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2501 HUDSON ROAD ST. PAUL, MINN. 55119

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Report No. MMM(3418)-22
C-92A
M3679 (39th Edition)

This document consists
of 102 pages

AEC RESEARCH AND DEVELOPMENT REPORT

H.C. 300. - 65

This report has been prepared under contract AT (30-1) 3418
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DATE 4/28/67

For The Atomic Energy Commission

H. F. Arnold
to

Chief, Declassification Branch

SNAP-23

TERRESTRIAL RADIOISOTOPE FUELED
THERMOELECTRIC POWER SUPPLY SYSTEM (U)

QUARTERLY REPORT NO. 4

1 May 1965 to 31 July 1965

Published August 1965

Prepared by:

J. C. Murphy

Approved by:

R. L. Sisler
Program Manager

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Report No. MMM(3418)-22

Quarterly Report No. 4
1 May 1965 to 31 July 1965

SNAP-23

**TERRESTRIAL RADIOISOTOPE FUELED
THERMOELECTRIC POWER SUPPLY SYSTEM**

By

J. C. Murphy
R. L. Sisler

ABSTRACT

The assembly of the first SNAP-23 system generator component (3M-39-P1) has been completed. The excellent performance demonstrated during initial testing of this generator indicates that a significant milestone has been reached in the design and operation of thermoelectric conversion devices. This achievement is significant in that actual performance has met earlier predictions.

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Report No. MMM(3418)-22

QUARTERLY REPORT NO. 4
1 May 1965 to 31 July 1965

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

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Quarterly Report No. 4
1 May 1965 to 31 July 1965

SNAP-23
TERRESTRIAL RADIOISOTOPE-FUELED
THERMOELECTRIC POWER SUPPLY SYSTEM (U)
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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Report No. MMM(3418)-22

Quarterly Report No. 4
1 May 1965 to 31 July 1965

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

SUMMARY

In this report the progress of the program is recorded for the period of time between 1 May 1965 and 31 July 1965. Work accomplished in each of the major design areas during this period is as follows:

Assembly of all major system components was completed in preparation for component testing early in August, 1965.

The assembly of the first SNAP-23 system generator component (3M-39-P1) was completed. The excellent performance demonstrated during initial testing of this generator indicates that a significant milestone has been reached in the design and operation of thermoelectric conversion devices. This achievement is significant in that actual performance has met earlier predictions.

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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 over-all 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

- Two thermoelectric generators were completed and placed on test.
- Servicing tools were designed and demonstrated for field servicing of the system.

1.3 TECHNICAL DISCUSSION

1.3.1 THERMOELECTRIC GENERATOR ASSEMBLY

Two thermoelectric generators, each suitable for system usage, were assembled during this quarter.

1.3.2 SPECIAL TOOLS

A removal tool was designed to assist in generator field replacement. It consists of a hydraulic fitting which attaches to the generator, a hydraulic hand pump, and associated piping. A mockup of the system was successfully demonstrated in the laboratory after operating generator 3M-39-P1 at temperature for a period of several days.

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The cooling fin assembly is removable from the thermoelectric generator under field conditions. In order to eliminate any problem of overheating the generator during servicing, the generator must first be separated from the system before the fins may be removed. A special wrench has been designed and will be required for fin loosening.

A lifting cradle was fabricated to facilitate removal of the heat source from the insulation envelope.

1.3.3 SYSTEM ENVIRONMENTAL DESIGN

System environmental design analyses indicate that the current system design, as built, will withstand the following shock environments:

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

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

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 996 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).

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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.

Figure 1-1. Electrical Fuel Capsule Simulator

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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	6.03% BOL 6.85% 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	1075°F nominal BOL 975°F nominal EOL
Cold Junction Temperature	195°F nominal BOL 180°F nominal EOL
Segmenting Temperature P N	526°F 370°F
Electrical Contacting Method Hot Cold	Pressure Soldered bond

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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

- Two thermoelectric generators, designated 3M-39-P1 and 3M-39-P2, were assembled and placed on test.
- Comparison of thermoelectric performance of prototype generator and 6-couple module testing indicates that the thermoelectric couples are performing according to predicted expectations.

2.3 TECHNICAL DISCUSSION

2.3.1 PROTOTYPE GENERATOR ASSEMBLY

Assembly of two prototype generators, designated 3M-39-P1 and 3M-39-P2 was completed; each was processed, and placed on test. The assembly sequence was originally reported in Report No. MMM(3418)-17, and has been included as Appendix B of this report.

The generator processing schedule includes alternate evacuation-backfill cycles while the generator is being heated. Eleven cycles were completed. The maximum temperature

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during the vacuum cycle was 600⁰F and 1100⁰F during the backfill cycle. Backfilling consisted of filling the generator with hydrogen gas to a pressure of 2 psig. Included in the schedule were four periods of recording pressure rise versus time during a vacuum cycle, and four 8 - 12 hour heat soak periods when the generator was backfilled with hydrogen. The pressure rise versus time is correlated to the outgassing rate of the generator and is an indicator of processing effectiveness.

2.3.2 PROTOTYPE GENERATOR PERFORMANCE

Prototype 3M-39-P1 was placed on test June 21, 1965. Prototype 3M-39-P2 was placed on test July 22, 1965.

To fully evaluate the performance of these generators, the physical, chemical, and mechanical characteristics of the thermoelectric elements contained within each must be considered.

Both generators contain segmented, simultaneously pressed N-legs and segmented, simultaneously pressed P-legs. The physical and chemical characteristics of these elements are summarized in Table 2-1. A complete description of these elements can be found in Appendix A of Quarterly Progress Report #3.

Table 2-1. Thermoelectric Element Data 3M-39-P1 and 3M-39-P2

Leg	Segment	Material	L	D	Lc/L	L/A
N	Cold	M-13	-----	-----	0.250	-----
	Hot	M-10	-----	-----	-----	-----
	Total	-----	0.502	0.188	-----	18.2
P	Cold	M-29	-----	-----	0.350	-----
	Hot	M-76	-----	-----	-----	-----
	Total	-----	0.356	0.188	-----	12.9

L - Total length (inch)

D - Diameter (inch)

Lc - Cold segment length (inch)

A - Cross sectional area (inch)²

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Typical performance data for 3M-39-P1 is shown in Table 2-2, and preliminary performance data for 3M-39-P2 is shown in Table 2-3. In these tables the following nomenclature is used:

$T_h(^{\circ}\text{F})$	Average hot electrode temperature
$T_c(^{\circ}\text{F})$	Average cold electrode temperature
$E_o(\text{Volt})$	Open circuit voltage
$E_L(\text{Volt})$	Load Voltage
$I_L(\text{Amp})$	Load current
$R_g(\text{Ohm})$	Internal electrical resistance
$P_o(\text{Watt})$	Power delivered to load

The data in Table 2-2 shows that prototype 3M-39-P1 is continuing to operate satisfactorily after 627 hours of operation. The data in Table 2-3 shows that prototype 3M-39-P2 is also operating satisfactorily and has electrical characteristics nearly identical to those of prototype 3M-39-P1. Table 2-4 shows the computer predicted and current experimentally observed performance for the two generators. Both generators are operating within one percent of the predicted voltage and power.

The average hot electrode temperature of both generators is being limited to 1070°F , rather than the original design point of 1100°F . This is in keeping with a recent program decision to limit the maximum hot electrode temperature to 1100°F . This action was necessary to ensure stable generator performance over prolonged periods of time. Very little information is available on the stability of the thermoelectric elements in question at temperatures greater than 1100°F .

A comparison of the performance of each of the generators as reported in previous publications to the performance as reported in this report shows an apparent small decrease in the performance of both units.

This decrease is due in part to a small increase in internal resistance (usually observed for this type generator in a 1000-3000 hour "settling out" period), but also due to a change of thermal environment. The previously reported data was collected while the generators were being cooled with water jackets, whereas the data reported herein was collected while the generators were being cooled with convective fins. The change of cooling mechanism has altered the thermal environment of the individual elements, thereby causing a slight change in performance.

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Table 2-2. Typical Performance Data 3M-39-P1

Date	Hours	T_h	T_c	E_o	E_L	I_L	R_g	P_o
7-14-65	299	1066 ¹	198 ²	51.0	25.5	2.66	9.58	67.83
7-22-65	484	1069 ¹	199 ²	51.5	25.7	2.63	9.81	67.59
7-28-65	627	1073 ¹	200 ²	51.9	26.0	2.61	9.92	67.80

1 - Based on average of four hot electrode thermocouples.

2 - Based on average of four cold electrode thermocouples.

Table 2-3. Preliminary Performance Data 3M-39-P2

Date	Hours	T_h	T_c	E_o	E_L	I_L	R_g	P_o
8-9-65	456	1065 ¹	200 ²	50.8	25.4	2.70	9.41	68.56

1 - Based on average of four hot electrode thermocouples.

2 - Based on average of four cold electrode thermocouples.

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Table 2-4. Predicted and Current Generator Performance Data

Computer Prediction		Experimental	
		3M-39-P1*	3M-39-P2**
$T_h (^{\circ}\text{F})$	1070	1073	1065
$T_c (^{\circ}\text{F})$	200	200	200
$E_o (\text{Volt})$	51.18	51.90	50.80
$E_L (\text{Volt})$	25.59	26.00	25.40
$I_L (\text{Amp})$	2.68	2.61	2.70
$R_g (\text{Ohm})$	9.54	9.92	9.41
$P_o (\text{Watt})$	68.64	67.80	68.56

*Based on data of 7-28-65

**Based on data of 8-9-65

2.3.3 SIX-COUPLE MODULE PERFORMANCE

The performance data for 3M-39-A2 and A3 is summarized in Table 2-5. The average power output measured on July 30, 1965, was 1.60 watts or 98 percent of design power. The average module internal resistance was 0.238 or 99 percent of design prediction.

Test module 3M-39-A2 was accepted for test on March 10, 1965, and by July 30, 1965, had completed 3440 hours. Test performance data is tabulated in Table 2-6, and compared with other module data in Table 2-5.

The power output of the module has shown a 15 percent increase since the unit was placed on test and has retained this increase while keeping a steady power output. The module power output is 1.65 watts, which is 101 percent of predicted power. A plot of performance is illustrated in Figure 2-1.

Test module 3M-39-A3 was accepted for test on March 12, 1965, and had completed 3320 hours by July 30, 1965. Test performance data is tabulated in Table 2-7 and is compared with other module data in Table 2-5.

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Table 2-5. Predicted and Current Module Performance Data

Parameter	Design Prediction	Test Module No. 3M-39 A2 and A3			Experimental Design %
		A2	A3	Average	
T_h ($\pm 10^\circ\text{F}$)	1100	1100	1100	1100	
T_c ($\pm 5^\circ\text{F}$)	200	200	200	200	
E_o (Volt)	1.27	1.21	1.27	1.24	
E_L (Volt)		0.667	0.618	0.642	
R (Ohm)	0.240	0.218	0.257	0.238	99
I_L (Amp)		2.54	2.52	2.53	98
P (Watt)	1.63	1.65	1.56	1.60	
Accumulated Test Hours at		3440	3320		
Data Taken		7-30	7-30		

Table 2-6. Module 3M-39-A2 Initial and Stability 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 (Ohm)
5-3-65	1100	200	1.21	0.653	2.57	1.67	0.218
5-12-65	1100	200	1.21	0.646	2.55	1.64	0.222
5-19-65	1100	200	1.21	0.654	2.59	1.68	0.218
5-25-65	1100	200	1.20	0.652	2.58	1.60	0.216
6-3-65	1100	200	1.21	0.657	2.60	1.70	0.213
6-11-65	1100	200	1.20	0.656	2.58	1.69	0.215
6-18-65	1100	200	1.21	0.635	2.68	1.67	0.215
6-25-65	1100	200	1.20	0.633	2.67	1.66	0.216
7-2-65	1100	200	1.20	0.604	2.76	1.66	0.217
7-9-65	1100	200	1.20	0.606	2.77	1.66	0.216
7-16-65	1100	200	1.20	0.605	2.76	1.64	0.219
7-23-65	1100	200	1.20	0.604	2.75	1.64	0.220
7-30-65	1100	200	1.21	0.667	2.54	1.65	0.218

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- PREDICTED POWER
- EXPERIMENTAL POWER
- ◇ PREDICTED VOLTAGE
- ◆ EXPERIMENTAL VOLTAGE

$$T_H = 1100^{\circ}\text{F} \pm 10^{\circ}\text{F}$$

$$T_C = 200^{\circ}\text{F} \pm 5^{\circ}\text{F}$$

Figure 2-1. Module 3M-39-A2 Performance

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Table 2-7. Module 3M-39-A3 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)
5-3-65	1100	200	1.27	0.597	2.55	1.53	0.263
5-12-65	1100	200	1.27	0.595	2.57	1.53	0.262
5-19-65	1100	200	1.27	0.598	2.59	1.55	0.261
5-25-65	1100	200	1.27	0.596	2.58	1.54	0.259
6-3-65	1100	200	1.27	0.597	2.59	1.55	0.260
6-11-65	1100	200	1.27	0.598	2.58	1.55	0.260
6-18-65	1100	200	1.27	0.597	2.58	1.55	0.260
6-25-65	1100	200	1.27	0.642	2.42	1.55	0.259
7-2-65	1100	200	1.28	0.645	2.43	1.56	0.260
7-9-65	1100	200	1.27	0.644	2.43	1.55	0.259
7-16-65	1100	200	1.27	0.644	2.42	1.55	0.259
7-23-65	1100	200	1.27	0.646	2.43	1.56	0.259
7-30-65	1100	200	1.27	0.618	2.52	1.56	0.257

The power output of this module shows stable performance for the last 2600 test hours. The module power output is 1.56 watts or 96 percent of the design prediction. A plot of the performance is illustrated by Figure 2-2.

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

	Module 3M-39-A2	Module 3M-39-A3
P-LEG		
Size	0.188 Diameter 0.356 Length	0.188 Diameter 0.356 Length
Material:		
Hot Segment	TPM 15	TPM 76
Cold Segment	TPM 29	TPM 29
Manufacturing Method	Segments powder pressed, then bonded together	Segments simultaneously powder pressed
N-LEG		
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

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2.3.4 COMPARISON OF PROTOTYPE GENERATORS WITH 6-COUPLE MODULES

In comparing the generators with the modules, two important differences should be kept in mind. The 6-couple modules are operating between 1100⁰F and 200⁰F, making a temperature differential of 900⁰F. The generators are operating between 1070⁰ and 200⁰, making a temperature differential of 870⁰.

The second difference is that the modules have over 3300 operating hours each, while the generators 3M-39-P1 and P2 have only 627 and 456 hours, respectively.

Table 2-8 compares the parameters of the modules with the generators. Keeping the differences in mind, it can be seen that the two different units have performed quite similarly. The figures shown here have been averaged for both generator and module performance. Symbols used in Table 2-8 are the same as those used in previous tables. The figures for the generator have been adjusted so as to compare with the same number of couples as used in the modules.

The 6-couple modules have maintained a constant power output close to 1.60 for over 3300 hours. The prototype generators are performing almost identically during their relatively shorter life at the same power level. The 6-couple module internal resistance has been decreasing slightly with time and appears to be quite close to the generator internal resistance. As can be noted from Table 2-8, the two groups of parameters have a similar pattern.

Another way of comparing the 6-couple modules with the generators is to compare them at the same time level. The two modules have been averaged out to show performance after the same length of operation as that of the generators by July 30, 1965.

It is interesting to note that at both time levels the values of the modules and the generators compare favorably. The slight differences in the two types of units could be partially due to the temperature differential. The power level of the modules is a little lower than the generators, but it has, with time, exceeded the generator level. As more data is obtained from the generators, a more significant comparison between the two types of units can be made.

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

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Table 2-8. Comparison of the Six-Couple Modules with the Prototype Generators

	Six-Couple Modules	Prototype Generators
E_o	1.24	1.22
E_L	0.642	0.612
R_g	0.238	0.229
I_L	0.253	0.265
P_o	1.60	1.62

Table 2-9. Comparison of the Six-Couple Modules with the Prototype Generators at the Same Length of Operation

	Six-Couple Modules	3M-39-P1
	627 Hours	
E_o	1.245	1.235
E_L	0.627	0.618
R_g	0.245	0.236
I_L	2.535	2.61
P_o	1.595	1.61
	Six-Couple Modules	3M-39-P2
	456 Hours	
E_o	1.248	1.210
E_L	0.6220	0.605
R_g	0.2475	0.224
I_L	2.533	2.7
P_o	1.57	1.63

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3.0 INSULATION ENVELOPE DEVELOPMENT

3.1 PLANNED OBJECTIVES

- To develop two insulation envelope concepts, each of which will contribute to the system efficiency by minimizing the system shunt heat losses. The features of each concept are as follows:
 - An insulation envelope using Johns-Manville MIN-K 1301[®] insulating material, operating in an inert gas atmosphere. Features minimum maintenance and ultimate reliability since no long-term vacuum re-tention is required. Suggested for use with those systems with broad weight and size specifications.
 - An insulation envelope using the high vacuum reflective shield insulating concept. Features excellent thermal insulating characteristics with minimum size and weight requirements.
 - Insulation Envelope Boundary Conditions

Maximum hot wall temperature	1500 ⁰ F
Operating temperatures	Hot wall: 1400 ⁰ F Cold wall: ambient air
Ambient air temperature	70 ⁰ F ± 10 ⁰ F
Heat loss	Optimize for minimum heat loss
Total load bearing requirements	900 pounds

3.2 PROGRESS THIS QUARTER

- The gas-filled insulation envelope assembly was completed and is ready for system integration.
- Extensive envelope conditioning was done before leak-checking the envelope with helium mass spectrometer equipment.
- Argon was selected as the backfill gas. A cost analysis of fuel versus the originally planned xenon backfill gas indicated that approximately \$4,000 of xenon would be required to save \$1,900 of fuel.

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- The binder removal process for MIN-K 1301 was improved. The simplified process demonstrated an excellent yield of processed MIN-K even when processing 200-pound batches.

3.3 TECHNICAL DISCUSSION

3.3.1 ENVELOPE ASSEMBLY

After assembly of the gas-filled insulation envelope, extensive secondary conditioning of the MIN-K 1301 was performed in order to evacuate the envelope sufficiently for leak-checking with helium mass spectrometer equipment.

The envelope is a Dewar type vessel which has been filled with block form MIN-K 1301. Figure 3-1 illustrates how the MIN-K was fabricated and assembled into the envelope. Figure 3-2 further illustrates the envelope with the inner cylinder installed. Block-form MIN-K 1301 was used because of its shock resistance characteristics (Reference: Report MMM(3418)-17, paragraph 4.3.3).

The stainless steel top was welded into place forming the final envelope closure. Figure 3-3 illustrates the completed envelope.

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Figure 3-1. Envelope Assembly with MIN-K 1301 Installed

Figure 3-2. Envelope Assembly with MIN-K and Inner Cylinder in Place

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Figure 3-3. Complete Envelope Assembly

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3.3.2 ENVELOPE CONDITIONING

The envelope conditioning process consisted of the following steps:

- Apply heat to the envelope both through the heat source cavity and the outer wall. Nominal temperatures were 1200⁰F and 260⁰F.
- Evacuate the envelope by using conventional mechanical vacuum pumps.
- Introduce dry argon (-80⁰F dew point) into the envelope.
- Alternate vacuum cycles and argon cycles.

The following observations were noted after the conditioning process:

- The envelope could be evacuated to 20 microns after 12 hours of vacuum pumping.
- Condensate collected in a dry ice-acetone cold trap during evacuation of the first argon backfill. This condensate was an opaque colloidal-type liquid, slightly more viscous than water. An estimated 28 grams of this fluid was removed during an 8-hour pumping cycle.
- Continued combination argon backfill and vacuum cycles ultimately caused the residual moisture to be driven from the insulating material. This was verified by observing the following events:
 - 1) Reduction of the argon exhaust gas dew point temperature to -60⁰F.
 - 2) The attainment of 20 microns of internal envelope pressure.
 - 3) The absence of any significant amounts of condensate collecting in a liquid nitrogen cold trap.

3.3.3 ARGON BACKFILLING

During the final envelope backfilling, the argon flow rate versus time was recorded. The envelope was backfilled to one psig while operating at 1400⁰F maximum. Approximately six cubic feet of argon was required to complete the backfill operation.

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The justification for selecting argon as the backfill gas is as follows:

- Use of argon would increase the envelope heat loss approximately twelve percent, or ten watts (maximum), according to data obtained from similar testing done under contract AT(30-1)-3209.
- Projected Hipp Plant fuel cost estimates of 12 cents per curie of Sr-90 indicates that an additional 10 watts of fuel would cost \$1890 (derived from fuel specifications of 33 curies per gram and 0.21 watts per gram).
- At the current prices, the cost of the originally planned xenon used for backfilling would be \$4250 to backfill the envelope to 1 psig, at 1400⁰F. By comparison, the cost of argon for backfilling is approximately 24 cents for six cubic feet.
- It was concluded that the increased fuel cost did not justify the expenditure required for backfilling the envelope with xenon.

The decision to backfill the envelope while at operating temperature was made to minimize internal gas pressure build-up which would occur as a cold-filled envelope was heated by the system.

3.3.4 MIN-K 1301 BINDER REMOVAL

Test blocks of MIN-K 1301, each measuring 36 inches x 18 inches x 2 inches, were placed into an air atmosphere furnace and heated to 1100⁰F for 48 hours to oxidize the organic binder within the material. Although the furnace temperature was accurately controlled, upon opening the furnace it was readily apparent that the MIN-K had been seriously overheated. Since the processing schedule used for these blocks had been successfully followed for earlier batches of MIN-K, it was believed that the quantity of material being processed had exceeded the previous schedule limits.

It was hypothesized that an exothermic reaction occurred as a result of the rapidly oxidizing organic binder. The presence of an exothermic reaction contained by an excellent insulator caused the block center temperature to rise sharply. The validity of this hypothesis was established by laboratory testing wherein block center temperatures of 1600⁰F were observed although the furnace temperature was controlled at 1000⁰F.

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The processing schedule was revised to include the following:

- Separate blocks of MIN-K at least two inches during processing.
- Adjust furnace temperature to 300°F, and maintain this temperature during the first 3 hours of processing.
- Increase furnace temperature at a rate of 25°F per hour until the furnace temperature reaches 1000°F.
- Maintain 1000°F furnace temperature for two hours.
- Reduce furnace temperature at a rate of 100°F per hour.

Twenty-one MIN-K blocks were successfully processed with the above schedule. Figure 3-4 illustrates the comparison of block center temperature and furnace temperature as a function of total elapsed processing time. Evidence of the exothermic reaction may be noted at the 12-hour processing point at which time the block center temperature exceeded the furnace 125°F.

3.3.5 HIGH VACUUM INSULATION DEVELOPMENT

Test fixtures have been fabricated which will permit testing of insulation materials in vacuum. The thermal conductivity of the various materials will be compared with the conductivity of a module assembled with MIN-K 1301 and backfilled with argon. The argon-MIN-K 1301 combination is representative of the insulating materials used in the gas-filled insulation envelope, already assembled for this program. Thus, this test fixture will be used as a control or reference sample by which the various high vacuum tests may be compared.

In addition to testing the control sample of MIN-K 1301 and argon, three additional high vacuum tests are currently planned:

- 1) Powdered MIN-K 1301 operating in vacuum.
- 2) Laminates of 0.0005-inch thick copper foil and 0.040-inch thick carborundum Fiberfrax® #970-FH separation material operating in a vacuum.
- 3) Laminates of 0.0005-inch thick copper foil and 0.020-inch thick 3M Company brand CM-2 paper (Burnil Microplates®) operating in a vacuum.

Figure 3-4. Block MIN-K Center Temperature vs. Furnace Temperature

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Figure 3-5. Insulation Test Fixture

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During this quarter test preparations included the following:

- Design and fabrication of two test fixtures.
- Design and assembly of a test station.
- Purchase of insulating materials.

3.3.6 TEST FIXTURE DESCRIPTION

The insulation test fixture being used for these tests was fabricated, and is shown in Figure 3-5. Figure 3-6 is a photograph of the components of the fixture and Figure 3-7 is a photograph of the fixture in assembly stages. It should be noted that this test fixture was designed specifically to have a low heat leakage and to be easily assembled. Thermocouple instrumentation is provided on the heater block wall and on the exterior of the container wall. Careful measurement of the input power coupled with the hot and cold temperature indications provides a relative method of determining an effective thermal conductivity of the material in question. It is expected that this device will be most useful in determining relative degrees of performance between different materials, rather than the absolute conductivity of each. However, a careful accounting of the heat losses should give a fair indication of absolute conductivity values also.

3.3.7 TEST STATION DESCRIPTION

Figure 3-8 illustrates the assembly of the test station to be used for the testing. Included in this station are facilities for evacuation, gas backfilling, temperature and vacuum measurement, plus electrical power to heat the test fixture.

3.3.8 ION VACUUM PUMP

An additional objective of the high-vacuum development program is to demonstrate a self-generating vacuum insulation envelope. The gettering will be accomplished by applying a Varian Vac Ion[®] vacuum pump to the system.

The important feature of this application is that the vacuum pump will operate from a portion of the electrical energy rejected by the power flattening voltage regulator. Thus, the vacuum pump will be powered from the thermoelectric generator, yet not require any additional system fuel or power increase from the thermoelectric generator.

An ion vacuum pump has been ordered and it is currently planned that initial testing will be limited chiefly to demonstrating vacuum pumping of the test fixtures described in Section 3.3.6 of this report.

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Figure 3-6. Test Fixture Components

Figure 3-7. Test Fixture Assembly

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Figure 3-8. Test Station

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4.0 HEAT SOURCE DESIGN

4.1 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.

4.2 PROGRESS THIS QUARTER

- The electrically-heated heat source was assembled and ready for system integration.
- The biological shield was hermetically sealed into a stainless steel enclosure. The enclosure was metallized by flame spraying copper onto those surfaces contacting the depleted uranium. The void between the shield and liner was backfilled with argon gas.
- Oxidization protection of the heat accumulator was accomplished by chrome plating all exposed copper surfaces.
- Fuel capsule fabrication was completed.
- Fuel capsule fire, thermal shock and weld testing was completed. Hydrostatic testing was used to assist in weld design improvement.
- Exploratory meetings were conducted with Battelle Northwest Laboratories to determine nondestructive test procedures for proving weld integrity.

4.3 TECHNICAL DISCUSSION

4.3.1 HEAT SOURCE OXIDIZATION PROTECTION

The depleted uranium shield is enclosed by a stainless steel liner; however, as previously reported, a materials incompatibility exists between the uranium and stainless steel which requires that an isolating barrier be used to completely separate the two materials. In Section 5.3.3, Report MMM(3418)-17, it was reported that the stainless steel would be copper plated to gain the required isolation.

Due to plating process problems, a revision was made, and the stainless steel shield liner was metallized by flame spraying. A 0.005 inch thickness of molybdenum followed by a 0.005 inch thick layer of copper was applied. The thinner section liner components (0.015 inch) will be separated from the depleted uranium by a 0.010 inch thick copper foil. Flame spraying is unsatisfactory for metallizing thin section materials because the excessive air and material velocities and heat permanently deform the material being metallized.

The enclosed shield was hermetically sealed with argon gas backfilled into the void between the depleted uranium and its liner. The argon will prevent the occurrence of any oxidization within the shield liner.

The method previously discussed for protecting the shield is complicated due to the difficulties in fabricating the shield enclosure. As a result, an alternate method of shield protection is being studied.

A uranium specimen was flame sprayed with a molybdenum base coat and followed with a copper final coat. The flame sprayed specimen was then placed into a stainless steel enclosure. Because this was the first temperature test of metallized depleted uranium, the enclosure was vented to the atmosphere. This vent was to prevent any excessive pressure buildup which may occur should the metallizing barrier fail and an exothermic reaction between the shield and its liner take place.

The specimen was placed into a furnace and slowly heated to 1300°F. After four hours at temperature, the specimen was removed from the furnace and air cooled.

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Examination of the uranium specimen revealed that the copper coating had separated from the depleted uranium, leaving the uranium exposed to the atmosphere. The specimen was heavily coated with a black oxide which was classified as U_3O_8 , uranium oxide.

It was concluded that because of the porosity of the metallized coating, any available oxygen may diffuse through the metallized coating and oxidize the depleted uranium.

To eliminate the oxygen exposure, argon was backfilled into the void separating the shield from its liner.

Additional testing of subjecting the flame sprayed uranium to temperature in an argon atmosphere would be required to conclusively establish that this form of metallizing is feasible for depleted uranium.

Figure 4-1 illustrates the bottom end of the assembled heat source. The depleted uranium shield has been installed into the shield assembly, the internal tube inserted into the shield, and the liner base welded into place. Figure 4-2 shows a cross sectional view of the assembled system heat source.

Figure 4-1. Heat Source Assembly - Bottom End

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4.3.2 ACCUMULATOR OXIDIZATION PROTECTION

The copper accumulator was electroplated on all surfaces to protect the copper from oxidization. The plating consists of 0.0001 to 0.00025 electroless nickel substrate and chromium plating thickness of 0.00005 to 0.00015 inch.

Testing of the plated accumulator consists of a visual examination of the plated surface following exposure to 1500⁰F for 10 minutes. The part is acceptable providing no evidence of plating blistering is noted.

Figure 4-3 illustrates both the copper flame sprayed internal shield liner and the chrome plated copper heat accumulator.

The nonsprayed areas at each end of the liner are weld areas used to hermetically seal the shield from the atmosphere. One may note the nonlocking taper on the accumulator and a matching taper on the internal liner. This taper engages a similar taper inside the biological shield and prevents accumulator or fuel capsule removal from the generator end of the heat source.

4.3.3 FUEL CAPSULE FABRICATION

Five test fuel capsules were originally assembled for analysis of weld strength. The five capsules were tested in the following catagories:

	Test	Method
1 Capsule	Weld sectioning	
1 Capsule	Fire test	Capsule placed in furnace and heated for two hours per ASTM-E-119-61 test.
1 Capsule	Thermal shock and hydrostatic	Rapid quenching of capsule from 1850 ⁰ F to 50 ⁰ F.
2 Capsules	Hydrostatic	

After being subjected to the above tests all non-failed welds were tested using the General Mills SPOTCHECK[®] method. No evidence of fissures or holes was noted from those welds tested.

Figure 4-2. Shield Assembly

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Figure 4-3. Shield Liner and Heat Accumulator

Left: Copper Flame Sprayed Internal Shield Liner
Right: Chrome Plated Copper Heat Accumulator

4.3.4 FUEL CAPSULE TESTING - HYDROSTATIC

Hydrostatic testing of test fuel capsules was conducted to provide additional fuel capsule weld data.

Three capsules were tested in this manner. One capsule had been previously exposed to a thermal shock test and the remaining two capsules had not been subjected to previous testing. The fillet welds of the capsules failed at 6500 psi, 14,500 psi and 16,500 psi respectively.

Analysis of the weld failures indicated that all welds had failed due to excessive shear forces in the fillet weld - parent material interface. In addition, visual examination revealed crystal elongation and carbide precipitation in those areas.

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The fillet weld design was modified to provide for more shear resistance. A comparison of the original and improved weld design is illustrated in Figures 4-4A and 4-4B.

Figure 4-4A. Original Fillet Weld

Figure 4-4B. Improved Fillet Weld Design

The improved weld design results in higher shear strength due to the increased load bearing area of the end cap. The first weld pass is a fusion pass followed by subsequent filler weld passes. This reduces secondary machining requirements between end cap welding and final closure welding.

Six additional capsules were assembled with mock fuel to establish the weld schedules necessary for maintaining weld integrity of the fueled capsule. Two capsules were of the original weld design and four were the improved weld design (Figure 4-4B).

4.3.5 FUEL CAPSULE WELD SCHEDULES

Fuel Capsule Weld Schedule

ORNL Closure Weld

The inner and outer capsules were cleaned with trichlorethylene to degrease them. Three small "V" grooves were filed in each cap to aid in pump down. All capsules were welded in a remote pressure pot type welder. The chamber was purged by pumping down to 400 microns pressure and backfilling to 10 psig with a 65 percent argon - 35 percent helium mixture. This purging procedure was repeated three times for each capsule before welding as follows:

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Capsule No. 1

1st pass - 135 amps, 10 volts
2nd pass - 120 amps, 8 volts
3rd pass - 90 amps, 8 volts
Welding speed - 9.8 in/min.

Capsule No. 2

3 passes - each pass at 140 amps,
10 volts
Welding speed - 9.8 in/min.

Capsule No. 3

1st pass - 150 amps, 10 volts
2nd pass - 110 amps, 8 volts
3rd pass - 110 amps, 10 volts
Welding speed - 9.8 in/min.

Capsule No. 4

1st pass - 150 amps, 10 volts
2nd pass - 110 amps, 8 volts
3rd pass - 110 amps, 8 volts
4th pass - 100 amps, 10 volts
Welding speed - 9.8 in/min.

Capsule No. 5

1st pass - 145 amps, 10 volts
2nd pass - 100 amps, 10 volts
3rd pass - 90 amps, 10 volts
4th pass - 110 amps, 10 volts
Welding speed - 9.8 in/min.

All capsules were dye checked and vacuum leak tested after welding. No leaks or weld cracks were detected.

Welding was done with a 3/32-inch diameter, 2 percent thoriated tungsten electrode positioned ~ 1/16 inch from the work. Capsule No. 2 was the first specimen welded

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and the first pass was made with the electrode positioned in the center of the outer rim and the successive passes worked inward to the middle of the cap rim. This procedure resulted in excessive "run-over" on the outer diameter of the capsule and on sectioning. It was noted that full penetration had not been obtained on part of the weld. The remaining specimens were welded by positioning the electrode to the outside of the capsule wall on the first pass, in the center of the inner (cover) rim on the second pass, and in the center of the outer rim on the third pass.

- Fuel Capsule Bottom Fillet Weld (Current Design)

The bottom end caps of the SNAP-23 fuel capsules were welded by 3M personnel. The welder data is as follows:

Miller Welder, Model 320 A/BP
AC-DC Inert Gas
High Frequency Start
Straight Polarity
Amp Range 10-160 Amps

The electrode used for the welding procedures was one-eighth inch 2 percent thoriated tungsten electrode using argon gas flowing at a rate of 20 cubic ft/hour. The filler rod was one-eighth inch diameter, Hastelloy "C" tubing.

A clamp was used to hold the end cap in place during tacking. Three passes at 100 amps (10 volts) were made on each capsule, with the third pass finishing the filling and leaving enough material to allow machining to a smooth surface. Weld speed was 1.5 inches per minute.

- Fuel Capsule Bottom Fillet Weld (Improved Design)

Limited testing has been done to develop the necessary weld schedules for the proposed and improved fillet weld. The preliminary schedule is as follows:

Miller Welder, Model 320 A/BP
AC-DC Inert Gas
High Frequency Start
Straight Polarity
Amp Range 10-160 Amps
Variable Speed Chuck with Remote Foot Control

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The electrode used for the welding procedures was one-eighth inch diameter, two percent thoriated tungsten electrode using argon gas flowing at a rate of 20 cubic ft/hour. The filler rod was Hastelloy "C" tubing one-eighth inch in diameter.

A "C" clamp was used to hold the end cap in place while tacking the cap at 90 degree intervals.

First pass: fusion weld, 10 volts, 30 amps, 1.5 inches/minute

Second and third passes: filler passes using 10 volts, 80-100 amps,
1.5 inches/minute

4.3.6 NONDESTRUCTIVE TESTING

Several meetings have been held with representatives from ORNL and Battelle Northwest Laboratories (BNWL) to discuss methods for nondestructive inspection of fueled capsules. BNWL is currently evaluating ultra-sonic techniques and all indications are that this may be a promising technique for that purpose.

The problems of handling the fueled assemblies were discussed and equipment modifications suggested. Several test specimens are being forwarded so that the investigation may continue leading to establishment of standards for the capsule materials, weld configuration, surface finish, as well as other parameters.

4.3.7 HASTELLOY ALLOY "C" MATERIALS TESTING

Tensile strength testing was conducted for samples of material obtained from both the end caps and capsule wall. The capsule wall material tensile strength at average room temperature conditions was 115,499 psi. End cap samples under similar conditions were found to have an average tensile strength of 97,250 psi.

Although the values obtained were somewhat lower than those listed by the materials manufacturer, they are acceptable values. Samples were subjected to spectro-chemical analysis to verify the vendor material certification.

4.3.8 MOCK FUEL

Mock fuel pellets fabricated from ALSiMAG 614 were inserted into six fuel capsules before the final closure weld. The physical properties of the mock fuel closely approximate the properties of strontium titanate. Table 4-1 lists these properties.

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Table 4-1. Physical Properties of SrTiO_3 vs AlSiMag[®] 614

	AlSiMag [®] 614	SrTiO_3
Density (lbs/in.^3)	0.134	0.134
Coefficient of expansion ($^{\circ}\text{F}^{-1}$)	4×10^{-6}	6×10^{-6}
Compressive strength (lb/in.^2)	315,000	---
Thermal Conductivity (1500 $^{\circ}\text{F}$) BTU/hr-ft- $^{\circ}\text{F}$	4.8	2.4
Melting Point $^{\circ}\text{F}$	3000	3450

The selection criteria of AlSiMag[®] 614 for mock fuel was based upon the following:

- Physical properties closely resemble properties of radioactive SrTiO_3 .
- Cost is about 5 percent of the cost of nonradioactive SrTiO_3 .
- The unfired material is easily machinable.
- The unfired material shelf-life is long, thus permitting mock fuel to be ordered early in a test program while retaining dimensional flexibility of the pellet up to the time the fired pellet is required for the program.

Figure 4-5 shows a mock fuel pellet.

Figure 4-5. Mock Fuel Pellet

5.0 VOLTAGE REGULATOR DEVELOPMENT

5.1 PLANNED OBJECTIVES

- Operating voltage 24 volts $\pm$ 1 volt
- Operating life Five-year objective
- Ambient temperature Operating nominal: 70^oF $\pm$ 10^oF
Storage maximum: +140^oF
Storage minimum: - 40^oF
- 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)

5.2 PROGRESS THIS QUARTER

- Two prototype regulators were completed.
- A tendency of the regulator to oscillate was discovered and corrected.
- The regulation characteristic of the regulator was measured and found to be within specifications.
- The thermal characteristics of the regulator were measured and found to be within specifications.

5.3 TECHNICAL DISCUSSION

5.3.1 PROTOTYPE REGULATOR TESTING

Two prototype voltage regulators, designated HPR-B1 and HPR-B2, were assembled. The typical prototype assembly details are shown in Figure 5-1. Each regulator was burned in for a minimum of 250 hours before final closure of the regulator assembly.

The final closure of the regulators will consist of welding a cover to the regulator, leak-checking the weld, backfilling the regulator with nitrogen-helium mixture and sealing off the unit. The objective of backfilling is to eliminate oxygen and water vapor from contact with the regulator circuit board. A 2.77% helium trace was specified for leak-checking purposes. The cold backfill pressure will be 11 psig.

Figure 5-2 illustrates the front of the regulator test fixture. Voltage and current measurement points are brought out to jacks on the panel. A 0.25 percent shunt is

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Figure 5-1. Prototype Regulator

Figure 5-2. Regulator Test Fixture

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used to convert the current to a voltage. Both current and voltage are measured with a differential voltmeter having an accuracy of 0.05 percent.

Table 5-1 tabulates the performance data for test regulators HPR-B1 and HPR-B2. The units have passed the 250-hour minimum burn-in test, but have not yet received the final closure and backfilling. Figure 5-3 illustrates the typical volt-amp characteristic of the test regulators. Table 5-1 and Figure 5-3 both verify that the regulators are operating within the 24-volt $\pm$ 1-volt specification.

Table 5-1. Performance of Regulators in Test Fixture No. 2

Operating Hours	No Load Voltage	
	HPR-B-1	HPR-B-2
37	23.97	23.42
135	23.92	23.43
205	23.92	23.44
325	23.93	23.48
373	23.91	23.42

5.3.2 REGULATOR CIRCUIT TESTING

During initial circuit testing the device would break into oscillation when operated at extremely light loads or during overload. It was determined that these oscillations were caused by the circuit being driven to a non-linear operating state by the load extremes.

The circuit was modified to correct the oscillations phenomena. Figure 5-4 is a schematic of the modified circuit. After modification, the circuit performance complied with the voltage regulator specifications.

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Figure 5-3. Terminal Voltage and Current Drawn by Regulator

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Figure 5-4. Schematic Diagram - Voltage Regulator Circuit HPR-B

5.3.3 LONG TERM REGULATOR TESTING

Long term performance data, originally reported in Report No. MMM(3418)-17, has been updated to reflect the current status and the data tabulated in Table 5-2. All units reported by this data are operating within the specifications.

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Appendix A

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Appendix A¹

**SNAP-23 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 section of Quarterly Reports.

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: 8-18-65

SYSTEM AND GENERATOR DATA

System Concept: PbTe - T/E - Cylindrical Type

Fuel: Sr-90 TiO₃

Major System Assemblies: Single module generator, insulation envelope, fuel capsules and shield, and voltage regulator.

		<u>Total System²</u>	<u>Generator</u>
Design Life	years	5	5
Weight	pounds	1475	51
Length	inches	37.12	8
Diameter	inches	34 O. D. Maximum	23

¹Design data only. Test data pending.

²Based on larger MIN-K insulation system.

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		<u>Total System</u>		<u>Generator</u>	
		<u>Start of Life</u>	<u>End of Life</u>	<u>Start of Life</u>	<u>End of Life</u>
Electrical output	watt (e)	60	60	68.7	60.4
Thermal input	watt (th)	996	877	845	747
Efficiency	percent	6.03	6.85	8.14	8.08
Specific power	watt (e) pound				
Open circuit voltage	volts	24	24	50.3	44.0
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	1521 ⁰ F
Fuel capsule surface	1450 ⁰ F
Hot junction or T _h	1075 ⁰ F
Cold junction or T _c	195 ⁰ F
Base of fins	150 ⁰ F
Ambient, Air	80 ⁰ F

HEAT DISTRIBUTION

(START OF LIFE)

Total thermal input	996	100%
Heat to T/E couples	793	80%
Heat loss through T/E insulation	14	1%
Other system heat losses	190	19%
Heat rejected from housing	38	4%
Heat rejected T/E couples	724	73%

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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:	$1.4 \times 10^6 \text{ R}$	200 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 curries/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	$3 \times 10^{-10}^*$ μ c/cc
MPC water	$4 \times 10^{-6}^*$ μ c/cc
Toxicity:	N/A

*168-hour week

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HEAT SOURCE

System

Thermal Input:

Start of life	996 watt (th)
End of life	877 (th)
Capsules per generator	2
Isotope(s) and chemical form	Sr-90, SrTiO ₃

Capsule

Over-all length	4.894 inches
Over-all diameter	4.001 inches
Length/Area	0.389 inch ⁻¹
Fuel Loading per capsule (start of life)	498 watts 2380 gms 78,400 curies

Internal volume per capsule

Total	40.5 inches ³
Fuel	38.2 inches ³
Void	2.3 inches ³
Internal pressure	50 maximum psi @ 1400°F after 1 year

<u>Material</u>		<u>Capsule</u>	<u>Capsule Liner</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	5.6	0.1
Melting point	°F	2310-2450	2550-2600
Thermal Conductivity	BTU/ hr-ft-°F	9.9 @ 1112°F	12.9 @ 1110°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	
Electrical resistance:	
Generator	8.02 ohms (end of life)
Module	N/A
Couple	31.8 milliohms
Type of circuit:	series

THERMOELECTRIC LEGS

		P	N
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 (EOL)	°F	975	975
Cold Junction Temperature (EOL)	°F	180	180
Segment Temperature @ Max Eff	°F	526	370
Open Circuit Voltage	mv	83	92.4
Load Voltage @ Max Eff	mv	48.5	52.8
Resistance	mΩ	15.04	16.71
Current @ Max Eff	amps	2.3	2.37
Power @ Max Eff	watts	0.1115	0.1253
Rate of Heat Rejection	watts	1.22	1.26
Rate of Heat Absorption	watts	1.34	1.39
Material Efficiency	percent	8.32	8.99

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

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) - 0.029 ohms (typ.)
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	2.5	2.5
Input power	watt(e)	69	60.07
Input voltage	volts	24	24
Input current	amps	2.87	2.503
Operating temperature		70 ±10°F	

Voltage regulation	± 1 volt (Max) . 0.1 volt (typ.)
Transistor losses	0.007 watt (Max)

OTHER COMPONENTS

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

Material and Dimensions	MIN-K 1301 insulation powder-packed and zenon backfilled in all generator void space. Micro quartz insulation in felt form located strategic locations to prevent powder shifting.
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Estimated Thermal Conductivity	0.0192 BTU/hr-ft- ⁰ F
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Electrical Insulation for T/E Circuit

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.
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Construction	Double-walled vessel with nominal 9 inches side and 6 inches bottom wall separation. Void filled with block type MIN-K 1301 with an argon inert atmosphere.
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Internal Pressure (Hot)	1 Atmosphere
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Estimated Thermal Conductivity	0.020 BTU/hr-ft- ⁰ F
--------------------------------	---------------------------------

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 ⁰ F @ 80 ⁰ F ambient

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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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Appendix B

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Appendix B

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 B-1 illustrates the mechanical positioning of the hot shoes into the insulating strip. Figure B-2 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 B-3, 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 B-4 illustrates the positioning of one row of thermoelectric couples onto the hot frame.
- The followers and springs are inserted into the cold frame (Figure B-5), and individually compressed by the special fixtures, as illustrated in Figure B-6. After compressing each follower spring, the locking pin is extended past the follower hole. Figure B-7 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 B-8 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.

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Figure B-1. Placement of Hot Shoes into Insulating Strip

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

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Figure B-3. Couple Assembly Tool

Figure B-4.
Typical Positioning of One Row of
Couples onto Hot Frame

Figure B-5.
Inserting Row of Couples into Generator

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Figure B-6. Locking Couples into Generator

Figure B-7. One Row of Couples with Locking Pin Installed

B-4

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Figure B-8. One Row of Couples Installed into Generator

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