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AEC RESEARCH AND DEVELOPMENT REPORT

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with the Atomic Energy Commission

SNAP-23

**TERRESTRIAL RADIOISOTOPE FUELED
THERMOELECTRIC POWER SUPPLY SYSTEM (U)**

QUARTERLY REPORT NO. 3

1 February 1965 to 30 April 1965

Published May 1965

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For The Atomic Energy Commission

H. F. Draper
To

Chief, Declassification Branch

Issued by:

ISOTOPE POWER LABORATORY
ELECTRICAL PRODUCTS DIVISION

MINNESOTA MINING AND MANUFACTURING COMPANY

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Report No. MMM(3418)-17

Quarterly Report No. 3
1 February 1965 to 30 April 1965

SNAP 23
TERRESTRIAL RADIOISOTOPE-FUELED
THERMOELECTRIC POWER SUPPLY SYSTEM

By
J. C. Murphy
R. L. Sisler

ABSTRACT

The scope of this program encompasses the design and development of a Sr-90 isotope-fueled thermoelectric generator for terrestrial applications.

This report records the progress of the program between 1 February 1965 and 30 April 1965.

The system is designed to withstand the following shock loading in the assembled configuration:

Vertical axis: 10 g half-sine

Radial axis: 5 g half-sine

Thermoelectric couple testing in six-couple modules continued. The current thermoelectric couple design is producing the designed power while operating in six-couple test modules.

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Report No. MMM(3418)-17

Monthly Report
1 February 1965 to 30 April 1965

SNAP-23 PROGRAM
TERRESTRIAL RADIOISOTOPE FUELED
THERMOELECTRIC POWER SUPPLY SYSTEM (U)

Contract AT(30-1) 3418

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Report No. MMM(3418)-17

Quarterly Report No. 3
1 February 1965 to 30 April 1965

SNAP 23
TERRESTRIAL RADIOISOTOPE-FUELED
THERMOELECTRIC POWER SUPPLY SYSTEM
Contract AT(30-1)-3418

INTRODUCTION

The Minnesota Mining and Manufacturing Company has contracted to the U. S. Atomic Energy Commission to design and develop a 60-watt radioisotope-fueled thermoelectric power generator system for terrestrial applications. The system design requirements include the following:

- 60 watts, 24 volts output while operating in an 80⁰F ambient air environment
- Five-year life
- High efficiency
- High reliability
- Sr-90 titanate fuel
- Field serviceable without hot cell facility

The system design concept being pursued consists of three subsystems which are as follows:

- Thermoelectric generator
- Insulation envelope
- Heat source

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Quarterly Report No. 3
1 February 1965 to 30 April 1965

SNAP 23
TERRESTRIAL RADIOISOTOPE-FUELED
THERMOELECTRIC POWER SUPPLY SYSTEM

SUMMARY

In this report the progress of the program is recorded for the period of time between 1 February 1965 and 30 April 1965. Work accomplished in each of the major design areas during this period is as follows:

- The current system design will withstand the following shock loading in the assembled configuration:

Vertical: 10 g (peak), 11 millisecond duration, half-sine

Radial: 5 g (peak), 11 millisecond duration, half-sine

The system will sustain the above shock loadings without external load supporting superstructure.

- Six-couple module testing was continued. Data analysis indicates that the designed thermoelectric couples will produce the design power while operating at BOC design temperatures.
- Insulation envelope design was completed. The importance of xenon as a fill gas was analyzed relative to the retardation effect that an inert atmosphere has on high temperature degradation of MIN-K 1301®.
- The biological shield design was released and the fabrication order placed.
- Test fuel capsules were sent to ORNL for closure welding. Testing was started after receipt of the welded fuel capsules from ORNL.
- Voltage regulator circuit design was completed. Testing of the Trio Laboratories regulator continues.

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1.0 POWER SUPPLY SYSTEM

1.1 PLANNED OBJECTIVES

- To design an isotope-fueled thermoelectric power supply system capable of producing a minimum of 60 watts of electrical power at 24 volts for the five-year design life.
- To design a terrestrial environment system capable of unattended operation during the design life.
- To develop the system for the best utilization of the Sr-90 isotope fuel as the state-of-the-art will permit; the overall system efficiency will exceed 6.00 percent during the design life.
- To perform parametric studies in order to predict the system parameters for operation in various terrestrial environments, and also to facilitate prediction of these parameters for similar units at a variety of power levels.

1.2 PROGRESS THIS QUARTER

- The conductivity of the thermal path between the fuel capsules and the thermoelectric generator was improved by modifying the design of the heat accumulator. Currently, the heat accumulator extends into the heat source to completely enclose the fuel capsules in copper.
- Work continued toward the completion of the design and development of both a high vacuum insulation envelope and a MIN-K 1301 xenon filled insulation envelope.
- The assembled system shock specifications were defined as 10 g in the vertical axis, basedown, and 5 g in the radial axes.
- The fuel loading for the heat source is 975 watts (BOL); however, 1070 watts of fuel may be safely installed into the heat source by altering the fuel capsules. The heat source capacity may be further expanded to contain a maximum of 1100 watts (173×10^3 curies) of fuel without requiring redesign of the biological shield.
- The design of an electric heater was completed and released for fabrication. This heater will be used for powering the electrically heated model.

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1.3 TECHNICAL DISCUSSION

1.3.1 IMPROVED HEAT COLLECTOR DESIGN

The thermal path between the fuel capsules and the thermoelectric generator was improved by extending the copper accumulator into the shield and thereby enclosing the fuel capsules. This modification results in the reduction of fuel centerline temperature, in addition to reducing the shield surface temperatures to a more conservative temperature. The lowered shield surface temperature results in less heat loss through the insulation envelope.

1.3.2 INSULATION ENVELOPE DESIGN

It has been previously reported that two insulation envelope concepts were being developed for this program.

The salient feature of the MIN-K 1301-xenon gas envelope is expected good reliability since the performance of the envelope is not contingent upon vacuum retention, but retention of one atmosphere of xenon. The system load is carried directly by the MIN-K, thereby eliminating the need for additional internal load supports. The assembled system will require a space of 34 inches O.D. and 36 inches height, using this envelope.

The high vacuum insulation envelope is being developed for systems of critical weight and space requirements. Because of the heat loss of the internal shock load supporting members, the maximum thermal insulating characteristics of the high vacuum envelope may not be fully utilized; therefore, the heat loss of this envelope has been estimated to be only slightly less than the MIN-K envelope. The assembled system, utilizing this type of envelope, will require a space of 25 inches O.D. and 30 inches height. The heat source and thermoelectric generator are interchangeable with either insulation envelope.

1.3.3 SYSTEM ENVIRONMENTAL TESTING

Tests were made to determine the load bearing characteristics of MIN-K 1301 during environmental testing. The results of these tests were interpreted to indicate that the current system design, as built, would reasonably withstand the following shock environments:

Vertical axis, basedown: 10 g, 11 ms, half-sine

Radial axes, 5 g, 11 ms, half-sine

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Included in the current design are provisions for an external supporting superstructure to sustain greater shock loadings. The use of this superstructure strengthens the system to permit its withstanding 30 g shock levels in both vertical axes and 10 g shock levels in the radial axes. Once on site, the superstructure must be removed to permit the system to operate at its designed thermal efficiency.

1.3.4 HEAT SOURCE FUEL LOADING DESIGN

Isotope Fuel

The current system fuel loading is 975 watts (BOL); however, should later system testing demonstrate the need for additional fuel, the fuel capsule volume may safely be increased to contain available fuel loading to 1070 watts.

Another method of increasing the fuel loading is to specify fuel with power densities greater than the current 0.8 watt/cc; however, the state-of-the-art of fuel fabrication does not justify specifying higher power density fuel as a primary method for increasing fuel loading. Although increased power densities of fuel have been achieved, 0.8 watt/cc is the highest fuel power density presently available. The current shield design will accommodate a maximum fuel activity concentration of 173×10^3 curies (1100 watts).

Electrical Heater

An electrical heater was designed and is being procured for heating the assembled system. This heater is dimensionally equivalent to two fuel capsules and will be installed into the fuel capsule cavity of the heat source. The heater consists of six 500-watt heaters (Figure 1-1). Three heaters will be used to heat the system and the remaining three will be utilized as back-up, should one of the primary heaters fail.

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NOTES

1. MATL. - TYPE 416 STAINLESS STEEL
 2. SPECIFICATIONS
TOTAL CAPACITY:
 1500 WATTS @ 115 VAC PRIMARY (500 W/HTR)
 1500 WATTS STANDBY
TEMPERATURE CONTROL:
 VARIABLE VOLTAGE TRANSFORMER
INSULATION:
 INDIVIDUAL HEATER ELEMENTS TO BE
 ELECTRICALLY ISOLATED FROM THE
 STAINLESS STEEL HEAT SOURCE
ATMOSPHERE:
 HEAT SOURCE TO OPERATE IN AIR
TEMPERATURE:
 MAX SURFACE TEMPERATURE 1600°F
- ANTICIPATED LIFE:
 1 YEAR
- LEAD WIRES:
 (2) COMMON LEADS - #10 AWG SOLID NICKEL,
 (6) INDIVIDUAL HEATER LEADS - #15 AWG
 SOLID NICKEL, EACH COVERED WITH
 CERAMIC BEADS NOT TO EXCEED 0.260 O.D.

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Figure 1-1. Heat Source - Electric

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LEGEND	
ITEM	NAME
1	FUEL SUPPLY
2	FUEL SHIELDING
3	INSULATION
4	INSULATION COVER
5	HEAT ACCUMULATOR
6	COLD FRAME
7	FINS
8	ELECTRICAL PANEL

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Figure 1-2. Terrestrial 3M-39 Generator

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Table 1-1. Summary of System Design

Power Output	60 watts
Output Voltage	24 volts ± 1 volt regulated
Output Current	2.5 amps
Design Life	5 years
Number of Couples	252 series connected
Fuel	Sr-90 titanate
Fuel Power Density	0.8 watt/cc
Fuel Loading	156×10^3 Curies
Fuel Volume	74.4 in. ³
System Efficiency	6.15% BOL 7.00% EOL
Thermoelectric Material (Powder Pressed)	N-segmented M-13/M-10 PbTe P-segmented M-29/M-76 (BiSb) Te (PbSn) Te
Leg Diameter	0.187 inch
Leg Length N P	0.502 inch 0.356 inch
Cold Segment Length N P	0.125 inch 0.124 inch
Hot Junction Temperature	1100°F nominal BOL 975°F nominal EOL
Cold Junction Temperature	200°F nominal BOL 175°F nominal EOL
Segmenting Temperature P N	594°F 414°F
Electrical Contacting Method Hot Cold	Pressure Soldered bond

2.0 THERMOELECTRIC GENERATOR DESIGN

2.1 PLANNED OBJECTIVES

The planned objectives are as follows:

- To design, develop, and fabricate a thermoelectric generator which shall deliver a power output of 60 watts at 24 volts.
- To design, develop, and fabricate a generator to provide the rated output for five years.
- To design a generator to withstand the environmental conditions as specified in the contract technical provisions.
- To design, develop, and fabricate a generator capable of field removal from, or installation into, the generating system.
- To design, develop, and fabricate generator hardware to effect maximum efficiency using currently available thermoelectric materials.

2.2 PROGRESS THIS QUARTER

- The heat accumulator design was modified to reduce the maximum surface temperature of the biological shield.
- The cooling fin material was changed from 0.045 inch thick copper to 0.050 inch thick aluminum to reduce the weight of the thermoelectric generator, and to ease fabrication.
- The thermoelectric couple fabrication process was improved to permit a more uniform thermoelectric couple assembly.
- Tooling fixtures were designed and fabricated to assist in the assembly of the thermoelectric generator.
- Six-couple module testing was continued. Data analysis indicates that the designed thermoelectric couples will produce design power while operating at BOL design temperature.

2.3 TECHNICAL DISCUSSION

2.3.1 GENERATOR DESIGN

Design of the first generator was completed and the drawings released for fabrication.

Heat Accumulator

The heat accumulator design was modified to eliminate dependence upon the depleted uranium thermal conductivity to conduct the heat to the thermoelectric generator. The heat source surface temperature was reduced by this modification. The accumulator was modified to extend into the heat source to completely encase the fuel capsules in a high thermal conductivity (compared to depleted uranium) envelope.

For mechanical strength the thermoelectric generator was modified to engage the accumulator through a 3⁰ locking taper. In addition the generator will be secured to the accumulator by a single short bolt and a Belleville spring.

Cooling Fin Design

The following two significant modifications were made to the cooling fin design:

The fin material was changed from 0.045 inch thick high conductivity copper to 0.050 high conductivity aluminum to reduce generator weight. The change in heat dissipation of the aluminum cooling fins was calculated and judged to be within the limits of the cooling fin specification.

The fin assembly was modified to permit removal from the generator. This feature permits the generator to be water cooled during parametric testing, in addition to permitting the use of higher or lower capacity fin assemblies on the system for special application.

Thermal Analysis

Figure 2-1 illustrates the system temperature distribution after modification of the heat accumulator and addition of aluminum cooling fins.

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Figure 2-1. SNAP-23 Temperature Distribution (BOL)

2.3.2 THERMOELECTRIC COUPLE FABRICATION

The thermoelectric couple fabricating process was improved to provide a more uniform thermoelectric couple assembly.

Fine silver wire was originally planned to be used for the cold junction straps, but the results of fabrication tests have permitted an improved cold junction strap to be developed from copper wire. Currently, the straps are fabricated from 22 AWG OFHC copper wire. Figure 2-2 illustrates the current thermoelectric couple arrangement.

Nickel-plated tellurium copper cold-end electrodes are assembled with the cold junction strap and placed into a carbon fixture. Eutectic ®#1801 silver solder is used as the soldering material. The carbon fixtures are then placed into a brazing furnace with a forming gas atmosphere, for soldering and held at temperature for ten minutes.

After the carbon fixtures have cooled, the cold cap subassemblies are removed, inspected and transferred to the manufacturing area for subsequent soldering of the thermoelectric legs to the cold-end electrodes.

2.3.3 ASSEMBLY OF THE THERMOELECTRIC GENERATOR

The high thermoelectric couple packing within the generator required that several tools and fixtures be designed and fabricated prior to assembly of the generator. With the aid of these tools, each row of thermoelectric couples may be accurately installed within the generator with minimum labor.

The sequence of thermoelectric couple assembly into the generator is as follows:

Each row of couples is assembled onto its boron nitride insulating strip. Figure 2-3 illustrates the mechanical positioning of the hot shoes into the insulating strip. Figure 2-4 illustrates the placement of the thermoelectric couples into the hot end caps.

A tool is clamped about the assembled row of couples. The function of this tool, as illustrated in Figure 2-5, is to firmly clamp each couple to maintain its proper orientation with the adjacent couples and hot-end hardware components.

The clamped row of couples is then inserted into the generator. The insulating strip is positioned by the locating pins of the hot frame; Figure 2-6 illustrates the positioning of one row of thermoelectric couples onto the hot frame.

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Figure 2-2. Thermocouple Layout - SNAP-23

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Figure 2-3. Placement of Hot Shoes into Insulating Strip

Figure 2-4. Placement of Couples onto Hot End Caps

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The followers and springs are inserted into the cold frame (Figure 2-7), and individually compressed by the special fixtures, as illustrated in Figure 2-8. After compressing each follower spring, the locking pin is extended past the follower hole. Figure 2-9 shows the locking pin installed for one row of couples. A secondary assembly operation is necessary to install the end couples which interconnect adjacent rows of couples.

The couple holding clamp is removed after the row has been locked into position. Figure 2-10 illustrates one row of couples installed in the generator with the tools removed. The cold frame is next indexed and another row of couples installed in a like manner.

2.3.4 THERMOELECTRIC COUPLE TESTING

2.3.4.1 Thermoelectric Couple Test Objectives

The objectives of thermoelectric couple testing are as follows:

- Experimentally verify the initial performance characteristics of SNAP-23 thermoelectric couples.
- Experimentally determine the stability performance characteristics of the thermoelectric couples at BOL temperatures.
- Conduct development testing of 1500 hours duration in hermetically sealed modules, each containing six thermoelectric couples and associated components typical of those used in the generator design.

2.3.4.2 Progress This Quarter

- After analyzing the test data, it is judged that the designed thermoelectric couples will comply with the generator specifications and no additional six-couple modules will be required.
- Three six-couple modules were fabricated and placed on test as follows:

Module test 39A-1 was placed on test February 6, 1965.

Early data indicated that the module initial performance was 96.5 percent of design power; however, a malfunction of the heater block thermocouple caused the module to be unacceptable for long term testing. The test was terminated February 16, 1965.

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Figure 2-5. Couple Assembly Tool

Figure 2-6.
Typical Positioning of One Row of Couples
onto Hot Frame

Figure 2-7.
Inserting Row of Couples into Generator

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Figure 2-8. Locking Couples into Generator

Figure 2-9. One Row of Couples with Locking Pin Installed

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Figure 2-10. One Row of Couples Installed into Generator

Module test 39A-2 was started March 10, 1965, and is producing 105 percent of design power after operating at BOL design temperatures for 1248 hours.

Module test 39A-3 was started March 12, 1965, and is producing 96.5 percent of design power after 1200 hours of continuous testing at BOL design temperatures.

2.3.4.3 Technical Discussion Test Conclusions

The test performance data for the three modules is summarized in Table 2-1. The average power output measured on April 27, 1965, is 1.61 watts or 98.8 percent of the predicted design power. The average module internal resistance was 0.240 ohm and equal to the design prediction.

Test Module Performance

Test 39A-1: Initial performance data is tabulated in Table 2-2 and performance data compared with other tests in Table 2-1. This module developed 1.57 watts or 96.3 percent of the predicted 1.63 watts.

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Table 2-1. Predicted and Current Module Performance Data

Parameter	Design Prediction	Test Module No.				Experimental Design %
		A1	A2	A3	Average	
T_h ($\pm 10^\circ\text{F}$)	1100	1100	1100	1100	1100	100
T_c ($\pm 5^\circ\text{F}$)	200	200	200	200	200	
E_o (Volt)	1.27	1.22	1.22	1.28	1.24	
E_L (Volt)		0.623	0.649	0.596		
R (Ohm)	0.240	0.238	0.223	0.260	0.240	
I_L (Amp)		2.50	2.56	2.65		98.8
P (Watt)	1.63	1.57	1.67	1.58	0.161	
Accumulated Test Hours		Initial Performance Test Only	1248	1200		
Data Taken		2-9-65	4-27-65	4-27-65		

Table 2-2. Module 3M-29A1 Initial Performance Test

Date	T_h $^\circ\text{F}$ ($\pm 10^\circ\text{F}$)	T_c $^\circ\text{F}$ ($\pm 5^\circ\text{F}$)	E_o (Volts)	E_L (Volts)	I_L (Amps)	P_o (Watt)	R (M-Ohm)
2-9-65	1100	200	1.22	0.623	2.50	1.57	0.238

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Test Module 3M-39A2

This test module was accepted for test on March 10, 1965. Test performance data is tabulated in Table 2-3 and compared with other module data in Table 2-1.

The power output of the module has shown a 15 percent increase since the unit was placed on test. This is a result of a corresponding decrease in the internal resistance. The module power output is 1.67 watts which is 103 percent of predicted power. After 1248 accumulated test hours, the module continues to show an increasing power output trend. A plot of the performance is illustrated in Figure 2-11.

Table 2-3. Module 3M-39A2 Initial and Stability Performance Test

Date	T_h °F ($\pm 10^\circ$ F)	T_c °F ($\pm 5^\circ$ F)	E_o (Volts)	E_L (Volts)	I_L (Amps)	P_o (Watt)	R(Ohm)
3-10-65	1100	200	1.22	0.606	2.30	1.41	0.265
3-15-65	1100	200	1.22	0.632	2.33	1.48	0.252
3-19-65	1100	200	1.22	0.626	2.30	1.44	0.258
3-24-65	1100	200	1.21	0.609	2.39	1.47	0.251
3-31-65	1100	200	1.22	0.621	2.46	1.52	0.244
4-7-65	1100	200	1.22	0.634	2.49	1.58	0.235
4-12-65	1100	200	1.22	0.638	2.50	1.60	0.232
4-19-65	1100	200	1.22	0.647	2.55	1.65	0.225
4-27-65	1100	200	1.22	0.649	2.56	1.67	0.223

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Figure 2-11. Module 3M-39A2 Performance

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Test Module 3M-39A3

This test module was accepted for test on 3-12-65. Test performance data is tabulated in Table 2-4 and compared with other module data in Table 2-1.

The power output of this module shows stable performance after 1200 accumulated test hours. The module power output is 1.58 watts or 97 percent of the design prediction. A plot of the performance is illustrated by Figure 2-12.

Table 2-4. Module 3M-39A3 Initial and Stability Performance Test

Date	T_h °F ($\pm 10^\circ\text{F}$)	T_c °F ($\pm 5^\circ\text{F}$)	E_o (Volts)	E_L (Volts)	I_L (Amps)	P_o (Watt)	R(Ohm)
3-12-65	1100	200	1.26	0.596	2.76	1.65	0.240
3-19-65	1100	200	1.27	0.632	2.55	1.61	0.251
3-24-65	1100	200	1.27	0.629	2.58	1.62	0.248
3-31-65	1100	200	1.27	0.626	2.50	1.58	0.256
4-7-65	1100	200	1.28	0.617	2.55	1.58	0.257
4-12-65	1100	200	1.27	0.620	2.51	1.56	0.259
4-19-65	1100	200	1.28	0.615	2.53	1.57	0.261
4-27-65	1100	200	1.28	0.596	2.65	1.58	0.260

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Figure 2-12. Module 3M-39A3 Performance

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Test Module Specifications

The following is a summary of the thermoelectric specifications for tests 39A1, A2, and A3:

	Module 3M-39A1 and A3	Module 3M-39A2
<u>P-LEG</u>		
Size	0.188 Diameter 0.356 Length	0.188 Diameter 0.356 Length
Material:		
Hot Segment	TPM 76	TPM 15
Cold Segment	TPM 29	TPM 29
Manufacturing Method	Segments simultaneously powder pressed	Segments powder pressed, then bonded together
<u>N-LEG</u>		
Size	0.188 Diameter 0.502 Length	0.188 Diameter 0.502 Length
Material:		
Hot Segment	TPM 10	TPM 10
Cold Segment	TPM 13	TPM 13
Manufacturing Method	Segments simultaneously powder pressed	Segments simultaneously powder pressed

3.0 SYSTEM APPLICATION

3.1 PLANNED OBJECTIVES

- To demonstrate system design flexibility to adapt to specific load problems.

3.2 TECHNICAL DISCUSSION

3.2.1 60 WATT DESIGN MODIFICATION METHODS

There are three possible methods of modifying the present 60 watt power supply design to provide power to less than 60 watt loads. These methods are summarized as follows and are arranged in ascending complexity.

3.2.1.1 Changing Load Resistance

Increasing load resistance will result in a corresponding increase in load voltage. The output power of the system will decrease by mismatching. Figure 3-1 illustrates the load power and voltage characteristic as a function of load resistance. This typical example was derived from the system described as Item 1, Table 3-2.

3.2.1.2 Reduced Fuel Loading

Decreasing the system fuel loading will result in a lower power output and a decreased load voltage. Table 3-1 is an analysis for a typical load of 21.5 ohms. The interpretation of this table is as follows:

- (a) Each item number represents an end-of-life system operating condition.
(Except Item 1)
- (b) The item immediately above each end-of-life item represents the beginning-of-life parameters necessary to produce the desired end-of-life results.

3.2.1.3 Tapped Thermopile

The thermoelectric generator may be tapped at various locations to satisfy an unlimited number of voltage, power, load resistance combinations.

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Figure 3-1. Load Resistance versus Output Parameters
Fuel Loading at 1000 Watts

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Table 3-1. Thermoelectric Generator Performance Under Actual Load Conditions ($R_L = 21.5\Omega$)

Item	Q_{in}	T_h	T_c	T_a	V	I	P
(1)	1000	1100	200	80	36.0	1.67	60
(2)	883	975	175	80	31.8	1.47	46.8
(3)	780	870	164	80	28.8	1.33	38.3
(4)	688	772	154	80	24.9	1.15	28.7
(4a)	688	793	212	140	23.7	1.1	26
(5)	608	696	145	80	21.8	0.98	21.3
(5a)	608	719	202	140	20.9	0.97	20.2
(6)	537	623	137	80	18.5	0.86	15.8

Table 3-2. Thermoelectric Generator Performance Under Normal Ambient Temperature and Matched Load Conditions

Item	Q_{in}	T_h	T_c	E	R_L	V	I	P	% Efficiency
(1)	1000	1100	200	53.2	10.34	26.6	2.57	68.5	6.85
(2)	883	975	175	45.8	9.6	24.0	2.50	60.0	6.8
(3)	780	870	164	38.8	7.47	19.9	2.62	52.1	6.7
(4)	688	772	154	32.4	6.46	16.2	2.51	40.7	5.92
(5)	608	696	145	27.5	5.63	13.8	2.45	33.8	5.6
(6)	537	625	137	22.7	4.9	11.4	2.33	26.6	5.0

Q_{in} - Input Power in Watts

T - Temperature in $^{\circ}F$

E - Seebeck Voltage in Volts

R_L - Resistance of Load in Ohms

V - Load Voltage in Volts

I - Load Current in Amperes

P - Delivered Power in Watts

T_h - Hot Junction Temperature

T_c - Cold Junction Temperature

T_a - Ambient Temperature

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3.2.2 APPLICATION FEATURES

Change Load Resistance

The chief feature of this method is that the reduced power and/or increased terminal voltage may be accomplished after the system has been installed on-site. This change of operating point would require that the voltage regulator be readjusted to the new reference voltage. Although the present system specifications do not require an adjustable voltage regulator output, the inclusion of this feature into subsequent systems is not considered to present any major problem.

Reduced Fuel Loading

The salient feature of this method is that the fuel utilization is improved. The planned load requirements may be integrated into the fuel loading operation to provide optimum output power with minimum fuel.

Typical operating conditions have been calculated and summarized in Table 3-2.

Tapped Thermopile

This method provides for loads requiring several output voltage levels. The thermopile would be tapped to provide not only the proper voltage levels but in addition the relative polarities of the several voltages.

One feature of this method is that more than one voltage regulator or convertor may be connected to the thermoelectric generator to further assist in compliance with the load voltage specifications.

Normally the thermopile would be center-tapped to provide +12 volts and -12 volts; in addition each half would be center-tapped to provide ± 6 volt increments.

The possible voltage and power combinations available from a tapped-generator power system are almost infinite, because in addition to tapping the thermoelectric generator, the fuel loading may be reduced or the load resistance may be changed from optimum conditions.

4.0 INSULATION ENVELOPE DEVELOPMENT

4.1 PLANNED OBJECTIVES

- To develop an insulation envelope concept based upon an extension of an insulation study conducted during AEC Contract AT(30-1)3209, with respect to the use of Johns-Manville MIN-K 1301 insulating materials and an inert gas such as xenon.
- To develop an insulation envelope by using the high-vacuum reflective shield insulation concept.
- To select one of the above concepts developed for incorporation into the design of this isotope-fueled thermoelectric power supply system. The criteria for this selection are as follows:
 - A comparison will be made of the direct labor, materials and tooling costs required to manufacture each envelope concept for pilot-run quantities.
 - A comparison will be made of the thermal watts loss each envelope concept would extract from the power generation system. This comparison would be further analyzed to determine the cost of the isotope fuel necessary to sustain these losses.
 - A comparison will be made of the predicted reliability of each insulation concept tested.
- Insulation Envelope Boundary Conditions

Maximum hot wall temperature	1500°F
Operating temperatures	Hot wall: 1400°F Cold wall: ambient air
Ambient air temperature	70°F ± 10°F
Heat loss	Best effort-optimize for minimum heat loss
Total load bearing requirements	900 pounds

4.2 PROGRESS THIS QUARTER

- Processing was started to simultaneously remove the binder and water from MIN-K 1301; however, the work was terminated because the by-products of this process were incompatible with the vendor's equipment.
- The use of xenon gas in the insulation envelope serves a two-fold purpose of reducing the envelope heat losses in addition to prolonging the service life of the MIN-K 1301.
- Work continued to complete the MIN-K insulation envelope design. Included in this work was MIN-K 1301 processing, heat loss calculations and load support design.
- Tests were conducted to document the load bearing characteristics of MIN-K 1301.

4.3 TECHNICAL DISCUSSION

4.3.1 MIN-K 1301 PROCESSING

Processing of the MIN-K 1301 to be used in the insulation envelope was started during February. Originally the plan was to eliminate the insulation binder and dry the insulation in one operation. This required that the insulating blocks be processed at 1150°F in alternate vacuum and nitrogen purge cycles. This processing plan was terminated after it became apparent that the by-products of this process were incompatible with the vendor's equipment. Because of this forced termination, the binder was removed from the insulating material by conventional oxidizing methods.

High Temperature Operation - MIN-K 1301

The results of recent heat loss calculations predict that the heat loss through the insulation envelope will be 70 watts, or about 7 percent of the total system fuel load.

Data available from the Johns-Manville Company indicates that the thermal conductivity of MIN-K 1301, operating in air at 1300°F, will increase 15 percent in approximately 200 hours. In a similar manner the conductivity will change the same amount per the following schedule:

1000 hours @ 1200°F

5000 hours @ 1000°F

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Operating MIN-K 1301 in an inert atmosphere appears to prolong the service life of the insulating material indefinitely according to further information received from the Johns-Manville Company.

Thus the addition of xenon into the insulation envelope not only reduces the heat loss of the insulation envelope, but also inhibits the rapid degradation of MIN-K 1301 operating in an air atmosphere.

4.3.2 INSULATION ENVELOPE DESIGN

The insulation envelope consists of a cylindrical outer wall, and an inner cavity to support the heat source. Nominally, nine inches of MIN-K 1301 separate the outer wall and inner cavity. The top of the inner cavity consists of a thin stainless steel member, which eliminates a bellows at the top of the cavity as previously reported in Report No. MMM(3418)-8. The void between the inner cavity and outer wall will consist of block-form MIN-K 1301 carefully shaped to match the contours of both the inner cavity and outer shell. The properties of the MIN-K 1301 are adequate to directly support the loaded cavity without requiring additional load supports.

4.3.3 MIN-K 1301 LOAD SUPPORT TESTS

Tests were made to document the load bearing characteristics of MIN-K 1301 under extreme conditions of mechanical shock loading. The test modules were designed to subject both powdered and block-form MIN-K to typical pressure loads (psi) which the insulation envelope would receive in the assembled system.

Each test module was filled with MIN-K 1301 which was packed to a density of 18 to 20 pounds per cubic foot. Modules were tested on an AVCO SM005 shock machine, starting with three shock tests at low g loads and progressively increasing the g loading until the data indicated catastrophic failure of the MIN-K. During all tests, the displacement of the MIN-K and the g level were recorded.

Figure 4-1 is a photograph of the vertical axis test module being tested on the AVCO shock machine.

The test results are illustrated in Figures 4-2, 4-3, and 4-4. The test conclusions verified calculations and are summarized as follows:

- The load bearing characteristics of block-form MIN-K 1301 are adequate to support the assembled system during vertical shock levels of up to 10 g for a half-sine duration of 11 milliseconds.

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Figure 4-2. Crushed MIN-K 1301 Load Bearing Test - Vertical Axis Test, March 30, 1965

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Figure 4-3. Block Form MIN-K 1301 Load Bearing Test - Vertical Axis Test, March 30, 1965

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Figure 4-4. Crushed MIN-K 1301 Load Bearing Test -
Radial Axis Test, March 30, 1965

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Figure 4-5. Insulation Envelope Heat Loss versus Outer Diameter (12-inch I.D.)

5.0 HEAT SOURCE DESIGN

5.1 PLANNED OBJECTIVES

- To design a fuel capsule to contain the required amount of fuel.
- To design a fuel capsule capable of complete fuel containment under all conditions of intended use, credible accidents, and for a period of at least 300 years.
- To design a safe fuel capsule to withstand specified environmental testing of vibration, fire, and corrosion.
- To design a biological radiation shield to reduce the radiation intensity at the system surface to 200 mr/hr.
- To design a heat source such that the generator components can be replaced and/or repaired without the use of hot cell facilities and with a minimum use of special equipment.
- To design a fuel capsule such that fuel encapsulation may be readily accomplished by governmental facilities.

5.2 PROGRESS THIS QUARTER

- The heat source design was modified to reduce the maximum surface temperature of the biological shield.
- Radiation exposure rates were calculated and found to be 1 r/hr at the shield surface, 240 to 260 mr/hr at the fin tips, and 200 mr/hr at 17 inches radial from the fuel capsules (system surface).
- The heat source will be sealed into a copper-plated stainless steel enclosure for oxidization protection.
- Fabrication of the fuel capsules for the test program was completed and testing started.

5.3 TECHNICAL DISCUSSION

5.3.1 MODIFICATION OF HEAT SOURCE DESIGN

The results of thermal analysis justified a modification of the heat source to reduce the maximum predicted surface temperature of the biological shield. Dependence

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upon the poor thermal conductivity of depleted uranium was the largest contributor to the high shield temperature. To reduce the surface temperatures to a conservative 1300°F, it was determined that an improved thermal conductive path between the heat source and the thermoelectric generator would be necessary. This was done by thermally connecting the fuel capsules to the thermoelectric generator through a copper accumulator which envelopes the fuel capsules and extends upward to the thermoelectric generator hot frame. Figure 5-1 schematically illustrates the improved heat source configuration.

While conducting the parametric studies of the heat accumulator, it was determined that the copper radiation attenuation was insufficient to reduce the radiation level at the top of the accumulator to acceptable limits. The size and shape of the depleted uranium shield cap was designed to provide minimum disturbance to the heat flow in the accumulator yet provide the necessary radiation attenuation.

5.3.2 HEAT SOURCE RADIATION LEVEL

Applying the inverse square method for calculating radiation exposure to the heat source, it was determined that the shield surface radiation rate was 1 r/hr for the following conditions:

Fuel loading	1100 watts (BOL)
Overall system diameter	34 inches
System surface radiation level	200 mr/hr

The system radiation level at 25 inches system diameter has been estimated to be 240 to 260 mr/hr. These levels are considered to be within the acceptable safe limits of radiation.

In designing the upper portion of the shield, all of the fuel activity was assumed to be at a point located in the center of the top capsule. From this point straight lines were drawn to indicate the radiation path through the shield, shield cap, and heat accumulator. By this method, the equivalent uranium attenuation could be determined for the copper shield and shield cap. The necessary shield thickness to reduce the radiation to 200 mr/hr was then calculated. This value is then the additional thickness of depleted uranium which must be added to compensate for the heat accumulator penetrating the shield. A sketch showing this arrangement is shown in Figure 5-2.

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Figure 5-1. Heat Source Configuration

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Figure 5-2. Determination of Radiation Level at Shield to Top

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5.3.3 SHIELD OXIDIZATION PROTECTION

It has been previously reported that the use of depleted uranium for the biological shield required that the shield surface be protected from exposure to air while at operating temperature. In addition, the characteristics of the depleted uranium alloy are such that certain incompatibility configurations must be avoided if the material is to remain intact during the design life of the system.

The oxidization protection portion of the shield design was modified to satisfy the following objectives:

- To use the shield in the "as cast" configuration or with minimum secondary machining.
- To enclose the shield in a stainless steel enclosure, thereby utilizing conventional materials with known fabrication characteristics.

The features of the current design are summarized as follows:

- The shield will be enclosed by welding a fabricated 300 series stainless steel enclosure around the shield.
- The stainless steel enclosure will be copper plated a nominal 0.005 inch on those areas directly contacting the depleted uranium.
- The depleted uranium will not require any surface treatment because all incompatibility barriers are an integral part of the stainless steel enclosure.

5.3.4 FUEL CAPSULE FABRICATION

Fuel capsule fabrication was completed during this quarter. This fabrication included welding the end caps into the stainless steel tubing forming the fuel capsule liner; in addition, the bottom end cap was welded to the Hastelloy Alloy C fuel capsule tubing. The fuel capsules were remachined to clean-up the bottom inside diameter of any weld material deposited there by the bottom end cap fillet weld. The fillet-weld was intentionally made less than 100 percent penetration to minimize any stray deposits of weld material or other deformation from appearing on the inside diameter of the fuel capsule.

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Five capsules were shipped to ORNL for final weld closure. Prior to returning the welded capsules, ORNL sectioned one of the fuel capsules in preparation for metallographic analysis. The photographs of this section are shown in Figure 5-3. The final determination of weld integrity will be made upon completion of the fuel capsule test program; however, from the results of the metallographic analysis shown in Figure 5-3, a preliminary judgment is that the fuel capsule welds have been accomplished per the specifications.

5.3.5 USE OF MOCK FUEL

The five fuel capsules shipped to ORNL for final closure did not contain mock fuel. Only the stainless steel fuel capsule liner was included in the fuel capsule. An additional number of capsules are to be processed with mock fuel to determine the effect of the fuel on the weld penetration.

5.3.6 FUEL CAPSULE TESTING

The fuel capsule test program was started near the end of this report period. Two completed capsules were heated and held for one hour at 1850°F in an electrically heated furnace. One capsule was removed while at temperature and quenched in water. The other was allowed to cool to room temperature in the furnace. There were no visible failures; however, these capsules will be evaluated more precisely using methods outlined in the Fuel Capsule Test Program.

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Figure 5-3. Fuel Capsule Welding

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6.0 VOLTAGE REGULATOR DEVELOPMENT

6.1 PLANNED OBJECTIVES

- Operating voltage 24 volts ± 1 volt
- Operating life Five-year objective
- Ambient temperature Operating nominal: $70^{\circ}\text{F} \pm 10^{\circ}\text{F}$
Storage maximum: $+140^{\circ}\text{F}$
Storage minimum: -40°F
- Operating current range 0 to 3.1 amperes
- Operating power 78.1 watts maximum
- Loss in regulator during standby Typically 0.12 percent (0.072 watt)

6.2 PROGRESS THIS QUARTER

- The voltage regulator circuit design was completed.
- The regulator module has been designed for installation external of the system.
- Testing continued with six Trio Laboratories regulators for use as an alternate regulator for the system.
- Amphenol Type 48 connectors were selected for the interconnecting plugs between the system and the voltage regulator module.

6.3 TECHNICAL DISCUSSION

6.3.1 CIRCUIT DESIGN

Development work continued with the breadboard regulator circuit, and after minor modifications, the circuit was judged to be adequate to meet the system regulator specifications. The schematic diagram for this circuit is shown by Figure 6-1.

The features of this design are that all critical electronic components have been selected on the basis of their predicted performance for extended periods. In addition, the components were derated to ensure their adequate predicted reliability. The power dissipation capacity will be sufficient to require the use of only one regulator per system.

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A portion of the terminal voltage is reduced to a lower voltage by R_1 and R_2 . Transistor Q_1 compares this reduced voltage with the voltage reference diodes ZD-1, ZD-2 and ZD-3. The collection current of Q_1 is proportional to the difference between the reduced voltage and the reference voltage. This "error" current is amplified by Q_2 , Q_3 and Q_4 .

If the terminal voltage is too high, the current through Q_4 will increase and reduce the terminal voltage to the correct value. If the terminal voltage is too low, the current through Q_4 will reduce and allow the terminal voltage to reach the correct value.

Figure 6-1. Schematic Diagram - Voltage Regulator Circuit HPR-B

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Since the voltage regulator is a system accessory, the regulator package was designed for operation external to the system. Although the module may be mechanically attached to the system for convenience, the basic design feature is that the regulator requires only electrical connections to the thermoelectric generator. This feature permits flexibility in substitution of other regulator modules, converters, inverters, etc.

Another circuit design feature is that a resistor (R_8) is in series with the main power transistor, Q_4 , and therefore reduces the maximum power dissipation requirements of Q_4 . This feature permits the regulator to dissipate 78 watts, yet the maximum power transistor dissipation is about 33 percent of maximum power or 26 watts.

6.3.2 CIRCUIT TESTING

The breadboard circuit design has been designated HPR-A for design and testing accountability. Upgrading circuit modifications change the circuit designator to the next alphabetic letter, thus the next circuit will be designated HPR-B. As each circuit is assembled, a number suffix is added for identification purposes.

Work has started to fabricate a voltage regulator of the HPR-B circuit. Two regulators will be assembled for testing and be designated test HPR-B-1 and test HPR-B-2.

Testing is continuing on the HPR-A module. The operating point of the test regulator was selected to correspond to the most severe power dissipation condition of the regulator power transistor. This test is being conducted at 20.76 watts power transistor dissipation which is the approximate maximum power dissipation for HPR-A.

6.3.3 TRIO LABORATORIES "SUPER REG" TESTING

Six purchased voltage regulators (manufactured by Trio Laboratories, Inc., Long Island, New York) were placed on long term development tests. One unit quickly failed because of a faulty internal resistor and another was destroyed by a malfunction of the test fixture.

Two regulators of this type are required to dissipate the system power because the manufacturer rates each unit at 50 watts dissipation when operated at 75°C (167°F) case temperature. The circuit operation of each unit is such that all power is dissipated in the power transistor [refer to Report No. MMM(3418)-8, page 6-3]; therefore, each test unit is dissipating 39 watts or one half system power.

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Testing of the Trio Laboratories units is being conducted to support work on this program in addition to the SNAP-21B program. In this manner, more diverse data is available than would be available by separate testing of these units for each program. It is currently planned that the Trio Laboratories regulator will be used as a back-up or alternate system regulator.

The performance of the Trio Laboratory tests has been summarized in Table 6-1. The data for test HPR-A is also included in this table. In these tests, the absolute output voltage level is not a test objective; but the character of any electrical drift of the output voltage with time is a primary test objective. From Table 6-1 it can be seen that all regulators currently on test are operating within the ± 1 volt specification.

A regulated power supply is supplying power for the voltage regulator test fixture. The output voltage of this supply has been periodically checked and found to control the current to the test regulators to within ± 0.5 percent.

6.3.4 ELECTRICAL CONNECTORS

Studies were made to aid in the selection of the system electrical connector. The selected connector is the Amphenol Series 48 connector. The manufacturer's rating for this connector indicates compliance with Military Specification MIL-C-26500 in addition to having an excellent predicted reliability from other sources. Figure 6-2, an extract from Amphenol's Miniature Catalog MC-1, illustrates the construction details of this connector.

Low contact resistance was one of the criteria used for connector selection. The contact resistance range of the Type 48 connector was measured and found to be 1.45 to 2.55 milliohms, with a mean resistance of 1.78 milliohms. Sixty-four measurements were made with an 8-pin connector to determine the contact resistance. The actual connector is expected to have a somewhat lower resistance. Individual connector pins and lead wires will be installed in parallel to improve reliability.

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Table 6-1. Performance of Regulators in Test Fixture

Operating Hours	No Load Voltage						Operating Hours	
	A	B	C	D	E	F	HPR-A	HPR-A
0	21.7	Bad	21.92	22.58	Burned	21.96	26.78	0
168	21.84	Resistor	21.97	22.58	out due	22.02	26.79	96
312	21.82	---	21.96	22.55	to test	21.97	26.76	168
384	21.83	---	21.97	22.58	fixture	22.04	26.71	283
480	21.81	---	21.95	22.55	short	22.02	26.65	331
552	21.82	---	21.96	22.56	---	22.04	26.67	451
648	21.83	---	21.97	22.57	---	22.03	26.75	499
698	21.80	---	21.94	22.56	---	22.01	26.77	595
794	21.80	---	21.94	22.55	---	21.96	26.72	667
866	21.81	---	21.96	22.56	---	22.00	26.70	955
881	21.82	---	21.96	22.54	---	21.99	26.73	1051
1029	21.83	---	21.98	22.56	---	22.08	26.76	1267
1149	21.82	---	21.97	22.57	---	22.04	26.80	1435
1197	21.81	---	21.94	22.56	---	22.00	26.77	1507
1293	21.80	---	21.92	22.54	---	21.95	26.76	1603
1365	21.82	---	21.95	22.55	---	21.99	26.74	1651
1653	21.81	---	21.93	22.54	---	21.98	26.78	1795
1749	21.78	---	21.89	22.51	---	21.95	26.81	1939
1965	21.82	---	21.93	22.55	---	21.98	26.76	2107
2133	21.81	---	21.92	22.55	---	21.97	26.78	2179
2205	21.82	---	21.93	22.56	---	21.97	26.77	2275
2301	21.81	---	21.92	22.55	---	21.96	26.79	2346
2349	21.80	---	21.92	22.55	---	21.98	26.78	2467
2493	21.81	---	21.92	22.55	---	21.99	26.79	2539
2537	21.81	---	21.91	22.55	---	21.98	26.79	2611
2709	21.80	---	21.90	22.54	---	21.99		
2805	21.81	---	21.92	22.55	---	22.00		
2877	21.82	---	21.92	22.56	---	21.97		
2973	21.80	---	21.91	22.54	---	21.97		
3045	21.80	---	21.89	22.54	---	22.00		
3165	21.80	---	21.89	22.54	---	21.97		
3237	21.80	---	21.89	22.54	---	21.97		
3309	21.80	---	21.90	22.55	---	21.98		

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- A. POSITIVE LOCATION CAPTIVATED INSERT (MECHANICAL INTERLOCK)
- B. RESILIENT REAR INSERT
- C. CLOSED ENTRY HARD DIELECTRIC "ULTRAMATE" FRONT INSERT
- D. INSERT STATIC FACE SEAL
- E. PIN CONTACT, MIL-C-26636
- F. CONTACT PRESSURIZING SEAL
- G. ANTI-DEFLECTION DISC
- H. RESILIENT PIN INSERT
- I. INSERT RIM SEAL
- J. DYNAMIC "O" RING SHELL SEAL
- K. FIVE KEY SHELL POLARIZATION
- L. RELEASING SLEEVE
- M. METAL TO METAL SHOULDER
- N. BAYONET OR THREADED COUPLING, PERMANENT CAPTIVATION
- O. CONTACT RETENTION CLIP
- P. SOCKET CONTACT, MIL-C-26636
- Q. WIRE SEALING RISERS
- R. GROMMET

Figure 6-2. Amphenol Type 48 Connector

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SNAP-23 RADIOISOTOPE POWER SUPPLY PRELIMINARY ENGINEERING DESIGN SUMMARY

ENGINEERING DESIGN SUMMARY of:	SNAP-23 Terrestrial Radioisotope-Fueled Thermoelectric Power Supply System.
Contractor:	Minnesota Mining and Manufacturing Company
Contract No.	AT(30-1)-3418
User(s) and Mission:	N/A
Status:	Prototype Design Being Prepared
Date Prepared:	5-15-65

System Concept:	PbTe - T/E - Cylindrical Type
Fuel:	Sr-90 TiO ₃
Major System Assemblies:	Single module generator, insulation envelope, fuel capsules and shield, and voltage regulator.

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		<u>Total System</u>		<u>Generator</u>	
		Start of Life	End of Life	Start of Life	End of Life
Electric output	watt (e)	60	60	70.3	60.7
Thermal input	watt (th)	975	858	790	700
Efficiency	percent	6.15	7.00	8.90	8.68
Specific power	watt (e) pound				
Open circuit voltage	volts	24	24	53.2	45.8
Design voltage	volts	24	24	24	24
Design current	amps	2.5	2.5	2.5	2.5

Temperature Profile

Design Basis: Start of Life

Fuel maximum	1581 ^o F
Fuel capsule surface	1502 ^o F
Hot junction or T _h	1100 ^o F
Cold junction or T _c	200 ^o F
Thermionic T _v	N/A
Tip of fins	N/A
Converter housing	N/A
Ambient, Air	80 ^o F

HEAT DISTRIBUTION
(START OF LIFE)

Total thermal input	975	100%
Heat to T/E	790	81%
Heat loss through T/E insulation		
Other system heat losses		
Heat rejected from housing	35	
Heat rejected T/E couples	635	65%

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SYSTEM ENVIRONMENTAL CAPABILITIES

Operational Environment (including transportation)

Temperature	70°F ± 10°F (nominal) -40°F to +140°F (extreme range)
Pressure	10 to 32 in. of Hg
Humidity	Minimum - N/A Maximum - 100% in salt atmosphere
Shock	5 g radial axes, 10 g vertical (upward), 1 g downward, 11 ms, half-sine
Vibration	Frequency: 15-55 cycles per second Sweep: 1 cps/sec; +5 cps, -0 cps Double Amplitude: 0.015 in. 3 mutually perpendicular axes 45 minutes per axis
Acceleration	As incurred in vibration
Storage Life	5 years
Storage Temperature	90°F ± 50°F
Pressure	12 to 18 psi
Humidity	100% relative humidity

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SAFETY DATA

Operation, Handling and Transportation

Radiation Dose Rates

	Unshielded at 1 Meter from Center of System, Maximum	Shielded at System Surface	Shielded at 1 Meter
Total Bremsstrahlung/hr:	1.4×10^6 R	MR	10 MR
Total neutron mr/hr:	None	None	
Regulations adhered to:	AEC-ICC shipping regulations		

System Design to Maintain Fuel Capsule Integrity

Accident:	Separation of fuel capsules from biological shield
Maximum temperature:	1425°F
Maximum pressure	10,000 psi
Impact velocity (capsule intact)	N/A
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, Sr-89
Chemical form	SrTiO ₃

Physical Properties

Melting point	1900°F
Boiling point	N/A
Kindling temperature	N/A
Maximum continuous operating temperature	

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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

<u>Type</u>	<u>t 1/2 (yrs)</u>	<u>Energy (mev)</u>	<u>Percent</u>	<u>Remarks</u>
Bremsstrahlung	27.7	2.18 max	100	Primary beta absorbed in fuel, secondary bremsstrahlung radiation

Determined Dose Rates

<u>Type of radiation</u>	<u>Dose rate (mr/hr)</u>	<u>Remarks</u>
Bremsstrahlung	200	At system surface

Chemical Properties

Chemical reactions	None applicable
Corrosion effects	None

Health Data

Half-lives:

Radiological	27.7 years
Biological	50 years
Effective	18 years
Maximum permissible body burden	20 μ c
MPC air	3×10^{-10} * μ c/cc
MPC water	4×10^{-6} * μ c/cc

Toxicity: N/A

*168-hour week

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HEAT SOURCE

System

Thermal Input:

Start of life	975 watt (th)
End of life	858.6 (th)
Capsules per generator	2
Isotope(s) and chemical form	Sr-90, SrTiO ₃

Capsule

Overall length	4.894 inches
Overall diameter	4.001 inches
Length/Area	0.389 inch ⁻¹
Fuel Loading per capsule (start of life)	488 watts 2324 gms 76,700 curies

Internal volume per capsule

Total	40.5 inches ³
Fuel	37.22 inches ³
Void	3.3 inches ³

Internal Pressure 50 maximum psi @ 1400⁰F after 1 year

		<u>Capsule</u>	<u>Capsule Liner</u>
<u>Material</u>		Hastelloy Alloy C	SS 321
Inside diameter	inches	3.580	3.532
Inside length	inches	4.373	4.370
Wall thickness, sides	inches	0.210	0.020
Wall thickness, ends	inches	0.210/0.310	0.063
Total weight	pounds	6.8	0.1
Melting point	⁰ F	2310-2450	2550-2600
Thermal Conductivity	BTU/hr-ft- ⁰ F	9.9 @ 1112 ⁰ F	12.9 @ 1110 ⁰ F

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Linear expansion coefficient	$10^{-6}/^{\circ}\text{F}$	7.73 @ 70-1200 $^{\circ}\text{F}$	10.47 @ 70-1200 $^{\circ}\text{F}$
Density	pounds/inch ³	0.323 @ 70 $^{\circ}\text{F}$	0.290 @ 72 $^{\circ}\text{F}$
Strength-Tensile	psi	118,000 @ 70 $^{\circ}\text{F}$	85,000 @ 70 $^{\circ}\text{F}$
Yield	psi	57,000 @ 70 $^{\circ}\text{F}$	33,000 @ 70 $^{\circ}\text{F}$
Closure-Method		TIG weld	TIG weld
Material		Hastelloy Alloy C	SS 316
Penetration	inch	0.100	0.020
Shear strength		100 percent	100 percent

THERMOELECTRIC CONVERSION ASSEMBLY

Couples/generator	252
Modules/generator	1
Couples/module	N/A
Electrical resistance:	
Generator	7.55 ohms (end of life)
Module	N/A
Couple	29.98 milliohms

Type of circuit: series

<u>THERMOELECTRIC LEGS</u>		<u>P</u>	<u>N</u>
Thermoelectric Material (Segmented)		M-29/M-76 (BiSb) ₂ Te ₃ -PbTe, SnTe	M-13/M-10 PbTe-PbTe
Fabrication Method		Powder Pressed	Powder Pressed
Hot segment length	inch	0.232	0.377
Cold segment length	inch	0.124	0.125
Total Leg length	inch	0.356	0.502
Diameter	inch	0.188	0.188
Length/area	inch ⁻¹	12.9	18.2
L _C /L		0.350	0.250

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Hot Junction Temperature	^o F	1100	1100
Cold Junction Temperature	^o F	200	200
Segment Temperature @Max Eff	^o F	594	414
Open Circuit Voltage	mv	97.5	113.5
Load Voltage @Max Eff	mv	57.6	65.1
Average Resistivity	$\mu \Omega$ in.	1221	1092
Current @Max Eff	amps	2.5	2.5
Power @Max Eff	watts	0.146	0.158
Rate of Heat Rejection	watts	1.45	1.37
Rate of Heat Absorption	watts	1.59	1.53
Material Efficiency	percent	9.03	10.07

Hot Shoe

Material	Copper
Thickness	0.040 inch
Length x Width	0.475 x 0.215
Bond (material, thickness and method)	N/A
Diffusion barrier (material and thickness)	Hot end cap 0.015 thick, iron

Cold Shoe

Material	Copper
Thickness	P 0.321 N 0.175
Diameter	0.188 inch
Bond (material, thickness and method)	Tin Solder
Diffusion barrier (material and thickness)	N/A

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Electrical Leads Between Couples

Material	Copper
Diameter	22 AWG
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 Report No. MMM(3418)-7, Figure 2-2.]

VOLTAGE REGULATOR

Circuit type:	Shunt
Converters/system:	1
Principal components:	Transistors, capacitors, resistors, zener diodes
Weight	10 pounds
Length	8 inches
Impedance	0.58 ohm (max)
Width and Height	8 x 10.6 inches
Transistor material	Silicon

		<u>Start of life</u>	<u>End of life</u>
Efficiency	percent		99.86 minimum
Output voltage(s)	volts	24.0	24.0
Output current(s)	amps	0.421	0.421
Input power	watt(e)	78	60.07
Input voltage	volts	24	24
Input current	amps	3.25	2.503
Operating temperature		-67, +140°F	

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Voltage regulation	± 3.0 percent
Transistor losses	0.007 watt (max)

OTHER COMPONENTS

Fill Gas or Vacuum

Composition, percent and purpose	Vacuum in space occupied by thermal insulation between shield and pressure vessel
Pressure	1 to 15×10^{-3} mm Hg
Temperature Range	80°F to 1400°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.
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Insulation Envelope

Purpose	Minimize shunt heat losses from heat source to ambient air.
Construction	Double-walled vessel with nominal 9 inches side and 6 inches bottom wall separation. Void filled with block type MIN-K 1301 with a xenon inert atmosphere.
Internal Pressure (cold)	1 Atmosphere
Estimated Thermal Conductivity	0.018 BTU/hr-ft-°F

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Cooling Fins

Number of Required Fins/System	100
Material	Type 1100 aluminum
Height	5 inches
Length	7.0 inches
Thickness	0.050 inch
Fin Base Temperature (BOL)	150°F @ 80°F ambient

Seals

<u>Type</u>	<u>#/System</u>	<u>Material</u>	<u>O.D.(in.)</u>	<u>Thickness(in.)</u>	<u>Remarks</u>
"O"-Ring	1	Buna N	28-1/2	3/16	Restricts atmosphere surrounding heat source
"O"-Ring	2	Rubber	5/8	-	Seals pressure transducer outlets
Lee Plugs	5	Metal	0.25 (1) 0.656 (4)	- -	Final seal-off for generator and insulation system
Gland	5	Teflon	5/16	3/16	Instrumentation lead feed-through connectors

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