frac{3EI}{L^3M}} \text{ cps}$$

$$f_n = \frac{1}{2\pi} \sqrt{\frac{3(24.4 \times 10^6)(0.5146)}{(6.75)^3 (0.7)}} \text{ cps}$$

$$f_n \simeq 67 \text{ cps}$$

3. Torsional Vibration Frequency (rigid mass with massless beam)

$$f_n = \frac{1}{2\pi} \sqrt{K_t/I} \text{ cps}$$

where

$$K_t, \text{ torsional stiffness of beam} = \frac{\pi G(d_o^4 - d_i^4)}{32 L}$$

$$K_t \simeq 2.88 \times 10^6 \text{ lb-in-radian}^{-1}$$

I, mass moment of shield

$$I \simeq 3.73 \text{ lb-in-sec}^{-2}$$

$$f_n = \frac{1}{2\pi} \sqrt{2.88 \times 10^6 / 3.73} \simeq 140 \text{ cps}$$

Considering no damping, magnification or vibrational deflection/static deflection, x_o/x_{st} , is estimated from the following equation as a function of forced vibration frequency/natural frequency, $f(\omega/\omega_n)$.

$$\frac{x_o}{x_{st}} = \frac{1}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + 2 \left(\frac{c}{C_c}\right) \left(\frac{\omega}{\omega_n}\right)^2}}$$

In that support tube natural frequency for all modes > 5 to 32 cps band, maximum magnification values are obtained using the highest forcing frequency, 32 cps.

Mode	Natural Frequency	Static Deflection	Magnification	Vibrational Deflection*
Compression	~ 675 cps	0.000477 inches	1.0	~0.000477 inches
Tension	~ 675 cps	0.000715 inches	1.0	~0.000715 inches
Bending	~ 67 cps	0.000808 inches	1.2	~0.001000 inches
Torsion	~ 140 cps	0.001400 inches	1.0	~0.001400 inches

*Vibrational deflections not including flange displacements

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The above vibrational deflections appear small relative to the following thermal displacements:

Longitudinal Expansion:

$$\Delta L \text{ } 50^{\circ} \text{ F} \rightarrow 1325^{\circ} \text{ F} = L \alpha \Delta T \text{ in.}$$

where α , mean coefficient of linear expansion $\simeq 8.5 \times 10^{-6}$ in/in/ $^{\circ}$ F (reference 1)

$$\Delta L \text{ } 50^{\circ} \text{ F} \rightarrow 1325^{\circ} \text{ F} = 2.385 (8.5 \times 10^{-6})(1275) \simeq 0.0258 \text{ in.}$$

Diametral Expansion:

$$\Delta d \text{ } 50^{\circ} \text{ F} \rightarrow 1325^{\circ} \text{ F} = d \alpha \Delta T \text{ in.}$$

$$\Delta d \text{ } 50^{\circ} \text{ F} \rightarrow 1325^{\circ} \text{ F} = 4.932 (8.5 \times 10^{-6})(1275) \simeq 0.0541 \text{ in.}$$

In view of Unit 2 shield mass relative to Unit 3, revised maximum acceleration loads are as follows:

$$\frac{\text{Unit 3 Shield Mass}}{\text{Unit 2 Shield Mass}} = \frac{270}{125} \simeq 216$$

$$\text{Maximum g level Unit 2} = 216 (3) \simeq 6.486$$

Vibration pattern of Units 2 and 3 to produce equivalent support tube stress levels is shown below:

Figure B-5. Amplitude versus Forced Vibration of the Support Tube

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The Unit 2 pattern will be used for simulation of 3 g Unit 3 support stress levels during vibration testing.

6.0 THERMAL PERFORMANCE

Heat Loss through Support Tube

$$q_{\text{support tube}} = \bar{K}(1325^{\circ}\text{F} - 50^{\circ}\text{F})A \Delta T / \Delta L \text{ BTU/hr}$$

$$\bar{K} \text{ } 1325^{\circ}\text{F} - 50^{\circ}\text{F} = \text{mean thermal conductivity of Inconel X-750}$$

$$\bar{K} \simeq 115 \text{ BTU-in/ft}^2 \text{ hr } ^{\circ}\text{F (reference 1)}$$

$$A \simeq 0.168 \text{ in}^2$$

$$\Delta L, \text{ effective support length } \simeq 1.70 \text{ in. } \Delta T = 1325^{\circ}\text{F} - 50^{\circ}\text{F} = 1275^{\circ}\text{F}$$

$$q_{\text{support tube}} \simeq 100 \text{ BTU/hr (29.6 watts)}$$

Heat Loss through Insulation

$$q_{\text{insulation}} = K_a A \Delta T / \Delta L \text{ BTU/hr}$$

$$K_a (1325^{\circ}\text{F} - 50^{\circ}\text{F}) \simeq 0.0008 \text{ BTU/hr ft } ^{\circ}\text{F}$$

$$A, \text{ insulation surface area } \simeq 3.44 \text{ ft}^2$$

$$\Delta L, \text{ insulation thickness } \simeq 1.72 \text{ in. (0.143 ft)}$$

$$\Delta T = (1325^{\circ}\text{F} - 50^{\circ}\text{F}) = 1275^{\circ}\text{F}$$

$$q_{\text{insulation}} \simeq 24.5 \text{ BTU/hr (7.2 watts)}$$

$$\text{Estimated thermal performance } \simeq 29.6 + 7.2 \simeq 36.8 \text{ watts}$$

Heat Loss through Support Tube (Unit 3 Preliminary)

$$\Delta L, \text{ effective support length } \simeq 2.18 \text{ in.}$$

$$q_{\text{support tube}} \simeq 78.5 \text{ BTU/hr (23.1 watts)}$$

$$\text{Estimated thermal performance } \simeq 23.1 + 7.2 \simeq 30.3 \text{ watts}$$

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