UNCLASSIFIED

MASTER

This document contains information affecting the National defense of the United States within the meaning of the Espionage Laws, Title 18, U. S. C., Sections 793 and 794. Its transmission or the revealing of its contents in any manner to an unauthorized person is prohibited by law.

GROUP 3-DOWNGRADED AT 12
YEAR INTERVALS. NOT
AUTOMATICALLY DECLASSIFIED

~~CONFIDENTIAL~~

UNCLASSIFIED

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information apparatus, method, or process disclosed in this report may not infringe privately owned rights, or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

~~CONFIDENTIAL~~

UNCLASSIFIED

Report No. MMM (3418)-5
C-92A
M3679 (35th Edition)

This Document Consists
of 132 pages

AEC RESEARCH AND DEVELOPMENT REPORT

C701. 110003

H.C. \$ 300; M.R. 65

This report has been prepared under contract AT (30-1) 3418
with the Atomic Energy Commission

CLASSIFICATION CANCELLED

DATE 4/28/67

For The Atomic Energy Commission

H. F. Carroll
TC

Chief, Declassification Branch

SNAP 23 PROGRAM

TERRESTRIAL RADIOISOTOPE FUELED
THERMOELECTRIC POWER SUPPLY SYSTEM

QUARTERLY REPORT NO. 1

15 June 1964 to 31 October 1964

Published November 1964

Prepared by:

J. C. Murphy

Approved by:

A. H. Mayala
Program Manager

This document contains information affecting the National defense of the United States within the meaning of the Espionage Laws, Title 18, U. S. C. Sections 793 and 794. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

GROUP 1
DOWNGRADED AT 12 YEAR INTER -
VALS. NOT AUTOMATICALLY
DECLASSIFIED. DoD DIR 5200.10

Issued by:

ISOTOPE POWER LABORATORY
ELECTRICAL PRODUCTS DIVISION
MINNESOTA MINING AND MANUFACTURING COMPANY
ST. PAUL, MINNESOTA 55119

1-0820

Printed in U.S.A. Charge \$2.45. Available from the U.S. Atomic Energy Commission, Division of Technical Information Extension, P.O. Box 1001, Oak Ridge, Tennessee. Please direct to the same address inquiries covering the procurement of other classified AEC reports.

~~CONFIDENTIAL~~

UNCLASSIFIED

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

UNCLASSIFIED

~~CONFIDENTIAL~~

Report No. MMM(3418)-5

LEGAL NOTICE

This report was prepared as an account of Government-sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, expressed or implied with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method or process disclosed in this report may not infringe privately owned rights; or
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

DISTRIBUTION

Distribution of this document in accordance with M 3679 (35th Edition) Category C-92a will be accomplished. Immediate external and internal distribution shall be limited to the following:

	<u>Copy Nos.</u>
Chief Isotopic SNAP Branch	TEP # 594
New York Operations Office	595
U.S. Atomic Energy Commission	596
New York 14, New York	
Isotopic Power Branch	TEP # 597
Division of Reactor Development	598
U.S. Atomic Energy Commission	599
Washington, D.C.	
Chief, New York Patent Group	TEP # 600
U.S. Atomic Energy Commission	
Upton, New York	
Minnesota Mining and Manufacturing Co.	TEP # 601
2501 Hudson Road	602
St. Paul, Minnesota 55119	603
	604
	605

UNCLASSIFIED

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

UNCLASSIFIED

Report No. MMM(3418)-5

QUARTERLY REPORT 1
15 June 1964 to 31 October 1964

SNAP 23 PROGRAM
TERRESTRIAL RADIOISOTOPE-FUELED
THERMOELECTRIC POWER SUPPLY SYSTEM

ABSTRACT

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

This thermoelectric generator will produce 60 watts at 24 volts, direct current. A dc-dc converter will not be used, however, a shunt type voltage regulator will be provided.

The objective of the program is to produce a system which will permit the most efficient utilization of radioactive SR-90 fuel while secondarily limiting size and weight to a minimum.

The power supply system consists of three major components, which are listed as follows:

- Thermoelectric generator
- Insulation envelope
- Heat source

These three components can be assembled to form the power system without the use of hot cell facilities.

The thermoelectric generator consists of the thermoelectric conversion hardware and the cooling fins. The heat source consists of two doubly encapsulated fuel capsules surrounded by a biological shield of a depleted uranium alloy. To minimize heat losses, the heat source is placed in an insulation envelope.

The system design provides two major advantages which are as follows:

- Field installation or service can be accomplished without hot cell facilities
- Development time is minimized by parallel development of each subsystem.

UNCLASSIFIED

~~CONFIDENTIAL~~

~~UNCLASSIFIED~~

~~CONFIDENTIAL~~

Report No. MMM(3418)-5

Also included in the scope of work for the contract is the assembly of an electrically heated model generator system and the development of three insulation systems. The insulation development includes a system supplied by Linde Division of Union Carbide Corp., incorporating their "Super Insulation",[®] and two 3M-developed insulation envelopes. One of the 3M systems will be a high molecular gas-filled concept and the other an evacuated system.

~~UNCLASSIFIED~~

~~CONFIDENTIAL~~

TABLE OF CONTENTS

Section	Page
Legal Notice	ii
Abstract	iii
Table of Contents	v
List of Illustrations	ix
List of Tables	xi
Introduction	xiii
Summary	xv
Thermoelectric Power Supply System Thermal Analysis	xv
Thermoelectric Generator	xv
Heat Source	xvi
Cooling Fins	xvii
Heat Accumulator Fabrication	xvii
Insulation Envelope	xviii
System Analysis	xviii
1.0 POWER SUPPLY SYSTEM	1-1
1.1 Planned Objectives	1-1
1.2 Progress This Quarter	1-1
1.3 Technical Discussion	1-1
Vital Interface Locations	1-1
2.0 THERMOELECTRIC GENERATOR DESIGN	2-1
2.1 Planned Objectives	2-1
2.2 Progress This Quarter	2-1
2.3 Technical Discussion	2-2
Thermoelectric Couple Hardware	2-2
Heat Accumulator Design	2-5
Support Cone	2-6
Thermal Analysis	2-7
2.4 Selection of Thermoelectric Materials	2-7
2.4.1 Planned Objectives	2-7
2.4.2 Progress This Quarter	2-8
2.4.3 Technical Discussion	2-8
Thermoelectric Materials Selection	2-8
Thermoelectric Leg Design	2-14

Section	Page
3.0 HEAT ACCUMULATOR MATERIAL FABRICATION DEVELOPMENT	3-1
3.1 Planned Objectives	3-1
3.2 Progress This Quarter	3-1
3.3 Technical Discussion	3-3
Cladding	3-3
Shrink Fit	3-6
Brazing	3-6
Test Fixture	3-7
4.0 COOLING FIN DESIGN AND DEVELOPMENT	4-1
4.1 Planned Objectives	4-1
4.2 Progress This Quarter	4-1
4.3 Technical Discussion	4-1
Cooling Fins	4-1
Test Results	4-2
Cooling Fin Test Fixture	4-2
5.0 INSULATION ENVELOPE DEVELOPMENT	5-1
5.1 Planned Objectives	5-1
5.2 Progress This Quarter	5-2
5.3 Technical Discussion	5-2
6.0 HEAT SOURCE DESIGN	6-1
6.1 Planned Objectives	6-1
6.2 Progress This Quarter	6-1
6.3 Technical Discussion	6-2
Fuel Requirements	6-2
Fuel Capsule Fabrication	6-2
Biological Shield	6-5
7.0 VOLTAGE REGULATOR DEVELOPMENT	7-1
7.1 Planned Objectives	7-1
7.2 Progress This Quarter	7-1
7.3 Technical Discussion	7-1
8.0 GROWTH SYSTEM PREDICTIONS	8-1
8.1 Planned Objectives	8-1
8.2 Progress This Quarter	8-1
8.3 Technical Discussion	8-1

Section	Page
Appendix A	Thermoelectric Materials Electrical and Mechanical Performance
Appendix B	System Weight Analysis
Appendix C	Support Cone Analysis - Buckling
Appendix D	Cooling Fin Analysis
Appendix E	Heat Loss Calculations - Gas Filled Insulation Envelope
Appendix F	Thermal Analysis
Appendix G	Heat Source Calculations

~~CONFIDENTIAL~~

BLANK PAGE

037029 ~~CONFIDENTIAL~~

LIST OF ILLUSTRATIONS

Figure		Page
1-1	Isometric View - SNAP-23	1-3
2-1	Thermocouple Layout - SNAP-23	2-3
2-2	Figure of Merit vs. Temperature for N-Type (PbTe)	2-10
2-3	Figure of Merit vs. Temperature for P-Type Material	2-10
2-4	Seebeck Coefficient vs. Temperature for N-Type Material (PbTe)	2-11
2-5	Resistivity vs. Temperature for N-Type Material (PbTe)	2-11
2-6	Seebeck Coefficient vs. Temperature for P-Type Material	2-12
2-7	Resistivity vs. Temperature for P-Type Material	2-12
2-8	Thermal Conductivity vs. Temperature for N-Type Material (PbTe)	2-13
2-9	Thermal Conductivity vs. Temperature for P-Type Material	2-13
3-1	Heat Accumulator Fixture	3-2
3-2	Heat Accumulator Fixture	3-2
3-3	Heat Accumulator Fixture	3-3
3-4	Heat Accumulator Fixture	3-3
3-5	Photo-microphotograph - Stainless Steel Clad Copper	3-4
3-6	Photo-micrograph - Stainless Steel Clad Copper	3-5
4-1	Thermocouple Locations	4-3
4-2	Simulated Environmental Set-ups - Cooling Fin Test Fixture	4-4
6-1	Assembly - Fuel Capsule and Liner 3M-39	6-3
A-1	Calculated and Measured Resistance vs. Hot Junction Temperature	A-15
A-2	Calculated and Measured Voltage vs. Hot Junction Temperature	A-15
A-3	Calculated and Measured Heat Flux vs. Hot Junction Temperature	A-16
A-4	Calculated and Measured Voltage vs. Hot Junction Temperature (Complete Generator)	A-16
A-5	Calculated and Measured Resistance vs. Hot Junction Temperature (Complete Generator)	A-17

Figure		Page
A-6	Stress-Strain Relationship for Equilibrium Annealed Lead Telluride	A-19
A-7	Creep Characteristics of Lead Telluride at High Temperature	A-20
D-1	Fin Design Parameters - Free Convection	D-2
D-2	Fin Analysis "C" and "D" Curve Identity	D-3
D-3	Fin Analysis - C Curves	D-4
D-4	Fin Analysis - D Curves	D-5
D-5	Heat Dissipated by Fins vs. Fin Base Temperature Less Ambient Temperature	D-6
F-1	Fin Heat Dissipation	F-1
F-2	Heat Flow and Temperature Distribution of System	F-3
G-1	Spatial Relationship of Fuel Capsule to Generator Components	G-2
G-2	Function $F(\phi, \mu t)$ vs. μt	G-9
G-3	Dose Rate vs. Shield Thickness	G-14
G-4	Shield Thickness vs. System Diameter	G-15

LIST OF TABLES

Table		Page
2-1	Summary - Thermoelectric Couple Configuration	2-15
2-2	Predicted Results of Designed Thermoelectric Couples and Legs	2-16
2-3	Summary of System Design	2-17
6-1	Properties - Hastelloy Alloy C	6-4
D-1	Fin Analysis - Various Lengths (C-Curves)	D-7
D-2	Fin Analysis - Various Heights (D-Curves)	D-9
F-1	Heat Flo (Preliminary)	F-4
F-2	Temperature Profile	F-5
G-1	Linear Absorption Coefficients cm^{-1}	G-2
G-2	Attenuation Exponents μt	G-3
G-3	Σ Attenuation Exponents μt	G-4
G-4	Self Absorption Exponents $\mu_c t_c$	G-5
G-5	Self Absorption Parameters as a Function of Fuel Radius	G-6
G-6	Self Absorption Parameter $\mu_c t_c / m$	G-7
G-7	$F(, \mu t)$	G-10
G-8	Photon Flux at Surface of Housing	G-11
G-9	Photon Energy vs. $\mu a / \text{Pa}$ and K	G-12
G-10	Build-up Factors	G-12
G-11	KBC	G-12
G-12	Dose Rates in R/Hr through U-8 Mo Shield at Housing Surface	G-13

~~CONFIDENTIAL~~

BLANK PAGE

037229 ~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Report No. MMM(3418)-5

QUARTERLY REPORT 1
15 June 1964 to 31 October 1964

SNAP 23 PROGRAM
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 at 24 volts output
- Five-year life
- High efficiency
- High reliability
- Weight less than 900 pounds
- Size less than 25 inches diameter by 25 inches high
- SR-90 titanate fuel
- Designed ambient air temperature of $70^{\circ}\text{F} \pm 10^{\circ}\text{F}$
- 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

During this reporting period, the major effort has been in the design and development areas of the program. Since the bulk of the testing activities has been scheduled for the second quarter of the program, this report consists chiefly of design data and engineering predictions governing the hardware to be subsequently tested.

xiii/xiv

~~CONFIDENTIAL~~ ~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

BLANK PAGE

03712291038 ~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Report No. MMM(3418)-5

QUARTERLY REPORT 1
15 June 1964 to 31 October 1964

SNAP 23 PROGRAM
TERRESTRIAL RADIOISOTOPE-FUELED
THERMOELECTRIC POWER SUPPLY SYSTEM

SUMMARY

This report describes the progress of the program between the effective date of the contract and 31 October 1964. Approximately the first six weeks of the program was devoted to information acquisition and definition of ground rules, with major technical work starting approximately 1 August 1964. During this reporting period, the major accomplishments were in the following areas:

Thermoelectric Power Supply System Thermal Analysis

An iterative calculation process was established to determine the relationship of thermal parameters for the thermoelectric generator and the shunt heat losses of the system with respect to the thermal watts of fuel required. This calculation process was based first upon the end-of-life conditions, and then extrapolated to the beginning-of-life fuel requirements in order to accommodate the decay of the isotope fuel.

The results of this series of calculations have continually changed as various parameters have been defined by design changes and test results.

Thermoelectric Generator

The generator is designed in a cylindrical configuration with the thermoelectric legs positioned in spring-loaded compression between two concentric cylinders. Hardware design follows proven 3M Company techniques which utilize the pressure-contacted hot junction approach. The generator will have an all welded, hermetically-sealed enclosure to accommodate the chemical and physical requirements of the thermoelectric materials. The preliminary design has been completed.

~~CONFIDENTIAL~~

Thermoelectric Summary

P leg	3M materials specification: M30/M15 (BiSbTe/PbSnTe) segmented
N leg	3M materials specification: M13/M10 (LTN 400/LTN 120) segmented
Length	P = N = 0.479 inch
Diameter	P = N = 0.187 inch
Number of couples	245, series connected
Nominal hot junction temperature	1100° F (BOL) 970° F (EOL)
Nominal cold junction temperature	190° F (BOL) 170° F (EOL)
Thermopile input	770 watts (BOL-thermal)

Heat Source

The heat source will consist of two fuel capsules fabricated from Hastelloy Alloy C and secured into a biological shield. The shield will be fabricated by casting a depleted uranium (8% molybdenum alloy) into the necessary size and shape. A two-piece titanium cover will provide the necessary mechanical isolation for the heat source to prevent any incompatibility between the depleted uranium and the group VIII metals (iron, cobalt, nickel, etc.) commonly used in stainless steel alloys. A similar liner will be used to isolate the fuel capsules from the biological shield. These liners will be a simple slip-fit over the components and are not intended to be a part of any hermetic sealing.

Each fuel capsule will be double encapsulated, as recommended by the Oak Ridge National Laboratories, in order to minimize the hot cell decontamination time after fueling.

Heat Source Summary

Fuel loading	900 watts (thermal) (BOL)
Fuel type	SrTiO ₃
Curies	137 x 10 ³ SR-90
Fuel weight	9.2 pounds
Shield thickness (nominal)	3.2 inches
Shield weight	714 pounds

Cooling Fins

To confirm the cooling fin subassembly designed for the thermoelectric generator, a full-size mock-up of this subassembly was assembled and operated. Operating this test fixture in the various simulated environments confirmed that the cooling fin design configuration was adequate.

Cooling Fin Summary

Number of fins	100
Fin length	7 inches
Fin height	5 inches
Fin thickness	0.045 inch
Fin material	Copper, 200 BTU/hour-foot-° F
Fin base temperature	140° F
Heat dissipation	680 watts thermal
Ambient temperature	70° ± 10° F

Heat Accumulator Fabrication

The accumulator conducts thermal energy from the heat source into the thermoelectric generator. It must, moreover, be structurally sound since it is the main support member of the generator and also forms part of the hermetic seal for the generator.

Four methods were investigated to determine the best mode of fabricating this component. These methods are listed as follows with the most desirable method appearing first:

- Stainless steel may be clad onto a copper ingot. A metallographic bond is formed at the stainless steel-copper interface during the cladding process. This process has related problems of high expense and long lead times for delivery.
- A stainless steel tube may be shrink-fitted onto a copper ingot. Fabrication techniques are well known and economical. Requires further testing to determine the integrity of the stainless steel-copper interface as a function of time and temperature.

- Casting the copper into a stainless steel tube was investigated and rejected. This rejection was based on the predicted difficulty of establishing a sound metallurgical bond at the copper-stainless steel interface.
- Brazing was investigated as a method for attaching stainless steel to a copper ingot. Tests indicated that a definite need must be apparent to justify the extensive effort required to develop this method.

Insulation Envelope

Two insulation design concepts are being developed to produce an efficient, reliable insulation envelope for the power generation system. These concepts are:

1. High vacuum system
2. High molecular gas-filled system

Two high vacuum systems are being developed. The first will be in conjunction with the Linde Division of Union Carbide Corporation using their Super Insulation materials. A second high vacuum system employing techniques developed by the New Products Division of the 3M Co. will also be developed.

The gas-filled system will employ MIN-K^(R) #1301 insulation, back-filled with a high molecular weight gas such as Xenon.

System Analysis

A parallel work effort was started to establish a computer program which would predict the interrelated parameters of the power supply system. The results of this program will be used to predict the salient parameters for terrestrial power supply systems requiring power outputs below and above the 60-watt system being developed by this contract.

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 direct current) for the five-year design life.
- To engineer the system to permit unattended operation during the design life while operating in terrestrial environments.
- To develop the system for the best utilization of the SR-90 isotope fuel as the state-of-the-art permits; however, the overall system efficiency will be at least 6.75% 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

System interface specifications were defined at each point as soon as the conceptual design of the principal components surrounding the interface was defined.

1.3 TECHNICAL DISCUSSION

Vital Interface Locations

An interface exists between the thermoelectric generator and the insulation envelope. This interface contains a rubber O-ring which forms a type of hermetic seal between the generator and the insulation envelope. The purpose of this seal is not for any primary structural support, but to prevent a "breathing" phenomena of the assembled system as it is influenced by changing barometric pressures. In time, this breathing would allow the insulating materials (MIN-K #1301) covering the heat source to be affected by humidity, and the breathing would also allow the heat source to oxidize more rapidly. By using this O-ring seal, the entrapped atmosphere

~~CONFIDENTIAL~~

will have its active oxygen removed by a "gettering process" as the biological shield oxidizes in the presence of this entrapped atmosphere.

Another interface exists at the lower end of the heat accumulator as it contacts the heat source. This interface is thermally sensitive since all productive thermal energy must cross the two contacting surfaces in order to reach the heat accumulator and in turn the thermoelectric generator. This pressure contact interface is made possible by a 0.625 inch diameter molybdenum stud which passes through the accumulator and terminates into the heat source. This stud is fabricated from molybdenum in order to prevent a possible eutectic solution from forming, as would occur between the group VIII alloys of a stainless steel stud and the depleted uranium heat source. (See Section 6.0, this report.)

Each of the subsequent sections of this report will elaborate upon the progress of the design and development of the major system components.

Figure 1-1 illustrates the present system design.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

MINNESOTA MINING & MANUFACTURING CO ST. PAUL 5, MINNESOTA	D	PD-39-1042	A
--	---	------------	---

Figure 1-1. Isometric View - SNAP-23

~~CONFIDENTIAL~~

2.0 THERMOELECTRIC GENERATOR DESIGN

2.1 PLANNED OBJECTIVES

The planned objectives are:

- 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 to the generating system without special tools.
- To design, develop, and fabricate generator hardware to effect maximum efficiency using currently available thermoelectric materials.

2.2 PROGRESS THIS QUARTER

- The generator will be attached directly to the heat source by a single stud which extends through the center of the accumulator.
- The following pertinent temperatures and watts of heat were derived from the Q and T balance of the system (EOL, five years, at 70° F ambient).

Thermoelectric legs	$T_h = 970^\circ \text{F}$
	$T_c = 170^\circ \text{F}$
Generator Input at 60 watts(e) Output	$Q = 680 \text{ watts (th)}$

- The current generator design requires 245 thermoelectric couples with each thermoelectric leg being 0.187 inch in diameter and 0.479 inch long. Both P and N legs are of equal length.

- The heat accumulator is designed to be 7 inches in length and 3 inches in diameter. The thermoelectric generator contacts the top 3.75 inches (called the active length) of the accumulator.
- The current design utilizes a stainless-steel clad copper ingot for the accumulator materials.
- The hot and cold end hardware is illustrated in Figure 2-1 of this report,
- MIN-K #1301 will be used for the thermal insulation between the thermoelectric legs. The atmosphere will be Xenon gas to improve the thermal insulation and provide an inert atmosphere for the thermoelectric legs.
- The cooling fins are brazed to a cylindrical steel jacket. This jacket has a shrink-fitted interface with the cold frame of the generator.

2.3 TECHNICAL DISCUSSION

Figure 2-1 illustrates the thermoelectric couple layout dimensions and the expected principal temperatures associated with this portion of the thermoelectric generator.

Thermoelectric Couple Hardware

The hot end hardware consists of a thin steel cup which envelops the end of each leg and rests on a 0.040-inch thick by 0.219-inch wide copper hot junction electrode. The cup thus positioned provides the electrical connection and heat accumulation for the leg. A double layer of 0.005-inch mica provides electrical insulation from the accumulator.

The cold end hardware consists of a spherical copper cold cap soldered onto each thermoelectric leg (by using an 18-gauge, 0.040-inch diameter silver jumper wire, the N and P-type legs are joined to form thermoelectric couples). Each spherical cold cap is fitted into a socket in the end of an aluminum follower. The follower extends 0.75 inch into the cold frame to provide a heat dissipating surface and has an aluminum hardcoat for electrical insulation from the cold frame. The individual leg assemblies are spring-loaded within the cold frame to provide pressure-contact at the hot end.

The cold ends of the thermoelectric couples are designed to utilize the "ball and socket" hardware concept. This concept has the following material advantages:

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

MINNESOTA MINING & MANUFACTURING CO ST. PAUL 6 MINNESOTA	B	PD-39-1037	A
---	---	------------	---

Figure 2-1. Thermocouple Layout - SNAP-23

2-3/2-4

~~CONFIDENTIAL~~

0317228.0030

~~CONFIDENTIAL~~

- Reliable cold end termination is provided offering mechanical flexibility between the cold cap interface of the thermoelectric leg and its follower.
- Each thermoelectric leg is permitted to have a possible small misalignment which might be caused during assembly of the thermoelectric generator or during subsequent exposure of the generator to severe shock and vibration environments.
- If misalignment occurs, a uniform pressure will continue to be applied on the leg to maintain the hot end contact. It is a well known property of thermoelectric materials that they will reseal or heal their hot end contact after it has been disturbed providing that the contact pressure is still applied.
- Because of the mechanical flexibility of the ball and socket concept, the quality assurance effort during the assembly of the generator is boosted since the exact placement or alignment of each thermoelectric couple within the generator becomes less critical. Considering that this generator will utilize 245 thermoelectric couples with 490 cold cap-follower interface points, this feature of the ball and socket concept is a distinct quality assurance advantage.
- The calculated 10° F temperature drop across the ball and socket interface is comparable to other methods for cold end pressure contacting.

Heat Accumulator Design

The heat accumulator consists of a 3-inch diameter by 7-inch long solid, high conductive copper ingot. To provide environmental protection, the copper is encapsulated by stainless steel having a wall thickness of 0.040 inch.* The copper ingot collects heat from the top of the heat source and transfers it along a portion of the length (3.25 inch inactive). Heat is then dissipated radially along a 3.75-inch active length into the thermoelectric legs. The temperature drop along the inactive length (end of life) of the accumulator is approximately 71° F from the heat source to the first column thermoelectric legs. A non-linear temperature difference of 41° F exists along the active length of the accumulator (end of life). The

*See Section 3.0 for discussion of heat accumulator fabrication processes.

~~CONFIDENTIAL~~

mean temperature drop along the active length of the accumulator is 29° F. In summary, the heat source is at approximately 100° F higher temperature than the mean temperature point on the heat accumulator for end-of-life conditions.

An estimated 680 watts (thermal-EOL) will be conducted from the active area of the accumulator through 0.010 inch of mica, through the copper hot junction electrodes and steel hot end caps, and thence to the thermoelectric couples. This heat flux represents that energy available for thermoelectric conversion by the thermoelectric couples. No temperature drop was assumed between the accumulator and the hot ends of the thermoelectric couples.

Reliable data predicting the creep rate for various copper alloys operating in excess of 1000° F for periods of five years is not available. In lieu of this data, Belleville springs are being investigated for possible incorporation into the design. The springs will be used to preload the accumulator to the heat source. The initial preload will also be maintained during thermal expansion of the principal materials and during subsequent accumulator shortening resulting from the material creep of copper. A more detailed analysis will subsequently be conducted to determine the exact properties of the Belleville springs. It is evident that by using Belleville springs high orders of force for small mechanical deflections can be attained.

Support Cone

A thin-walled (0.010-inch material) stainless steel cone connects the heat source end of the accumulator to the outer case at a point just below the cold frame. This seals off the generator interior permitting backfill with an inert gas atmosphere. As pointed out in the preceding paragraph, the accumulator is enclosed by a stainless steel jacket, and since the generator outer case is also stainless steel, compatibility of materials for welding is provided so that this portion of the generator enclosure may be closed off. The cone structure heat loss was calculated to be 13 watts. The enclosure (accumulator to outer case) for the top end of the generator has not been defined for the current design; however, heat loss through the top end enclosure can be estimated to be approximately 10 watts.

~~CONFIDENTIAL~~

Thermal Analysis

The total shunt heat losses for the thermoelectric generator have been calculated to be approximately 50 watts (thermal - EOL). These losses occur in the following areas:

Losses through the non-active portion of the heat accumulator

Losses through the insulation surrounding the non-active portion of the accumulator

Losses through the generator structure

Losses through the top of the heat accumulator

Appendix F outlines the thermal analysis for this system in more detail.

2.4 SELECTION OF THERMOELECTRIC MATERIALS

2.4.1 Planned Objectives

To select the thermoelectric materials, define the length and diameter of the thermoelectric legs, and determine the number of thermoelectric couples necessary to provide the following:

Output voltage	24 volts $\pm$ 1 volt, EOL
Output power	60 watts, EOL
Electrical configuration	Series connected, shunt type voltage regulator
Load	Resistive load, matched for maximum efficiency
Thermoelectric leg efficiency	8.7%
Design life	Five years
Design hot junction temperature	970° F nominal EOL
Design cold junction temperature	170° F nominal EOL
Maximum hot junction temperature	1100° F nominal BOL

2.4.2 Progress This Quarter

Thermoelectric materials selected:

N-leg:	M#10 (PbTe) hot end segment
	M#13 (PbTe) cold end segment
P-leg:	M#15 (PbSn)Te hot end segment
	M#30 (Bi-Sb) ₂ Te ₃ cold end segment

Thermoelectric leg dimensions: P = N = 0.187 inch diameter x 0.479 inch long

2.4.3 Technical Discussion

Thermoelectric Materials Selection

The thermoelectric materials for this application are chosen to provide maximum efficiency over the operating temperature range. Since thermal output of the SR-90 heat source decreases with time, the generator must be designed to produce the required output with the heat available at the end of the operating life.

The efficiency of a thermoelectric leg is determined by the equation:

$$\eta = \frac{I (E - I^2 R)}{Q_c + Q_p - \frac{1}{2}Q_j - \frac{1}{2}Q_t}$$

where:

I	=	load current
E	=	load voltage
R	=	resistance
Q _c	=	conducted heat
Q _p	=	Peltier heat
Q _j	=	Joule heat
Q _t	=	Thompson heat

Appendix A describes the mathematical processes by which each of the above quantities is calculated.

A number of different materials and material combinations were compared under the specified conditions to obtain an optimum design. The materials to be utilized in segmented thermoelectric legs are selected on the basis of their being chemically, thermally, and mechanically compatible. Also, to minimize internal Joulean heat losses, the segments must be closely matched in terms of the optimum current for maximum efficiency per watt of conducted heat.

The actual thermoelectric materials exhibit measured maxima of the figure of merit at different points over the desired temperature range. For optimum performance the thermoelectric leg is formed by joining together a pair of homogeneous segments of different compositions. The temperature of the common interface between the two segments, known as the segmenting temperature, therefore becomes an influential temperature to be considered during the development of the thermoelectric generator.

Selection of the design segmenting temperature is based on the maximum efficiency of the complete leg. It can be seen in Figure 2-2 that the chosen segmenting temperature for the N leg is not at the intersection of the figure of merit curves of the selected materials. This is due to the current being non-optimum for each segment; however, for the design load current, the segmenting temperature of 462° F yields the maximum efficiency for the leg.

For this generator, the N-type legs are formed of differently doped segments of PbTe; the hot end of PbTe M10 having a room temperature resistivity of 120 micro-ohm inches, the cold end of PbTe M13 having a room temperature resistivity of 400 micro-ohm inches. From an examination of the curves of Figure 2-2, it will be seen that the combination of these two materials gives a higher figure of merit over a larger temperature range than can be obtained from the non-segmented leg formed of either material. The P-type legs are formed of two different telluride materials: the hot segment is (PbSn)Te, material M15; the cold segment is (BiSb)Te, material M30. Figures of merit of the P-leg segments are shown in Figure 2-3. Summarizing:

<u>Location</u>	<u>N-Type</u>	<u>P-Type</u>
Hot Segment	M10, PbTe	M15, (PbSn)Te Alloy
Cold Segment	M13, PbTe	M30, (BiSb)Te Alloy

~~CONFIDENTIAL~~

Figure 2-2. Figure of Merit vs. Temperature for N-Type Material (PbTe)

Figure 2-3. Figure of Merit vs. Temperature for P-Type Material

~~CONFIDENTIAL~~

Figure 2-4. Seebeck Coefficient vs. Temperature for N-Type Material (PbTe)

Figure 2-5. Resistivity vs. Temperature for N-Type Material (PbTe)

Figure 2-6. Seebeck Coefficient vs. Temperature for P-Type Material

Figure 2-7. Resistivity vs. Temperature for P-Type Material

Figure 2-8. Thermal Conductivity vs. Temperature for N-Type Material (PbTe)

Figure 2-9. Thermal Conductivity vs. Temperature for P-Type Material

Thermoelectric Leg Design

The preliminary electrical analysis based on the methods discussed in Appendix A showed that the optimum design for the thermoelectric legs can be obtained when the length-to-area (L/A) ratio is somewhat different for the N and the P-legs.

Choosing the size of the thermoelectric legs is based primarily on mechanical strength and fabrication considerations. Theoretically there are an infinite number of combinations of length and diameter that will result in the same L/A . Practically, with higher L/A ratio, the smallest diameter that can be readily fabricated is usually the best choice; however, the choice of length also enters into the decision since the shunt heat losses increase as the length decreases. Very small diameter legs with high L/A ratios are also subject to buckling which would introduce undesirable tensile forces in the legs.

The compromise diameter selected was 0.187 of an inch. The theoretical optimum length of the legs would then be 0.494 inch and 0.463 inch for the N and P-legs, respectively.

For assembly considerations and uniformity of cold junction hardware, it is desirable to have legs of equal lengths. Fortunately, since the L/A ratios of the N and P-legs are very close for the selected materials, the loss in efficiency of the couple due to the increase in internal heat losses from a current mismatch is very slight. For the selected length of 0.479 inch, the loss in efficiency is only 0.01%.

Table 2-1. Summary - Thermoelectric Couple Configuration

Material Specification - M30/M15 M13/M10	Equal Length	Optimum
$T_{h_{EOL}}$ (°F)	970	970
$T_{c_{EOL}}$ (°F)	170	170
T_{S_p} (BOL)	650	
T_{S_N} (BOL)	462	
No. of Couples	245	245
$(L_c/L)_N$	0.311	0.311
$(L_c/L)_p$	0.504	0.504
$(L/A)_N$	17.35	17.88
$(L/A)_p$	17.35	16.80
A_N (in. ²)	0.0276	0.0276
A_p (in. ²)	0.0276	0.0276
L_N (in.)	0.479	0.494
L_p (in.)	0.479	0.463
L_{CN} (in.)	0.149	0.154
L_{CP} (in.)	0.242	0.234
η %	8.69	8.70

T = Temperature, °F

T_S = Segmenting Temperature, °F

L = Total length

L_c = Length, cold segment

L_h = Length, hot segment

A = Area

Subscripts designate "N" or "P" leg,
hot (h) or cold (c) end

Table 2-2. Predicted Results of Designed Thermoelectric Couples and Legs

Type		T_h	T_c	E	R	P
N-Leg	BOL	1100	190	117.4	20.1	0.172
	EOL	970	170	100.3	16.5	0.153
P-Leg	BOL	1100	190	94.0	16.7	0.132
	EOL	970	170	79.6	14.3	0.111
Couple	BOL	1100	190	211.4	36.7	0.303
	EOL	970	170	179.9	30.8	0.262

T_h = Temperature, °F, hot electrode

T_c = Temperature, °F, cold electrode

E = Open circuit, emf., in millivolts

R = Internal resistance in milliohms

P = Maximum power output, watts

~~CONFIDENTIAL~~

Table 2-3. 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	245 series connected
Fuel	SR-90 Titanate
Fuel Power Density	0.8 watts/cc
Fuel Loading	137×10^3 Curies
Fuel Volume	68.6 inches ³
Heat Input	900 watts BOL
System Efficiency	6.65% BOL 7.60% EOL
Thermoelectric Material (Powder pressed)	N - Segmented M13/M10 PbTe P - Segmented M30/M15 (BiSb)Te (PbSn)Te
Leg Diameter	0.187 inch
Leg Length N and P	0.479 inch
Cold Segment Length	N - 0.149 inch P - 0.242 inch
Hot Junction Temperature	1100°F nominal BOL 970°F nominal EOL
Cold Junction Temperature	190°F nominal BOL 170°F nominal EOL
Segmenting Temperature	P - 650°F N - 462°F
Electrical Contacting Method	Hot - pressure Cold - soldered bond

~~CONFIDENTIAL~~ ~~SECRET~~

3.0 HEAT ACCUMULATOR MATERIAL FABRICATION DEVELOPMENT

3.1 PLANNED OBJECTIVES

The purpose of the heat accumulator is to transmit the thermal energy from the heat source to the hot junctions of the thermoelectric generator. The shape of the accumulator is cylindrical to provide the most efficient use of the area with minimum thermal losses. It is the main support member between the thermoelectric generator and the heat source and must maintain a good interface fit at this point for maximum heat transfer.

Materials of the accumulator must be compatible with the materials of the heat source and the thermoelectric materials. They must be inert to environmental atmospheres and exhibit maximum thermal conductance characteristics. Since the accumulator forms an integral part of the hermetically sealed thermoelectric generator, its materials must also exhibit good welding characteristics.

The method of fabricating the heat accumulator consistent with the interface temperature distribution and the integrity of the stainless steel-copper interface will be determined.

3.2 PROGRESS THIS QUARTER

The following methods of fabrication were investigated:

1. cladding stainless steel on copper
2. shrink fitting stainless steel on copper
3. brazing stainless steel on copper
4. casting copper into a stainless cylinder

Casting copper into a stainless steel cylinder was eliminated when consultation with fabricators disclosed the unlikelihood of achieving an intimate bond between the copper and the stainless steel.

Brazing was eliminated after test results indicated the need for a large development effort in order to perfect this method. The problem was one of determining the time-temperature relation necessary to accomplish the brazed bond.

A shrink fit test sample was fabricated and is currently being tested.

A sample of stainless clad copper was obtained from the Revere Copper Company and tested with satisfactory results. Material for the preliminary design has been ordered and is expected to be delivered by the end of December.

A heat accumulator test fixture was fabricated. Temperature distribution and temperature drops will be measured under design heat conditions. Photographs of this test fixture are shown in Figures 3-1, 3-2, 3-3, and 3-4.

Figure 3-1. Accumulator Showing
A. Water Cooling Coil
B. Accumulator
C. Heat Conductor Fins

Figure 3-2. End View of
A. Accumulator
B. Heat Conductor Fins

Figure 3-3. Accumulator with Heat Conductor Fins, Water Cooling Coils, Heater, and Instrumentation Partly Insulated Before Being Enclosed in Hemetic Container

Figure 3-4. Hemetic Container for Testing Accumulator

3.3 TECHNICAL DISCUSSION

Cladding

Ten companies were contacted in an attempt to locate a vendor with the facilities and techniques to clad a 3-inch diameter copper ingot with 0.040-inch thick stainless steel. Of the ten companies contacted, only the Revere Copper and Brass Company at Rome, New York, indicated that they had the facilities to clad this large diameter material.

Two test specimens 0.25-inch long by 0.608-inch diameter were taken from the sample of stainless steel clad copper submitted by the Revere Company. One was

subjected to a temperature of 1200° F for 16 hours in an open furnace. After removing it from the furnace a photomicrograph comparison (Figures 3-5 and 3-6) was made with the specimen which was not subjected to the heat treatment. The comparison failed to show any parting of the stainless steel from the cladding. A peeling test was performed which failed to show any oxidation between the copper and stainless steel.

Figure 3-5. Photo-Micrograph of
Stainless Steel Clad
Free High Conductivity Copper
Sample Showing Interface
Bond After Heat Soak at
1200° F for 16 hours

Figure 3-6. Photo-Micrograph of
Stainless Steel Clad
Free High Conductivity Copper
Sample Showing Interface
Bond as Received From
Revere Copper Co.

As a result of the testing of this sample, the Revere Copper Company was requested to submit a price quotation for supplying the following: one bar consisting of Type 321 stainless steel clad onto an oxygen-free high-conductivity copper ingot, and one bar of Type 304 stainless steel clad onto an O.F.H.C. copper ingot. The stainless steel was specified to be 0.040 of an inch thick and the outside diameter of the bar to be 3.0 inches.

Shrink Fit

Another method tested for the fabrication of the accumulator is the shrink fit method whereby stainless steel tubing is fitted over a copper ingot.

A sample was made to test the possibilities of shrink fitting Type 347 stainless steel to a copper ingot. The copper ingot was 2.910 inches in diameter by 6 inches long. A stainless steel sleeve was machined to a 6-inch length with a 2.905-inch inside diameter and with an outside diameter of 3.5 inches. The copper ingot was then immersed in a mixture of acetone and dry ice and the stainless steel sleeve was heated to 500° F. After one-half hour the pieces were removed and the stainless steel sleeve was mounted over the copper ingot. The stainless steel was then machined down to a wall thickness of 0.040 of an inch.

This method of fabrication is being tested for the interface temperature drop between the stainless steel and the copper ingot.

The use of electron beam welding has been investigated as a back-up solution to the shrink fit method of fabricating the accumulator. The welding will be used in case the results of testing this fabrication method indicate that the copper-stainless steel interface must be hermetically sealed to prevent oxidation of the copper at its operating temperature.

Brazing

A third method of fabricating a stainless steel covered copper ingot was tested by brazing a stainless steel sleeve to the copper. The test samples were of Type 321 stainless steel and were 1 inch in length with a 2.912-inch inside diameter and a 3.125 outside diameter. The copper was then plated with 0.003-inch thick pure silver on the circumferential area with a 2.913-inch finished outside diameter.

The stainless steel ring was thermally expanded and fit over the copper. The complete part was then placed into a hydrogen atmosphere and heated to 1800° F. After one hour of heating, the specimen showed that a eutectic solution had developed between the copper and silver and that this solution had begun to flow away from the joint leaving a gap in certain areas.

~~CONFIDENTIAL~~

An identical sample was then tested at an equal temperature but for only eight minutes. After testing, no external defects were apparent, but when the piece was segmented and applied to a pull test, the stainless steel pulled away from the copper with very little applied force. This separation of the stainless steel-copper segments was made possible by the failure of the silver. Examination showed that heat had caused the silver to bond to both the stainless steel and copper.

Test Fixture

The test fixture, fabricated to determine the interface thermal losses, was completed at the end of the reporting period. This fixture has a heater at one end and is water cooled by rings at the other end. This simulates the flow of thermal energy into the accumulator that would be required by the thermoelectric legs of the generator. The complete unit is mounted inside of a hermetically-sealed chamber to permit operation with or without a controlled atmosphere. Temperatures will be monitored at several points on each side of the copper-stainless steel interface and on the water cooled rings. The test should provide information on how well the interface between the copper ingot and the heater can be maintained under the loading which the copper must be capable of supporting at 1200° F. The results of operating the test fixture will be reported.

~~CONFIDENTIAL~~

4.0 COOLING FIN DESIGN AND DEVELOPMENT

4.1 PLANNED OBJECTIVES

- To design cooling fins which will maintain the cold junction temperature while dissipating the rejected heat throughout the design temperature range of $70^{\circ}\text{F} \pm 10^{\circ}\text{F}$.

4.2 PROGRESS THIS QUARTER

Calculations (see Appendix D) utilizing classical empirical formulas for predicting the behavior of cooling fins were conducted to determine the number of fins, and their geometry, necessary to support the cooling requirements of the thermoelectric generator.

Because the EOL cold junction temperature for the thermopile has been calculated to be 170°F , or well below the cold junction temperature of conventional thermoelectric generators, it was imperative that predictions derived from empirical formulas be valid. A full-size cooling fin test fixture was fabricated to make this confirmation.

4.3 TECHNICAL DISCUSSION

Cooling Fins

When designing a thermoelectric generator, it is important that the cold junction temperature be determined as early as possible; therefore the design of the cooling fins becomes of prime importance. Theoretical calculations were made as outlined in Appendix D. To verify the necessary assumptions on the convective heat transfer coefficient, a test fixture was fabricated.

The quantitative value of the testing was not absolute since the heat dissipated was based upon calculated values derived from a preliminary design. As the thermoelectric generator design and other test programs progress, the quantitative data may be extracted from this fin test. The test was run over a sufficiently wide range to permit changes in generator configuration without jeopardizing the validity of original cold junction assumptions.

The qualitative value of this test fixture was that it allowed data to be quickly obtained with a minimum of laboratory effort. This permitted the following design areas to be investigated:

- the effects of using a 6-inch long cooling fin, instead of a 7-inch long fin
- the effects of a thermal shadow caused when the insulation envelope restricts the air flow at the base of the fins
- a qualitative determination of heat losses from the top of the insulation envelope, and how these losses influence the cooling fin performance
- an examination of the change in performance of the cooling fins when a 12-inch high stack is added

Test Results

These tests proved that the current cooling fin design was adequate to support the cooling requirements of the planned thermoelectric generator. With the assurance that the fins could maintain the desired EOL 170°F cold junction temperature, the design of the thermoelectric generator started.

As the testing progresses for the thermoelectric generator, the cooling fin fixture will be utilized to assist in optimizing the cooling fin requirements. The one single data input required for this optimization study is the numerical value of thermal watts rejected by the thermoelectric generator as determined by actual testing.

Cooling Fin Test Fixture

The cooling fin fixture consists of 100 fins made of 0.045-inch copper sheet which is 5 inches high, 7 inches long, and equally spaced on a 8.50-inch outside diameter stainless steel cylinder. Three 1000-watt heaters are installed into a block of aluminum and placed within the cylinder supporting the fins to simulate the heat source. Thermocouples are located so that a temperature profile of the fin may be obtained (Figure 4-1).

*Thermocouples are in similar positions but on fins positioned 90° from each other.

Figure 4-1. Thermocouple Locations

Figure 4-2 summarizes the design areas tested and the significance of each test.

It was determined that for the generator design end-of-life heat input of 680 watts and beginning-of-life heat input of 770 watts, cooling fin capacity was adequate as designed.

Cooling Fin Test Fixture
Note Auxiliary Heater Ring
to Simulate a 60-watt Heat
Input Contributed by
the Insulation Envelope

Fins Blocked to Simulate
a 6-inch Cooling Fin Length

Shroud Simulating Outer
Protective Shield of
Power Generation System

Shroud to Test a 12-inch
Stack Effect

Figure 4-2. Simulated Environmental Set-ups - Cooling Fin Test Fixture

5.0 INSULATION ENVELOPE DEVELOPMENT

5.1 PLANNED OBJECTIVES

- To develop an insulation envelope, designed by the 3M Company, fabricated by the Linde Division of the Union Carbide Corporation, and using the Linde Super Insulation materials.
- 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 insulation concept. This work shall utilize the techniques and materials available through the New Products Division of the 3M Company.
- To compare the insulating properties of the three systems tested and select one concept for incorporating into the design of this isotope-fueled thermoelectric power supply system.

Insulation Envelope Boundary Conditions

Maximum hot wall temperature	1350° F
Operating temperatures	Hot wall: 1200° F Cold wall: ambient air
Ambient air temperature	70° F $\pm$ 10° F
Heat loss	Best effort - optimize for minimum heat loss
Total load bearing requirements	800 pounds

5.2 PROGRESS THIS QUARTER

Linde-Produced Envelope

- Negotiations were started between the 3M Company and the Linde Division for their supplying one insulation envelope.
- At the end of the reporting period, the Linde Division's price quotation was received; negotiations have been started, and an order should be placed by December 15.

Gas-filled Insulation Envelope

- The conceptual design was completed for this envelope and the engineering drawings were started for the fabrication of this envelope. Initial vendor contacts were made for their supplying the components for this envelope.

High Vacuum Insulation Envelope

- Preliminary material investigations have been started for the insulation materials and support system. Mechanical design concepts are being evaluated.
- It is anticipated the design will consist of a parallel effort on materials selection and on mechanical design.

5.3 TECHNICAL DISCUSSION

Appendix E outlines the calculations for predicting the heat loss characteristics of the MIN-K inert gas envelope.

The heat loss calculations for each of the insulation envelope design concepts predict:

Linde	45 watts
3M gas-filled MIN-K #1301	43 watts
3M high vacuum	48 watts

These heat loss values represent a qualitative number only since none of the basic assumptions made for these calculations have been tested for application to this program.

~~CONFIDENTIAL~~

This selection of the insulation envelope concept to be used will depend chiefly upon an analysis of the following data generated during the development of each envelope concept:

- A comparison of the direct labor, materials, and tooling costs required to manufacture each envelope concept for pilot-run quantities.
- A comparison 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.

The selection will, therefore, be an integration of the manufacturing cost of each envelope, the increased fuel cost necessary to sustain the losses of each envelope, and the predicted reliability of the envelope.

~~CONFIDENTIAL~~

6.0 HEAT SOURCE DESIGN

6.1 PLANNED OBJECTIVES

- To design a fuel capsule to contain the required amount of fuel.
- To design a 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 handled with a minimum use of special equipment.
- To design a fuel capsule such that fuel encapsulation may be readily accomplished by governmental facilities.

6.2 PROGRESS THIS QUARTER

The following is a summary of the preliminary design of the heat source:

Fuel loading	900 watts (thermal)
Curies	137×10^3 SR-90
Fuel type	SrTiO_3
Fuel volume	68.6 inches ³ (total)
Fuel weight	9.2 pounds (total)
Fuel power density	0.8 watts/cm ³
Fuel capsules required	2
Fuel capsule material	Hastelloy Alloy C
Inner capsule material	Stainless steel, Type 321
Biological shield material	Depleted Uranium (8% Molybdenum)
Nominal thickness	3.2 inches
Shield weight	714 pounds

6.3 TECHNICAL DISCUSSION

Fuel Requirements

The end-of-life estimated thermal requirement for the thermoelectric generator is 680 watts, and by including the shunt heat losses of the system, the EOL heat requirements are predicted to be 792 watts (thermal). Because of the 27.5-year half-life of SR-90 and the five-year design life of the power supply system, a correction factor is needed to obtain the beginning-of-life power requirement. This amount is currently estimated to be 900 watts. The fuel volume was calculated by using a power density factor of 0.8 watts/cm³. The fuel volume for the SNAP 23 generator was calculated to be 68.6 inches³.

The diameter of a fuel pellet has a maximum value of 3.5 inches. Using current technology, the fuel height would be 7.13 inches with a diameter of 3.5 inches, but the Hastelloy Alloy C tubing required for fabrication of the fuel capsule would require a special fabrication run because this size would not be standard. The closest standard size tubing was 4.0-inch outside diameter. Using suggested tolerances for the fuel pellets and allowing space for an inner capsule, the fuel diameter was defined to be 3.3 inches, thus allowing the use of the standard tubing.

The decrease in fuel diameter would increase the fuel length to 8.04 inches. However, encapsulation of fuel in this size of fuel capsule could lead to problems with centerline temperature and welding difficulties. To alleviate these potential problems, two fuel capsules would be used with each capsule containing one-half of the SR-90 fuel. It is possible that this fuel capsule could also be used in the generator adaptable size units (25, 100, 200 w).

Fuel Capsule Fabrication

The fuel capsules will be fabricated from Hastelloy Alloy C tubing. This tubing will be supplied by the SWEPCO Tube Corporation of Clifton, New Jersey. This selection resulted from the published rate of corrosion of Hastelloy Alloy C which is 0.0001 inch per year when immersed in 50°F sea water.

The technical provisions for this program require containment of the fuel for 300 years (minimum) when the capsule is immersed in sea water. Applying the published corrosion rate, the capsule wall thickness must be at least 0.030 inch thick.

CONFIDENTIAL

The high temperature properties of this material were desirable for the high temperature-strength requirements of fuel capsules.

To best utilize existing tooling for fabricating the fuel capsules, the outside diameter for the capsules was selected to be 4.0 inches, with a 0.312-inch wall thickness.

Table 6-1 outlines the properties of Hastelloy Alloy C.

The current capsule design specifies a two-component assembly. An inner capsule made of thin wall stainless steel tubing will be used to reduce the decontamination problems associated with fueling a capsule. At the present time, the fueling facility state-of-the-art does not include using filler material welding in the hot cell. The end caps were designed taking this into account. All closures will be made using tungsten inert gas welding. Figure 6-1 illustrates the assembled fuel capsule.

Note:

1. T.I.G. weld all around 0.10-inch weld penetration
2. T.I.G. weld all around filler material required

MINNESOTA MINING & MANUFACTURING CO. ST. PAUL 6 MINNESOTA	B	PD-39-1014	B
--	---	------------	---

Figure 6-1. Assembly - Fuel Capsule and Liner 3M-39

CONFIDENTIAL

~~CONFIDENTIAL~~

Table 6-1. Properties - Hastelloy Alloy C

Source	Union Carbide Corporation, Stellite Company Publications
	1. "Hastelloy Alloy C", dated June, 1963
	2. "Corrosion Resistance of Haynes Alloys", dated March, 1964
Composition (%) (Approximate)	Co 2.5 Ni 54 Cr 15.5 Mo 16 W 4 Fe 5 C 0.08 Other 3
Density	0.323 pound/inch ³
Melting Range	2318 to 2381°F
Thermal Conductivity (1112°F)	118 BTU-inch/foot ² -hour-°F
Mean Coefficient of Thermal Expansion (32° to 1800°F)	8.5 microinches/inch-°F
Modulus of Elasticity (psi)	29.8 × 10 ⁶ (1000°F) 19.5 × 10 ⁶ (1500°F)
Ultimate Tensile Strength (psi)	99,300 (1000°F) 56,400 (1600°F)
Yield Strength (psi)	43,900 (1000°F) 36,500 (1600°F)
Elongation (in 2 inches)	52 (1000°F) 47 (1600°F)
Hardness (Brinell)	184 (1000°F)
Creep Rupture Strength (1500°F)	18,000 psi at 100 hours 12,500 psi at 1000 hours

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Biological Shield

The uranium-8% molybdenum alloy was selected for the biological shield because of its excellent shielding properties and temperature stability. There are no phase changes in the anticipated temperature range of the heat source. At temperatures above 1500° F, this alloy will form eutectic solutions with group VIII metals. This eutectic formation requires that a physical separation be maintained between the radiation shield, the capsule material, and also the cavity of the insulation envelope. Currently two methods are being investigated to solve this problem: (1) form a titanium liner around the shield and also around the fuel capsules, and (2) cast the depleted uranium shield into a titanium liner.

The thickness of shielding material required to reduce the radiation intensity to the specified level was calculated using shielding calculations in the Nuclear Engineering Handbook. The value for shield thickness obtained from these calculations agrees quite well with one obtained by using graphs prepared from ORNL computer data. A complete shielding calculation treatment is shown in Appendix H.

The biological shield will, after being fueled, have a surface radiation exposure rate of 500 mr/hr. Because the current design provides that the system be assembled on site, the radiation exposure rate versus personnel exposure during assembly must be carefully analyzed for compliance with the applicable AEC regulations governing radiation exposure. Current objectives towards personnel exposure during system assembly are as follows:

Less than 1 REM, whole body
Less than 2 REM, extremities

A provision has been incorporated into the design of the biological shield for lifting and handling the shield at the site of component assembly. Three eye-bolts spaced 120 degrees apart and positioned at the top of the shield will be used to lift the shield from the shipping container and lower it into the insulation cavity. These bolts will be replaced with plugs once the heat source is in position.

6-5/6-6

~~CONFIDENTIAL~~

7.0 VOLTAGE REGULATOR DEVELOPMENT

7.1 PLANNED OBJECTIVES

Operating voltage	24 volts $\pm$ 1 volt
Operating life	Five-year objective
Ambient temperature	Operating nominal: 70° F $\pm$ 10° F Storage maximum: +140° F minimum: - 40° F
Operating current range	Zero to 3.1 amperes
Operating power	78.1 watts
Loss in regulator during standby	Less than 1%

7.2 PROGRESS THIS QUARTER

Work on the voltage regulator for this quarter was limited to a study of the reliability of zener diodes and to a preliminary analysis of other circuit concepts for shunt type voltage regulators.

7.3 TECHNICAL DISCUSSION

Early in this program the use of the zener diode system for voltage regulation appeared to be the best solution for stabilizing the output of the thermoelectric generator; however, currently there is some suspicion that the use of zener diodes will sacrifice reliability and control for simplicity.

The zener diode will be continuously evaluated for applicability to this program as more data is published concerning the performance of the zener diode, and as reliability specifications are generated for the program.

Reliability will be a design objective; however, complete experimental proof of the reliability is beyond the scope of the program.

8.0 GROWTH SYSTEM PREDICTIONS

8.1 PLANNED OBJECTIVES

- To define a program which is parametrically capable of predicting the performance characteristics for thermoelectric power generation systems of 25, 100, and 200 watts electrical output.

8.2 PROGRESS THIS QUARTER

A computer program was written in FORTRAN-63 for the CDC-1604 computer. After debugging the program, sample data was inserted and the program was run.

Conceptually the program ran successfully, but an error in the basic logic indicated that the program must be reworked before it could predict the desired data with reliability.

The program was reworked; however, it was not tested during this reporting period.

8.3 TECHNICAL DISCUSSION

The geometrical configuration is the prerequisite for predicting the performance characteristics of any isotopic-fueled thermoelectric generation system. To accurately predict the performance characteristics, experimental test data must be incorporated into the calculations. The current development program will be used as a source of the necessary experimental test data and will establish the geometrical configuration for the growth systems.

To economically perform the necessary calculations and to integrate the experimental test data, a computer program was generated.

An additional benefit of this computer program is that it will assist in the final design of the sixty-watt thermoelectric power system being developed during this program.

~~CONFIDENTIAL~~

The first computer program written for this system specified that the power supply system would be sectionalized, or cut up into its rectangular coordinates. Each of these coordinates was unique by its geographical location within the system, and each was addressed by its "X" and "Y" coordinates within the system. Each of these coordinates, called nodes, represented a point in the system. Each node was connected to its neighboring node by a thermal conductor. Each thermal conductor consisted of a finite material possessing a known thermal conductivity, and each may experience a ΔT along its length.

The system was assumed to receive all of its thermal energy at one node. It was this assumption which curtailed the completely successful operation of this program.

In theory, if all the thermal energy of the system were injected at one node, it should diffuse into the system along each of the thermal conductors. The computer would then compute this diffusion and predict the heat flow and any node temperature for the entire system.

In practice, the point source injection of thermal energy implied unrealistic temperature distributions within the system. Although the node concept for describing this system was basically successful, to maintain harmony within the system a new subroutine was written for a different method of injecting the thermal energy into the program.

With the new subroutine, the thermal energy is injected into the program via a node concept. Preliminary data received from the original program and its modified thermal energy injection method indicates that reliable predictions will be received from the program as it is run with realistic meaningful data.

~~CONFIDENTIAL~~

APPENDIX A
THERMOELECTRIC MATERIALS ELECTRICAL
AND MECHANICAL PERFORMANCE

1. THERMOELECTRIC COUPLE PERFORMANCE

a. Determination of Thermoelectric Properties

The thermoelectric properties are the Seebeck Coefficient S , the electrical resistivity ρ , and the thermal conductivity k , which are functions of the temperature T . These properties cannot be measured directly but are determined by finding the dependence of measurable quantities on an independent variable, usually the temperature. The thermoelectric properties are defined by definite integrals where the experimental variables appear as the limits on the integral. It will be convenient to first treat a general case.

$$\phi(\alpha) = \int_{u_o(\alpha)}^{u_1(\alpha)} f(x, \alpha) dx \quad (1)$$

Now apply "Leibniz" Rule for Differentiation Under the Integral Sign" to Equation (1) and obtain:

$$\frac{d\phi}{d\alpha} = f(u_1, \alpha) \frac{du_1}{d\alpha} - f(u_o, \alpha) \frac{du_o}{d\alpha} + \int_{u_o(\alpha)}^{u_1(\alpha)} \left[\frac{\partial f}{\partial \alpha} (x, \alpha) \right] dx \quad (2)$$

These mathematical procedures can now be applied to the determination of the thermoelectric properties.

• Seebeck Coefficient

The voltage E developed across a thermoelectric leg having a Seebeck Coefficient S , operating between a cold junction temperature T_c and a hot junction temperature T_h is given by

$$E = \int_{T_c}^{T_h} S(T) dT \quad (3)$$

Now apply Equation (2) to Equation (3) below:

$$\frac{dE}{dT_h} = S(T_h) \frac{dT_c}{dT_h} - S(T_c) \frac{dT_c}{dT_h} + \int_{T_c}^{T_h} \left[\frac{\partial S(T)}{\partial T_h} \right] dT \quad (4)$$

Since S is a property of the system $\frac{\partial S(T)}{\partial T_h} = 0$ and Equation (4) becomes

$$S(T_h) = \frac{dE}{dT_h} + S(T_c) \frac{dT_c}{dT_h} \quad (5)$$

The measurement technique used is to measure the voltage E while varying the junction temperatures T_h and T_c and applying Equation (5) to the experimental data.

It is often possible experimentally to hold the cold junction temperature constant

in which case $\frac{dT_c}{dT_h} = 0$, and Equation (5) reduces to

$$S(T_h) = \frac{dE}{dT_h} \quad (6)$$

- Thermal Conductivity

It will be assumed that the heat flow is one-dimensional. Convective heat losses can be effectively eliminated by providing a high vacuum environment. Although radiative heat losses exist, it has been shown that in a plane perpendicular to the cylindrical axis the temperature on the surface of the sample is not significantly different than the temperature in the center.

For one-dimensional heat flow, the heat flow Q is given by

$$Q = k(T) A \frac{dT}{dx} \quad (7)$$

where A is the cross sectional area.

If the leg has a length L , boundary conditions can be defined as

$$T = T_c \text{ at } X = 0$$

and

$$T = T_h \text{ at } X = L$$

Equation (7) can be written as

$$Q dx = k(T) A dT$$

and integrating both sides

$$\int_0^L Q dx = \int_{T_c}^{T_h} k(T) A dT$$

Since Q is independent of x

$$Q \frac{L}{A} = \int_{T_c}^{T_h} k(T) dT \quad (8)$$

Now apply Equation (2) to (8) below:

$$\frac{L}{A} \frac{dQ}{dT_h} = k(T_h) \frac{dT_c}{dT_h} - k(T_c) \frac{dT_c}{dT_h} + \int_{T_c}^{T_h} \left[\frac{\partial k(T)}{\partial T_h} \right] dT \quad (9)$$

Since $k(T)$ is a property of the system $\frac{\partial k(T)}{\partial T_h} = 0$, Equation (9) becomes

$$k(T_h) = \frac{L}{A} \frac{dQ}{dT_h} + k(T_c) \frac{dT_c}{dT_h} \quad (10)$$

The experimental procedure is to measure the heat conducted across the cold junction of the leg, Q_m , into a calorimeter. But Q in Equation (10) is the heat conducted across the hot junction, so radiation losses from the sides of the element must be taken into account. The heat radiated from a differential element, dx , radiating to a black body at temperature T_a , is given by

$$dQ_r = \pi D \epsilon \sigma (T^4 - T_a^4) dx \quad (11)$$

where ϵ is the emissivity

and D is the diameter.

The independent variable in (11) can be changed from x to T by

$$dx = \frac{dx}{dT} dT$$

But from (7)

$$\frac{dx}{dT} = \frac{k(T)}{Q} A \quad (12)$$

Substituting (12) into (11)

$$dQ_r = \frac{\pi D \epsilon \sigma}{Q} A k(T) (T^4 - T_a^4) dT$$

or

$$Q_r = \frac{\pi D \epsilon \sigma}{Q} A \int_{T_c}^{T_h} k(T) (T^4 - T_a^4) dT \quad (13)$$

The procedure is to calculate $k(T)$ from (10), then use this result to find Q_r from (13). Then find a new $k(T)$ from (10) using $Q = Q_m + Q_r$. Convergence between (10) and (13) will occur rapidly since in general Q_r will be small compared to Q_m .

- Electrical Resistivity

The resistance R of a leg of length L is given by

$$R = \frac{1}{A} \int_0^L \rho(T) dx \quad (14)$$

If a temperature difference exists across the leg then Equation (14) cannot be used to determine $\rho(T)$ unless the explicit relation between T and X is known. The independent variable in (14) can be changed from X to T to give

$$R = \frac{1}{A} \int_{T_c}^{T_h} \frac{\rho(T)}{\frac{dT}{dx}} dt \quad (15)$$

By substituting Equation (12) into (15)

$$R = \int_{T_c}^{T_h} \frac{\rho(T) k(T)}{Q} dT \quad (16)$$

Now apply (2) to (16) and get

$$\frac{dR}{dT_h} = \frac{\rho(T_h) k(T_h)}{Q} \frac{dT_h}{dT_c} - \frac{\rho(T_c) k(T_c)}{Q} \frac{dT_c}{dT_h} + \int_{T_c}^{T_h} \frac{\partial}{\partial T_h} \left[\frac{\rho(T) k(T)}{Q} \right] dT \quad (17)$$

Expanding the third term of (17) we get:

$$\int_{T_c}^{T_h} \frac{\partial}{\partial T_h} \left[\frac{\rho(T) k(T)}{Q} \right] dT =$$

$$\int_{T_c}^{T_h} \left\{ \frac{Q \left[\rho(T) \frac{\partial k(T)}{\partial T_h} + k(T) \frac{\partial \rho(T)}{\partial T_h} \right] - \rho(T) k(T) \frac{\partial Q}{\partial T_h}}{Q^2} \right\} dT$$

But since:

$$\frac{\partial k(T)}{\partial T_h} = \frac{\partial \rho(T)}{\partial T_h} = 0,$$

the third term reduces to:

$$- \int_{T_c}^{T_h} \frac{\rho(T) k(T) \frac{\partial Q}{\partial T_h}}{Q^2} dT$$

Since Q and $\frac{\partial Q}{\partial T_h}$ are independent of T , the third term becomes:

$$- \frac{\frac{\partial Q}{\partial T_h}}{Q} \int_{T_c}^{T_h} \frac{\rho(T) k(T)}{Q} dT$$

Substituting from (16), the third term becomes

$$-\frac{\frac{\partial Q}{\partial T_h}}{Q} R$$

so Equation (17) becomes:

$$\frac{dR}{dT_h} = \frac{\rho(T_h) k(T_h)}{Q} - \left[\frac{\rho(T_c) k(T_c)}{Q} \right] \frac{dT_c}{dT_h} - \frac{\frac{\partial Q}{\partial T_h}}{Q} R \quad (18)$$

Solving (18) for $\rho(T_h)$ and using (10) for $k(T_h)$:

$$\rho(T_h) = \frac{Q}{\frac{L}{A} \frac{dQ}{dT_h} + k(T_c) \frac{dT_c}{dT_h}} \left[\frac{dR}{dT_h} + \frac{\rho(T_c) k(T_c)}{Q} \frac{dT_c}{dT_h} + \frac{R}{Q} \frac{dQ}{dT_h} \right] \quad (19)$$

The Q in Equation (19) is the heat flowing past the hot junction so the measured heat through the cold junction must be corrected for radiation as in the previous section.

Equations (3) through (19) describe a procedure for determining all the thermoelectric properties in a single in-gradient experiment. In addition, the measured quantities E , R and Q completely describe the performance of the thermoelectric leg as a function of the junction temperatures.

b. Calculation of the Performance of a Thermoelectric Leg

The object of this section is to present a method for predicting the performance of a thermoelectric leg from the material properties. In addition to one-dimensional heat flow, it is necessary to assume, further, that the temperature distribution in the leg does not change between open circuit and closed circuit (i.e., matched load) conditions for fixed junction temperatures. This has been verified experimentally to be a good approximation for present day thermoelectric materials.

Consider a thermoelectric leg of length L , cross sectional area A , having properties $S(T)$, $\rho(T)$, and $k(T)$ operating between a heat source at temperature T_h and a heat sink at temperature T_c . Assume the leg to be in a non-convective environment and that radiation losses can be calculated as above. Define an axial coordinate X , such that

$$T = T_c \text{ at } X = 0$$

$$T = T_h \text{ at } X = L$$

For one-dimensional heat flow, the conducted heat Q_c , is given by

$$Q_c = k(T) A \frac{dT}{dx} \quad (20)$$

Neither Q_c nor A depend on either T or X so the variables can be separated and Equation (20) can be integrated

$$\frac{Q_c}{A} \int_0^L dx = \int_{T_c}^{T_h} k(T) dT$$

or

$$Q_c \frac{L}{A} = \int_{T_c}^{T_h} k(T) dT \quad (21)$$

The open circuit or Seebeck voltage E is given by

$$E = \int_{T_c}^{T_h} S(T) dT \quad (22)$$

The resistance of the leg R is given by

$$R = \frac{1}{A} \int_0^L \rho(T) dx \quad (23)$$

In order to perform the integration in (23) the independent variable is first changed from X to T.

$$R = \frac{1}{A} \int_{T_c}^{T_h} \rho(T) \frac{dx}{dT} dT \quad (24)$$

from (20)

$$\frac{dx}{dT} = \frac{k(T)A}{Q_c} \quad (25)$$

So (24) becomes

$$R = \int_{T_c}^{T_h} \frac{\rho(T) k(T)}{Q_c} dT \quad (26)$$

And since Q_c is independent of T

$$RQ_c = \int_{T_c}^{T_h} \rho(T) k(T) dT \quad (27)$$

It was shown that the properties can be measured as a function of the temperature. Using the "Method of Least Squares", these properties can be expressed explicitly as power series of the temperature. When this has been done the right hand side of Equations (21), (22) and (27) can be calculated directly. For example, suppose that

$$S(T) = A_0 + A_1 T + A_2 T^2 + \dots A_n T^n$$

Then

$$\int_{T_c}^{T_h} S(T) dT = A_o (T_h - T_c) + \frac{A_1}{2} (T_h^2 - T_c^2) + \dots + \frac{A_n}{n+1} (T_h^{n+1} - T_c^{n+1})$$

Thus Q_c is found from (21), E from (22) and R from (27).

The only variable remaining is the way the leg is loaded, which will specify the current. For the general case, let the current be I .

The power P delivered to the load is

$$P = I(E - IR) \quad (28)$$

The Peltier heat absorbed at the hot junction, Q_{p_h} , is

$$Q_{p_h} = S(T_h) T_h I \quad (29)$$

The Peltier heat rejected at the cold junction, Q_{p_c} , is

$$Q_{p_c} = S(T_c) T_c I \quad (30)$$

The Joulean heat generated in the leg, Q_j , is

$$Q_j = I^2 R \quad (31)$$

The Thompson heat generated (or absorbed) in the leg, Q_t , is

$$Q_t = I \int_{T_c}^{T_h} T \frac{dS}{dT} dT \quad (32)$$

The efficiency η is given by the ratio of the power delivered to the load to the power required at the hot junction, which is

$$\eta = \frac{I(E - IR)}{Q_c + Q_{ph}} \quad (33)$$

The heat that must be dissipated at the cold junction, Q_d , is

$$Q_d = Q_c + Q_{pc} \quad (34)$$

Notice that neither the Joulean nor the Thompson heats appear in (34). This is because it was assumed that the temperature distribution is unchanged between open and closed circuit conditions, so these heat terms are included in Q_c .

In practice, the leg is often operated at matched load conditions so as to obtain maximum power, in which case the matched load current I_{ML} is

$$I_{ML} = \frac{E}{2R} \quad (35)$$

and the quantities defined in (28) through (34) can be found using this particular current.

- Segmented Legs

When operating a thermoelectric leg across a large temperature difference it is often desirable to place two or more thermoelectric materials thermally in series so as to obtain the best properties in a given temperature range. In segmentation one knows at what temperature the segmenting junction should be, but in order to construct such a leg, the lengths of each segment must be known. The method described above can answer this question, and in addition can describe the performance of the entire leg.

~~CONFIDENTIAL~~

Consider a thermoelectric leg consisting of N segments operating under the conditions previously described. Now look at the i^{th} segment, which has a length l_i and cross sectional area A_i (each segment must have uniform cross sectional area, but each of the N segments need not have the same cross sectional area), and operates between temperatures T_{i-1} and T_i .

$$E_i = \int_{T_{i-1}}^{T_i} S_i(T) dT \quad (36)$$

$$Q_i l_i = A_i \int_{T_{i-1}}^{T_i} k_i(T) dT \quad (37)$$

(Notice that Q_c is the same for all segments)

$$\text{and } R_i Q_i = \int_{T_{i-1}}^{T_i} i(T) k_i(T) dT \quad (38)$$

A similar set of equations can be written for each of the N segments, and as before, the right hand side of (36), (37) and (38) can be calculated directly. The length of the entire leg L containing the N segments is

$$L = \sum_{i=1}^N l_i \quad (39)$$

Now add together all equations of type (37) and get

$$Q_c = \frac{1}{L} \sum_{i=1}^N \int_{T_{i-1}}^{T_i} A_i k_i(T) dT \quad (40)$$

~~CONFIDENTIAL~~

Since Q_c is now known it can be substituted into (37) to determine the l_i and into (38) to determine the R_i . For the entire leg, it follows that

$$E = \sum_{i=1}^N E_i \quad (41)$$

and

$$R = \sum_{i=1}^N R_i \quad (42)$$

Thus the length of each segment is known and since E , R , and Q_c are known for the entire leg, the other performance parameters for the leg can be calculated as before.

c. Comparison with Experiment

- Measurement of Thermoelectric Properties

The principal advantage of the measurement technique described in Section 4-B, 1-a, is that all of the thermoelectric properties can be measured simultaneously. There are, however, other methods of measuring each of the properties in separate experiments.

The most common method of measuring the Seebeck Coefficient is to place the leg between a variable temperature heat source and a fixed temperature heat sink. Under these conditions Equation (6) applies and

$$S(T_h) = \frac{dE}{dT_n}$$

The most common method of measuring the electrical resistivity is to maintain the entire sample at a fixed temperature. Under these conditions Equation (14) becomes

$$R = \frac{L}{A} \rho(T)$$

or

$$\rho(T) = RA/L \text{ (since } \rho(T) \text{ is independent of } x)$$

The experiment can be repeated at several different temperatures to get ρ as a function of T .

The accuracy with which thermoelectric performance can be predicted from property measurements, and analysis attests to the reliability of the foregoing procedures.

- Performance of Thermoelectric Legs

The good agreement between predicted and measured performance of a thermoelectric leg will be illustrated in this section. The properties used in the calculation were measured by both of the techniques described above.

Figures A-1, A-2, and A-3 show predicted and measured values of E versus T_h , R versus T_h , and Q versus T_h , respectively, of an N-type thermoelectric leg which has a diameter of 0.375 inch and a length of 0.225 inch. The agreement between measured and predicted values seems quite acceptable. Differences can arise through experimental errors, or to the fact that these thermoelectric materials are doped semiconductors whose properties are very dependent on the chemical composition, and some compositional variation is to be expected between batches.

Figures A-4 and A-5 show predicted and measured values of E versus T_h and R versus T_h for a model 3M-19 thermoelectric generator which contains 80 thermocouples connected electrically in series and thermally in parallel. The agreement between predicted and measured values of the voltage is quite good. The generator resistance requires some additional comment. This resistance is made up of several parts: the resistance of the individual thermoelectric legs, the resistance of hot junction and cold junction electrodes, the resistance of lead wires and terminals, and contact resistance between the thermoelectric legs and the electrodes. Better agreement between measured and predicted values could be achieved by merely adjusting one of the resistance parameters other than the thermoelectric leg resistance. The most important result is the fact that the temperature dependence of the generator resistance has been accurately predicted. This result together with

Figure A-1. Calculated and Measured Resistance vs. Hot Junction Temperature

Figure A-2. Calculated and Measured Voltage vs. Hot Junction Temperature

Figure A-3. Calculated and Measured Heat Flux vs. Hot Junction Temperature

Figure A-4. Calculated and Measured Voltage vs. Hot Junction Temperature (Complete Generator)

~~CONFIDENTIAL~~

Figure A-5. Calculated and Measured Resistance vs. Hot Junction Temperature (Complete Generator)

Equation (27) allows the conclusion that the temperature dependence of the thermal conductivity is also correct, for if this were not so, the correct resistance could not be predicted as a function of the temperature.

2. THERMOELECTRIC COUPLE MECHANICAL DESIGN

The literature on thermoelectricity is predominantly devoted to the electrical and thermal properties of materials. On the other hand, very little information is available concerning the *mechanical* properties of these same materials. This omission has resulted in some unfortunate mechanical failures.

The high thermal gradients that are imposed in a thermoelectric structure may produce stresses that result in fracture of the usually fragile thermoelectric materials. It is the purpose of this discussion to point out principal stress areas that are encountered in the design of thermoelectric devices, and to suggest possible corrective measures. Unfortunately, empirical analysis can not be as quantitatively applied to the mechanical problems as it may be to the electrical and thermal

~~CONFIDENTIAL~~

design. This is due, in no small measure, to the fact that mechanical characteristics of thermoelectric materials are more variable, at the present state-of-the-art, than the thermal and electrical characteristics.

In thermoelectric material dynamic thermal or mechanical loads may result in highly localized stresses. This characteristic is intrinsic to good thermoelectric material, in that they have a low lattice thermal conductivity, which by definition presents a high impedance to thermal or accoustical phonons so that stress gradients will be necessarily higher than may be expected for metallic materials under similar dynamic load. Unfortunately, this problem does not lend itself to a tractable analytical solution. The procedure to be avoided is the lumping of the dynamic problems with the other problems that shall be discussed later. Trial and error method, at the present level of mechanical design is unavoidable; but analysis can be of great value in expediting the final result.

The most important mechanical difficulties encountered in the design of thermoelectric devices are the result of thermal expansion. It is necessary to identify the principle "thermal expansion" induced stresses in order to establish a procedure for mechanical design. Some pertinent physical properties data are given in Figures A-6 and A-7.

An important stress area that is subject to thermal expansion induced stresses is where the thermoelectric member is joined to a metallic connecting member. Ideally, the material selected for the metallic contacting member would have the same thermal expansion coefficient as the thermoelectric material. The requirement that the metallic connector be chemically inert with respect to the thermoelectric material limits the number of choices available. If the metallic member has a thermal expansion coefficient less than the thermoelectric element the stress in the element will be compressive and less objectionable. Also, the stress due to the thermal expansion difference will be highest at the periphery of the thermoelectric member and will be proportional to the diameter of the element. This means that some diameter will be within the stress limitations of the thermoelectric element.

Another mechanical reaction that may occur at the metal to thermoelectric member junction, less obvious than the simple thermal expansion difference referred to above,

~~CONFIDENTIAL~~

Figure A-6. Stress-Strain Relationship for Equilibrium Annealed Lead Telluride

is the stress due to a thermal gradient. When all members are at the same temperature there is no relative distortion and the metallic member and the thermoelectric element, if joined, would be stress free. However, when a thermal gradient is imposed, there is a distortion due to differential thermal expansion. The metal contact member is less distorted than the element, which results because of the difference in the thermal conductivity. For the same heat flux, the thermal gradient in the metal is much less than in the thermoelectric member, so that the metal will distort less than the thermoelectric member. Obviously, if the two members were to be intimately joined, a stress would exist. The nature of the stresses will be discussed later using the assumption that the metallic member is an undistorted plane surface restricting the bending of the thermoelectric member.

Another stress condition that is apparent due to thermal expansion is a dimensional change in operation of the hot junction electrode without a corresponding change in the cold junction electrode. Consider an elementary case where the cold electrodes

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Figure A-7. Creep Characteristics of Lead Telluride at High Temperature

are held rigid and the hot electrodes are allowed to expand. The deflection of the hot junction electrode must equal the deflection of the hot ends of the elements.

$$d(T_n - T_c) l - \frac{F l}{(A)(E)} = 2 \frac{F}{A_2 G} l_2$$

α = Coefficient thermal expansion

G = Modulus of rigidity

F = Compressive force in hot junction electrode

E = Modulus of elasticity of hot junction electrode

E_2 = Modulus of elasticity of thermoelectric member

l_1 = Spacing of legs

l_2 = Length of legs

~~CONFIDENTIAL~~

to solve for F, assume $G \approx \frac{E_2}{2}$

then (2)

$$F = \frac{\alpha(T_n - T_c) l_1}{\frac{4l_2}{A_2 E_2} + \frac{l_1}{E_1}}$$

The stresses from the bending moment are greatest at the cold junction and will be tensile on the side of the elements closest together. Stress analysis of actual design with lead telluride type alloy show that unless flexibility is incorporated in the mechanical system, thermoelectric member fracture is extremely probable. There are many ways in which flexibility may be incorporated into designs. A thermal gradient stress factor is the result of restraining movement at the hot and cold junction areas by the soldering or welding of the thermoelectric member to a metallic strap. An example from Gatewood, "Thermal Stresses", McGraw Hill, New York, 1957, will serve to illustrate the nature of the problem. For the plate shown, and with a thermal gradient in the Y direction, the stresses away from the edges are:

$$\sigma_x = \sigma_z = \frac{E T(y)}{1 - \nu} + \frac{1}{2c(1 - \nu)} \int_{-c}^c \alpha E T(y) dy + \int_{-c}^c \alpha E T(y) Y dY \quad (43)$$

E = Young's Modulus

σ = Stress

ν = Poisson's Ratio

This equation is valid for the completely unstrained case. If the plate is restrained in compression along the x and z axes, the correct stress may be obtained by dropping the second term. If the plate is restrained in bending (i.e., not allowed to warp) the correct stress is obtained by dropping the third term. Tensile stresses will have a positive sign and compressive stresses a negative sign. For the purpose of obtaining an approximation we may assume that the temperature function is linear so that

$$T_{(y)} = \frac{\Delta T}{2} (1 + Y/C) \quad (44)$$

If we further assume Poisson's ratio, ν is zero and substitute Equation (44) into Equation (43) and evaluate the integral,

$$\sigma_x = -\frac{\alpha E \Delta T}{2} (1 + Y/C) + \frac{\alpha E \Delta T}{2} + \frac{\alpha E \Delta T Y}{2C} = 0 \quad (45)$$

From Equation (45) it is seen that for an unrestrained plate with a linear temperature profile the stresses are all zero. This result is completely general. Any isotropic, unrestrained body of any shape has no thermal stresses whenever the temperature varies according to the linear law.

In a thermoelectric device utilizing bonded junctions, the elements are kept from bending at the hot and cold junction areas, but are not restrained in the x and z direction, Equation (45) becomes

$$\sigma_x = -\frac{\alpha E \Delta T}{2} (Y/C) \quad (46)$$

The elements will thus be in compression for $Y > 0$ (i.e., near the hot end), and in tension for $Y < 0$ (i.e., near the cold end). The elements would like to bow in a convex manner at the hot end and a concave manner at the cold end; when a thermoelectric element is prevented from doing so by bonding to the connecting metal the above stress is produced.

For lead telluride, the thermal gradient is not linear, but is steeper at the hot end. By expressing the thermal gradient in polynomial form it may be shown that this characteristic has the beneficial result of reducing the tensile stress at the cold junction.

For the purpose of demonstration it is convenient to restrict the consideration to a one-dimensional problem. Consider a thermoelectric element as the thin strip shown:

The member tends to bend so that the hot surface is convex. In actuality, the forces are distributed more uniformly over the ends of the element. The shear force diagram for the member is given below.

There is therefore a shear force $F/2$ acting in the plane perpendicular to the x-axis in the Y direction over the entire beam. The magnitude of F necessary to keep the element from bending can be calculated from the expression for the bending moment caused by the temperature profile.

$$M = b \int_{-c}^c \alpha E T_{(Y)} Y dY \quad (47)$$

Knowing the equation for the temperature profile will give a solution for the bending moment and therefore a solution for the shear stresses. One shear stress will be in the plane perpendicular to x in the Y direction and an equal shear stress in the plane perpendicular to y acting in X direction. From the theory of beams it can be said that the stresses are distributed non-uniformly over the beam according to:

$$S_{xy} = S_{yx} = \frac{V}{2I} (C^2 - Y^2) \quad (48)$$

V = total shear force

I = moment of inertia

It can be seen from Equation (48) that the shear forces will be maximum at $Y = 0$ and be zero at $Y = \pm C$.

These shear forces, if calculated for practical designs, are usually not as serious as the stresses discussed earlier but they are high enough to warrant detailed examination.

From the foregoing discussion, the mechanical disadvantages of firmly bonding or welding the hot junction to a metallic joining strap are obvious. Nearly all the important stress areas can be minimized by the use of a pressure at the hot junction, rather than a bonded joint.

~~CONFIDENTIAL~~

References:

1. Materials Selector Issue of Materials in Design Engineering, Vol. 56, No. 5, Oct. 1962, Reinhold Publ. Co., 1963.
2. Terzaghi, K., and Peck, R.B., Soil Mechanics in Engineering Practice, Wiley, 1950.
3. Timoshenko, S., Strength of Materials Part II, 3rd Edition, Van Nostrand, 1956.
4. McAdams, W.H., Heat Transmission, Third Edition, McGraw Hill, 1954, p. 388.
5. Timoshenko, S. and Goodier, J.N., Theory of Elasticity, Second Edition, McGraw Hill, 1951, p. 400.
6. Nystrom, T.L. and Richards, J.D., A New Technique for Simultaneous Measurement of Thermoelectric Material Properties as Functions of Temperature, April, 1961.
7. Brandt, J.A., Solutions to the Differential Equations Describing the Temperature Distribution and Thermal Efficiency of a Thermoelectric Element with Variable Properties and Cross Sectional Area, 3M Research Report.

~~CONFIDENTIAL~~

**APPENDIX B
SYSTEM WEIGHT ANALYSIS**

A preliminary design weight analysis was conducted for the major generator components:

1. Fins: Assume 100 fins 0.045 - 0.047 inch thick, 7 inches long, 5 inches high (Copper-density 0.324 pound per cubic inch).

$$\text{Volume} = N t l h = 100 \times 0.046 \times 7 \times 5 = 161 \text{ cubic inches.}$$

$$\text{Weight} = 161 \text{ cubic inches} \times 0.324 \text{ pound per cubic inch} = 51 \text{ pounds.}$$

2. Outer Case (cylinder): 0.030 inch thick x 8.5 inches mean diameter x 5.5 inches high (Steel-density 0.284 pound per cubic inch).

$$\text{Volume} = \pi D L t = 3.14 \times 8.5 \times 5.5 \times 0.030 = 4.4 \text{ cubic inches.}$$

$$\text{Weight} = \text{volume} \times \text{density} = 4.4 \times 0.284 = 1.25 \text{ pounds.}$$

3. Outer Case (Top disk): 0.040 inch thick x 8.5 inches diameter steel.

$$\text{Volume} = \frac{\pi D^2}{4} \times t = \frac{3.14 \times 8.5^2}{4} \times 0.040 = 2.27 \text{ cubic inches.}$$

$$\text{Weight} = \text{volume} \times \text{density} = 2.27 \times 0.284 = 0.65 \text{ pound.}$$

4. Top plate: 0.200 inch thick x 4.25 inches diameter steel.

$$\text{Volume} = \frac{\pi D^2}{4} \times t = 0.7854 \times 4.25^2 \times 0.2 = 2.84 \text{ cubic inches}$$

$$\text{Weight} = \text{volume} \times \text{density} = (2.84) (0.285) = 0.81 \text{ pound}$$

5. Cold Frame: 4 inches long, 4.25 inside diameter, 8.5 outside diameter has 450 holes, 0.219 inch in diameter.

$$(\text{alum. density} = 0.1 \text{ pound per cubic inch}) t = 8.5 \frac{4.25}{2} = \frac{4.25}{2} - 2.125$$

$$\text{Volume} = \pi l t (D - t) - N \frac{\pi d^2 t}{4}$$

$$\begin{aligned} &= 3.14 \times 4 \times 2.125 (8.5 - 2.125) - 450 \times \frac{3.14}{4} \times 0.219^2 \times 2.125 \\ &= 171 - 450 \times 0.0801 \\ &= 171 - 36 = 135 \text{ cubic inches} \end{aligned}$$

$$\text{Weight} = \text{volume} \times \text{density} = 135 \times 0.1 = \underline{13.5 \text{ pounds}}$$

6. Followers 1.125 inches long x 0.218 inch diameter, 450 required
(alum. density = 0.1 pound per cubic inch)

$$\begin{aligned} \text{Volume} &= N \times \frac{\pi d^2}{4} l = 450 \times 0.7854 \times 0.218^2 \times 1.125 \\ &= 450 \times 0.0421 = 18.95 \text{ cubic inches} \\ \text{Weight} &= \text{volume} \times \text{density} = 18.95 \times 0.100 = \underline{1.9 \text{ pounds}} \end{aligned}$$

7. Springs

Assume springs are 20 gauge (0.032 inch) stainless steel which weighs
0.323 pound per 100 feet.

$$\begin{aligned} \text{approximate spring length}^* &= \text{turns} \times \pi D \\ &= 22 \times 3.14 \times 0.18 \\ &= 12.5 \text{ inches} \end{aligned}$$

$$\text{Total feet} = 450 \times \frac{12.5}{12} = 468 \text{ feet}$$

$$\text{Weight} = \frac{0.323 \text{ pound}}{100 \text{ feet}} \times 468 \text{ feet} = 1.5 \text{ pounds}$$

8. Elements: 0.187 inch diameter x 0.4 inch long, 450 required
(density = 0.25 pound per cubic inch)

$$\begin{aligned} \text{Volume} &= \frac{\pi D^2}{4} l N = 0.7854 \times 0.188^2 \times 0.4 \times 450 = 0.0111 \times 450 \\ &= 4.96 \text{ cubic inches} \\ \text{Weight} &= \text{volume} \times \text{density} = 5 \times 0.25 = \underline{1.25 \text{ pounds}} \end{aligned}$$

9. Hot Junction Electrode: 0.060 inch thick x 0.25 x 0.5, 225 required
(Iron density 0.285 pound per cubic inch)

$$\begin{aligned} \text{Volume} &= (t \times L \times D) N = 0.060 \times 0.25 \times 0.50 \times 225 = 0.0075 \times 2.25 \\ &= 1.69 \text{ cubic inches} \\ \text{Weight} &= 0.285 \times 1.69 = 0.5 \text{ pound} \end{aligned}$$

*Spring Data Computer - Raymond Manufacturing Company

~~CONFIDENTIAL~~

10. Accumulator: 3 inches diameter x 6 inches long (Copper density = 0.324 pound per cubic inch)

$$\text{Volume} = \frac{\pi D^2}{4} \times L = 0.7854 \times 9 \times 6 = 42.5 \text{ cubic inches}$$

$$\text{Volume} \times \text{density} = 42.5 \times 0.324 = \underline{13.75 \text{ pounds}}$$

Total calculated generator weight = 86 pounds.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

APPENDIX C SUPPORT CONE ANALYSIS—BUCKLING

Stress analysis of the support cone was performed, and buckling was determined to be the governing mode of failure. See source reference.*

$$P_{CR} = 2\pi C E t^2 \cos^2 \theta$$

$$\sigma_{CR} = \frac{C E t \cos \theta}{r}$$

where

P_{CR} = Axial Buckling Load (pounds)

E = Young's Modulus

σ_{CR} = Critical Buckling Stress (pounds per square inch)

t = Material Thickness (inches)

π = 3.1416

r = Radius of Cone Measured Normal to Axis of Cone (inches)(inches)

C = Correction Factor (from graph)

θ = Semi-vertex Angle of Cone

Graph Values for C Assumes

$$P_{CR} (\text{cone}) = P_{CR} (\text{cylinder}) \cos^2 \theta \quad \text{(Poisson's Ratio) of 0.3 and (surface unevenness factor) of 0.0003}$$

*"Buckling of Circular Cones Under Axial Compression"; Transactions of the ASME; Journal of Applied Mechanics, September, 1960.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Graph Values of C versus R/T Cos θ

C	0.5	0.4	0.3	0.2	0.1
R/t Cos θ	30	120	270	620	1000

where R = outer radius of cone measured normal
to axis of cone (inches)

As σ_{CR} is inversely dependent upon r then lowest critical stress is at largest radius of cone.

Sample Calculation

$$r \text{ max} = 4.25 \text{ inches}$$

$$E = 30 \times 10^6 \text{ (pounds per square inch) stainless steel}$$

$$t = 0.010 \text{ inch}$$

$$\theta = 60^\circ \text{ Cos } 60^\circ = 0.5$$

$$C = 0.16$$

$$R/t \text{ Cos } \theta = \frac{4.25}{0.0 \times 0.5} = 850$$

$$\left(\sigma_{CR} = \frac{C E t \text{ Cos } \theta}{r} = \frac{0.16 \times 30 \times 10^6 \times 0.010 \times 0.5}{4.25} = 5650 \text{ pounds per square inch} \right)$$

- Buckling stress (σ_{CR}) is lower than expected yield stress of material, thus cone will buckle before material yields.

$$P_{CR} = 2 \pi C E t^2 \text{ Cos}^2 \theta$$

$$= 2 \times 3.1416 \times 0.16 \times 30 \times 10^6 \times 0.010^2 \times 0.5^2$$

$$= 750 \text{ pounds}$$

- 0.010 thickness satisfactory as the generator load (p) is less than 100 pounds.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

APPENDIX D COOLING FIN ANALYSIS

The objective of this analysis was to calculate and plot the performance curves of various fin configurations. From these calculations the number and geometry of the cooling fins required to cool the thermoelectric generator may be selected.

The analysis is based on ASME paper No. 62-HT-7 which optimizes fin sizing and spacing to give maximum heat dissipation. The optimization is based upon a rectangular structure which would give conservative results when used as a basis for fins placed axially on an upright cylinder.

The design analysis optimization was trial and error as the volume size or configuration was not fixed.

The optimization study was calculated with the fixed height (5 inches) and various lengths (5 to 9 inches in 1-inch increments) and with a fixed length (7 inches) and various heights (4 to 8 inches in 1-inch increments). It must be noted that these are not the only possible configurations which could be used.

The results of the above study are shown in Figures D-2 and D-3. The solid line curves of these figures were calculated using an imaginary base diameter (11 inches) larger than the true base diameter (8.5 inches) to approach a realistic optimum analysis for a fin system having an increasing air gap from fin base to fin tip. It was intended to test a system having the increased number of fins given by this larger diameter; however, an error in the calculation resulted in the number of fins (100) being correct for the 8.5-inch diameter analysis rather than the 11-inch diameter - (approximately 120 fins) analysis.

The fin analysis required calculating the heat dissipation from a base area without fins and then using a multiplication factor "M" obtained from an empirical curve plotted against a value " τ ". See Figure D-1 for curve and formula. After the desired fin configuration volume was selected the fin thickness "b" and the fin spacing "a + b" ($S = a + b$) was obtained from curves of Figure D-1.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

M = Multiplication Factor

$$S = \frac{b}{a+b} = \frac{\text{Fin Thickness (ft)}}{\text{Fin Spacing (ft)}}$$

$$\frac{b}{\ell} = \frac{\text{Fin Thickness (ft)}}{\text{Fin Length (ft)}}$$

$$\text{versus } \tau = \ell \left(\frac{\Delta T}{H} \right)^{1/4} = \text{ft} \left(\frac{^{\circ}\text{F}}{\text{ft}} \right)^{1/4}$$

where

ℓ = Fin Length in Feet

ΔT = $^{\circ}\text{F}$ Fin Base Less $^{\circ}\text{F}$ Air

H = Fin Height in Feet

Then

$$Q = M Q_o;$$

$$Q_o = hA\Delta T;$$

$$h = 0.28 \left(\frac{\Delta T}{H} \right)^{1/4}$$

Q = Total Heat
Dissipated

Q_o = Heat Dissipated from
Fin Base (No Fins)

A = HL

L is Stacked Length
of Fins in Feet

Figure D-1. Fin Design Parameters - Free Convection
for Material with $K = 200$ (BTU/hr-ft- $^{\circ}\text{F}$)
(Taken from Figures 14, 18, 19 of ASME Paper #62-HT-7)

~~CONFIDENTIAL~~

A. Solid - dashed lines

1. Solid lines based on 11-inch reference diameter
2. Dashed lines based on 8.5-inch reference diameter

Note: The above diameters determine the number of fins, which are

11-inch diameter	approximately 100
8.5-inch diameter	approximately 80

The fin thickness is constant at 0.045 inch

B. The "C" curves are for 5-inch high fins having lengths as follows:

- $C_1 = 5$ inches
- $C_2 = 6$ inches
- $C_3 = 7$ inches
- $C_4 = 8$ inches
- $C_5 = 9$ inches

C. The "D" curves are for 7-inch long fins having heights as follows:

- $D_1 = 4$ inches
- $D_2 = 5$ inches
- $D_3 = 6$ inches
- $D_4 = 7$ inches
- $D_5 = 8$ inches

D. Preliminary Design Selection

1. Initial Testing - C_3 solid (straight fin)
2. Backup Design - C_5 solid (special forming)

Figure D-2. Fin Analysis - "C" and "D" Curve Identity

Figure D-3. Fin Analysis - C Curves

The fin analysis is presented in detail in order to show the flexibility of the fins and the flexibility of system size. Thus, if the present 24-inch diameter for the system needs to be reduced to a 20-inch diameter, the following approximate fin revision could be made:

	System O. D.	Fin Length		Fin Height
		Actual	Accumulative	
Present	24	7	7	5
Revised	20	5	6.5	5.5

the results would be a 0.5-inch increase in system height.

- The design parameters were:
Beginning of Life: $Q = 770$ watts (gen input)
End of Life: 680 watts

~~CONFIDENTIAL~~

Cold junction temperature BOL: 190° F

Cold junction temperature EOL: 170° F

ΔT Cold junction - fin base (EOL): 30° F

- The results of these calculations predicted:
100 fins required, 7 inches long, 5 inches high, 0.045 inch thick, copper
- Test Procedure

The Q input to the cooling fin was varied from 570 watts to 780 watts by the use of a variac. Temperatures were recorded (see Figure 4-1 for locations) with a Leeds & Northrup potentiometer for Q input in 30-watt increments. The procedure was repeated for each simulated environmental condition (see Figure 4-1). One hour stabilization between readings was allowed.

Figure D-4. Fin Analysis - D Curves

~~CONFIDENTIAL~~

- The following data (Figure D-5 for the various simulated environmental conditions indicates that the cooling fin subassembly has adequate thermal capacity. For an ambient temperature of 70°F, the fin base temperatures were from 10 to 20°F lower than the estimated fin base temperatures of the generator design for dissipation of 770 watts and 680 watts beginning and end of life respectively.

Figure D-5. Heat Dissipated by Fins vs. Fin Base Temperature Less Ambient Temperature

Table D-1. Fin Analysis - Various Lengths (C-Curves)
(Based on ASME Paper #62-HT-7)

ΔT	50	55	60	65	70	75	80	85	90
$\Delta T/H$	120	132	144	156	168	180	192	204	216
$(\Delta T/H)^{1/4}$	3.31	3.39	3.46	3.54	3.60	3.66	3.72	3.78	3.84
$h = 0.28$ $(\Delta T/H)^{1/4}$	0.927	0.949	0.968	0.992	1.008	1.024	1.040	1.057	1.075
$Q_0 = hA\Delta T$	42.9	48.3	53.6	58.9	65.2	71.1	76.9	83.0	89.4
$Q'_0 = hA'\Delta T$	55.5	62.6	69.7	77.4	84.7	92.2	99.8		
$\tau_1 = \ell_1$ $(\Delta T/H)^{1/4}$	1.380	1.415	1.443	1.475	1.500	1.525	1.550	1.575	1.600
M_1	23.0	23.4	23.8	24.2	24.6	24.9	25.2	25.5	25.8
$Q_1 = M_1 Q_0$							1940	2120	2305
$Q'_1 = M_1 Q'_0$					2080	2293	2520		
τ_2	1.655	1.695	1.730	1.770	1.80	1.83	1.86	1.89	1.92
M_2	26.3	26.7	27.1	27.5	27.9	28.2	28.5	28.8	29.1
Q_2						2005	2190	2390	2610
Q'_2				2125	2365	2600			
τ_3	1.930	1.978	2.015	2.060	2.100	2.135	2.170	2.205	2.240
M_3	29.1	29.5	29.9	30.3	30.7	31.0	31.3	31.6	31.9
Q_3				1785	2000	2205	2410	2615	
Q'_3			2080	2345	2600				
τ_4	2.205	2.260	2.305	2.360	2.400	2.44	2.48	2.52	2.56
M_4	31.6	32.0	32.4	32.8	33.2	33.55	33.9	34.25	34.60
Q_4				1930	2160	2385	2605		
Q'_4		2005	2260	2540					
τ_5	2.48	2.54	2.595	2.655	2.70	2.745	2.790	2.835	2.88
M_5	34.0	34.4	34.8	35.2	35.6	35.95	36.3	36.65	37.0
Q				2075	2320	2555			
Q'	1885	2155	2425	2725					

Note: Legend on following page

Legend for Table D-1

Height (H) = 5 inches = 0.4167 foot	$\ell_1 = 5 \text{ inches} = 0.4167 \text{ foot}$
Stack Length (L) = πD L = 26.7 inches = 2.22 feet	$\ell_2 = 6 \text{ inches} = 0.5000 \text{ foot}$
L' = 34.6 inches = 2.88 feet	$\ell_3 = 7 \text{ inches} = 0.583 \text{ foot}$
(D = 8.5 inches, D' = 11 inches)	$\ell_4 = 8 \text{ inches} = 0.667 \text{ foot}$
Base Area (A) = LH A = 0.925 foot ²	$\ell_5 = 9 \text{ inches} = 0.750 \text{ foot}$
A' = 1.20 foot ²	

Legend for Table D-2

Fin Length (ℓ) = 7 inches = 0.5833 foot	$H_1 = 4 \text{ inches} = 0.333 \text{ foot}$
Stack Length (L) = πD L = 26.7 inches = 2.22 feet	$H_3 = 6 \text{ inches} = 0.500 \text{ foot}$
L' = 34.6 inches = 2.88 feet	$H_4 = 7 \text{ inches} = 0.5833 \text{ foot}$
(D = 8.5 inches, D' = 11 inches)	$H_5 = 8 \text{ inches} = 0.6667 \text{ foot}$
A = HL	A' = HL'
$A_1 = 0.6975 \text{ foot}^2$	$A'_1 = 0.9025 \text{ foot}^2$
$A_3 = 1.046 \text{ foot}^2$	$A'_3 = 1.355 \text{ foot}^2$
$A_4 = 1.220 \text{ foot}^2$	$A'_4 = 1.58 \text{ foot}^2$
$A_5 = 1.395 \text{ foot}^2$	$A'_5 = 1.805 \text{ foot}^2$

Table D-2. Fin Analysis - Various Heights (D-Curves)
(Based on ASME Paper #62-HT-7)

ΔT	50	55	60	65	70	75	80	85	90
$\Delta T/H_1$	150		180		210		240		270
$(\Delta T/H_1)^{1/4}$	3.50		3.66		3.81		3.94		4.06
h_1	0.970		1.025		1.067		1.102		1.137
Q_1 no fin	35.9		45.6		55.4		65.3		75.8
τ_1	2.04		2.13		2.22		2.30		2.37
M	29.8		30.5		31.4		32.2		32.8
Q_1					1735		2105		2485
Q_1'			1800		2245		2725		
$\Delta T/H_3$	100		120		140	150	160		180
$(\Delta T/H_3)^{1/4}$	3.16		3.315		3.44	3.50	3.56		3.66
h_3	0.885		0.928		0.963	0.98	0.996		1.025
Q_3 no fin	49.2		61.8		75.0	81.6	88.7		101.5
τ_3	1.843		1.932		2.005	2.040	2.075		2.130
M	27.8		28.7		29.8	30.0	30.2		30.5
Q_3	1368		1775		2230	2455	2675		
Q_3'	1770		2300		2885				
$\Delta T/H_4$				111.5	120		137		154
$(\Delta T/H_4)^{1/4}$				3.255	3.31		3.42		3.52
h_4				0.911	0.926		0.958		0.985
Q_4 no fin				76.7	83.9		99.4		
τ_4				1.898	1.93		1.995		2.05
M				28.8	29.2		29.7		30.3
Q_4				2210	2450				
Q_4'	Est.		Est.	2860					
$\Delta T/H_5$			90	97.4					
$(\Delta T/H_5)^{1/4}$			3.08	3.14					
h_5			0.862	0.880					
Q_5 no fin			76.6	84.8					
τ_5			1.800	1.830					
M			27.9	28.1					
Q_5			2140	2390					
Q_5'	Est.		2770						

Note: Legend on previous page

~~CONFIDENTIAL~~

APPENDIX E
HEAT LOSS CALCULATIONS
GAS FILLED INSULATION ENVELOPE

INSULATION ENVELOPE

The thermal losses through the gas-filled insulation envelope may be calculated assuming one-directional conduction through side walls.

$$Q = \frac{2 \pi K L (T_S - T_A)}{\frac{R_o}{\ln \frac{R_o}{R_L}}}$$

L = 16.25 inches (envelope length)

T_S = 1200° F (shield temperature)

T_A = 70° F (ambient temperature)

R_O = 11.25 inches (envelope outer wall)

R_i = 5.38 inches (envelope inner wall)

K = 0.0058 BTU/hour-foot-° F (MIN-K #1301 in Xenon gas atmosphere)

$$Q = \frac{2 \pi (0.0058) (16.25) (1200 - 70)}{\ln \frac{11.25}{5.38}} = 74.7 \text{ BTU/hour or } 21.9 \text{ watts}$$

The thermal losses through the base considering one-directional heat flow and constant temperature across the heat shield base.

$$A = \frac{\pi D^2}{4} \text{ (Base area)}$$

K = 0.0058 BTU/hour-foot-° F

x = 6 inches insulation thickness

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

$T_{sb} = 1200^{\circ}\text{F}$ shield base temperature

$T_a = 70^{\circ}\text{F}$ ambient temperature

$$Q = \frac{K A (T_{sb} - T_a)}{x}$$

$$A = \frac{\pi D^2}{4} = \frac{\pi (22.5)^2}{4} = 392 \text{ square inches}$$

$$Q = \frac{0.0058 (392) (1200 - 70)}{\frac{6}{12} 144} = 35.7 \text{ BTU/hour or } 10.5 \text{ watts}$$

HERMETIC SEALING BELLOWS

A stainless steel bellows will form the hermetic seal between the inner wall of the insulation envelope and the generator mounting ring. The distance between the inner envelope wall and mounting ring is 3.75 inches with effective length of heat path increased to 5.50 inches by bellows.

$t = 0.010$ inch bellow wall thickness

$D = 10.75$ inches bellow diameter

$$A = \pi Dt = 3.14 \times 10.75 \times 0.010 = 0.338 \text{ square inch}$$

One-directional conduction

$$Q = \frac{KA (t_h - t_c)}{L}$$

$K = 9.5$ BTU/hour-foot- $^{\circ}\text{F}$ (Type 321 stainless steel)

$t_h = 1200^{\circ}\text{F}$ shield temperature

$t_c = 140^{\circ}\text{F}$ outer case temperature

$L = 5.50$ inches bellow effective length

$$Q = \frac{9.5 \times 0.338 (1200 - 140)}{144 \frac{5.5}{12}} = 51.8 \text{ BTU/hour or } 15.1 \text{ watts}$$

Total Loss: 47.5 watts

~~CONFIDENTIAL~~

APPENDIX F THERMAL ANALYSIS

The system heat flow and temperature profile must be fully analyzed to ensure that the total heat from the heat source, after accounting for all shunt heat losses, provides the required heat flow through the thermoelectric elements. The thermoelectric leg requirements are in turn dependent upon the analyzed temperature profile which is a result of the ambient temperature, the thermal gradients, and the temperatures of the limiting materials. The analysis was therefore one of trial and error balancing all factors, and the method of analysis was as follows:

1. The ambient temperature was specified.
2. The fin analysis was conducted, and the results of this analysis were plotted as heat dissipated versus the temperature drop across the fins (fin base to ambient temperature). Figure F-1 is the plot representing the selected fin design. Appendix D reports the fin analysis portion of the design.

Figure F-1. Fin Heat Dissipation

~~CONFIDENTIAL~~

3. The preliminary thermopile configuration resulted from a comparison of the following inputs.
 - a. The results of a computer program describing the parametric properties of the available thermoelectric materials.
 - b. The thermal watts (EOL) available to the thermoelectric couples.
 - c. The anticipated cold junction temperature for EOL.
 - d. The number of thermocouples necessary to support the EOL power output requirements.
4. The heat accumulator analysis and heat losses will not influence the preliminary thermopile analysis since these losses represent a small percentage loss for the total system.

Figure F-2 is a sketch showing the various heat flow paths and important design temperature points. The heat paths, and the amount of heat are shown in Table F-1. The temperature profile points are shown in Table F-2. These values were determined during the preliminary analysis at the beginning of this quarter. The changes in design and the influence of these changes on the Q and T balance are analyzed independently.

For the preliminary analysis the following parameters were used.

1. The design ambient: 75° F
2. The fin base to thermoelectric cold junction temperature difference was 25° F.
3. The heat dissipated by the fins included the following:
 - a. Heat to thermoelectric elements less electrical output ($Q_e - q_e$).

~~CONFIDENTIAL~~

CONFIDENTIAL

Figure F-2. Heat Flow and Temperature Distribution of System (Sketch)

b. Heat flow through the following generator "loss" paths

- (1) Active generator insulation q_6
- (2) Base of generator insulation q_5
- (3) Support cone of generator q_4

4. Thermoelectric elements hot junction temperature limited to 1000° F.
5. Because of the heat "loss" paths q_1 , q_2 and q_3 supplying heat to the ambient below the fins, and because the heat source insulation envelope protrudes out into the air stream to the fins, a 20% safety factor was added to the heat dissipation capacity of the fins.

The heat loss calculations are not included as they follow the established formulas for unidirectional heat flow. The formulas used are for single direction heat flow $Q = (K A \Delta T / L)$ and for radial flow of heat $Q = [2\pi K A \Delta T / \ln (R_o / R_i)]$.

CONFIDENTIAL

~~CONFIDENTIAL~~

Table F-1. Heat Flow (Preliminary)

(Refer Fig. F-3)

Item	Material	Configuration	Heat (watts)	Designation
Fuel	Strontium 90	---	750	Q
Capsule	Hastelloy C	Cylinders (2) 4.5 inches OD x 9.5 inches overall	750	-
Shield	Depleted Uranium	Cylinder 10.5 inches OD x 15.5 inches high	750	-
Linde Insul.	---		12	q_1
High Vac. Insul. Bellows System	---		28	q_2
MID-Ring Insul.	MIN-K and Air		30	q_3
			$\frac{-70}{680}$	Q_a
GEN Support Cone	Stainless Steel	0.010 thick, 3 inches ID, 8.5 inches OD	13	q_4
Base Insulation	MIN-K and Xenon		5	q_5
			$\frac{-18}{662}$	Q_a
Active Gen. Insul.	MIN-K #1301 & Xenon		16.5	q_6
Gen. Bellows	Stainless Steel		6.2	q_7
Top Plug	MIN-K and Air		2.3	q_8
			$\frac{-25}{637}$	Q_e
Available For T.E. Conversion				
Elect. Output	Reg. and Load		60	q_e
			$\frac{-60}{577}$	Q_{REJ}
Rejected Heat				
Items q_4 , q_5 , and q_6			$+35$	
Fins	Copper High Conductivity Radial Sheets (100)	5 x 7 x 0.045 inch thick	612	q_{FIN}
Items q_1 , q_2 , and q_3	(to AIR going to FINS)		$+70$	
Fin Dissipation Load			682	Q_{AMB}

~~CONFIDENTIAL~~

Table F-2. Temperature Profile

Item	Data on Item	End of Life (75° F amb.)	Beginning of Life		Designation
			(75° F amb.)	(140° F amb.)	
Fuel	Temperature Range	1200-1120	1340-1264	1405-1329	T_F
Capsule	Temperature Drop (average)	(-10)	(-11)	(-11)	
Shield	Temperature Drop (average)	(-40)	(-45)	(-45)	
Shield Accumulator Interface	3 inches diameter x 6 inches long Copper	1070	1203	1268	T_{ab}
Accumulator Inactive	2.25 inches long	(-46)	(-52)	(-52)	
Active	3.75 inches long	1024-988	1151-1109	1216-1174	
Accumulator Element Hot Junction		(-0)	(-0)	(-0)	
Nominal Element Hot Junction Temperature		1000	1123	1188	T_h
Element Cold Junction Temperature		170	180	245	T_c
Temperature Drop Element Cold Junction to Fin Base		(-25)	(-28)	(-28)	
Fin Base Temperature		145	152	217	T_{fb}
Temperature Drop Fin Base to Ambient Air		(-70)	(-77)	(-77)	T
Ambient Air Tempera- ture		75	75	140	T_{amb}

~~CONFIDENTIAL~~

The losses from the heat source insulation envelope were obtained by rationalizing the configuration of the preliminary design with the heat losses of the Linde insulation envelope. These losses were furnished by the Linde Company.

ACCUMULATOR THERMAL ANALYSIS

The active length (3.75 inches), which is within the cold frame cylinder of the thermoelectric generator, supplies the required heat to the thermoelectric elements and also structurally supports them.

Earlier calculations indicate a parabolic temperature gradient curve which results in the mean ΔT (taken from hot end) being 0.7 of the calculated total ΔT of the accumulator.

Simple calculation for uniform heat removal along its length

$$q \frac{L^2}{2} = K A \Delta T$$

$$\begin{aligned} q &= \text{Heat removed per inch length (watts/inch)} \\ &= (Q_e + q_g) / 3.75 = 656 / 3.75 = 175 \text{ watts/inch} \end{aligned}$$

$$L = \text{Active length} = 3.75 \text{ inches}$$

$$K = \text{Material conductivity } 4.89 \text{ watts/inch } ^\circ \text{F}$$

$$A = \text{Area of cross section (square inches)}$$

$$\begin{aligned} &\frac{d^2}{4} = \frac{3.14 \times 3^2}{4} = 7.05 \text{ square inches} \end{aligned}$$

$$\Delta T = \text{Temperature difference between ends } (^\circ \text{F})$$

$$q \frac{L^2}{2} = K A \Delta T$$

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

$$175 \times \frac{(3.75)^2}{2} = 4.89 \times 7.05 \times T$$

$$T = 35.8^\circ \text{F}$$

Then $0.7 (35.8) = 25^\circ \text{F}$ and if the mean T_R is to be 1000°F then T_{aa} has to be $1000 + 25 = 1025^\circ \text{F}$.

Inactive - (for direction heat transfer)

$$Q = \frac{K A \Delta T}{L}$$

where

Q = heat transferred (656 watts)

K = material conductivity (4.89 watts/in $^\circ \text{F}$)

L = material length (2.25 inches)

A = material cross section (7.05 square inches)

$$\Delta T = \frac{QL}{KA}$$

$$\begin{aligned} &= \frac{656 \times 2.25}{4.89 \times 7.05} \\ &= 43^\circ \text{F} \end{aligned}$$

~~CONFIDENTIAL~~

APPENDIX G
HEAT SOURCE CALCULATIONS

The maximum photon flux is expressed at the surface of the generator housing by:

$$\phi = \frac{pa^2}{2(Z + t_c)} F(\theta_2, \mu t + \mu_c t_c + \dots)$$

where p = photon density for a volume source $\text{cm}^{-3} \text{sec}^{-1}$

= (β source strength) (bremsstrahlung conversion intensity/source vol)

$$\begin{aligned} &= \frac{(274000 \text{ curies}) (3.7 \times 10^{10} \text{ d/s})C}{1125 \text{ cm}^3} \\ &= 9.02 \times 10^{12} \text{ d/s-cm}^3 \end{aligned}$$

The term $\mu t + \mu_c t_c + \dots$ is the total linear absorption coefficient. It is obtained for each of the energy intervals by summing the products obtained by multiplying the mass absorption coefficients for the individual absorbing mediums by their respective densities and thicknesses.

This analysis technique determines the shielding required to reduce the radiation intensity at the outer surface of the generator housing to 200 mr/hr or less.

A generator housing diameter of three different values was used in these calculations. Because of the iterative nature of the method, three shield thicknesses were selected which were estimated to bracket the required thickness.

<u>Generator Housing</u>			
<u>Radius (inches)</u>	<u>Z(cm)</u>	<u>Z/a*</u>	<u>(Z + a)</u>
9.0	17.8	4.25	22.0
11.0	22.8	5.44	27.0
12.5	26.7	6.38	30.9

*a = fuel radius - 4.2 cm

Results of the calculations are listed in tabular and graphical form. The spatial relationship of the system components used for calculating purposes is illustrated in Figure G-1.

Figure G-1. Spatial Relationship of Fuel Capsule to Generator Components

Table G-1. Linear Absorption Coefficients cm^{-1}

Photon Energy	μ_c SrTiO_3	μ_h Hastelloy	μ_u Uranium
0.11	1.153	2.91	102.0
0.33	0.385	0.921	6.44
0.55	0.294	0.689	2.70
0.77	0.251	0.581	1.72
0.99	0.218	0.514	1.26
1.21	0.201	0.467	1.10
1.43	0.185	0.436	0.983
1.65	0.172	0.410	0.909
1.87	0.164	0.386	0.861
2.09	0.161	0.369	0.826
Densities	3.7	8.95	17.4

~~CONFIDENTIAL~~

Table G-2. Attenuation Exponents μt

Shield thicknesses of 2.5, 3.0 and 3.5 inches (6.35, 7.62 and 8.89 cm) Uranium 8Mo			
<u>Energy(mev)</u>	<u>6.35</u>	<u>7.62</u>	<u>8.89</u>
0.55	17.15	20.6	24.0
0.77	10.91	13.1	15.3
0.99	8.0	9.6	11.2
1.21	6.99	8.38	9.77
1.43	6.24	7.49	8.75
1.65	5.77	6.93	8.08
1.87	5.46	6.56	7.66
2.09	5.25	6.30	7.35

Hastelloy capsule $t = 0.312$ inches = 0.792 cm			
Energy(mev)	μt		
0.55	0.545		
0.77	0.46		
0.99	0.406		
1.21	0.369		
1.43	0.345		
1.65	0.324		
1.87	0.306		
2.09	0.292		

~~CONFIDENTIAL~~

Table G-3. Σ Attenuation Exponents ut

Z/a = 4.25 - 18" diameter			
Energy	<u>6.35</u>	<u>7.62</u>	<u>8.89</u>
0.11	-	-	-
0.33	-	-	-
0.55	18.8	22.3	25.8
0.77	12.2	14.5	16.7
0.99	9.1	10.7	12.4
1.21	8.01	9.4	10.8
1.43	7.24	8.47	9.73
1.65	6.71	7.85	8.99
1.87	6.34	7.42	8.51
2.09	6.12	7.14	8.18
Z/a = 5.44 - 22" diameter			
0.55	18.84	22.3	25.8
0.77	12.16	14.4	16.7
0.99	9.18	10.7	12.3
1.21	8.0	9.38	10.8
1.43	7.2	8.42	9.67
1.65	6.68	7.82	8.96
1.87	6.34	7.43	8.51
2.09	6.12	7.13	8.18
Z/a = 6.38 - 25" diameter			
0.55	18.9	22.5	26.0
0.77	12.2	14.4	16.7
0.99	9.05	10.6	12.3
1.21	7.95	9.34	10.8
1.43	7.15	8.34	9.65
1.65	6.64	7.77	8.91
1.87	6.30	7.38	8.48
2.09	6.08	7.12	8.15

Table G-4. Self Absorption Exponents $\mu_c t_c$

18 inch diameter			
t_s	6.35	7.62	8.89
0.55	1.11	1.19	1.25
0.77	0.841	0.97	0.978
0.99	0.693	0.708	0.778
1.21	0.655	0.648	0.662
1.43	0.651	0.63	0.637
1.65	0.618	0.592	0.585
1.87	0.571	0.552	0.540
2.09	0.575	0.552	0.540
22 inch diameter			
0.55	1.15	1.17	1.27
0.77	0.789	0.875	0.930
0.99	0.671	0.68	0.697
1.21	0.640	0.632	0.648
1.43	0.614	0.585	0.577
1.65	0.588	0.566	0.553
1.87	0.578	0.567	0.544
2.09	0.580	0.547	0.535
25 inch diameter			
0.55	1.24	1.32	1.42
0.77	0.818	0.885	0.918
0.99	0.644	0.644	0.654
1.21	0.595	0.586	0.604
1.43	0.568	0.552	0.552
1.65	0.541	0.518	0.504
1.87	0.533	0.518	0.512
2.09	0.54	0.525	0.512

Table G-5. Self Absorption Parameters As a Function of Fuel Radius

Energy(mev)	9 inch $\mu_c(a + Z)$	M	11 inch $\mu_c(a + Z)$	M	12.5 inch $\mu_c(a + Z)$	M
0.55	6.47	0.95	7.84	1.15	9.08	1.42
0.77	5.52	0.85	6.77	0.95	7.75	1.12
0.99	4.8	0.77	5.89	0.85	6.75	0.92
1.21	4.42	0.72	5.43	0.81	6.21	0.85
1.43	4.06	0.7	4.99	0.74	5.72	0.8
1.65	3.78	0.65	4.65	0.7	5.32	0.74
1.87	3.61	0.6	4.43	0.68	5.06	0.72
2.09	3.54	0.6	4.35	0.66	4.98	0.72

~~CONFIDENTIAL~~

Table G-6. Self Absorption Parameter $\mu_c t_c / m^*$

18 inch diameter Z/a = 4.25			
<u>t_s U8Mo Energy</u>	<u>6.35</u>	<u>7.62</u>	<u>8.89</u>
0.11	-	-	-
0.33	-	-	-
0.55	1.17	1.25	1.32
0.77	0.99	1.14	1.15
0.99	0.90	0.92	1.01
1.21	0.01	0.90	0.92
1.43	0.93	0.90	0.91
1.65	0.95	0.91	0.90
1.87	0.95	0.92	0.90
2.09	0.96	0.92	0.90

22 inch diameter Z/a = 5.44			
0.55	1.0	1.02	1.10
0.77	0.83	0.92	0.98
0.99	0.79	0.80	0.82
1.21	0.79	0.78	0.80
1.43	0.83	0.79	0.78
1.65	0.84	0.81	0.79
1.87	0.85	0.82	0.80
2.09	0.88	0.83	0.81

25 inch diameter Z/a = 6.38			
0.55	0.87	0.93	1.0
0.77	0.73	0.79	0.82
0.99	0.70	0.70	0.71
1.21	0.70	0.69	0.71
1.43	0.71	0.69	0.69
1.65	0.73	0.70	0.68
1.87	0.74	0.72	0.71
2.09	0.75	0.73	0.71

~~CONFIDENTIAL~~

The values of t_c range from 3.18 to 4.83.

$$\begin{aligned}\text{Assume that } Z + t_c &= 17.8 + 4 = 21.8 \\ &= 22.8 + 4 = 26.8 \\ &= 26.7 + 4 = 30.7\end{aligned}$$

$$t_{an} \theta = \frac{12.05}{21.8} = 0.554 \quad \phi = 29.0^\circ$$

$$= \frac{12.05}{26.8} = 0.45 \quad \phi = 24.2^\circ$$

$$= \frac{12.05}{30.7} = 0.393 \quad \phi = 21.4^\circ$$

F (θ , μt) values were taken from Figure G-2 and appear in Table G-7.

The radiation dose rate is given by the relationship:

$$\begin{aligned}D &= 6.95 \times 10^{-5} (\mu_a p_a) E B O \\ &= KBOC\end{aligned}$$

where

μ_a/p = mass absorption coefficient of air

B = dose buildup factor from scattered photons (function of μt)

E = photon energy

C = Bremsstrahlung conversion factor

D is obtained in R/hour

~~CONFIDENTIAL~~

Figure G-2. Function $F(\theta, ut)$ vs. ut

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Table G-7. $F(\theta, ut)$

18 inch diameter $\theta = 29.0^\circ$			
Energy	6.35	7.62	8.89
0.55	1.7×10^{-9}	5.0×10^{-11}	-
0.77	1.4×10^{-6}	1.5×10^{-7}	1.5×10^{-6}
0.99	4.1×10^{-5}	8.0×10^{-6}	1.2×10^{-6}
1.21	1.3×10^{-4}	3.0×10^{-5}	7.2×10^{-6}
1.43	2.7×10^{-4}	7.8×10^{-5}	2.3×10^{-5}
1.65	4.6×10^{-4}	1.5×10^{-4}	4.5×10^{-5}
1.87	6.8×10^{-4}	2.3×10^{-4}	7.4×10^{-5}
2.09	8.7×10^{-4}	3.1×10^{-4}	1.1×10^{-4}
22 inch diameter $\theta = 24.2^\circ$			
0.55	1.7×10^{-9}	5.5×10^{-11}	-
0.77	1.4×10^{-6}	1.5×10^{-7}	1.5×10^{-8}
0.99	3.3×10^{-5}	7.0×10^{-6}	1.5×10^{-6}
1.21	1.1×10^{-4}	2.7×10^{-5}	6.2×10^{-6}
1.43	2.5×10^{-4}	7.0×10^{-5}	2.0×10^{-5}
1.65	4.4×10^{-4}	1.3×10^{-4}	4.1×10^{-5}
1.87	6.0×10^{-4}	1.9×10^{-4}	6.5×10^{-5}
2.09	7.6×10^{-4}	2.6×10^{-4}	9.2×10^{-5}
25 inch diameter $\theta = 21.4^\circ$			
0.55	-	-	-
0.77	1.4×10^{-6}	1.5×10^{-7}	1.5×10^{-8}
0.99	3.4×10^{-5}	7.0×10^{-6}	1.3×10^{-6}
1.21	1.0×10^{-4}	2.5×10^{-5}	5.6×10^{-6}
1.43	2.4×10^{-4}	6.7×10^{-5}	1.8×10^{-5}
1.65	4.1×10^{-4}	1.3×10^{-4}	3.9×10^{-5}
1.87	5.7×10^{-4}	1.9×10^{-4}	6.2×10^{-5}
2.09	7.2×10^{-4}	2.5×10^{-4}	8.6×10^{-5}

~~CONFIDENTIAL~~

CONFIDENTIAL

Table G-8. $\phi = [Pa^2/2(Z + t_c)] F(\theta, ut)$
(Photon flux at surface of housing)

18 inch diameter $\phi = 3.65 \times 10^{12} F(\theta, ut)$			
Mev	6.35cm	7.62cm	8.89cm
0.55	6.21×10^3	1.82×10^2	--
0.77	5.11×10^6	5.47×10^5	5.47×10^4
0.99	1.50×10^8	2.92×10^7	4.38×10^6
1.21	4.75×10^8	1.09×10^8	2.63×10^7
1.43	9.85×10^8	2.84×10^8	8.40×10^7
1.65	1.68×10^9	5.47×10^8	1.64×10^8
1.87	2.48×10^9	8.40×10^8	2.70×10^8
2.09	3.18×10^9	1.13×10^9	4.02×10^8
22 inch diameter $\phi = 2.96 \times 10^{12} F(\theta, ut)$			
0.55	5.04×10^3	1.63×10^2	--
0.77	4.15×10^6	4.45×10^5	4.45×10^4
0.99	9.77×10^7	2.07×10^7	4.45×10^6
1.21	3.26×10^8	7.98×10^7	1.84×10^7
1.43	7.4×10^8	2.07×10^8	5.92×10^7
1.65	1.31×10^9	3.85×10^8	1.21×10^8
1.87	1.78×10^9	5.62×10^8	1.93×10^8
2.09	2.25×10^9	7.7×10^8	2.73×10^8
25 inch diameter $\phi = 2.59 \times 10^{12} F(\theta, ut)$			
0.55	--	--	--
0.77	3.63×10^6	3.89×10^5	3.89×10^4
0.99	8.82×10^7	1.82×10^7	3.37×10^6
1.21	2.50×10^8	6.49×10^7	1.45×10^7
1.43	6.23×10^8	1.74×10^8	4.67×10^7
1.65	1.06×10^9	3.37×10^8	1.01×10^8
1.87	1.48×10^9	4.93×10^8	1.61×10^8
2.09	1.87×10^9	6.49×10^8	2.23×10^8

CONFIDENTIAL

UNCLASSIFIED

~~CONFIDENTIAL~~Table G-9. Photon Energy vs. μ_a/P_a & K

Photon Energy Mev	μ_a/P_a	
0.77	0.07	3.75×10^{-6}
0.99	0.06	4.14×10^{-6}
1.21	0.054	4.54×10^{-6}
1.43	0.05	4.96×10^{-6}
1.65	0.046	5.28×10^{-6}
1.87	0.044	5.71×10^{-6}
2.09	0.042	6.1×10^{-6}

Table G-10. Buildup Factors

Energy(Mev)	6.35cm	7.62cm	8.89cm	C
0.77	2.7	2.9	3.1	6.97×10^{-4}
0.99	2.9	3.1	3.3	2.83×10^{-4}
1.21	2.9	3.3	3.7	1.07×10^{-4}
1.43	3.0	3.3	3.6	3.75×10^{-5}
1.65	3.0	3.2	3.4	1.27×10^{-5}
1.87	3.0	3.2	3.4	3.54×10^{-6}
2.09	3.0	3.2	3.4	7.6×10^{-7}

Table G-11. KBC

Energy(Mev)	6.35cm	7.62cm	8.89cm
0.77	7.05×10^{-9}	7.57×10^{-9}	8.1×10^{-9}
0.99	3.39×10^{-9}	3.62×10^{-9}	3.86×10^{-9}
1.21	1.41×10^{-9}	1.61×10^{-9}	1.8×10^{-9}
1.43	5.59×10^{-10}	6.15×10^{-10}	6.7×10^{-10}
1.65	2.01×10^{-10}	2.15×10^{-10}	2.28×10^{-10}
1.87	6.06×10^{-11}	6.46×10^{-11}	6.88×10^{-11}
2.09	1.39×10^{-11}	1.48×10^{-11}	1.57×10^{-11}

UNCLASSIFIED

G-12

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

UNCLASSIFIED

Table G-12. KB/C (Ref. Figure G-3)

(Dose Rate in R/hr Through U-8 Mo Shield at Housing Surface)

18 inch diameter			
Energy	6.35	7.62	8.89
0.77	3.61×10^{-2}	4.14×10^{-3}	4.43×10^{-4}
0.99	5.08×10^{-1}	1.06×10^{-1}	1.69×10^{-2}
1.21	6.7×10^{-1}	1.75×10^{-1}	4.74×10^{-2}
1.43	5.5×10^{-1}	1.75×10^{-1}	5.62×10^{-2}
1.65	3.38×10^{-1}	1.18×10^{-1}	3.74×10^{-2}
1.87	1.51×10^{-1}	5.42×10^{-2}	1.86×10^{-2}
2.09	4.42×10^{-2}	1.67×10^{-2}	6.31×10^{-3}
Σ	2.297	0.585	0.183
22 inch diameter			
0.77	2.93×10^{-2}	3.37×10^{-3}	3.6×10^{-4}
0.99	3.31×10^{-1}	7.5×10^{-2}	1.72×10^{-2}
1.21	4.6×10^{-1}	1.28×10^{-1}	3.32×10^{-2}
1.43	4.14×10^{-1}	1.27×10^{-1}	3.97×10^{-2}
1.65	2.63×10^{-1}	8.27×10^{-2}	2.76×10^{-2}
1.87	1.08×10^{-2}	3.63×10^{-2}	1.33×10^{-2}
2.09	3.13×10^{-2}	1.14×10^{-2}	4.28×10^{-3}
Σ	1.64	0.464	0.136
25 inch diameter			
0.77	2.56×10^{-2}	2.94×10^{-3}	3.15×10^{-4}
0.99	2.99×10^{-1}	6.6×10^{-2}	1.3×10^{-2}
1.21	3.65×10^{-1}	1.04×10^{-1}	2.61×10^{-2}
1.43	3.48×10^{-1}	1.07×10^{-1}	3.13×10^{-2}
1.65	2.13×10^{-1}	7.25×10^{-2}	2.3×10^{-2}
1.87	8.89×10^{-2}	3.18×10^{-2}	1.11×10^{-2}
2.09	2.6×10^{-2}	9.6×10^{-3}	3.5×10^{-3}
Σ	1.37	0.394	0.108

UNCLASSIFIED

~~CONFIDENTIAL~~

Figure G-3. Dose Rate vs. Shield Thickness

~~CONFIDENTIAL~~

UNCLASSIFIED

The preceding analysis has been used for a 10 curie Sr-90 source and checked by actual measurement. (Reference: Quarterly Report, 9 March 1964 to 30 June 1964, SNAP-21B, Contract AT(30-1)3321.)

The results of both programs show a conservative estimate is obtained by calculations. As two different approaches to the shielding problem show the calculated thickness to be conservative, the shield thickness was reduced to 3.2 inches (the calculated being ~3.3 inches). (See Figure G-4).

Figure G-4. Shield Thickness vs. System Diameter
for 200 mr Surface Dose

UNCLASSIFIED

G-15/G-16

~~CONFIDENTIAL~~