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DECLASSIFIED

FINAL REPORT

ADVANCED LARGE MILLIWATT
RADIOISOTOPE GENERATOR
STUDY PROGRAM
VERSION

CLASSIFICATION CANCELLED

NOV 4 1966

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CESTI PRICES

AEC Contract No. AT(30-1)-3627

H C \$ 3.00, MN. 65

May 31, 1966

By

HITTMAN ASSOCIATES, INC.
BALTIMORE, MARYLAND

Prepared for the

United States Atomic Energy Commission
Division of Reactor Development

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FOREWORD

This report presents a summary of the parametric and design study effort conducted for the United States Atomic Energy Commission by Hittman Associates, Inc. on the Advanced Large Milliwatt Radioisotope Generator Study Program--AEC Contract Number AT(30-1)-3627. The purpose of the program was to conduct a parametric study to determine the general characteristics of various advanced large milliwatt thermoelectric generator systems within the state-of-the-art and then to conduct design studies resulting in preliminary specifications for certain systems selected on the basis of a requirement survey.

This report is organized to present a complete program summary in the first two sections. Technical details are then presented in the latter sections.

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I. INTRODUCTION

"The Advanced Large Milliwatt Radioisotope Thermoelectric Generator (RTG) Study Program", sponsored by the United States Atomic Energy Commission, encompassed three areas of endeavor--1) a cursory market survey; 2) a unique parametric study; and 3) a design study. The market survey was intended to uncover logical and economical uses for RTGs in the power range from 150 to 1000 milliwatts(e). The parametric study was aimed at helping prospective users to determine quickly the pertinent physical characteristics of RTGs which could suit their potential applications. Finally, the design study was to more fully define four systems satisfying specific applications.

A. Background

Radioisotope thermoelectric generators are compact, highly reliable systems capable of producing electrical power from microwatts to kilowatts for extended time periods. Their power output is continuous and over an operational lifetime, they produce large total amounts of energy. Thus, they are appropriate power sources for any operation requiring high reliability in which unattended operation is mandatory and maintenance infrequent. Space and oceanographic systems are obvious applications. Less obvious uses lie in ordnance, intelligence and biological systems, systems located in unpopulated regions like the Arctic and in rugged mountain terrain.

RTG systems have been developed and used at power levels from 1 milliwatt(e) to 60 watts(e). They have been used literally from pole to pole over the earth's surface, undersea, and in space. RTGs, to broaden the range from 100 microwatts(e) to 10 kilowatts(e), are currently in the early stages of development. These systems have uses ranging from "in vivo" power to supply a heart pacer to primary electrical power for manned space stations.

RTG systems have been developed so far to fit specifically needed power levels. The range from 1 to 100 milliwatts(e) was covered by SNAP-15A, B, and C*, 5 to 60 watts(e) by SNAP-3, 7, 9A, 19 and 27, and the higher power levels by SNAP-29 and systems yet to be designated.

Obviously, then there are "gaps" in the power level band not covered by existing RTGs or by systems under development. One of the gaps is the power range from 100 milliwatts(e) to the low watt(e) range; and this is the power output range on which this study has concentrated.

* SNAP is an acronym for Systems for Nuclear Auxilliary Power

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B. Market Survey

The market survey performed under this study, though rather cursory and heavily oceanographic applications oriented, provides several excellent illustrative examples of prime applications for RTGs.

Two distinct applications were found in the oceanographic area: 1) power for underwater research instruments, and 2) sound generators, or "pingers". Oceanographers currently use life-limited chemical batteries in both cases. Underwater research instruments were found to require power on a steady state basis between 10 and 300 milliwatts(e). The sound generators need between 500 milliwatts(e) and 1.5 watts(e).

Chemical batteries limit the overall system life, so that it is difficult now to perform undersea experiments utilizing powered instrumentation for more than several months at a time. Underwater pingers, which are used to mark offshore oil well heads or experiments and as navigational aids, are currently limited to about one month's life by their chemical battery power supplies. In both these instances, RTGs would supply an economical and reliable solution to the problem of system life limitation.

The primary terrestrial application found by the survey was power supplies for micro-wave repeater stations. As in the oceanographic application, the system logistics for such stations in extremely rugged mountain terrain make long lived and unattended operation necessary. Again, chemical batteries are now being employed; but use of RTGs would eliminate the necessity of frequent replacement.

Less pressing applications were also noted in the area of underwater repeater stations, ordnance fusing, and intelligence power supplies.

C. Parametric Study

A major deterrent to more widespread use of RTGs has probably been that potential users simply are not familiar with them. The average person who needs a power supply is likely to be knowledgeable about batteries, motor-generators and other such power systems. He usually knows or can determine quickly how large such a power system will be, how long it will last and, perhaps most important, how much it will cost. Because of the relatively limited usage of RTGs to date, such information is not readily available for them and this represents a distinct disadvantage. Consequently, they may not even be considered for a system application in which they are the most logical power source. An attempt has therefore been made in this study to supply a quick method for determining the characteristics of RTGs to fit various applications.

An RTG consists of six major components: 1) the fuel, 2) its containment vessel, 3) thermal insulation, 4) the thermopile, 5) a case and 6) a dc-dc converter. A parametric study was performed on each component. However, to determine the characteristics of a specific RTG, the components must be "matched". For example, the generator case may not be sized smaller than the fuel containment capsule. To allow possible users to match the subcomponents, the parametric data

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have been put into the form of combined graphs and nomograms--or, to use a coined expression, "nomographs". These are presented in such a way that possible users can readily determine the RTG characteristics fitting their own applications.

D. Design Study

Four RTG conceptual designs were developed as representative in meeting applications found in the market survey. These are:

- (1) 1 watt(e), strontium-90 fueled, fully-shielded oceanographic system
- (2) 1 watt(e), strontium-90 fueled, removable-shield oceanographic system
- (3) 300 milliwatt(e), strontium-90 fueled, fully shielded terrestrial system
- (4) 1 watt(e), plutonium-238 fueled oceanographic system

The first two are intended to meet the requirements for underwater sound generators, the only difference being that one incorporates a removable radiation shield which would be retained when the RTG is put overboard. This results in a lower use cost. The plutonium-238 system requires no radiation shield under any circumstances. It was designed for use as an underwater repeater station power system. The 300 milliwatt(e), strontium-90 system was designed as a possible fusing device for terrestrial ordnance.

The four design concepts presented are by no means exhaustive. Those presented are merely intended to illustrate typical systems--to physically define the RTG and its versatility in meeting many power applications.

II. PROGRAM SYNOPSIS

The "Advanced Large Milliwatt Radioisotope Thermoelectric Generator Study Program" has accomplished all intended goals. The market survey uncovered several prime applications for RTGs in the 100 milliwatt(e) to 1 watt(e) power range. The parametric study resulted in the production of a unique analytical design tool--the "nomograph"--which enables prospective users to determine the characteristics of an RTG suitable for their application. The design study verified that low power RTGs meeting current application requirements can be produced economically and within the state-of-the-art.

It is hoped that the results of this study can be utilized to stimulate further interest in these type systems. Further, it is hoped that the study will show prospective users that RTGs meeting their specific needs can be produced economically and used easily.

A. Market Survey

The intention of the market survey performed under this study was not to uncover purchasers for milliwatt(e) level RTGs but rather to discover the best use examples for illustrative purposes. Therefore, in comparison to most such surveys, the one described here is less economically oriented and more limited in scope.

Initially, a "brain storming" session was held between Hittman Associates, Aerojet General Nucleonics, and USAEC personnel to determine possible uses of large milliwatt(e) RTGs. The potential use areas covered oceanographic research, underwater and terrestrial weapons, offshore oil and underground oil rigs, underwater cable booster systems, navigational aids, intelligence, and remote repeater station applications. A list of corporations and government agencies engaged in these areas of endeavor was then compiled. From this list were selected the seven agencies most likely to have a promising use for large milliwatt(e) RTGs. These agencies were:

(1)	Naval Ordnance Laboratory	White Oak, Maryland
(2)	Woods Hole Oceanographic Institute	Woods Hole, Massachusetts
(3)	Alpine Geophysical Associates, Inc.	Norwood, New Jersey
(4)	ITT	New York, New York
(5)	Global Marine Inc.	Los Angeles, California
(6)	Sandia Corporation	Albuquerque, New Mexico
(7)	Naval Civil Engineering Laboratory	Port Hueneme, California

Each of the listed agencies were contacted and personal conferences arranged to explore in detail possible RTG use areas. A preconference information list was compiled and sent to each agency. The list was as follows:

- (1) Description(s) of the intended use for the Radioisotope Thermoelectric Generator (RTG) and associated power conditioning equipment
- (2) The extent of human access to the device
- (3) Whether the use will be overt or covert and if there would be any chance that an alien nation might recover the system
- (4) Will the device be "recoverable"
- (5) Definition of the operating environment:
 - (a) Temperatures
 - (b) Pressures
 - (c) Terrestrial or underwater
 - (d) Storage requirements
 - (e) Heat sink availability
 - (f) Vibration and shock
 - (g) Acceptable radiation levels for power use components
- (6) Electrical output requirements:
 - (a) Power level
 - (b) Voltage specifications, including allowable ripple
 - (c) Power histogram or duty cycle
 - (d) Inductance and capacitance of load
 - (e) Regulation
- (7) System life and reliability specifications
- (8) Maintenance and repair capabilities
- (9) Weight and dimensional limitations
- (10) Numbers needed and date required
- (11) Competitive cost bracket-or mission information required to conduct cost/effectiveness analysis

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From the information gleaned on these trip conferences, sixteen possible large milliwatt(e) RTG systems were selected as being representative of the most promising use applications. Of these sixteen possible applications, four were designated for Hittman Associates, Inc. and four for AGN to produce conceptual designs. These selections did not encompass half of the possible concepts as several were redundant. Of the eight selections, three were on 1 watt(e), strontium-90 fueled systems.

The four concepts selected for conceptual design study by Hittman Associates, Inc. are summarized as follows:

- (1) 1 watt(e), strontium-90 fueled, fully shielded underwater system

Almost all the oceanographic users indicated a need for a 1 watt(e) system to power underwater sound generators. It was emphasized that the systems required long life (~ several years) and economical and reliable operation. "Pingers", which utilize batteries are currently employed and are subsequently life limited to several months by the power supply. These sound generators can be used as navigational aids and to mark offshore well heads and experiments. Economy and long life dictated the use of strontium-90 as a fuel.

- (2) 1 watt(e), strontium-90 fueled, removable shield underwater system

This system was selected for the same uses as previously described. The removable shield concept is simply an attempt to reduce system cost by enabling retainment of the RTG radiation shield. The system was designed to affect remote handling and shield removal on board a ship with only a crane as remote handling equipment.

- (3) 300 milliwatt(e), strontium-90 fueled, fully shielded terrestrial system

The market survey accomplished its intended function--that of providing many excellent illustrative use examples for RTG systems.

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B. Parametric Study

The generalized nature of the parametric study resulted in a large quantity of data, in many cases as a result of computerized investigations. These data have been correlated and reduced to four summary charts, which are summarized in this section, along with the technique of data presentation. The nomographs are included in the Appendix of this report.

1. Data Presentation

Radioisotope fueled thermoelectric generators in the large milliwatt(e) range may be considered parametrically by analyzing each of the major generator components and combining the results. This reduces the number of variables which must be considered for any one separate analysis to manageable proportions. For example, the thermoelements in the generator may be considered, insofar as the overall generator characteristics are concerned, by defining the thermoelectric material and the hot and cold junction temperatures. The thermoelectric efficiency may be determined immediately by suitable calculation techniques.

Although this approach allows each of the major components to be analyzed and answers obtained, there still remains the problem of combining the results from each of the separate analyses. Approximately 20 independent variables are required to define the characteristics of a RTG. The choice of this number of independent variables defines roughly the same number of dependent variables. The presentation of this quantity of data in easily usable form represents a formidable task. The use of tables or purely graphical presentations must be eliminated if the detailed system characteristics are desired because of the quantity of data. An alternate approach is to use graphical techniques to present information for specific characteristics, for example the thermoelectric characteristics, and combine the results of specific areas through nomogram techniques. While this "nomograph" does not directly present all of the desired information, it does enable the rapid calculation of the effect of various parametric selections. This approach was chosen for this study.

The milliwatt RTG characteristics are presented in nomograph #1, which shows the interrelationships between the power conditioner, thermoelements, thermal insulation, fuel design life, fuel capsule configuration, and shielding requirements. Nomograph #2 presents a computation technique for analytically designing the external generator configuration to satisfy the required surface temperature characteristics. Nomograph #3 presents cost information in terms of the characteristics obtained from nomograph #1. Nomograph #4 enables the calculation of detailed thermoelement dimensions and associated characteristics.

2. Nomograph Use

Use of the nomographs, although it appears very complicated at first glance, becomes relatively simple and rapid with a little practice. Each step in the calculation process is numbered sequentially, and arrows indicate the direction to the next sequence point. To begin calculations, one need only find the first numbered reference and follow the defined path of selections or operations from that point. For example, in nomograph #1 the starting point is near

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the right hand side, roughly one-third of the way down from the top. A large arrowhead at the circled number indicates that the initial direction is upward. At position one, the hot junction temperature is to be selected. A list of typical data (which may be utilized until an engineering feel for the generator behavior is obtained) is located in the top center of the nomograph. This list indicates that hot junction temperatures typically range from 350-800°F for generators in this size category. The sample problem is based upon a choice of 550°F.

The indicated direction of travel leads to point two, where the cold junction temperature and thermoelectric material are to be selected. In the sample problem lead telluride has been chosen, operating at a cold junction temperature of 150°F. The next move is horizontally to point three, where the thermoelectric efficiency of 0.05 or 5 percent is obtained. The large arrowhead there indicates the direction to the next sequential point (four), where the power conditioner input voltage is to be selected. At point five, the power output requirement for the system is selected, and at point six the power conditioner efficiency is obtained. Point seven is now determined by connecting point six and point three by a straight line, and point eight is determined by the intersection of the horizontal line with the angular line as indicated. The majority of the calculations in this nomograph proceed in exactly this manner; and, with few exceptions, little additional information on use is required.

Two complicated areas in the nomograph may cause difficulty, and some special study of these areas may be required. They occur between points 22 and 30 (where the fuel capsule configuration is obtained by defining the length-to-diameter ratio of the capsule) and in the region between points 32 and 40 (which leads to the insulation thickness required). The first calculational difficulty may be avoided, for the most part, by selecting a length-to-diameter ratio of one for the fuel capsule. If this is done, all steps between points 22 and 30 may be ignored, and a vertical constructed from wherever point 22 occurs on the fuel capsule volume line to the capsule inside diameter line. The intersection thus becomes point 30. The required dimensions at this point will be immediately determined. A similar assumption at point 32 will avoid the second difficulty. In this case, it is only necessary to construct between points 32, 33 and 34. Other steps may be skipped and the process may be restarted at point 41. This will lead sequentially to a line passing through point 53 which will intersect with the vertical line as shown by the dash construction line. This determines the parameter z , which may be utilized immediately at point 55 to obtain the insulation thickness.

In the quantities required for the milliwatt generator, plutonium-238 and promethium-147 introduce negligible shielding requirements for handling purposes. This is not true for strontium-90, and points 57 through 70 on the nomograph are used to present the shield characteristics. These calculations are presented only for the case in which the shield has a length-to-diameter ratio of one (the minimum weight and minimum volume configuration). At point 57, the previously determined insulation thickness and the fuel requirement at beginning of life may be combined with a shield material to give the shield thickness which will provide a surface dose rate of less than 200 mr/hr. Point 58 enables the calculation of the shield weight. Points 59 through 70 may be utilized to determine the shield surface dose rate when other shield thicknesses are used. For example, the means of determining a Sr-90 shield which would weigh half that required for a 200 mr/hr dose rate is illustrated.

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Once the user becomes familiar with the nomograph, he may start at any point he wishes, and progress in any direction. This makes possible the rapid investigation of design perturbations without the necessity of going through all steps. For example, the effect of various insulation efficiencies upon the end-of-life fuel requirements may be obtained very quickly by considering only points 9, 10, 11 and 18. Similarly, the effect of insulation conductivity may be obtained by limiting the study to points 46 to 56, inclusive.

It is possible to select either a high (Pu metal) or a low power density fuel form [REDACTED] if the fuel choice is Pu-238. The low power density fuel form is presented parametric in void fraction, whereas a suitable void fraction has been included with the high power density fuel form on the nomograph. The latter should ordinarily be selected.

One of the "independent variables" which must be chosen separately in order to use nomograph #1 is the cold junction temperature. This also determines the RTG surface temperature, which is merely the cold junction temperature minus the temperature drop between the cold junction and the case. In reality, this parameter cannot be chosen quite so easily in many instances. However, suitable generator design will satisfy the independent choice. Such a design may be assured by using nomograph #2, which occasionally will be required after a complete parametric study has been conducted using nomograph #1. The first few steps in nomograph #2 define the temperature at which a bare generator of the selected dimensions will operate. Ordinarily, the length and diameter required in this nomograph are the outside dimensions of the shield (or if there is no shield, the outside dimensions of the thermal insulation). The generator case will generally be thin enough so that its thickness may be neglected here. If the generator surface temperature obtained in these first few steps is lower than the temperature assumed previously, then the generator characteristics which have been calculated may be considered as conservative. If, on the other hand, the temperature computed in the first few steps of nomograph #2 is higher than was previously assumed, the generator characteristics might have to be redetermined using nomograph #1. A more probable alternative is to employ fins on the surface of the generator to reduce its surface temperature when operating in air. If the generator is to be operated as an underwater power device, little problem should exist because of the high heat transfer coefficient between the generator surface and its surroundings. In the event that fins must be added to the generator, the remainder of nomograph #2 may be utilized to obtain the required size.

Nomograph #3 presents a brief initial calculation of the estimated generator cost. Suggested unencapsulated radioisotope fuel prices are estimated to be 560, 91 and 19 dollars per thermal watt for the Pu-238, Pm-147 and Sr-90 fuels respectively. The depleted uranium shield cost will be approximately four dollars per pound.

Nomograph #4 will need to be used only occasionally, when detailed characteristics of the thermoelements are required. It permits the determination of the number of thermoelements, the generator open circuit voltage and the thermoelement dimensional characteristics.

A number of independent variables are required to use the nomographs. Until the calculation technique becomes completely familiar, it is best to have a list of the values to be chosen prior to beginning work with the nomograph. This will prevent becoming "lost" in the construction process. The following variables are needed to use nomograph #1:

- (1) hot junction temperature
- (2) thermoelement material
- (3) cold junction temperature
- (4) power conditioner input voltage
- (5) insulation efficiency
- (6) system power output
- (7) system design life
- (8) fuel
- (9) void fraction (if fuel is plutonium)
- (10) fuel capsule length-to-diameter ratio (inside and outside)
- (11) capsule material and internal shield thicknesses
- (12) temperature drop between heat source and hot junction
- (13) temperature drop between cold junction and generator case
- (14) insulation thermal conductivity

In addition, if Sr-90 is used as the fuel and it is decided to obtain the shield characteristics, the shield material must be chosen. The other variables required in the shield calculation will have been computed in the process of following the nomograph. These other variables will include:

- (1) beginning-of-life fuel requirement
- (2) insulation thickness
- (3) inside shield radius

Further, if it is desired to investigate the shield requirement for other shield thicknesses (hence at surface dose rates of other than 200 mr/hr) the new and old outside shield radii will be required.

The following items will be required in nomograph #2 to determine the generator surface temperature when operating in air at 72°F:

- (1) case length
- (2) case diameter
- (3) heat rejection rate

If it is desired to put fins on the generator to reduce the operational temperature in 72°F air, the following items will be required in addition to those presented in the previous list:

- (1) desired surface temperature
- (2) fin thermal conductivity
- (3) number of fins
- (7) fin thickness

Nomograph #3, the generator cost analysis, will require the following items:

- (1) power conditioner efficiency
- (2) system power
- (3) insulation efficiency
- (4) thermoelectric efficiency
- (5) fuel
- (6) design life
- (7) fuel cost per watt
- (8) interest rate, if fuel is to be leased

Nomograph #4, the calculation of thermoelement size, requires the following items:

- (1) power conditioner efficiency
- (2) system power
- (3) hot junction temperature
- (4) cold junction temperature
- (5) thermoelectric material
- (6) generator load voltage (total)
- (7) thermoelement length (generally slightly less than the insulation thickness)

C. Design Study

The market survey performed under Contract AT(30-1)-3627 indicated sixteen possible applications for RTGs. Of these sixteen possible concepts, four were selected to be designed conceptually. These designs are primarily intended to indicate the versatility and adaptability of RTGs to various applications. A design description, operating specifications, and artist's concept are presented here for each system. These designs were formulated using data from the nomographs previously presented in the parametric study description--concrete proof of the effectiveness of this technique.

1. 1 Watt(e), Strontium-90, Powered RTG-Oceanographic Application (Fully Shielded)

The RTG produces power by converting the strontium-90 decay heat directly to electricity through the use of dissimilarly doped bismuth telluride semi-conductor thermoelectric couples. The generator component arrangement is shown in the accompanying artist's sketch (Figure II-1). Here the 1.80 by 1.80 inch right cylindrical fuel containment capsule is located in the center, surrounded by a blanket of Johns Manville Min-K thermal insulation approximately 0.5 inch thick. Located at the top end of the capsule is a 32-couple bismuth telluride thermopile. Each n- and p- leg of one thermocouple is connected electrically in series and thermally in parallel. Each one is 0.14 square inch in cross section and 0.5 inch high with nickel plated hot and cold shoe links. These links form two parallel chains of 16 couples each, and each couple in each chain is linked to the companion couple in the other chain to form a redundant grid matrix; a configuration which allows continuous power output even in case of multiple couple failure.

Radiation shielding is provided by a uranium shield which completely surrounds the generator. The bell jar shape of the shield allows the thick uranium walls to act as the pressure vessel for deep ocean operation. Attachment of the generator to a pinger or any similar anticipated device can be made through the Hastelloy-C flange by the eight 3/8 UNC bolts. An all-depth seal is mounted by a solid metal, heavy cross section, "O-ring" placed in the Hastelloy-C flange. This technique allows a high pressure seal to be obtained at moderate bolt loads. A 0.125 inch thick cladding, also of Hastelloy-C is used around the uranium shield for protection against seawater corrosion.

The solid state dc-dc voltage converter is located in the flange well above the uranium assembly plug. The converter takes the 0.5 volt input from the thermopile and transforms it to an 18 volt, 1.0 watt(e) output. Two terminal power output posts are provided at the top of the can, and two input terminals are provided at the bottom.

On the artist's sketch of the generator, the cutaway portion shows the relationship of the components to the fuel capsule in the center, thermopile at the top, the Min-K insulation, the surrounding shield/pressure vessels, etc. It shows the simplicity of design; and above all, it shows the ruggedness and reliability inherent in the generator. Also given are operating specifications for the RTG (Table II-1).

2. 1 Watt(e), Strontium-90, Powered RTG Oceanographic Application (Removable Shield)

The generator design is identical in purpose, system design and environment to the fully shielded 1 watt(e), strontium-90 RTG with the exception that it has a recoverable shield. The object is to reduce cost by allowing reuse of the considerable amount of shielding required. RTG operating specifications are given (Table II-2), and the unshielded generator interior is shown in the design sketch with the removable shield (Figure II-2).

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Figure II-1. 1 Watt(e), Strontium-90 Powered RTG - Oceanographic Application (Fully Shielded)

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TABLE II-1. 1 WATT(e), STRONTIUM-90, POWERED RTG-
OCEANOGRAPHIC APPLICATION (FULLY SHIELDED)

Operating Specification

Environment	Deep-sea operation to 18,000 feet, fully shielded
Power	1.0 watt(e)
Load voltage	18 volts
Impedance	0.2 ohms
Thermopile	Bismuth telluride semi- conductors
Thermopile temperature differential	280 ⁰ F
Ambient sea water range	20 ⁰ - 100 ⁰ F
Pressure vessel diameter	9.2 inches
Flange diameter	12.00 inches
Overall length	10.45 inches
Radiation surface dose rate	200 mrem/hr
Weight	315 pounds*

*This is low compared to the nomograph values because of the rounded shape
of the shield compared to the cylindrical shape analyzed in the nomograph.

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Figure II-2. 1 Watt(e), Strontium-90 Powered RTG - Oceanographic Application (Removable Shield)

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TABLE II-2. 1 WATT(e), STRONTIUM-90, POWERED RTG-
OCEANOGRAPHIC APPLICATION (REMOVABLE SHIELD)Operating Specification

Environment	Deep-sea operation to 18,000 feet, low shock, removable shield
Power	1 watt(e)
Load voltage	18 volts
Impedance	0.2 ohms
Thermopile	Bismuth-telluride semi-conductors
Thermopile temperature differential	280°F
Ambient seawater range	20° - 100°F
Pressure vessel diameter	3.55 inches
Flange diameter	7.25 inches
Overall length	8.50 inches
Radiation dose rate with removable shield on	200 mrem/hr
Weight (excluding shield)	61 pounds

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Since this generator is similar to the previously described system, ~~the details of the fuel capsule, insulation, thermopile, converter and watertight seals need not be repeated.~~ Only the internal uranium shield plug, plug tiedown, pressure vessel and, of course, the removable external shielding are different. The pressure vessel is again bell jar shaped for high strength, is made of Hastelloy-C and is 0.375 inches thick. A 1.25 inch thick flange with 4 bolts is used for attachment.

An internal shadow shield, consisting of a 2.84 inch thick, 2.80 inch diameter uranium cylinder is used to prevent radiation damage to the electronic components of the pinger and to the dc-dc converter attached to the generator. In addition, the plug provides an assembly access hole and a preload on the Min-K insulation. The preload is obtained by turning the large Hastelloy-C threaded nut below the uranium plug.

The removable shield is dome shaped, made of lead nominally 4.80 inches thick, and weighs 690 pounds--not including ancillary floats, the shielded generator is approximately 265 pounds. At a minimum cost of \$2.50 per pound of depleted uranium the shield represents \$663, and cost could reach \$6.00 per pound with machining and casting, or a total of \$1680 for each shield. Since in deep ocean systems recovery is often difficult or impossible, this material cost often could be lost with the device. Furthermore, since shielding is only required for surface operation, storage aboard ship, or shallow water operation, the nonremovable shield loss is unnecessary. The obvious alternative is to develop a removable shield concept which would allow shield reuse. The handling system description is not included, but in brief it is designed for use with even the limited facilities aboard small oceanographic ships. In fact, in its most simplified form, the generator and pinger can be swung overboard, released, and the shield recovered through the use of only a single boom. Enough versatility is incorporated to allow almost any handling option and also allow recovery even under conditions of large surface dirt buildup or encrustment on the generator surface. The system is low in cost, reliable, and safe since the shield will not release until the generator is under water. Details of the handling system are included in Section V.

3. 300 Milliwatt(e), Strontium-90 Powered RTG-Ordnance Application

The 300 milliwatt(e) RTG is similar in configuration to the other strontium-90 fueled designs. It has the fuel capsule in the center surrounded by the Min-K insulation, with the thermopile on top; and all are enclosed by a thick radiation shield of depleted uranium.

The fuel capsule is 1.49 inches in diameter and length and it is surrounded by 0.5 inch thick Min-K insulation. The bismuth telluride thermopile consist of 38 couples of two parallel chains of 19 each, again redundantly connected in a matrix grid. Each element is 0.139 square inch and 0.5 inch high; and all 38 couples form a rectangular module 1.10 inches by 1.2 inches. Radiation shielding is provided by 2.58 inches of uranium in a bell jar shape, also used as the pressure vessel. Access to the internal cavity for assembly is allowed by the notched and tapered uranium end plug.

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A 0.125 inch thick Hastelloy-C corrosion clad is also used around the shield. ~~The entire generator is held to the interfacing container by bolting through the internal flange with 6 T-bolts imbedded in the uranium.~~

In the artist's concept (Figure II-3), a one tap 18 volt, 300 milliwatt(e) converter sitting in the flange well below the generator is shown for illustration purposes only. It is to serve as a reminder that the dc-dc converter must be considered in most practical applications.

4. 1 Watt(e) Plutonium-238 Powered RTG Oceanographic Application

The 1 watt(e), plutonium-238 fueled RTG represents the most radical design, the most stringent of environmental requirements, and the longest lifetime requirement. It is designed for use as a power supply for an undersea repeater station. Design requirements include not only survival in seawater at great depth and pressure, surface handling, and air storage, but also survival after a high "g" load water impact, 20 year-life, high reliability, low radiation and negligible handling hazard. To meet the combined effects of all these requirements, an entirely different configuration had to be developed. This is shown in the artist's concept (Figure II-4). The operating specifications are given in Table II-4.

The fuel capsule is hemispherical with the fuel located on the inside surface of the flat end of the hemisphere and the thermopile at the outside of this surface. The fuel capsule diameter is 1.7 inches. Surrounding the fuel capsule is a hemisphere of Min-K insulation 0.6 inch thick, which is itself contained by a hemispherical pressure vessel. The pressure vessel is 0.25 inches thick, 3.58 inches in diameter and made of Hastelloy-C. It is designed to withstand pressures at depths of 18,000 feet and high "g" water impact. Here the prime advantage of the hemispherical shape is evident, for it can place a uniform radial compressive load on the insulation--which in turn produces evenly distributed loads on all components under any direction of shock. Therefore, for conditions of pressure and impact, the hemisphere shape presents a maximum strength configuration.

An external flange is shown, although an internal flange system could be used to reduce water impact loads. However, external flanges are more universal, and the internal flange may be too restrictive on the components of the repeater station due to the small diameter of the generator. Therefore, the large external flange is shown but should not be taken as a limiting size requirement. A separate cover plate is used to preload the insulation and form a separate seal for the generator. High insulation efficiency is obtained by backfilling with xenon gas. "O" ring seals are used for both the cover plate and the flange seal. The thermopile and converter are identical to those used in the previously presented RTG designs. A flange at the flat end of the vessel forms the attachment point to the repeater station.

Figure II-3. 300 Milliwatt(e), Strontium-90 Powered RTG - Ordnance Application

TABLE II-3. 300 MILLIWATT(e), STRONTIUM-90, POWERED RTG-
ORDNANCE APPLICATION

Operating Specifications

Environment

Power 300 milliwatt

Load voltage

Thermopile Bismuth telluride semi-conductor

Thermopile temperature differential 260°F

Ambient air temperature range $-65^{\circ}\text{F} + 120^{\circ}\text{F}$

Ambient sea temperature range $20^{\circ}\text{F} - 100^{\circ}\text{F}$

Length 8.90 inches

Diameter 8.07 inches diameter

Radiation surface dose rate 200 mrem/hr

Weight 237 pounds

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Figure II-4. 1 Watt(e) Plutonium-238 Powered RTG - Oceanographic Application

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TABLE II-4. 1 WATT(e), PLUTONIUM-238, POWERED RTG-
OCEANOGRAPHIC APPLICATION

Operating Specification

Environment	Deep-sea operation to 18,000 feet, high "g" water impact
Power	1000 milliwatts
Load voltage	18 volts
Impedance	0.2 ohms
Thermopile	Bismuth telluride semi- conductors
Thermopile temperature differential	280 ^o F
Ambient seawater range	20 ^o F-100 ^o F
Pressure vessel diameter	3.58 inches
Flange diameter	7.00 inches
Overall length	2.72 inches
Weight	9.93 pounds

The single outstanding difference between this third Sr-90 design and the first two is its ability to survive severe shock. The shock profile is typical of the loads expected of a fairly blunt - ended cylindrical shaped object impacting perpendicular to the water surface. In fact, water impact is the prime reason for the smooth external appearance of the generator. In particular, the attachment flange is placed internally to avoid any external projection which would show a larger profile to the water and thereby increase the entry "g" loads. Further, the rounded nose allows a smoother transition from the compressive phase to the drag phase and also reduces impact loads. Generator survival is also enhanced by using the mass strength of the uranium shield. Use of this mass is allowed by the bolt and flange attachment method, shown in the design sketch, which serves to tie together as a unit the uranium shield bell jar, the Hastelloy-C internal flange, and the flange on the remaining "device". Homogeneity of structure is also provided by the large nut behind the assembly plug by dumping the Min-K and thermopile preload directly into the Hastelloy-C flange which is in turn tied to the uranium shield as described. The total effect of the structural arrangement is to make it impossible for one component to move independent of any other component and, therefore, be able to take advantage of the strength of the entire structure.

D. Recommendations

Many possible applications of large milliwatt(e) RTG systems were uncovered in the Market Survey. The parametric and design study illustrates further that development of RTG systems meeting these applications within state-of-the-art is feasible. Based on these findings, it is recommended that development of one or more such systems be initiated.

The hardware development could take one of two possible courses of action. First, would be to select the system which exhibited the widest range of usage. This would be the 1 watt(e), strontium-90 fueled RTG either with or without a removable shield, although it is felt that the removable shield concept is the more economically promising. The second course of action would be to develop standard components for RTGs covering the entire power range from 100 to 1000 milliwatts(e). In other words, initiate development of modularized thermopiles and other components which comprise a complete system.

III. PARAMETRIC STUDY

The parametric study conducted under this program consisted of separating the milliwatt range generators into a number of components each of which could then be considered as a separate entity. This method of approach permitted the variables affecting each of the components to be fully examined, and the results of the independent studies could then be combined to realize overall system performance.

For analysis purposes, the generator may be divided into the fuel and fuel capsule, the thermoelements, the insulation, the generator case, and the power conditioner. Other considerations in the generator design involve the cost, reliability, shock and vibration, shielding, and radiological safety. Each of these items is discussed in detail in the following subsections.

A. Fuels Data

Three fuels were considered in this program, plutonium-238, promethium-147 and strontium-90. Pu-238 is basically an alpha-emitting radioisotope with a half-life of approximately 90 years. Pm-147 decays by the emission of low-energy betas and has a half-life slightly greater than 2-1/2 years. Sr-90 decays with the emission of high-energy betas, and its half-life is close to 30 years. Pu-238 and pure Pm-147 will introduce no shielding problems in large milliwatt size systems. Particularly, the plutonium will be attractive because of its relatively large power density and its long half-life. Promethium may be applicable to some of the shorter life requirement systems. Strontium-90 is attractive from the viewpoint of the long half-life, although its power density is relatively low. However, in systems of the large milliwatt type, this is not a serious consideration. Of more seriousness, is the high-energy beta particle generated as a result of the radioisotope decay. This particle interacts during the slowing down process to produce bremsstrahlung which, in turn, is a serious radiological consideration. As a result, Sr-90 systems must be shielded whenever personnel are to be in the vicinity.

A summary of the fuel specifications utilized in this program is presented in Table III-1, which was furnished with the original request for proposal on the Large Milliwatt Program (Reference 1).

1. Plutonium-238

The latest edition of "Plutonium-238 Fuel Data Sheets" (Reference 2) provides data on plutonium metal, plutonium-20A/O zirconium alloy and three compounds: plutonium dioxide, plutonium carbide, and plutonium nitride. The metal and oxide fuel forms have been extensively studied, but data for the other three fuel forms are very limited. Since the other forms have no obvious advantages over the metal and oxide, these were not considered for the large milliwatt program.

TABLE III-1. FUEL SPECIFICATIONS

(1)	Source Material	SrTiO_3
	Half-Life	27.7 years (Y-90---64.2 hrs)
	Radiation Emitted	$\text{Sr-90} \longrightarrow \text{Y-90}$ 100% beta - 0.54 Mev $\text{Y-90} \longrightarrow \text{Zr-90}$ $\sim 100\%$ beta - 2.26 Mev
	Density	3.83 g/cm^3
	Power Density	0.8 watts/cm^3
	Thermal Conductivity (cal/sec-cm- $^{\circ}\text{C}$)	0.01 (300°C); 0.008 (550°C)
	Melting Point	1920°C
	Vapor Pressure (atm)	$\sim 3 \times 10^{-7}$ at 1630°C
	Solubility	1-400 $\mu\text{g/cm}^2$ -day; initial solubility is high but reduces exponentially to lowest value; also dependent upon preparation and aging
	Compatibility	Limited data shows Hastelloy-C as being satisfactory, but does not rule out other materials
	Thermal Expansion (%)	$0.65 \times 730^{\circ}\text{C}$
	Linear Coefficient of Expansion	$9.4 \times 10^{-6} \text{ in/in-}^{\circ}\text{C}$ @ 21°C $11.2 \times 10^{-6} \text{ in/in-}^{\circ}\text{C}$ @ 700°C
(2)	Source Material	Pm_2O_3
	Half-Life	2.67 years (Pm-147)
	Radiation Emitted	$\text{Pm-147} \longrightarrow \text{Sm-147}$ $\sim 100\%$ beta - 0.225 Mev $\sim 0.003\%$ gamma - 0.12 Mev
	Density	6.6 g/cm^3
	Power Density	2.03 watts/cm^3

TABLE III-1. FUEL SPECIFICATIONS (CONT'D.)

	Thermal Conductivity (cal/sec cm °C)	$0.0045 + 1.414 \times 10^{-8} (1020 - T)^2$ for samarium
	Melting Point	2270°C
	Vapor Pressure (atm)	$(\log_{10} P = 15.62 - 39,800/T)$ for lanthanum
	Solubility	No data available, but believed very high
	Compatibility	Generally good with Mo, and the Hastelloys
	Thermal Expansion	No data available
	Linear Coefficient of Expansion	9×10^{-6} in/in-°C
(3)	Source Material	$\text{Pu}^{238}\text{O}_2$
	Half-Life	86.4 years
	Radiation Emitted	Primarily alpha with some neutrons at 2.5 Mev and gamma ranging from 0.044 - 0.875 Mev
	Density	11.4 g/cm^3 (crystalline form)
	Power Density	4.4 watts/cm^3 (crystalline form) $0.014 \text{ (cal/sec-cm-C}^\circ\text{) at } 400^\circ\text{C}$
	Thermal Conductivity	$0.0065 \text{ (cal/sec-cm-C}^\circ\text{) at } 700^\circ\text{C}$
	Melting Point	$\sim 2300^\circ\text{C}$
	Vapor Pressure	$\log P \text{ (atm)} = \frac{(-29,240 \pm 530)}{T} + 8.072 \pm 0.239$
	Solubility	$0.00213 \mu \text{ g/day/mm}^2$
	Compatibility	Satisfactory with Haynes, Tantalum and Hastelloy
	Linear Coefficient of Expansion	$9.1 \times 10^{-6} \text{ cm/cm/}^\circ\text{C}$
(4)*	Source Material	Plutonium-238 metal
	Density	$15-16 \text{ gm/cm}^3$

*Reference 2

TABLE III-1. FUEL SPECIFICATIONS (CONT'D.)

Power Density	6.8 - 7.3 W/cm ³
Thermal Conductivity	0.019 calories/cm ² -°C at 68°F 0.023 at 122°F 0.03 at 212°F 0.0375 at 302°F
Melting Point	1183°F
Solubility	Soluble
Compatibility	Satisfactory with tantalum, tantalum-10 tungsten

The melting point of pure plutonium metal is reported as 640°C (Reference 3). However, the plutonium fuel data sheets previously referenced, report that the production grade metal melts between 575 and 615°C. In comparison, the dioxide is recorded in the plutonium data sheets to melt at 2280°C. These data immediately indicate that the metal will be sufficient for most large milliwatt applications. The primary operational requirement is that the fuel may not be molten in the fuel capsule under any normal operational or handling conditions. This requirement stems from fuel containment considerations and the actions between the fuel form and its container materials, which will be drastically increased if the fuel is in the molten form. The dioxide has a lower power density, and would normally not be used except for temperature ranges where the metal phase condition (solid or molten) might be in question.

The plutonium-238 fuel presently available is a nominal 80 percent pure, and in the following discussion this purity will be referred to as "high quality" plutonium-238. This is generally formed in the following manner:

- (1) $\text{U-235} + \text{N} \rightarrow \text{U-236}$
- (2) $\text{U-236} + \text{N} \rightarrow \text{U-237}$
- (3) $\text{U-237} \rightarrow \text{Np-237} + \text{beta}$
- (4) $\text{Np-237} + \text{N} \rightarrow \text{Np-238} \rightarrow \text{Pu-238} + \text{beta}$

A so-called "low-grade" plutonium-238 may be produced by irradiating the highly enriched uranium shown in the series of reactions (1) to (4) above, without an intermediate reprocessing step to separate the neptunium-237. In this case, plutonium is formed as specified by reactions (1) through (4) and further by the capture of a neutron in uranium-238, which is present even in enriched uranium.

TABLE III-3. COMPATIBILITY OF PLUTONIUM-238 METAL WITH
CONTAINER MATERIALS AT 1022°F (550°C)

<u>Container</u>	<u>Time (days)</u>	<u>Results</u>
Molybdenum	32	Intergranular attack, 0.008 in.
Rhenium-50% Molybdenum	46	Intergranular attack, 0.004 in.
Tungsten-25 Rhenium	94	No attack
Rhenium	115	No attack
Tantalum	252	Intergranular attack, 0.001 in.
Tantalum-10 Tungsten	21	No attack

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The product in the latter case is plutonium-239, which results in further dilution of the plutonium-238 product.

The isotopic impurities in the low-grade plutonium-238 material have not been determined and are expected to be variable depending upon the starting material, number of cycles, neutron flux and irradiation time. A similar uncertainty will exist concerning any 80 percent plutonium-238 produced by the blending operation that has previously been discussed.

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It appears that the low-grade plutonium-238 will represent only a small fraction of the total supply in the next 15 years, and it does not represent a major new source of thermal energy. Further, any steps which are taken to increase the supply of the low-grade material will also result in an increase of the more desirable high-grade material. For this reason, it is felt that there will be no attractive advantages in applying a low grade plutonium-238 fuel to large milliwatt generators. Consequently, no further data are presented in use of the design using the low grade fuel.

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2. Promethium-147

A summary report covering promethium property data was published in early 1965 (Reference 5). Little additional data have been made available since this report, although work in the area is continuing. Most of the physical and chemical data that are reported have been based on work with analogs, particularly neodymium and samarium. Only the promethium metal and the oxide (Pm_2O_3) have been studied, and only the oxide is considered as the fuel form for the large milliwatt program. The metal melts at 1080°C , and it is conceivable that promethium metal could also be used in large milliwatt generators, but the application of this fuel form was outside the scope of this study.

Promethium is reported to have only the +3 valence state, and it is therefore expected that only the oxide Pm_2O_3 will be formed, and further, it is expected that this form will be stable in an oxidizing atmosphere (Reference 6). No specific data are available in regard to water solubility. However, sintered pellets of other lanthanon sesquioxides disintegrate in boiling water tests. An alkaline solution indicating the formation of a soluble lanthanon hydroxide is produced (Reference 7). The lanthanide sesquioxide dissolves rapidly in acid solutions (Reference 8).

Table III-4, which was taken from Van Tuyl, presents the available preliminary data concerning compatibility of promethium metal and oxide with encapsulation materials. These data indicate that molybdenum and probably tantalum will be acceptable containers for the oxide fuel form. There are no available mechanical properties at the present time.

Promethium-147 will be available in appreciable quantities when the Isochem facility at Hanford begins operation in 1968. The studies conducted by Battelle-Northwest are being continued so that increased data will be available prior to 1968. It is considered probable that insoluble promethium compounds, such as the titanates, can be produced so that the problems involved in fuel release will be decreased. This will, however, lower the available power density of the fuel form.

3. Strontium-90

Strontium-90 is a readily available fission product with a relatively low price. A suitable fuel form, the titanate, is available which has a very high melting point and is, for practical purposes, insoluble in most naturally occurring solvents.

A number of references show that strontium in the titanate form has good compatibility with René-41, tantalum-10 tungsten, Haynes-25, Hastelloy, and molybdenum. This form is quite inert and virtually no problems are involved in suitable containment materials.

B. Fuel Capsule

Past experience in working with the non-alpha emitting radioisotope fuels, such as promethium and strontium, have resulted in a considerable quantity of data being generated concerning suitable containment materials and fuel capsule thicknesses. As a result of this effort, it was not necessary to conduct a detailed fuel capsule analysis under the milliwatt program for nonhazardous configurations. This information was already available, and has been incorporated into the designs which are presented in Section IV.

This is not the situation with the alpha emitting fuels (plutonium-238). Here the physical size of the fuel containment vessel has a very strong bearing on the required wall thickness, as does the operational temperature, the void fraction selected, and the containment time for which the fuel capsule is designed. It was therefore necessary to conduct an analysis of suitable fuel capsule configurations under this program.

This analysis was conducted by first considering the behavior of a stressed material over a long period of time. Plutonium-238 is a fuel for which little long term containment information is readily available, and the available information, of a short term nature, is of lower than desirable quality. This lack of technological development was considered in the analysis of the fuel capsule, and it was decided that rather than use pure steady state relationships, it would be better to use an approach which accounted for the transient nature even though the accuracy was less than desirable. The reasoning is essentially that the predicted trends will be in the correct direction, though they may be off somewhat in magnitude. An allowance made for time degradation is a more desirable approach than an approach which does not consider any effect with capsule aging.

Larson-Miller curves for several fuel capsule materials are shown in Figures III-1 and III-2. These data were utilized in the sizing of a number of fuel capsules for this program.

The quantity of heat which must be made available at the beginning of generator life is given by the following equation:

$$Q_b = Q_e e^{\lambda t_e} \quad (\text{III-1})$$

where:

- t_e = useful operating lifetime of the capsule (yrs)
- λ = decay constant ($=0.693/T_{1/2}$)
- $T_{1/2}$ = half-life of the isotope (yrs)
- Q_e = heat at end of life (watts)

The fuel volume is:

$$V_f = Q_b / \rho_p \quad (\text{III-2})$$

where:

- ρ_p = power density (watts/cm³)

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Figure III-1. Tantalum-10W Tungsten Larson-Miller Plot

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Figure III-2. Haynes-25 Larson-Miller Plot

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and the fuel mass

$$W_f = V_f \rho_f \quad (\text{III-3})$$

where:

$$\rho_f = \text{fuel density (gm/cm}^3\text{)}$$

Two containment vessels, an inner and an outer, will be considered. The inner vessel will be denoted by the subscript 2, and the outer by the subscript 1. If only one container is desired, the thickness of the outer vessel will be equal to zero. The inner container will be treated as the pressure vessel.

It is assumed that the outside diameter is to be specified. The end wall thickness is assumed to be twice the side wall thickness (which is roughly what would result from a pressure vessel design).

A tolerance, or gap, between the fuel and capsule, and a gap between the two vessels will exist. Hence, the fuel diameter is:

$$D_f = D_c - 2(t_{s1} + t_{s2} + t_{g1} + t_{g2}) \quad (\text{III-4})$$

where:

- D_c = capsule outside diameter (cm)
- t_{s1} = outer container side wall thickness (cm)
- t_{s2} = inner container side wall thickness (cm)
- t_{g1} = radial thickness of gap between inner and outer container (cm)
- t_{g2} = radial thickness of gap between fuel and inner container (cm)

The fuel volume is $V_f = \frac{\pi D_f^2 L_f}{4}$, where D_f equals the fuel diameter (cm) and L_f equals fuel length (cm). Therefore:

$$L_f = \frac{4V_f}{\pi D_f^2} \quad (\text{III-5})$$

The outer container length is given by:

$$L_c = L_f + 4(t_{s1} + t_{s2} + t_{g1} + t_{g2}) \quad (\text{III-6})$$

The outer container mass is therefore:

$$W_1 = \rho_1 \left[\pi (D_c - 2t_{s1})^2 (t_{s1}) + \pi \left\{ \left(\frac{D_c}{2} \right)^2 - \left(\frac{D_c - 2t_{s1}}{2} \right)^2 \right\} L_c \right] \quad (\text{III-7})$$

where:

$$\rho_1 = \text{outer container density (gm/cm}^3\text{)}$$

and the inner container mass is:

$$W_2 = \left[\pi (D_f + 2t_{g2})^2 (t_{s2}) + \pi \left\{ \left(\frac{D_c - 2t_{s1} - 2t_{g1}}{2} \right)^2 - \left(\frac{D_f + 2t_{g2}}{2} \right)^2 \right\} (L_c - 4t_{s1} - 4t_{g1}) \right] \rho_2 \quad (\text{III-8})$$

where:

$$\rho_2 = \text{inner container density (gm/cm}^3\text{)}$$

The fuel container weight is:

$$W_c = W_1 + W_2 \quad (\text{III-9})$$

For the case of an alpha emitting isotope, a void fraction must be specified. For analysis purposes, this void is accounted for by increasing the capsule length, since the diameter is specified. It should be noted that the actual fuel configuration in the capsule can be changed without affecting computed results. By definition, the void fraction is:

$$f_v = \frac{V_v}{V_f + V_v} \quad (\text{III-10})$$

where:

$$V_v = \text{void volume (cm}^3\text{)}$$

therefore:

$$V_v = \frac{f_v V_f}{1 - f_v} \quad (\text{III-11})$$

and the total contained volume is:

$$V_c = V_v + V_f \quad (\text{III-12})$$

Alpha particles resulting from decay are assumed to be contained in the pressure vessel as free helium gas. The number of moles of helium buildup may be represented by:

$$\text{He} = \frac{W_F}{M. \text{Wt.}} (1 - e^{-\lambda t}) \quad (\text{III-13})$$

where:

t = time (yrs)

W_F = mass of fuel (gm)

$W_F = KW_f$

K = a constant to account for the different types of fuel composition

$M. Wt.$ = atomic weight of the isotope

The temperature of the helium at any time, t , is obtained from the approximation:

$$T = T_o e^{\frac{-0.693t}{4T_{1/2}}} \quad (III-14)$$

where:

T_o = the initial temperature

The four in the above expression results from an assumed heat rejection by means of radiation.

Since helium is an ideal gas under virtually all conditions, the pressure is given by:

$$P = \frac{HeRT}{V_v} \quad (III-15)$$

where:

R = gas constant

T = average temperature of the void at any time t ($^{\circ}R$)

The stress can then be calculated from:

$$S = \frac{PR'}{t_{s2}} \quad (III-16)$$

where:

R' = average radius

Using this stress and a Larson-Miller plot for the material in question, one can obtain a calculated containment time, t_c . If a forward difference technique is assumed, with a time differential of Δt , then the fraction of life used under these conditions is $\Delta t/t_c$. Hence, if the previous equations are evaluated at time $t = \Delta t$, the fraction of life used between time $t = 0$ and time Δt is obtained. If one then computes conditions at time $2\Delta t$, the fraction of life used between time Δt and $2\Delta t$ is obtained. This process may be continued until the total fraction exceeds

one, indicating failure, or until the desired containment time has been realized without failure. In the former case, the thickness is increased so that the stress is reduced, and the process is repeated starting at time $t = \Delta t$.

Larson-Miller data are usually plotted as stress (lb/in^2) to rupture versus P , and P is defined as $T(b + \log_{10} t_c) 10^{-3}$.

where:

- T = temperature in $^{\circ}\text{R}$
- t_c = containment time in hours
- b = constant associated with the specific Larson-Miller data

The resulting equation is generally linear, so that:

$$t_e = 10^{\left(\frac{\log S - 10^{-3} abT - c}{10^{-3} aT} \right)} \quad (\text{III-18})$$

where:

- a = slope of the Larson-Miller curve
- c = intercept of the Larson-Miller curve

If Larson-Miller data are not available, then stress-temperature relationships can be used. Generally, one can use these data in the form:

$$S = bT + c \quad (\text{III-19})$$

where:

- b = slope of the stress-temperature curve
- c = intercept of the stress-temperature curve
- S = stress (lb/in^2)
- T = temperature ($^{\circ}\text{R}$)

The thickness required for the particular values of P , R' , and S can be obtained from:

$$t_p = \frac{PR'}{S} \quad (\text{III-20})$$

(Note: Since creep is not accounted for, the stress should be reduced to be conservative.)

The use of Larson-Miller parameters for this application could introduce error to the analysis. The data available for the materials of interest in this study seldom exceed a test time of a few hours, but they are being extrapolated to test times of the magnitude of years. The trends predicted by the calculation technique are correct, but obviously large errors in the predicted behavior can occur. Unfortunately, a better technique is not known with present technology.

One further modification is required in the plot of Larson-Miller characteristics. To avoid error in the calculation procedure at very small time values, where the Larson-Miller approach results in unrealistically large allowable stresses, a discontinuity in the curve must be artificially incorporated so that the allowable stresses for the short term ends of the curves remain realistic.

This calculation procedure has been utilized for a number of parametric studies conducted under this program. In general, it was found that the fuel capsule weights were negligibly small and there are consequently no presentations of the resulting weights in this report. The required wall thicknesses for the alpha emitting radioisotope plutonium-238 for all systems investigated ranged from 20 to 40 mils thickness. Since approximately 40 or 50 mils of wall thickness would be required for other structural reasons as well as manufacturing purposes, it was immediately concluded that for void fractions of greater than 0.5, all capsules could be considered as having 50 mil thick walls. Again, no detailed presentation of the results of the parametric study is considered necessary.

The calculation technique outlined above has been incorporated into a computer program written for the Univac 1107 or 1108 (it may be immediately applied to the IBM 7090 or 7094 by simply recompiling the source deck). This program was written so that the necessary parametric studies could be quickly and economically conducted for the milliwatt program. Further details of this program are available in Reference 9.

C. Thermoelectric Analysis and Performance

Thermoelectric theory is comparatively well understood insofar as its application to engineering problems is concerned. The proper application of the theory allows highly accurate answers to be obtained. The errors result for practical purposes only from the uncertainty of the physical property data.

1. Theoretical Analysis

Thermoelement analysis may be performed by considering two irreversible and three thermodynamically reversible phenomena. Heat conduction through the thermoelements and the Joule heating due to the resistance of thermoelectric material to the flow of electricity constitute the irreversible effects. The thermodynamically reversible effects are the Thomson, Peltier, and Seebeck effects. The Thomson effect is the phenomenon of heat generation or absorption that occurs when an electrical current flows in the presence of a temperature gradient. The Peltier effect is the phenomenon of heat generation or absorption that occurs at a junction between two dissimilar materials when an electrical current is caused to flow through the junction. The Seebeck effect is the phenomenon of electricity flow which occurs in a closed loop composed of two dissimilar materials when the junctions between the materials are maintained at different temperatures.

Several very good assumptions may be made in addition to the application of these phenomena to analyze thermoelements. These are:

- (1) The thermoelements are homogeneous
- (2) The thermoelement lateral surface is adiabatic
- (3) There is no temperature gradient within the thermoelement normal to the axis
- (4) Thermoelement behavior may be analyzed by considering steady state operation

Generally, every effort is made in the manufacture of a thermoelement to assure homogeneous behavior so that it will be both physically strong and electrically attractive. The error involved in this assumption will normally be negligibly small. The lateral surface of thermoelements when installed in radioisotope fueled thermoelectric generators will almost always be well insulated, and the temperature gradient in the thermal insulation which would result normally approximates that in the thermoelement. This results in a true adiabatic behavior insofar as the lateral surface is concerned, and little or negligible error is involved in this assumption. The assumption that no temperature gradient exists normal to the axis, or perpendicular to the lateral surface, follows immediately and need not be stated. Finally, most radioisotope fueled thermoelectric generators are applied under steady state conditions, and the analysis of thermoelectric behavior with the same assumption is an excellent one.

Lyon and Bustard (Reference 10) have applied these assumptions to derive the following differential equation:

$$\frac{d}{dx} (kA \frac{dT}{dx}) + \frac{I^2 \rho}{A} + \gamma I \frac{dT}{dx} = 0 \quad (\text{III-21})$$

where:

- x = refers to position within the thermoelement measured from the hot end
- k = thermal conductivity
- T = absolute temperature
- A = thermoelement cross sectional area measured normal to the axis
- I = electrical current flow rate
- ρ = electrical resistivity
- γ = Thomson coefficient

This equation was solved by Lyon and Bustard using numerical techniques in conjunction with high speed digital computers. As boundary conditions, they included merely the hot and cold junction temperatures. This introduced no error and their computed results are very accurate. They went on to incorporate the contact resistance effect and accurately computed the other characteristics of the thermoelement such as the area-to-length ratio (the shape factor) and the efficiency. The calculation technique which they used was relatively slow, and as a result they performed further studies wherein several additional assumptions were incorporated. The additional assumptions

were that the thermoelement behavior could be represented by suitable average physical properties rather than incorporating point properties as a function of the temperature, and that the Thomson coefficient could be neglected. When this is done, the equation of Lyon and Bustard reduces to a form which may be readily solved analytically. This analytical approach immediately leads to results which are identical to those normally used for manual calculations, except that the contact resistance is incorporated into the analysis.

A comparison of the computer and analytical results presented by Lyon and Bustard as well as other independent comparisons have shown that the error involved in the assumption of averaged properties is negligibly small, of the order of only 1 or 2 percent. This is a strong indication that if a different approach is used in the use of a computer to analyze thermoelectric behavior, a considerable improvement in the computation time may be obtained. This approach was used for the analysis conducted under this program. Since the differential equation, if solved, eventually results in a solution which is identical to that obtained by taking an overall energy balance, the overall energy balance approach was utilized in the derivation.

When the physical properties of each thermoelement are assumed constant (represented by suitable averages), then the following effects occur at the hot junction:

(1) Peltier Cooling

$$q = \alpha_H I T_H \quad (\text{III-22})$$

where: q = heat absorption rate
 α = Seebeck coefficient
 I = electrical current
 T = temperature

and: $\alpha = |\alpha_N| + |\alpha_P| \quad (\text{III-23})$

N refers to the negative thermoelement

P refers to the positive thermoelement

H refers to the hot junction

(2) Heat Conduction

$$q = \left[\frac{K_N A_N}{L_N} + \frac{K_P A_P}{L_P} \right] [T_H - T_C] \quad (\text{III-24})$$

where: K = average thermal conductivity
 A = thermoelement cross sectional area
 L = thermoelement length

(3) Internal Joule Heating

$$q = - \frac{I^2 R_i}{2} \quad (III-25)$$

where: R_i = thermocouple internal resistance

(4) Heat generated at the hot junction due to Joule heating at the junction contact

$$q = - I^2 R_{CH} \quad (III-26)$$

where: R_{CH} = contact resistance at the hot junction

Since the energy delivered to the external load is $I^2 R_e$, where R_e is the external load resistance, the thermoelectric efficiency is:

$$\eta = \frac{I^2 R_e}{\alpha_H I T_H + \left[\frac{K_N A_N}{L_N} + \frac{K_P A_P}{L_P} \right] [T_H - T_C] - \frac{I^2 R_i}{2} - I^2 R_{CH}} \quad (III-27)$$

The current flowing in the circuit is, from Ohm's law:

$$I = \frac{E}{R_i + R_e + R_{CH} + R_{CC}} \quad (III-28)$$

where: E = open circuit voltage

R_{CC} = cold junction contact resistance

The open circuit voltage is:

$$E = \alpha [T_H - T_C] \quad (III-29)$$

so that:

$$\eta = \frac{I^2 \left[\frac{\alpha [T_H - T_C]}{I} - R_i - R_{CH} - R_{CC} \right]}{\alpha_H I T_H + \left[\frac{K_N A_N}{L_N} + \frac{K_P A_P}{L_P} \right] [T_H - T_C] - \frac{I^2 R_i}{2} - I^2 R_{CH}} \quad (III-30)$$

Now define:

$$S = \text{Shape Factor} = \frac{A}{L} \quad (III-31)$$

and note that:

$$R_i = \frac{\rho_P}{S_P} + \frac{\rho_N}{S_N} \quad (\text{III-32})$$

where: ρ = thermoelement electrical resistivity

At this point, if contact resistances are considered, it is usual to assume that the behavior can be represented by a contact resistivity. This introduces the contact resistance as a function of inverse thermoelement cross sectional area. There is little experimental evidence to support this assumption for a general analysis and it will not be made here. Instead, for analytical purposes, we will assume the contact resistance to be constant. This has several advantages for the purposes for which this analysis will be used. These advantages are:

- (1) Any contact resistance that has been experimentally measured can be used and the thermoelement will be optimized for the value.
- (2) The effect of variable contact resistance can still be obtained by using various values and investigating the optimum thermoelement which results.
- (3) The effect of internal wiring and thermoelement shoes can be included in the optimization procedure instead of merely throwing in an over-design factor. The resistances on the hot side can be added to the actual hot contact resistance to obtain a value for analysis purposes, and similarly for the cold side.

Substituting Equations (III-31) and (III-32) into (III-30) yields:

$$\eta = \frac{\frac{\alpha_H T_H}{I} - \frac{\rho_P}{S_P} - \frac{\rho_N}{S_N} - R_{CH} - R_{CC}}{\frac{\alpha_H T_H}{I} + [K_N S_N + K_P S_P] \frac{T_H - T_C}{I^2} - \frac{\rho_P}{2S_P} - \frac{\rho_N}{2S_N} - R_{CH}} \quad (\text{III-33})$$

We wish to maximize η . Consequently, we will first maximize with respect to S_N , and then with respect to S_P , in each case holding the other shape factor constant. The resulting expressions will be set equal to zero to obtain the maximized expressions.

$$\frac{\partial \eta}{\partial S_N} = \left\{ \rho_N \left[\frac{\alpha_H T_H}{I} + (K_N S_N + K_P S_P) \frac{T_H - T_C}{I^2} - \frac{\rho_P}{2S_P} - \frac{\rho_N}{2S_N} - R_{CH} \right] - \right. \quad (\text{III-34})$$

$$- \left[\frac{\bar{\alpha}}{I} (T_H - T_C) - \frac{\rho_P}{S_P} - \frac{\rho_N}{S_N} - R_{CH} - R_{CC} \right] \left[K_N S_N^2 \frac{T_H - T_C}{I^2} + \frac{\rho_N}{2} \right] \left[* \right]^{-2} S_N^{-2} \quad (III-34)$$

For this to be zero requires either that the denominator be infinite or that the numerator be zero. Rejecting the former, we find:

$$S_P^2 + \frac{1}{K_P} \left\{ \frac{K_N}{\rho_N} \left[- \frac{\bar{\alpha} (T_H - T_C)}{I} + R_{CH} + R_{CC} \right] S_N^2 + 2K_N S_N + \frac{I^2}{2(T_H - T_C)} \left[- R_{CH} + R_{CC} + \frac{2\alpha_H T_H}{I} - \frac{\bar{\alpha} (T_H - T_C)}{I} \right] \right\} S_P + \frac{K_N S_N^2 \rho_P}{\rho_N K_P} = 0 \quad (III-35)$$

By inspection of Equation (III-34), we see that the equation for S_N is identical to Equation (III-35), except that the subscripts N and P are reversed.

Analytical solution of the resulting two simultaneous equations involves much algebraic complexity. Therefore, they are solved numerically. A number of different forms and computer codes can be used, many of which will be unstable. The one chosen is to rewrite Equation (III-35) as:

$$S_N = \left[\frac{S_P^2 K_P + \left\{ 2K_N S_N + \frac{I^2}{2(T_H - T_C)} \left[\frac{2\alpha_H T_H}{I} - \frac{(T_H - T_C)}{I} - R_{CH} + R_{CC} \right] \right\} S_P}{\frac{K_N}{\rho_N} \left[\frac{(T_H - T_C)}{I} - R_{CH} - R_{CC} \right] S_P - \rho_P} \right]^{1/2}$$

Similarly: (III-36)

$$S_P = \left[\frac{S_N^2 K_N + \left\{ 2K_P S_P + \frac{I^2}{2(T_H - T_C)} \left[\frac{2\alpha_H T_H}{I} - \frac{(T_H - T_C)}{I} - R_{CH} + R_{CC} \right] \right\} S_N}{\frac{K_P}{\rho_P} \left[\frac{(T_H - T_C)}{I} - R_{CH} - R_{CC} \right] S_N - \rho_N} \right]^{1/2} \quad (III-37)$$

* Some denominator which need not be defined here.

These are stable over the range of interest when solved by first assuming S_N and S_P as 0.5, recalculating S_N and S_P , using the recalculated value as a new guess, etc., until suitable convergence is obtained.

These equations have been programmed for a number of computers, including the Univac 1107 and 1108, the Control Data 3600, and the IBM 7090 and 7094. The running time for a parametric study was, as expected, considerably reduced over that which resulted from the highly accurate approach. Typically, of the order of 0.075 to 0.22 sec/investigation is required, the actual time span being a function of the number of investigations and the computer used in the study.*

2. Thermoelectric Materials

A number of thermoelectric materials are readily available for use in radioisotope fueled thermoelectric generators. These include the metallics, and the semi-conductors bismuth telluride, lead telluride and silicon germanium. Metallic thermoelements, which in reality are nothing but thermocouple wires, are attractive because they may be easily constructed in long thin geometries and large numbers may be connected in series to develop a high output voltage. This type of electrical conversion from heat is unattractive because the efficiency is low. The bismuth and lead tellurides convert heat to electricity at a high efficiency, but are brittle and cannot be constructed with small area to length ratios. Silicon germanium is attractive for many applications, but is basically a high temperature material with a low conversion efficiency at low temperatures. Since a milliwatt size generator would be unattractively inefficient if designed for high temperature operation because of excessive losses through the thermal insulation, the use of silicon germanium for this system was not considered.

Telluride material cannot be constructed with small area to length ratios, thus only a few thermoelements may be used in any one milliwatt generator. This causes the output voltage to be low, and a power conditioner is necessary to obtain attractive system voltage levels. The voltage furnished by the thermoelectric generator will normally be lower in these power ranges than for the larger radioisotope fuel systems where most of the experience has been obtained. The power conditioner aspects of this system are discussed in Section III-F.

Bismuth telluride is the most efficient thermoelectric material that is readily available for application to this system. Its properties are well known, and the level of technological development is good. There appear to be few problems involved in bonding the hot and cold shoes to the thermoelectric material. Unfortunately, the maximum temperature to which bismuth telluride can be exposed for extended periods of time is in the range of 500 to 550°F in an inert atmosphere, and somewhat lower for air or vacuum conditions. Since the milliwatt size generators will ordinarily have low hot junction temperatures because of the effect of losses through the thermal insulation, the use of

* Further information concerning the computer program is given in Reference 11.

bismuth telluride becomes particularly attractive. This attractiveness is further increased if the proposed application is an oceanographic use where operational cold junction temperatures are generally of the order of 100°F.

Up to date physical properties for bismuth telluride are presented in Figure III-3. These data have been utilized in the thermoelectric code discussed in the previous subsection, and optimized thermoelement characteristics have been obtained. The efficiency characteristics obtained in this study are presented in nomograph 1. Other desirable thermoelement characteristics are correlated in nomograph 4.

Lead telluride is similar to bismuth telluride in many respects. Its efficiency is somewhat lower in the low temperature regions, but becomes attractively high as the temperature is increased. The maximum operational temperature in an inert or slightly reducing atmosphere is of the order of 1000 to 1100°F. At these temperature levels, with a cold junction temperature in the range of 100 to 300°F, lead telluride becomes a very attractive thermoelectric material. Some of the larger milliwatt size generators may be attractive with hot junction temperatures higher than can be obtained with bismuth telluride, and for this reason the characteristics of lead telluride have been included in this study. Physical property data for lead telluride are shown in Figure III-4. Optimized efficiency characteristics for this material are presented in nomograph 1. Other characteristics of interest are correlated using nomograph 4.

A number of metallic thermocouples were considered for use in this program. These included cupron-tophel, iron-constantan, copper-constantan, and chromel constantan. Of these, cupron-tophel is the most attractive with respect to efficiency. Chromel-constantan characteristics are very close to cupron-tophel, and since the physical properties of the copper-constantan are more readily available, this material was selected for presentation for use in the milliwatt generator. Again, optimized physical property data are shown in Figure III-5.

The contact resistances presented by the correlations in the nomographs are all assumed to be negligible. This assumption is quite good for bismuth telluride, it is excellent for the metallics, provided proper allowance is made for material which operates in an isothermal region, but is not as good for lead telluride. For this reason, an over design allowance of the order of 10 or 15 percent should be incorporated as a safety factor for the contact resistance losses in lead telluride designs.

D. Insulation

1. Introduction

Generators in the milliwatt range require smaller quantities of heat for thermopile operation than is normally observed for radioisotope fueled thermoelectric generators in the larger sizes. This results in small heat sources, which in turn have large surface areas per unit of

*These nomographs are improperly labeled "Copper-Constantan".

Figure III-3. Bismuth Telluride Physical Properties

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Figure III-4. Lead Telluride Physical Properties

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Figure III-5. Chromel-Constantan Physical Properties

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contained volume. Immediately, the effect of the thermal insulation becomes very important. The extraneous heat losses must be minimized so that the quantity of heat delivered to the thermopile is maximized. Several techniques are normally utilized to reduce extraneous losses. These include:

- (1) Reduction of heat transfer surface area by the choice of a spherical shape heat source.
- (2) Selection of a low conductivity insulation.
- (3) Reduction of heat source operating temperatures compared to those used for larger systems.
- (4) Utilization of the selected insulation to support the heat source.

Selection of the hot junction temperature, and hence the heat source temperature, depends upon an optimization which involves a tradeoff between the insulation heat loss and the thermopile conversion efficiency. The thicker the insulation, the lower will be the heat loss. Thus, selection of an insulation thickness is reduced to an engineering judgment of what constitutes an acceptable volume, which is compared to the gain in insulation efficiency obtained if the thickness is increased further. The selection of a hot junction temperature is made by an optimization of the generator efficiency with respect to temperature. High hot junction temperatures yield high thermoelectric efficiencies and a low overall insulation effectiveness. This generally results in a low overall generator efficiency. Normally, the hot junction temperature is chosen at the maximum point. However, this maximum is found to be a strong function of the insulation thickness utilized in this study, and again engineering judgment becomes a consideration in determining the allowable sizes. Further, the weight of the system may be significantly affected by these choices. The most drastic effect will occur if the fuel requires large quantities of shielding, and the insulation is placed inside of the shield. In this situation, increases in insulation thickness obviously necessitate very large increases in shield weight.

Engineering judgment must be used with respect to the placement of the shield. Several alternate shielding techniques exist. The shield may be placed either inside or outside of the thermal insulation, or a portion of the shield may be placed inside of the insulation, and a portion placed outside. Shield placement outside of the thermal insulation minimizes the quantity of fuel required, but results in a large increase in system weight. Placement of the shield inside of the thermal insulation will minimize weight, but will increase the quantity of fuel required. A continuous curve of weight and fuel behavior may be obtained by splitting the shield, with a portion inside the insulation and the remaining portion outside.

Economic considerations may also be involved in the placement of the shield. For example, depleted uranium shields may cost in the range of 10 to 20 dollars per pound, and if a small quantity of strontium-90 is required, a more inexpensive system may be obtained by placing the shield internal to the thermal insulation, and accepting the penalty of the extra fuel

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loading. It is also possible that the selection of an inexpensive shield material, such as cast iron, would allow placement of the shield outside of the thermal insulation. It could easily be expected that combinations of shield materials, with an expensive shield inside of the thermal insulation and an inexpensive shield outside of the thermal insulation, would lead to the most inexpensive generators.

Paramount to all of these considerations is the selection of the thermal insulation. As previously mentioned, a thermal insulation with attractive structural properties as well as a low thermal conductivity is desirable. Of further importance is its long life behavior in a closed environment. An insulation that degrades with an increase in thermal conductivity is obviously unattractive. An insulation that decomposes and introduces decomposition products which affect the thermal conductivity or attack other generator components is also unattractive. All of these items must be considered in the selection of a suitable insulation material for use in a radioisotope fueled thermoelectric generator. The parametric study conducted under this program has been set up so that such analyses may be obtained.

2. Insulation Data

A survey of insulation materials suitable for use in milliwatt generators has been conducted. This survey was limited to materials which have demonstrated chemical, mechanical, and physical stability under continuous conditions in a 500 to 1100°F environment, and to materials with thermal conductivities of less than 1 Btu-in/hr-ft²-°F.

There are four general types of insulation material which may be considered for use in a radioisotope fueled thermoelectric generator. These constitute the powders, fibers, foams and multi-layer (super) insulations. It was immediately apparent that the powder insulation could be rejected because of poor physical and mechanical stability due to shrinkage, sintering and densification. The multi-layer insulations involved serious problems with maintenance of the required vacuum conditions, and destruction of the vacuum by outgassing from the foil surfaces. As a result, only one of the "super insulations" was considered in the study. The foam type materials have relatively high thermal conductivities when compared to the fibrous materials, but these have been included in the survey for comparison purposes.

The following insulations were surveyed as having potential application to the milliwatt generator:

1. Fiberfrax - (Carborundum Co.). This material is an alumina-silica fiber composition commercially available in blanket, bulk, strip and other forms, with or without an organic fiber. Fiber lengths are of the order of one inch with a mean fiber diameter of 2.5 microns. This material with the organic binder has excellent handling properties but the binder must be removed before this insulation can be incorporated into the thermoelectric generator system.

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2. WRP-X-AQ Felt - (Refractory Products Co.). This felt is composed of a high alumina fiber and an inorganic bond. It is available in one inch thick sheets of 24" x 36", has good handling qualities and is easily formed to any shape or contour.

3. Micro-Fiber Felt - (Johns-Manville). Micro-Fiber felts are made by water deposition of fine borosilicate glass fibers. The resultant felt is a clean, binder-free felt with good handling properties and flexibility. It is available in thicknesses of up to one inch and in sheets 36" wide by 60" long.

4. Potassium Titanate - (DuPont). This is a crystalline fibrous form of potassium titanate of the formula $K_2O \cdot (TiO_2)_n$ where n is 4 to 7 depending on the method of preparation. The fibers are available in lump material and shapes such as mats, blocks, cylinders, etc. which are prepared from the lump material by felting techniques without the use of organic binders.

5. Fiberfrax Lo-Con - (Carborundum Co.). Fiberfrax Lo-Con felt is made from Fiberfrax bulk ceramic fiber, interlocked and collected by a wet process, with an organic binder added. It is available in thicknesses of 3/8" to 1" in 4' x 25' rolls.

6. Zirconia A Fiber Heat Felt - (Hitco). Fine zirconia fibers of 1" length x 0.0001" - 0.0003" diameter are processed into felt of 1" thickness. No binder addition is used with the felt during the felting process. Available size limitations have not been specified.

7. Min-K - (Johns-Manville). This is a very efficient thermal insulation material composed of a bonded structure reinforced with fibrous media and containing appreciable quantities of a fine particulate matter. The composition of the Min-K is not given. Min-K has good strength, fabricability and vibration resistance, however, it contains an organic bonding agent which must be removed by a bake-out process before use in a thermoelectric generator. It is available in many forms, as molded parts, sheets, slabs, etc.

8. Dyna-Quartz - (Johns-Manville). Dyna-Quartz is composed of 99 percent SiO_2 fibers with no binder addition. It is prepared into semi-rigid tiles or blocks by water felting and heat treating at 2750°F and rough machined to size. It is available in sizes of 1/4" to 3" thick x 14" x 12".

9. Thermoflex R.F. Felt - (Johns-Manville). Thermoflex felt is a fiber insulation composed of alumina and silica which may be air deposited into a uniform felt-like blanket. It may also be felted with an organic binder. It is available in thicknesses of up to 2" in sheets of 4' x 8'.

10. Micro-Quartz Felt - (Johns-Manville). This felt is made by water deposition of fine 98.5 percent pure silica fibers. It is available in 3/16" and 1/2" thicknesses in sheets of 3' x 6'.

11. Thermacomb Foam ZrO_2 - (3M). This is a sintered, highly porous foamed ceramic body for high operating temperature and corrosion resistance. It can be formed into many shapes but is limited in available sizes.

12. Foamsil - (Pittsburgh Corning). Foamsil is a 99 percent pure fused, foamed silica with a non-interconnecting cellular structure. It is available in blocks of 3" x 17" x 22" which may be cut or ground to various shapes.

13. Super Insulation - (Linde). The Linde Super Insulation is a combination of a number of highly reflective metal shields of copper, nickel or stainless steel separated by mats of glass fiber or quartz fiber. The entire assembly must be contained in a vacuum of more than 10^{-3} mm Hg. This insulation is far superior to any other insulation in a high vacuum. The problem with this insulation is the vacuum requirement and the fact that the thermal insulation property is directional, i. e., high heat losses will be encountered in the direction along the metal foils.

A summary of the insulation materials is given in Table III-5 and Figure III-6. It is immediately seen that the Linde Super Insulation has a much lower thermal conductivity than any other type. Of the remaining insulations, the Min-K family are much more attractive from the thermal conductivity, and therefore the heat loss standpoint.

The Linde Super Insulation appears very promising from a theoretical standpoint, but practical requirements have resulted in our recommendation that it not be utilized in presently proposed milliwatt systems. Its thermal conductivity is attractive only in a direction perpendicular to the surface of the foils. This means that an insulated structure, to be suitable for use with this insulation, should have no points where heat may be conducted from a hot to a cold region in the plane of the foils. This introduces a serious problem in the design and fabrication of an insulation envelope which allows the insertion of a heat source. Any gaps left between foils or any short circuiting of foils will result in a heat leakage path, which must be avoided if the insulation capability is to be maintained. The problem is serious enough in large systems, but becomes compounded almost to the point of being unsolvable for very small milliwatt size systems. The only possible exception to this problem would be in applications where the shield is to be located totally internal to the thermal insulation, so that sufficient room could be provided for the necessary discontinuities to occur.

The foil type insulations also must operate in a vacuum condition. This means that any provision for the insertion of a heat source into the insulation must have either a thermal short circuit between the hot and cold side of the insulation to maintain a vacuum, or the vacuum envelope must be formed after the insertion of the fuel by suitable closure techniques. It has been found that the maintenance of the required vacuum when only the foils are contained within the envelope is a serious problem because of outgassing from the foil surfaces. In addition, it is felt that the inclusion of the heat source and possible contamination of the foil surfaces would significantly

TABLE III-5. THERMAL INSULATION MATERIALS

No.	Insulation	Insulation Type	Density lbs/cu. ft.	Max. Serv. Temp. - °F	Melting Point - °F	Thermal ⁽¹⁾ Conductivity	Manufacturer
1.	Fiberfrax	Fiber	6	2300	3200	See Figure III-6	Carborundum
2.	WRP-X-AQ Felt	Fiber	18	2200	> 3200	See Figure III-6	Refractory Prod.
3.	Micro-Fiber Felt	Fiber	5	1200	----	See Figure III-6	Johns-Manville
4.	Potassium Titanate	Fiber	3.4	2200	2500	See Figure III-6	DuPont
5.	Fiberfrax Lo-Con	Fiber	6	2300	3200	See Figure III-6	Carborundum
6.	Zirconia A Fiber Felt	Fiber	17	3000	4600	See Figure III-6	Hitco
7.	Min-K 2000	Fiber + Powder	20	1800	----	See Figure III-6	Johns-Manville
8.	Dyna-Quartz	Fiber	6	>2000	2900	See Figure III-6	Johns-Manville
9.	Thermoflex R. F.	Fiber	12	>2000	3200	See Figure III-6	Johns-Manville
10.	Micro-Quartz Felt	Fiber	6	>2000	2700	See Figure III-6	Johns-Manville
11.	Thermocomb Foam	Foam	35	3200	4500	See Figure III-6	3M
12.	Foamsil	Foam	12	2200	3000	See Figure III-6	Pitts-Corning
13.	Super Insulation ⁽²⁾	Multi-Layer	13	2200	----	See Figure III-6 ⁽³⁾	Linde
14.	Min-K 1301	Fiber + Powder	20	1300	----	See Figure III-6 ⁽⁴⁾	Johns-Manville
15.	Min-K 503	Fiber + Powder	20	500	----	See Figure III-6	Johns-Manville

(1) All measurements made in air at 760 mm except numbers 13A and 13B which were measured in a high vacuum.

(2) No. 13A measured under 15 psi load; No. 13B with no load bearing.

(3) Temperatures for 13A and 13B, shown in Figure III-6, are hot face temperatures.

(4) No. 14 measured at 1 atmosphere, 14A measured at 0.07 atmospheres.

increase the outgassing problem. Provision of a seal between the hot and the cold side of the foil type insulation to eliminate the outgassing problem resulting from the fuel capsule surface and associated contamination creates a leakage path for heat. Since the quantity of fuel in milliwatt sized systems will be small, the heat leakage along this seal would be relatively substantial. If any real consideration is given to the use of a foil type insulation, this leakage must be very carefully investigated, since it is expected that the leakage would be significantly larger than all other heat losses put together.

Special provisions must be made for the use of foil type insulations as a support structure. Linde has performed work toward this end, and has apparently been successful in designing load bearing types of foil insulations. The load bearing areas will generally conduct more heat than will those portions of the insulation which do not bear a load, and it is very important in the utilization of the insulation that only compressive loads be applied.

The Min-K family of insulations are very attractive for use in milliwatt size radioisotope fueled thermoelectric generators. The insulation has excellent compressive load capabilities, and has a very low thermal conductivity. It may be readily formed into a number of shapes suitable for structural containment of heat sources and thermoelement modules. Min-K 2000 has the highest thermal conductivity of the Min-K family, and also has the highest service temperature. Min-K 503 has the lowest thermal conductivity, but is limited to an operational temperature of the order of 500°F. Min-K 1301 and Min-K 1302 are intermediate to these extremes, and have service temperatures in the range of 1000°F.

The gaseous atmosphere associated with the Min-K has a substantial effect on thermal conductivity. Use of high molecular weight inert gases instead of air results in a considerable reduction in the thermal conductivity. The maintenance of vacuum conditions will cause a further reduction in the thermal conductivity. These data are shown in Figure III-6.

A major problem with the use of Min-K thermal insulations is decomposition of the binder over an extended period of time and the accompanying outgassing problem. Many of the gases which result are of low molecular weight and have high thermal conductivities. In a closed environment, release of these gases will increase the thermal conductivity of the Min-K due to the introduction of a higher thermal conductivity gas and also due to the increase in pressure. This type of behavior may be avoided by an outgassing procedure prior to use of the insulation. Normally, the insulation must be baked at a temperature greater than its operational temperature for an extended period of time under a vacuum condition. Then the insulation should be back-filled with inert gas and reevacuated several times at high temperature.

Even this procedure will not completely eliminate all of the outgassing that will occur, but will reduce the problem so that the insulation may be effectively used in a closed environment. The insulation cannot be used in a closed vacuum environment because the vacuum will only exist for a short time. Hence, although pressures of the order of 0.50 atmospheres may be reasonable, the thermal conductivity corresponding to a vacuum should not be used if the insulation is installed in a closed system.

3. Theoretical Analysis

Present fuel capsule technology excludes the use of spherical fuel capsules. The next most attractive fuel capsule from a heat loss standpoint is cylindrical, which is completely within present technology. Consequently, a cylindrical configuration was chosen for analysis of heat losses in this study. If it is desired to consider advanced systems with other than cylindrical geometry, for example spherical geometry, the results of the cylindrical investigation may still be used. The heat losses from a right circular cylinder with length to diameter ratio of one would be roughly in the same category as heat losses from a sphere, although the former would, of course, be larger. As a first estimate, the cylindrical heat losses would be adequate.

It is not possible to describe the heat losses from the surface of a cylinder of a finite insulation thickness with a simple exact equation. If heat conduction theory is applied exactly, a set of simultaneous second order partial differential equations will result, which, although they may be solved manually, yield very complicated series type solutions that converge too slowly for practical purposes. The two approaches remaining from a practical consideration involve either the use of a computer with a suitable numerical solution, or the use of simplifying assumptions for the basic mathematics. The latter course was chosen for the parametric study of this program. This assumption was then checked for a selected case through the use of a digital computer program which is discussed in the next sub-section.

A relatively simple mathematical model (Figure III-7) results if it is assumed that an isothermal surface always exists in the thermal insulation, and that this surface is in the form of a right circular cylinder with the distance between the isothermal surface and the heat source everywhere the same. Implicit in this is the additional assumption that the isothermal surface is also equidistant from the outer surface of the thermal insulation. The equations which result from this selection are first order and linear, and may be readily solved.

The assumption that the thickness on the ends of the cylinder differs from that in the radial direction will result in a similar model. The heat loss can then be described by two simple differential equations, the solutions of which are readily obtained. This was used as the approach for the conduction type thermal insulation in this study and it was found that the radial heat loss could be expressed by:

$$Q = \frac{2\pi(L_1 - D_1)k(T_o - T_s)}{\ln \frac{L_1 D_3}{L_3 D_1}} \quad (\text{III-38})$$

where:

- Q_1 = radial heat loss (Btu/hr)
- L_1 = capsule length (inch)
- D_1 = capsule diameter (inch)
- D_3 = overall diameter (inch)

Figure III-7. Insulation Analytical Model

$$\begin{aligned}
 L_3 &= \text{overall length (inch)} \\
 k &= \text{insulation thermal conductivity (Btu/hr-in-}^{\circ}\text{F)} \\
 T_o &= \text{capsule surface temperature (}^{\circ}\text{F)} \\
 T_s &= \text{insulation outer surface temperature (}^{\circ}\text{F)}
 \end{aligned}$$

For the special case where $L/D = 1$, Equation (III-38) can be written as:

$$Q = \frac{2\pi k D_3 D_1}{(D_3 - D_1)} (T_o - T_s) \quad (\text{III-39})$$

The radial heat loss per inch of length is:

$$\frac{Q_r}{L} = \frac{2\pi k}{\ln(D_3/D_1)} (T_o - T_s) \quad (\text{III-40})$$

where: $\frac{Q_r}{L} = \text{radial heat loss (Btu/hr-in)}$

The axial heat loss from one end can be written as:

$$Q_2 = \frac{\pi k D_1 D_3}{4t} (T_o - T_s) \quad (\text{III-41})$$

where: $Q_2 = \text{axial heat loss (Btu/hr)}$
 $t = \text{insulation thickness (inch)}$

The axial loss per unit area can be expressed as:

$$Q/A = \frac{k}{t} (T_o - T_s) \quad (\text{III-42})$$

Therefore, the total loss from a capsule completely encased with insulation is:

$$Q_{TOT} = Q_1 + 2Q_2 \quad (\text{III-43})$$

The insulation weights are evaluated in a similar fashion to the approach used for the heat loss calculations.

The weight of insulation completely encasing the fuel capsule can be written as:

$$W_t = \frac{\pi}{4} \rho [D_3^2 L_3 - D_1^2 L_1] \quad (\text{III-44})$$

where: W_t = weight of insulation (pound)
 ρ = density of insulation (pound/in³)

The weight per unit length of capsule is:

$$\frac{W}{L} = \frac{\pi}{4} (D_3^2 - D_1^2) \rho \quad (\text{III-45})$$

The weight in the axial direction can simply be written as:

$$\frac{W}{A} = \frac{\rho}{t} \quad (\text{III-46})$$

An approach similar to that used for the conduction heat losses may be used for the application of a foil type insulation. In this case, a differential equation does not result, but a development of the behavior of each individual foil with consideration given to the increase in area as foils are added results in the following overall heat loss equation for the radial behavior:

$$Q_1 = \frac{B \sigma \epsilon (T_o^4 - T_s^4)}{\sum_{i=1}^{N-1} \left[\frac{1}{(D_1 + \frac{2it}{N}) (L_1 + \frac{2it}{N})} \right] + (1 - \epsilon) \sum_{i=1}^N \left[\frac{1}{(D_1 + \frac{2it}{N}) (L_1 + \frac{2it}{N})} \right]} \quad (\text{III-47})$$

where: All temperatures are in degrees Rankine

Q_1 = radial heat loss (Btu/hr)
 B = foil effectiveness factor
 ϵ = foil surface emissivity
 N = number of foil layers
 σ = Stefan Boltzmann constant

The factor B is introduced into the equations to account for "streaming" losses and also touching foils which decreases the overall effectiveness of the radiation structure.

The axial heat loss from one end can be written as:

$$Q_2 = \frac{B \sigma \epsilon (T_o^4 - T_s^4)}{(N+1) (2 - \epsilon)} \frac{\pi}{4} D_1 D_3 \quad (\text{III-48})$$

The heat loss per unit length of capsule is:

$$\frac{Q}{L} = \frac{B\sigma\epsilon(T_o^4 - T_s^4)}{\sum_{i=0}^{N-1} \left[\frac{1}{(D_1 + \frac{2it}{N})} \right]^+ (1 - \epsilon) \sum_{i=1}^N \frac{1}{\pi(D_1 + \frac{2it}{N})}} \quad (\text{III-49})$$

The axial loss per unit surface area can be expressed as:

$$\frac{Q}{A} = \frac{\epsilon B\sigma(T_o^4 - T_s^4)}{(N+1)(2-\epsilon)} \quad (\text{III-50})$$

The insulation weight equations are identical to those presented for the conductive case (Equations III-44, III-45, III-46). The density used within the equations is the effective density of the foil wraps, which normally is only a fraction of the foil material density.

These equations have been compiled into a digital computer code written for the Univac 1107 or Univac 1108. Recompile of the computer codes could be readily obtained for use on other equipment which utilizes the Fortran system.

A computer program was utilized so that the large number of parametric calculations required for the study could be obtained quickly and cheaply. The results of this study have been incorporated into nomograph #1, which in part correlates the heat loss from the fuel capsule in terms of all applicable independent variables. The presentation technique is such that portions or all of the nuclear shielding material may be placed inside of the insulation if desired. †

4. Calculation Accuracy

Although it was believed that the simplified mathematical model selected for analysis of the milliwatt generator heat losses was reasonable, a further investigation was performed for selected cases so that the calculation accuracy could be checked. One of the SNAP-15 generators was considered, allowance was made for the structural support behavior by increasing the thermal conductivity of the insulation in nomograph #1, and from a knowledge of the SNAP-15 fuel capsule dimensions and operating temperature as well as the experimental heat loss, a prediction of the thickness of insulation required was made. This predicted thickness was compared to the actual average thickness, and agreement to within 10 percent was obtained.

Hittman Associates commonly uses a large heat transfer computer program with highly flexible capabilities (Reference 13). This program was applied to a selected configuration that had also been analyzed using the approximate technique. The calculation was accurately performed using a relaxation technique based upon the analogy between heat conduction and electrical circuit behavior, with the use of 74 nodes for the simulation. A

* Further details concerning the computer program are available in Reference 12.

schematic of the generator analyzed, showing the heat source, thermopile, insulation and generator case is shown in Figure III-8. Indicated on this figure are the node center points for the case analyzed, and the temperatures which were computed for each of the nodes. The heat losses were calculated by two separate techniques. In one, a heat balance was written around the heat source and the heat loss from the center node to each of the immediately surrounding nodes was obtained from the known conductances. In the second calculation, a heat balance was obtained around the inside of the generator case, and a similar calculation made. The accuracy of the two computed techniques was better than four significant figures. The computed heat loss was then compared to the value obtained under similar conditions with the approximate mode. The numbers were within 5 percent, which confirms the accuracy of the approximate approach for the comparison which was made. Although this does not prove that the accuracy would be similarly excellent for all possible combinations of dimensions, it is certainly a good indication of the accuracy for generator sizes in the range considered herein.

E. Generator Case

Although the milliwatt generators will contain considerably less quantities of fuel than in most of the radioisotope fueled systems built to date, there will still be sufficient heat to introduce a cooling problem in many situations. This immediately introduces the concept of providing an extended surface on the generator case to reduce the external system temperature, as well as the thermoelement cold junction temperature. As a result, the use of fins of various configurations was considered in the parametric study.

The application of the generator to underwater use introduces no problem insofar as temperature is concerned. The large heat transfer coefficients which result between the generator case and the water surroundings reduce the temperature drop in this area to negligible proportions. However, if such a system is to be transported in an air environment, consideration must still be given to keeping it cool during the transportation process.

Typical fin arrangements which may be employed are illustrated in Figure III-9. The analysis of these fins and presentation of the results in an easily correlatable manner presented an interesting problem. It was finally assumed that the generator case would be treated as an isothermal surface, which would mean that all of the fin base temperatures were identical. This is a reasonable assumption since most of the generator cases will have high thermal conductances.

It was also assumed that the fins could be treated by neglecting the temperature gradient perpendicular to the fin surface, a commonly made assumption which is excellent, introducing negligible calculation error. Finally, it was assumed that a temperature gradient would exist only in the direction measured perpendicular to the surface to which the fin was attached. This assumption is also commonly made in fin analyses. With these assumptions, the fin analysis results in a differential equation which describes the temperature difference between the fin base and fin tip. This situation has been analyzed by Jakob and need not be repeated here (Reference 14).

Figure III-8. Milliwatt Generator Heat Loss Model
(Numbers are temperatures in °F)

(a) Longitudinal Fins

(b) Circular Fins

(c) End Fins (one or both ends)

(d) Concentric Fins (one or both ends)

Figure III-9. Fin Arrangements

With an expression to correlate the fin behavior in terms of its environment, it was then necessary to define the environmental effect. This was performed by using an equation to describe the natural convection film coefficient.* This equation represents the smaller value for the film coefficient, and is as follows:

$$h_1 = 0.245 \left[\frac{T_o - T_s}{D_1} \right]^{0.25} \quad (\text{III-51})$$

where: h_1 = film coefficient (Btu/hr-ft²-°F)
 T_o = case surface temperature, °F
 T_s = ambient temperature, °F
 D_1 = case diameter, feet

An effective film coefficient for radiation can be written as:

$$h_2 = \frac{\sigma \epsilon}{(T_o - T_s)} [T_o^4 - T_s^4] \quad (\text{III-52})$$

where: h_2 = film coefficient (Btu/hr-ft²-°F)
 σ = Boltzmann constant
 ϵ = surface emissivity

Therefore, the heat loss from a bare case can be written as:

$$Q_B = (h_1 + h_2) \pi [D_1 L + 0.5 D_1^2] (T_o - T_s) \quad (\text{III-53})$$

where: Q_B = heat loss (Btu/hr)
 L_c = case length (feet)

The fin evaluation was based on the determination of the fin effectiveness. The general heat loss equation from the fins by convection can be written as:

$$Q_f = h_1 A_s \eta (T_o - T_s) \quad (\text{III-54})$$

where: Q_f = heat loss, Btu/hr
 A_s = total surface area of fins, ft²
 η = fin effectiveness

* See for example, Reference 14, p. 529

The solution of the fin effectiveness was obtained by curve fitting the results of Harper and Brown* based on triangular fin profile data. The equation can be written as:

$$N = 1.0 - 0.2 W_f \sqrt{\frac{2h_1}{kt}} \quad (\text{III-55})$$

where: W_f = fin height, feet
 k = thermal conductivity, Btu/hr-ft-°F
 t = fin root thickness, feet

The above equation is based on longitudinal fins, however, the correction factor for circular fins is sufficiently small to be neglected.

The radiation loss associated with the finned surface was evaluated based on the "string method". Utilizing this method, the radiation loss for the longitudinal and radial fin configuration can be written as:

$$Q_R = h_2 \pi (D_1 + 2W_f) L_1 (T_o - T_s) \quad (\text{III-56})$$

where: Q_R = radiation heat loss from finned surface, Btu/hr

The total heat loss of a finned case is simply a summation of the case and fin losses. For the longitudinal fins the expression becomes:

$$Q_{\text{tot}} = (h_1 + h_2) \frac{\pi}{2} D_1^2 (T_o - T_s) + h_2 \pi (D_1 + 2W_f) L_1 (T_o - T_s) \\ + L_1 [\eta (2N W_f L_1) + (\pi D_1 - Nt) L_1] (T_o - T_s) \quad (\text{III-57})$$

where: N = number of fins

The weight of the fins is evaluated based on a rectangular profile since it represents a maximum value. For the longitudinal fin configuration the fin weight is:

$$W_f = N W_f L \rho \quad (\text{III-58})$$

where: W_f = fin weight, pounds
 ρ = fin density, pounds/cubic foot

The total heat loss and fin weight for the other fin configuration is evaluated in a similar manner. To obtain the total fin length for the cases of end mounted fins, the fins were assumed to be equally spaced. The individual equations will not be presented due to the close similarity of the remaining equations to those presented for the longitudinal case.

 * Presented in Reference 14

The analysis of the generator case, without fins, has been programmed for the Univac 1107 and 1108 computer. The program may readily be used for other computers by simply recompiling if the other installations have Fortran capability.

The results based upon this analysis have been correlated in nomograph #2. This enables a quick calculation to be performed for the unfinned generator temperature when operating in 72°F air. It also enables the fin characteristics to be evaluated if a temperature lower than that predicted for the unfinned configuration is desired.*

F. Power Conditioner

1. Introduction

In the field of thermoelectric or thermionic energy conversion the actual conversion device, be it a metallic or semiconducting thermoelectric element or a thermionic diode, is usually a low voltage, high current device. Output voltages typically range from several millivolts to about one volt. While it is possible to put the required number of elements in series to achieve a desired output voltage, doing so introduces reliability problems. As a result, some form of power conditioning is introduced to match the relatively low impedance of the source (low voltage, high current) to a normally high impedance load (high voltage, low current). Another potential need for conditioning devices is introduced if output voltage regulation is desired, since the output voltage of a thermoelectric generator is dependent on the applied load.

A thermoelectric generator as "seen" from the load has a resistance type of characteristic when a specified temperature difference exists between the hot and cold junctions. If the generator is short circuited, a maximum current flows. If the resistance applied to the generator is increased, the current decreases and the generator voltages increase until finally when the external load becomes infinite, a generator open circuit voltage is realized. Under short circuit conditions, the useful power produced by the generator is zero. As the external load resistance is increased, the useful generator power will also increase, reach a maximum point, and then decrease again to zero when the open circuit condition has been obtained. It may be readily shown that this maximum will occur when the internal generator resistance and the external load resistance are equal, subject to the provision that the hot and cold junction temperatures do not change.

In a radioisotope fueled thermoelectric generator, the hot and cold junction temperatures are not necessarily fixed, but instead the quantity of heat available at the hot junction is established. The maximum power point, as well as the maximum efficiency point, for this type of system will not occur when the so-called "matched load" condition exists. Instead, there is an interaction between the Peltier cooling at the hot junction and the current which shifts the optimum point. The amount of shift depends on the charac-

* Further details concerning the computer program may be obtained from Reference 15.

teristics of each individual system, and the ratio of the external to internal load voltage may be determined, if desired, from nomograph #4.

It is normally advantageous to design the power conditioner system so that the generator is operating at maximum efficiency at the end of life. At other points during the operational lifetime, the temperature difference between the hot and cold junctions will be higher because of the increased heat generation rate. This will both increase the power input and shift the optimum load resistance. The former effect is greater than the latter, and there will result sufficient power to more than overcome the non-optimum load characteristics when the system is designed for end of life behavior.

2. Circuit Description

The circuit chosen for analysis in the large milliwatt program is shown in Figure III-10. It is a single saturating core Royer circuit with a shunt regulator. This circuit was chosen over the commonly used nonsaturating, low loss power output transformer with a saturating bias feedback transformer because of its greater simplicity, greater reliability and smaller size compared to the two transformer circuit. The two transformer circuit normally will have a higher efficiency because the large output power transformer is operated in a non-saturating mode. The small saturating transformer is used for switching and the only power required from this is that required for the transistor drive. However, it may not be possible to obtain the theoretical advantages of this transformer system at low voltage and current conditions anticipated for the low power regions of this study. This occurs because of mechanical considerations in the transformer construction. Further, the losses involved will be quite small and as a result the study emphasis was placed upon a single transformer system.

Preliminary considerations were given to the use of tunnel diodes in the construction of power conditioners. However, the preliminary results were not promising, and no further effort was expended in these concepts.

Figure III-10 is basically a standard Royer circuit with a shunt voltage regulator which will reflect a constant load back to the RTG for load conditions varying from no load to full load. A regulator has been included for completeness since most potential applications of the large milliwatt generator would require voltage regulation. The precise design of the regulator would only be known once the exact power level and output voltage were specified. Full load power consumption of the regulator is typically one percent of the output power. However, during the efficiency calculations, a more conservative two percent loss was assumed.

In operation, when a voltage is applied to the input terminals by the RTG, both transistors will be initially forward biased. R_1 is a current limiting resistor and C_2 is a speedup capacitor. Due to inextricable circuit variations, one transistor, Q_1 for example, will conduct more current than the other, Q_2 . This larger current in turn induces a feedback voltage in N_2

Figure III-10. Large Milliwatt Converter

which further turns on Q_1 and turns off Q_2 . In a very short time Q_1 is completely turned on (saturated), and Q_2 is turned off. While Q_1 is saturated, the constant current flowing through it causes a linear increase in the transformer flux with respect to time. When the transformer saturation flux is reached, the magnetic field collapses and induces a reverse bias voltage to Q_1 and Q_2 . This now causes Q_1 to turn off and Q_2 to turn on and the entire half cycle repeats itself.

The despiking capacitor, C_1 helps protect Q_1 and Q_2 against switching voltage transients.

The almost perfect square-wave output of N_3 is rectified by D_1 D_2 , filtered by C_3 , and regulated by the same shunt regulator.

The shunt regulator operates through the maintenance of a constant reference voltage at point A by Zener diode ZD_1 and R_7 . A sample of the output of the rectifier-filter is maintained at point B by the voltage divider consisting of R_{10} and R_3 . Output voltage fluctuations appearing at point B are compared with the constant reference voltage at point A by the differential amplifier Q_3 . Any voltage difference between points A and B will be amplified and will appear between points C and D. This amplified signal will provide drive for Q_4 which in turn drives Q_5 which controls the current through R_9 , thus loading down the rectifier-filter and providing the required regulation. Q_5 and R_9 represent a variable load which, together with a varying external load, will reflect a constant load back to the RTG. Consequently, no temperature fluctuations in the RTG will be caused by electrical load variations. Under full external load conditions, the shunt regulator will be inoperative and will dissipate only about two percent of the output power.

3. Component Selection and Circuit Function

a. Transistors. The transistor is used to alternately switch current through the primary winding N_1 (Figure III-10). To optimize the transistor switching efficiency the transistor should have the lowest possible reverse leakage current, I_{CBO} ; the lowest possible saturation resistance, R_{SAT} ; the highest possible forward current gain, BETA, (h_{FE}); the shortest possible rise time t_R , and fall time t_F ; and the lowest possible base to emitter saturation voltage, $V_{BE(SAT)}$. (See Figures III-11 and III-12). Unfortunately, all of these desirable characteristics do not appear in the same transistor at the same time and it is necessary to select the best possible combination to minimize losses. Germanium, as opposed to silicon, transistors are best with respect to low $V_{BE(SAT)}$ and $V_{CE(SAT)}$ voltages. The actual transistor selected will also depend on size and weight limitations. Smaller transistors will generally have higher saturation resistances and voltages.

Figure III-11. Transistor Voltages and Currents

Figure III-12. Transistor Rise and Fall Times

To provide positive turn-off and saturation of the transistors, the feedback voltage is set equal to the saturation voltage of the transistor, $V_{VE(SAT)}$. The value of R_1 is then selected to limit the current to that level required to saturate the transistor. Hence:

$$R_1 = \frac{E}{I} = \frac{V_{IN}}{I_2} \quad (III-59)$$

At this point it should be noted that the minimum value of V_{IN} that will permit self starting of the converter is $V_{BE(SAT)}$. If V_{IN} is less than $V_{BE(SAT)}$, adequate drive cannot be supplied to initiate switching.

b. Transformers. The transformer core material chosen for overall performance and low loss is 2 mil thick Square Permalloy 80, made by Magnetics, Inc. (Reference 16) and was selected as typical of the low loss core material manufactured today.

The actual transformer, T_1 , is a saturating transformer with a square hysteresis loop. The parameters of T_1 establish the frequency of oscillation since it can be shown by Faraday's law that:

$$\text{Frequency, } F = \frac{V_{IN}}{2 \times N_1 \times 10^{-8} \times \phi_T} \quad (III-60)$$

where:

ϕ_T	=	$2B_S A_C$
V_{IN}	=	source voltage
N_1	=	number of primary turns
B_S	=	saturation flux of core material in Gauss (for Square Permalloy 80, $B_S = 7400$ Gauss)
A_C	=	cross sectional area of core in cm^2

(Note: In Equation (III-60), 2.00 is used instead of 2.22 because average voltages are used instead of RMS volts.)

A typical hysteresis loop for a saturating core is shown in Figure III-13.

Figure III-13. Hysteresis Loop

For Figure III-10 to function as a chopper, it is necessary for the magnetic flux excursions in T_1 to traverse the saturation region of the hysteresis loop of the magnetic material. When the instantaneous flux density B in Figure III-13 is traversing b to c or g to h , the magnetic field begins to collapse and the voltage induced in the base drive feedback windings decreases since the induced voltage is proportional to $\frac{dB}{dt}$. As the flux traverses c to d or h to j , called the "flyback" region, the decrease in flux causes a polarity reversal in the feedback voltages, which turns off transistor Q_1 and turns on transistor Q_2 .

c. Rectifiers. There are two approaches to select an efficient rectifier. The first is to use the collector-to-base junction of a transistor which generally has a low forward voltage drop. However, the use of such a transistor might be precluded if weight and size are important requirements. The other approach is to use a normal diode with its corresponding advantage in weight and size, but with the disadvantage of increased forward voltage drop. The choice of either a transistor or diode rectifier would be dictated by customer requirements. If weight and volume were crucial, the diode would be used and if efficiency were crucial, the transistor would be used.

The relative rectifying efficiency is indicated by the power loss, P_{RECT} , in the rectifier, Equation (III-61), which is the sum of forward conduction loss and reverse leakage loss. (For the remaining calculations in this analysis, an output voltage of 18 volts will be used.)

$$P_{RECT} = V_F I_3 + 18 I_L \quad (III-61)$$

where: V_F = forward voltage drop of the transistor or diode
 I_L = leakage current of the transistor or diode
 I_3 = output current

d. Filter and Regulator. Since the output of the full-wave rectifiers is almost pure dc except for the switching periods T_{SW} (See Figure III-14), capacitor C_3 is adequate as a filter. Regulation is obtained through the shunt regulator which achieves voltage regulation by loading down the output of the rectifier-filter and dissipating in R_9 and Q_5 the energy not used by the load.

4. Efficiency Calculations

The determination of an optimum power conditioner design for the large milliwatt system was based upon the selection of transistor parameters, the power output level, the core saturation flux, the input voltage, the number of primary transformer turns, and the frequency. The feedback and output turns ratios may then be calculated from the following equations:

$$N_2 = \frac{N_1 V_{BE(SAT)}}{V_{IN}} \quad (III-62)$$

$$N_3 = \frac{N_1 (18 + V_F)}{V_{IN}} \quad (III-63)$$

where: N_1 = number of primary turns
 N_2 = number of feedback turns
 N_3 = number of output turns
 $V_{BE(SAT)}$ = base to emitter saturation voltage
 V_{IN} = input voltage
 V_F = forward voltage drop at maximum load current at 25°C

The currents in the three windings are:

$$I_1 = \frac{P_o}{V_{IN} (0.8)} \quad \text{(assuming an efficiency of 80 percent)} \quad (III-64)$$

Figure III-14. Rectifier Output

$$I_2 = \frac{I_1}{\text{BETA}} \quad (\text{III-65})$$

$$I_3 = \frac{P_o}{18} \quad (\text{III-66})$$

where: P_o = power output level
 BETA = forward current gain = h_{FE}
 I_1 = primary current = collector current
 I_2 = feedback current = base current
 I_3 = output current = rectifier current

The general transformer core design philosophy is that of determining the core cross sectional area needed to support the specified voltage, calculating the needed wire sizes to handle the required currents, and finding the required window area to accommodate the windings. This procedure involves finding the optimum required number of turns and wire sizes, and then designing the transformer to fit the windings while maintaining minimum possible losses. Calculating directly from Faraday's law, the required core cross sectional area is:

$$A_C = \frac{(V_{IN} - V_{CE(SAT)})}{4 \cdot B_S \cdot N_1 \cdot F_1 \cdot 10^{-8}} \quad (\text{III-67})$$

where: $V_{CE(SAT)}$ = collector to emitter saturation voltage
 B_S = core saturation flux
 F = frequency

The transformer core is illustrated in Figures III-15 and III-16. The core material length or width is specified by:

$$\text{SQAC} = \sqrt{A_C} \quad (\text{III-68})$$

The standard tables for selecting a wire gage, once the current is specified, are quite awkward to use. However, if the tables are plotted on semilog paper it becomes immediately apparent that they may be expressed in logarithmic form. Assuming 1000 C.M.*/amp, the required wire gage for a current I_P in the P^{th} winding is:

$$\text{AWG}(P) = 20 - (10 \log \frac{I_P}{2}) \quad (\text{III-69})$$

 *C.M. = circular mils

Figure III-15. Overall Transformer Dimensions

Figure III-16. Transformer Cross Sectional View

Note that $\frac{I_P}{2}$ is used instead of I_P because each winding has only a 50 percent duty cycle. Since wire sizes only come in integer A.W.G. sizes, the calculated result is rounded off to the nearest integer. If the calculated value of A.W.G. is greater than 40, it is set equal to 40 since wire sizes with a diameter smaller than a 40 gage wire are too unwieldy to handle.

The cross sectional area of one turn of wire (including insulation) can be determined for the P^{th} winding from:

$$A_{WP} = \log^{-1} (-0.0954 \text{ AWG}(P) + 5.03) \quad (\text{III-70})$$

and the resistance per 1000 feet of wire from:

$$R'_P = \log^{-1} (0.1 \text{ AWG}(P) - 1) \quad (\text{III-71})$$

The total resistance, neglecting leads, of the P^{th} winding is given by

$$R''_P = \frac{(4.0 + P) \sqrt{A_C} \times N_P \times R'_P}{30.48 \times 10^3} \quad (\text{III-72})$$

The quantity $(4.0 + P) \sqrt{A_C}$ is an approximation of the mean circumference of one turn of wire in the P^{th} winding (see Figure III-17); N_P the number of turns in the P^{th} winding; and $\frac{R'_P}{30.48 \times 10^3} \text{ cm/1000 ft}$ the resistance per cm of winding.

The window area of the core, in circular mils (C.M.), required to accommodate the three windings is:

$$W_A = \frac{(2N_1 A_{W1}) + (2N_2 A_{W2}) + (2N_3 A_{W3})}{0.3} \quad (\text{III-73})$$

The quantity 0.3 is the empirical winding factor and represents the ratio of the total cross sectional area of wire that can be wound through the window area of the toroid to the total window area of the toroid.

The characteristic core loss for 2 mil thick Square Permalloy-80 was presented in graphic form by Magnetics, Inc. and was converted into a parametric equation:

Figure III-17. Winding Lengths

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$$PI' = \log^{-1} \left[1.28 \log F - \log^{-1} (1.186 - 0.15 \log B) \right] \quad (III-74)$$

where PI' is expressed in watts/lb of core material. The window area radius is (see Figure III-15):

$$R_W = \sqrt{\frac{W_A \cdot 50.65 \times 10^{-7}}{\pi}} \quad (III-75)$$

where $\frac{40.65 \times 10^{-7}}{\pi}$ is the conversion factor for C.M. to cm^2 . The total radius of the core is:

$$R_C = R_W + \sqrt{A_C} \quad (III-76)$$

and the volume of the core material is:

$$W_{\text{CORE}} = \pi \sqrt{A_C} (R_C^2 - R_W^2) \quad (III-77)$$

The weight of the core is:

$$W_{\text{CORE}} = 8.7 \times V_{\text{CORE}} \quad (III-78)$$

where 8.7 is the density of the core material in gm/cm^3 . The total "iron" core loss can now be found from:

$$P_I = \frac{PI' \times W_{\text{CORE}}}{453.6} \quad (III-79)$$

where 453.6 is the conversion factor from grams to pounds.

The total copper loss can be found from:

$$P_{\text{CU}} = I_1^2 R''_1 + I_2^2 R''_2 + I_3^2 R''_3 \quad (III-80)$$

The total transformer loss is:

$$P_{\text{XFMR}} = P_I + P_{\text{CU}} \quad (III-81)$$

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Total transistor loss, P_{XSTR} , consists of the drive, leakage, conduction and switching losses. The first three of these are (in order):

$$P_D = V_{BE(SAT)} I_2 \quad (III-82)$$

$$P_C = V_{CE(SAT)} I_1 (1 - 2 F T_{SW}) \quad (III-83)$$

where: $(1 - 2 F T_{SW})$ represents that fraction of a second devoted to conduction, i.e., duty factor.

$$T_{SW} = \text{switching time} = t_R + t_F$$

$$t_R = \text{rise time}$$

$$t_F = \text{fall time}$$

$$P_L = I_{CBO} (2V_{IN})$$

$2V_{IN}$ is used since the cutoff transistor sees the input voltage V_{IN} , plus an additional V_{IN} induced in winding N_1 . A generalized characteristic curve for a transistor is shown in Figure III-18. The load line of the transistor is line AB. Point Z is the operating point when the transistor is saturated and is passing a current I_1 ; point B is the operating point when the transistor is cut off. If the transistor had zero saturation resistance, point Z will be assumed to coincide with point A, and for this investigation, point Z will be assumed to coincide with point A. The assumption will introduce negligible error.

Curve P represents the power dissipated in the transistor at any point along load line AB and is simply the product of V and I. It has a peak point power above the Q on the load line AB. As line AB is traversed, the average power dissipated during the transition will be the average value of the curve P. The equation for line AB is:

$$I = I_1 - \frac{I_1}{V_{IN}} V \quad (III-84)$$

Multiplying by V:

$$P = VI = V (I_1 - \frac{I_1}{V_{IN}} V) = I_1 V - \frac{I_1}{V_{IN}} V^2 \quad (III-85)$$

The average value of P is:

Figure III-18. Generalized Transistor Characteristic Curves

$$\frac{\int_0^{V_{IN}} P \, dr}{\int_0^{V_{IN}} dr} = \frac{\int_0^{V_{IN}} -\frac{I_1}{V_{IN}} V^2 \, dr + \int_0^{V_{IN}} I_1 V \, dr}{V_{IN}} = \quad (III-86)$$

$$\frac{-\frac{I_1}{V_{IN}} \frac{V^3}{3} \Big|_0^{V_{IN}} + \frac{I_1 V^2}{2} \Big|_0^{V_{IN}}}{V_{IN}} = \frac{-\frac{I_1 V_{IN}^2}{3} + \frac{I_1 V_{IN}^2}{2}}{V_{IN}} = \frac{I_1 V_{IN}}{6} = P_{AV}$$

One complete switching cycle will look like Figure III-12, and will contain switching times consisting of two rise times t_T and two fall times t_F .

The fraction of time spent during switching (duty factor) is:

$$\text{Duty Factor} = F 2 T_{SW} \quad (III-87)$$

where: $T_{SW} = t_R + t_F$, and F = frequency of operation (III-88)

Consequently, the average switching loss per second will be the product of average power loss during the transition and the duty factor.

$$P_S = \frac{I_1 V_{IN} (F 2 T_{SW})}{3} = \frac{I_1 V_{IN} F T_{SW}}{3} \quad (III-89)$$

The total transistor loss is:

$$P_{XSTR} = P_D + P_S + P_C + P_L \quad (III-90)$$

The rectifier loss is the sum of the conduction and leakage losses:

$$P_{RECT} = V_F I_3 + 18 I_L \quad (III-91)$$

The full load regulator loss typically represents 1 percent of the total power regulated; however, a more conservative value 2 percent will be used in the actual computations:

$$P_{\text{REG}} = 0.02 P_O \quad (\text{III-92})$$

The power lost in the bias resistor is:

$$P_{\text{BIAS}} = (I_2)^2 R_1 \quad (\text{III-93})$$

Capacitor leakage losses will be almost insignificant but are included here for completeness:

$$P_{\text{CAPS}} = I_{C1} 2V_{\text{IN}} + I_{C2} V_{\text{IN}} + I_{C3} 18 \quad (\text{III-94})$$

$$\begin{aligned} I_{C1} &= \text{leakage current of } C_1 \text{ @ } 2 V_{\text{IN}} \\ I_{C2} &= \text{leakage current of } C_2 \text{ @ } V_{\text{IN}} \\ I_{C3} &= \text{leakage current of } C_3 \text{ @ } 18 \text{ volts} \end{aligned}$$

Typical capacitor leakage currents are:*

$$\begin{aligned} I_{C1} &= 10^{-8} \text{ amp} \\ I_{C2} &= 2 \times 10^{-7} \text{ amp} \\ I_{C3} &= 10^{-5} \text{ amp} \end{aligned}$$

Now that all power losses are known, the overall system efficiency is:

$$\eta = \frac{P_O}{P_O + P_{\text{XFMR}} + P_{\text{XSTR}} + P_{\text{RECT}} + P_{\text{REG}} + P_{\text{BIAS}} + P_{\text{CAPS}}} \quad (\text{III-95})$$

A digital computer program for the Univac 1107 or 1108 has been written so that the efficiency may be determined parametrically and an optimum configuration defined. Further details concerning this analysis can be obtained by consulting Reference 17.

The sum of the computed results at the lower voltage range was higher than has been obtained in practice. This was expected since several very small loss terms were not incorporated into the theoretical analysis, and these terms become more significant at the low voltages. As a result, the parametric power conditioner efficiencies were corrected to realistically

* Verbal communications with Mr. Robert L. Williams, Components Division, Westinghouse Electric Corporation, Friendship Airport, Maryland

represent the present technology. Power conditioner input voltages as low as 0.12 volt have been proposed, and as a result the study voltage exceeds the range ordinarily considered.*

The results of the power conditioner study have been incorporated into nomograph #1, which presents the power conditioner efficiency as a function of input voltage and power output.

G. Cost Analysis

The cost of a radioisotope fuel thermoelectric generator may be considered as falling into one of three categories: the materials cost exclusive of fuel, the fabrication labor cost, and the radioisotope fuel cost. Further, it is possible to purchase the radioisotope fuel outright or to use it on a lease rental basis. The lease cost is, in turn, based on payment for fuel depletion during the generator operation, plus an interest rate which is compounded annually and is based on the initial fuel inventory.

The generator cost can be expressed as:

$$C = R + L + M \quad (\text{III-96})$$

where: C = RTG cost
 R = the radioisotope cost
 L = the fabrication cost
 M = the materials cost

The materials cost will be a linear function of the RTG power level and can be expressed as:

$$M = mP \quad (\text{III-97})$$

where: m = materials cost per watt(e)
 P = RTG power level

During this study both the Minnesota Mining and Manufacturing Company and General Instrument were contacted to determine the materials cost, m. Both companies, based on their propane fired thermoelectric generators, gave costs between 50 and 55 dollars per watt for materials in quantity. The 3M systems used lead telluride and the GI systems used bismuth telluride. Consequently, the 50 to 55 dollars per watt figure is recommended and was used in this study.

The fabrication labor cost was found to be independent of the generator power level up to a value of 48 watts(e) for the propane fired systems. This cost was approximately 200 dollars per generator on a commercial basis.

* For further information regarding the behavior of very low voltage power conditioners, see Reference 18.

While these systems are relatively inexpensive, because they use a cheap fuel, it is balanced by the fact that the labor costs obtained include all the propane plumbing for the commercial system. These should prove to be balancing parameters.

Handling the radioisotope cost on a purchase basis consists simply of multiplying the RTG fuel loading by the radioisotope unit cost in the following manner:

$$R = \frac{Pr}{\eta} \quad (\text{III-98})$$

where: r = radioisotope cost per watt(t)
 η = RTG efficiency

The value of the parameter r is published bi-yearly by the USAEC-DID. The costs quoted in these publications include the current price and projected costs based on more widespread usage of the various nuclides. All costs quoted are on an unencapsulated basis.

The radioisotope costs can also be considered on a lease basis. Under this premise, the user would pay for the quantity of isotope decayed plus a yearly compounded interest on the initial fuel inventory. This is expressed as follows:

$$R = \frac{Pr}{\eta} (1 - e^{-\lambda t}) + (1 + i)^t - 1 \quad (\text{III-99})$$

where: λ = the decay constant
 t = the use time
 i = the interest rate

Currently, on special nuclear materials, the same type pricing arrangements can be obtained from the USAEC or certain commercial sources. The USAEC rate is 4.75 percent and the commercial rate is 9.5 percent.

These equations have been programmed for parametric solution on a digital computer and a parametric study has been performed. The analysis has also been incorporated into nomograph #3 so that prospective users may immediately determine an approximate cost for the generator when used on a quantity basis.*

* Further information on the digital computer code may be obtained from Reference 19.

H. Reliability

As was discussed in Section III-C the metallic type thermoelements are stronger than the semiconductor materials, and further may be joined by simple brazing and welding techniques, whereas the semiconductor materials have exhibited a considerable problem in many instances when incorporated into a circuit. Further, the metallic materials may be readily formed into strong compact arrangements using a small area to length ratio. As a result, in the very small power levels the use of metallic thermoelements may become attractive because of the increased probability of breakage of thin semiconductor materials when a reasonably large output voltage is necessary. In some instances, the optimum semiconductor configuration may require a thermoelement so thin that it cannot be manufactured using present techniques and non-optimum configurations are then required.

In this situation it may be necessary to use off-optimum semiconductor configurations with a resultant decrease in efficiency, which in extreme instances can make the metallic thermopile more efficient. The reliability of such a semiconductor configuration can become extremely low as indicated by considering bismuth telluride. This material is available in a minimum size range of approximately 40 mils on a side by 1/2 inch long. It is estimated that the mere fabrication of couples of this size using some of the existing techniques would result in better than 90 percent breakage of the thermoelements. Their incorporation into generators could be expected to cause further breakage, and the use of such semiconductor materials would be quite unreliable. This breakage problem is, in part, corrected by surrounding the semiconductor material by a strengthening member. However, this further reduces the efficiency because of extraneous heat losses. In the size ranges of 0.5 to 1 watt, these disadvantages are not anticipated to be significant, and in general the use of semiconductor material would be completely satisfactory from a reliability standpoint.

Reliability can be considerably enhanced by using a series/parallel type of circuitry. In this case, a wiring arrangement such that two or perhaps three couples are operating in parallel with each other assures that the loss of one couple due to an open circuit situation does not destroy the generator output. Instead, the loss is only due to that one couple plus the increased Joule heating loss in the other couple or couples in parallel. The perturbation on the generator output can be negligibly small.

The probability of failure of the heat source can be considered to be negligible. The radioisotope fuel will always decay regardless of what else happens, and heat will always be generated. The only failure which would perturb the generator output would be breakage of the fuel containment vessel. The chance that this could occur is considered to be negligibly small.

There have been a number of problems involved with generator thermal insulation in the past. These have resulted in a gradual decrease of the generator output power as a function of time as well as a degradation of the thermoelements and bonds between the thermoelements and shoes. These problems are recognized at the present time for Min-K, which is the insulation

material recommended for these systems. However, proper fabrication and assembly techniques can eliminate them. This, coupled to an adequate test program, should reduce the insulation probability of failure to essentially zero. The only postulated failure modes are breach of the generator case and loss of the contained inert atmosphere, or overheating. Overheating to the extent that the thermal insulation is destroyed would have far exceeded the capability of thermoelements and is not considered as applicable to the insulation. The breach of the generator case again is a different problem, and is not a function of the insulation.

Cases for milliwatt size systems should, in general, be designed to be sufficiently strong that they will withstand all of the expected environmental conditions. Since this is a function of each individual case design as well as the conditions to which it will be subjected, no attempt has been made to assign a reliability figure to the generator case. Instead, for analysis purposes it will be assumed that the case will remain intact and will contain an inert atmosphere.

With consideration given to the preceding discussion, the reliability of the system reduces to one of calculating the behavior of the thermoelements, subject to the assumption that reliability information is available under conditions similar to which the generator is to be placed. If this is the case, then the reliability of the RTG system may be calculated by:

$$R_{RTG} = e^{-Nt\lambda} = \Theta^N \quad (III-100)$$

where:

R_{RTG}	=	reliability of the RTG system
N	=	number of couples in series
t	=	time required for operation
Θ	=	single element reliability
λ	=	failure rate per unit time

This equation is applicable for a series system. For a series/parallel arrangement, the reliability is:

$$R_{RTG} = 1 - \sum_{i=1}^N (\text{probability of } M \text{ couples failing}) (\text{Probability of generator failure if } M \text{ couples fail}) \quad (III-101)$$

The probability of M failures is:

$$P_M = \frac{N!}{(N-M)! M!} \Theta^{(N-M)} (1 - \Theta) \quad (III-102)$$

The failure rate corresponding to these reliabilities is:

$$R = e^{-\lambda t}$$

(III-103)

For the results of this study, no attempt has been made to incorporate actual reliability numbers into the data presented. This is because the available data are insufficient for the vast ranges of environment to which the generators will be subjected. Instead, at present satisfactory generator performance requires careful construction techniques and excellent quality control which is coupled with a full understanding of the past failure modes and the techniques required to avoid them. If reliability data are required for a particular application, then sufficient tests must be conducted so that the reliability can be assured to an adequate confidence level.

I. Shock and Vibration

Incorporation of the effects of shock and vibration directly into the milliwatt parametric study would be extremely difficult and for the most part undesirable. The difficulty stems from a long list of items, the more prominent of which are the non-linearity of response, the inability to predict the interaction and effects of damping, spring rates, and mass on a complex system, and the phenomenon that both the shock pulse and the device's response to this pulse is a function of its design. The overall effect of design is that the complete survival to any dynamic load cannot be predicted until the design is precisely known, fixed and rechecked against the input load and response it will produce for itself. Simply stated, it means that the shock input loads and system response cannot be accurately predicted until the design is finalized, and obviously it will not be finalized in the parametric study.

Still another reason for not incorporating dynamic effects directly into the parametric study is best illustrated by the following simple example. It would be unwise to design a high speed aircraft from a satisfactory structural design viewpoint and the test in a wind tunnel. It is wiser, in fact mandatory, that the desired aerodynamic configuration be determined first and then the configuration analyzed structurally. True, reiteration will be necessary but the optimum or design goal is known. In a similar manner the optimum operational RTG configuration should be known before it is checked for survivability to dynamic loads. Further, it is probable that proper design based upon past experience will result in an RTG that satisfactorily meets a survivability test.

Although the entire system cannot be logically and completely analyzed from the shock and vibration standpoint in a parametric approach, there are some alternatives available. The most logical of these is to consider each of the various components which are common to all designs and investigate best and worst case models. By definition, the best case model is the configuration in its strongest design, the worst case being the weakest design. Comparison of the models for a particular application will then give an indication of the loads which it could always survive, those which it would probably survive, and those which it definitely could not survive.

A somewhat similar approach may be taken with respect to the expected loads. Again, simplified models may be selected and worst and best case conditions selected. Response of these models to a specified shock will then yield maximum and minimum loads which may be applied to the selected structural models.

In summary, final conclusions can only be made after the selection of parametric optimum designs and the recheck of these designs to component shock and vibration loads. Certain conclusions can be made at this time -- as evident from this analysis. These are:

- (1) Shock and vibration cannot be incorporated directly into the parametric designs but can be used as a check of the selected designs to their dynamic survival capability through the use of methods described here.
- (2) Severe shock as specified cannot be attenuated within practical dimensions.
- (3) Normal shock and severe and normal vibration can be attenuated within the dimensions of the RTG but only with the use of "soft" systems.
- (4) Soft systems are undesirable because of the possibility of amplifying loads of different time periods.
- (5) Hard or high frequency, structurally stiff, systems are recommended for they have the ability to withstand the greatest range of dynamic loads.
- (6) Components or selected designs found unsatisfactory to a specific dynamic load could still be used if a special carrying case could attenuate the load to a safe level and would be acceptable by the using agency.

Appendix A defines the technique utilized for dynamic analysis. Dynamic and structural models of general application are outlined for shock and vibration phenomena.

J. Shielding

1. Source Radiation Characteristics

a. Plutonium-238. A typical plutonium-238 fuel will have the composition as given in Table III-6.

The gamma activity of the Pu-238 product will consist of gammas from:

- (1) Decay of plutonium isotopes and their decay products

- (2) Prompt spontaneous fissions of Pu-238
- (3) Continuous production of fission products by the spontaneous fission of Pu-238
- (4) Radioactive impurities
- (5) Interaction of alpha particles with oxygen

TABLE III-6. ANALYSIS OF SAMPLES OF PU-238 PRODUCT
(Reference 20)

<u>Isotopic Composition</u>			<u>Cationic Impurities</u>		
Pu-236	0.00012%		Np -237	0.5	%
Pu-238	81	%	Th	0.01	%
Pu-239	15	%	U	0.005	%
Pu-240	2.9	%	Others	0.03	%
Pu-241	0.8	%			
Pu-242	0.1	%			

The important gammas from plutonium isotopes and their decay products come from the Pu-238 and Pu-236 isotopes. Because of the long half-lives and/or small quantities of Pu-239, Pu-240 and Pu-241 the decay of these isotopes do not contribute significantly to the gamma activity of the Pu-238 product. The gammas from pure Pu-238 are predominantly in the energy range of 0.04 to 0.50 Mev with gamma rays at 0.760, 0.810 and 0.875 Mev of relatively low abundance. As long as Pu-236 is at a low ppm level, the gammas (0.28 to 2.62 Mev) from the beta decay of Bi-212 and Tl-208 in the Pu-236 decay chain are the only gammas from that isotope and its decay chains that make a significant contribution to the Pu-238 product activity. If the Pu-236 does not remain at a low ppm level, gammas ranging in energy up to 0.65 Mev from the decay of Pu-236, U-232, Th-232, Pb-212, Po-212, Ra-224, Rn-220 and the alpha decay of Bi-212 become important.

Because of the low abundance and/or long spontaneous fission half-lives of the other plutonium isotopes, only the spontaneous fission process as well as the resulting fission products contribute significantly to the gamma activity of the Pu-238 product. The gammas from the spontaneous fission of Pu-238 range in energy from 0 to 7 Mev with approximately 91 percent below 2 Mev. The fission products approach equilibrium in the Pu-238 product a few hours after separation and decay with gammas in the 0.1 to 3.0 Mev range, approximately 95 percent being between 0.1 and 2.0 Mev.

Potential radioactive impurities in the Pu-238 product come from fission products formed in the irradiation process and neptunium from target elements. Since the concentration of fission product impurities can be reduced to negligible proportions and since the specific activity of Np-237 is low and it and its daughter, Pa-233, have no energetic gammas, the contribution to the gamma activity from this source is negligible.

The (α , n) reaction with the 0-18 isotope of PuO₂ product produces an excited state of Ne-21. Ne-21 decays by prompt gamma emission with gammas of 0.35 Mev (45 percent), 1.38 Mev (10 percent), 1.73 Mev (1 percent) and 2.84 Mev (2 percent). The abundance of these gammas is of the order of $10^3 - 10^4$ photons/sec per gram of product.

Other possible sources of gammas, such as inelastic neutron scattering, Co-59 activation in cladding material and generator structure, are generally negligible.

The composite gamma spectrum from all these sources for the PuO₂ product is given in Table III-7. For shielded sources the 0.5 - 1.0 Mev group is the major contributor to the dose rate.

Beta emitters in the PuO₂ product are Pu-241, U-237, fission product contaminants, decay products of Pu-236, and fission products produced by spontaneous fission. Beta radiation does not significantly contribute to the shielding requirements.

TABLE III-7. SIGNIFICANT GAMMAS FROM PuO₂ PRODUCT
AFTER 1 YEAR

(Reference 20)

<u>Gamma Energy</u> <u>(Mev)</u>	<u>Abundance</u> <u>(γ's/sec./w)</u>
0.04 - 0.5	6.0×10^8
0.5 - 1.0	9.71×10^5
1.0 - 2.0	1.43×10^4
2.0 - 3.0	2.69×10^4
3.0 - 5.0	4.00×10^2
5.0 - 7.0	6.57×10^1

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The principal source of neutrons in the PuO_2 produce is the (α , n) reaction with O-18. The spontaneous fission of Pu-238 also is a source of neutrons, but the number of neutrons from that process is only about one-fifteenth that from the (α , n) source.

The major portion of neutrons from the (α , n) reaction with oxygen are in the 0.2 to 4.2 Mev range. For spontaneous fission, neutrons range in energy up to 13 Mev with approximately 94 percent below 5 Mev. The total specific neutron activity of the PuO_2 product from these sources is of the order of 5.96×10^4 n's/sec/w. Table III-8 gives the (α , n), spontaneous fission, and PuO_2 product neutron spectrums.

TABLE III-8. NEUTRON ENERGY SPECTRUM FROM PuO_2

Neutron Energy Mev	α , n n's/sec./w	Spontaneous Fission n's/sec./w	Total n's/sec./w
0 - 0.5	3.40×10^2	6.29×10^2	9.69×10^2
0.5 - 1.0	1.77×10^3	8.29×10^2	2.60×10^3
1.0 - 2.0	1.55×10^4	1.69×10^3	1.72×10^4
2.0 - 3.0	2.61×10^4	1.03×10^3	2.72×10^4
3.0 - 4.0	9.89×10^3	5.14×10^2	1.04×10^4
4.0 - 5.0	6.29×10^2	3.71×10^2	1.00×10^3
5.0 - 7.0	-----	2.74×10^2	2.74×10^2
> 7.0	-----	7.54×10^1	7.54×10^1
Total	5.42×10^4	0.54×10^4	5.96×10^4

The gamma radiation from plutonium metal and from plutonium -20 percent (a/o) zirconium are essentially the same as for the oxide, since the gamma radiation from the (α , n) reaction contributes only slightly to the gamma radiation. The neutron radiation from these two sources is less than the oxide since there is no oxygen in the system except for impurities. There is enough oxygen contamination, however, in these sources to give a total neutron emission rate of approximately 1×10^4 n/sec per gram of Pu-238 (the oxide emission rate is 3.3×10^4 n/sec per gram of Pu-238). Since the neutron rate from the pure metal with no oxygen impurities is approximately 3×10^3 n/sec per gram of Pu-238, the neutrons from the (α , n) reaction with oxygen impurities contribute significantly to the neutron emission rate.

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b. SrTiO₃. Strontium-90 (half-life = 28 yrs) is produced in reactor operation along with Sr-89 (half-life = 51 days) and stable Sr-86 and Sr-88. As recovered, the strontium isotopic mixture consists of approximately 50 percent Sr-90. Unless the strontium is aged sufficiently, Sr-89 contributes a substantial fraction of heat from the isotopic mixture, and the source will show a high initial decrease in heat output characteristic of the short-lived Sr-89.

If the source is aged sufficiently, the major contributions to the heat and radiation will be made by Sr-90 and its daughter Y-90. Sr-90 decays by beta emission (0.545 Mev) to Y-90, which is in secular equilibrium and in turn decays by beta emission (2.26 Mev) to Zr-90. In approximately 0.02 percent of the Y-90 decays, the beta is accompanied by a 1.734 Mev gamma, but this source of radiation is negligible compared to the high-energy bremsstrahlung which results from the intense, high-energy beta activity. Table III-9 gives the gamma spectrum from SrTiO₃.

TABLE III-9. GAMMA ENERGY SPECTRUM FROM SrTiO₃

<u>Gamma Energy Mev</u>	<u>Abundance (γ's/sec./w)</u>
0.25	1.923×10^{11}
0.50	8.695×10^{10}
0.80	2.649×10^{10}
1.10	8.255×10^9
1.40	2.229×10^9
1.70	4.086×10^8
2.00	2.806×10^7

c. Pm₂O₃. Promethium-147 (half-life = 2.67 yrs) is the only isotope of promethium realized in appreciable yield from fission. Although its yield is only about half that of either Sr-90 or Cs-137, it must still be regarded as having a reasonably high yield. Since it has only one step in its decay scheme to "stable" Sm-147 (half-life = 10^{11} yrs), it may be regarded as a pure beta emitter. The energy of the beta emission is relatively low (0.225 Mev); therefore, the bremsstrahlung from the pure isotope will be of low energy.

The radiation characteristics of the promethium are complicated by traces of other promethium isotopes and possible europium contaminants. Pm-147 sources can be contaminated to such an extent with Eu-152 and Eu-154 that the activities of these isotopes easily control the shielding requirements. It is possible, however, to reduce the quantities of these isotopes to the extent that they have a negligible effect on the shielding requirements. The isotopic impurities present are Pm-148 (half-life = 42 days) and Pm-146 (half-life = 1.9 yr). The Pm-148 can be aged out so that its con-

tribution to the radiation level is negligible. Pm-146 has a half-life of the order of Pm-147 and a beta emitter with a somewhat higher energy beta emission (0.725 Mev) than Pm-147 so that it hardens the radiation characteristics.

Various amounts of Pm-146 in promethium from power reactors have been reported. Estimates have been as high as 837 ppm, but in promethium products from Hanford, VBWR and Yankee, the Pm-146 concentration is 0.25 ppm, 1 ppm, and 4 ppm, respectively. If the concentration of Pm-146 runs as high as 837 ppm, the shield required is approximately the same as that required for Sr-90. However, if the concentration is as low as 0.25 ppm, the shielding required compares favorably with Pu-238 sources (Reference 21). Table III-10 gives the gamma energy spectrum for aged Pm_2O_3 containing negligible amounts of europium and a concentration of 4 ppm for Pm-146.

TABLE III-10. GAMMA ENERGY SPECTRUM FROM Pm_2O_3

<u>Gamma Energy</u> Mev	<u>Abundance</u> γ 's/sec/w
0.156	9.015×10^9
0.25	2.909×10^8
0.45	3.211×10^8
0.75	3.211×10^8

2. Shield Materials

Depleted uranium, lead and iron were considered as possible gamma shielding materials. Selection of a shield material cannot be made solely on its radiation attenuation properties. Other factors, such as shield weight, structural characteristics, physical and chemical properties, fabricability, and availability must be considered. In shielding against gammas, materials with a high atomic number and a high density will result in a minimum shield weight, but may not be the best material to use due to other considerations.

The mass attenuation coefficients for depleted uranium (density = 18.7 gm/cc), lead (density = 11.4 gm/cc) and iron (density = 7.6 gm/cc) are listed in Table III-11. From the table it is obvious that uranium and lead are better shielding materials from an attenuation standpoint than iron. Of the two materials, lead and uranium, uranium is a much better attenuator at low energies but only slightly better from a mass attenuation standpoint at high energies.

TABLE III-11. MASS ATTENUATION COEFFICIENTS FOR IRON,
LEAD AND URANIUM

Energy Mev	Iron gm/cm ²	Lead gm/cm ²	Uranium gm/cm ²
0.20	0.138	0.896	1.17
0.50	0.0828	0.145	0.176
0.80	0.0664	0.0836	0.0952
1.00	0.0595	0.0684	0.0757
1.50	0.0485	0.0512	0.0548
2.00	0.0424	0.0457	0.0484
3.00	0.0360	0.0421	0.0445
4.00	0.0330	0.0420	0.0440
5.00	0.0313	0.0426	0.0446

3. Method of Analysis

a. Gamma. Gamma dose rates were calculated using SCIS-1 and SCIS-2, computer codes developed under the contract for this purpose. These codes are multi-energy, multi-material and multi-regional codes written in FORTRAN IV to perform gamma shielding analysis of isotopic sources in the form of a right circular cylinder. The codes replace the cylindrical source by a line source for radial dose rate calculations and by a disk source for axial calculations.

Each code computes the energy dependent uncollided particle flux, the energy dependent dose rate, the total uncollided flux and the total dose rate for gammas in both the radial and axial directions. The isotopic generator system can be divided into ten radial and axial materials including the source region and the source can be described by a maximum of eleven energy groups. Typically, a single problem involving 6 energy groups, 5 materials and 4 dose points per configuration runs for about 3 minutes and 15 seconds on the UNIVAC 1107 for eighty configurations.

The radial calculation techniques are those described by T. Rockwell, III (Reference 22) and used in part by E. D. Arnold (Reference 23). Using this technique, the cylindrical source is replaced by a line source and concentric cylindrical regions by slabs. The radial configuration is shown in Figure III-19.

The basic equation for the uncollided gamma flux of energy, E, from a cylindrical source with shield at the side and the dose point projection between the ends of the cylinder is:

Radial Configuration for Shielding Calculations

Axial Configuration for Shielding Calculations

Figure III-19. Geometric Configurations for Shielding Calculations

$$\phi_r(E_o) = \frac{S_v(E_o) R_o^2}{4(R + t_c)} R(\theta_2, \sum \mu_m t_m + \mu_c t_c) + F(\theta_1, \sum \mu_m t_m + \mu_c t_c) \quad (\text{III-104})$$

where:	$\Theta_r(E_o)$	=	uncollided particle flux, photons/cm ² -sec
	E_o	=	gamma enegy, Mev
	$S_v(E_o)$	=	volumetric source strength, photons/cm ³
	R_o	=	radius of cylinder, cm
	R	=	separation distance from edge of cylinder to dose point, cm
	t_c	=	self-absorption distance, cm
	μ_c	=	linear attenuation coefficient for a gamma of energy E_{o-1} for the material from which the source is fabricated, cm
	$\mu_c t_c$	=	self-absorption exponent
	μ_m	=	linear attenuation coefficient for a gamma ray of energy, E_o
	t_m	=	thickness of material m, cm
	θ_1	=	angle subtended at the dose point by a horizontal line and a line connecting the dose point with the intersection of the t_c line with the top of the cylinder
	θ_2	=	angle subtended at the dose point by a horizontal line and a line connecting the dose point with the intersection of the t_c line with the base of the cylinder
	$F(\theta, X)$	=	Sievert's Integral = $\int_0^\theta e^{-x \sec \theta' d \theta'}$

The value of t_c can be obtained from pages 361, 362 and 363 of Reference 22.

The dose rate (in millirads/hr) is determined from the flux by the following equation:

$$D(R, E_o) = 5.767 \times 10^{-2} (\mu_a / \rho) E_o \phi(E_o) \tau_m B_m(E_o, \mu_m t_m) \quad (\text{III-105})$$

where: $D(R, E_o)$ = dose rate at distance R from uncollided gamma of initial energy E_o , including buildup contribution, millirads/hr

(μ_a/ρ) = energy absorption mass attenuation coefficient
for tissue, cm^2/g

$$E_o = \text{photon energy, Mev}$$

$$B_m(E_o, \mu_{m^t m}) = A_m e^{-\mu_{m^t m}} + (1 - A_m) e^{-B_m \mu_{m^t m}} \quad (\text{III-106})$$

$$\prod_m B_m(E_o, \mu_{m^t m}) = \text{product of buildup factors for all materials}$$

The gamma fluxes and doses for each energy group are calculated and then summed over the total number of energy groups to obtain the total gamma flux and dose rate.

The axial calculation techniques are those described (Reference 22) for a disk source. The axial configuration is shown in Figure III-19. The source term, S_v , must be corrected for attenuation within the source by dividing it by the linear attenuation coefficient for the source.

The basic equation for the uncollided gamma flux of energy, E_o , from the end of the cylindrical source is

$$\phi_a(E_o, Z) = \frac{S_v(E_o)}{2\mu_c(E_o)} \left[E_1(\sum_m \mu_{m^t m}) - E_1(\sec \Theta \sum_m \mu_{m^t m}) \right] \quad (\text{III-107})$$

where all quantities are as defined for the radial calculations and

Θ = angle subtended at the dose point by a line passing through the center of the disk and the dose point and by a line passing through the edge of the disk and the dose point.

$$E_1(x) = \int_x^\infty \frac{e^{-y}}{y} dy$$

the energy dependent dose rate in millirads/hr is given by

$$D_a(E_o, z) = 5.767 \times 10^{-2} (\mu_a/\rho) E_o \phi_a(E_o) \prod_m B_m(E_o, \mu_{m^t m}) \quad (\text{III-108})$$

As in the case for the radial calculations, the total uncollided particle flux and total dose rates are obtained by summing the energy dependent results.

b. Neutrons. Neutron dose rates were calculated by the point kernel method. The source was replaced by a single point source and an eight energy group calculation was made. Due to the small size of the system, all neutron interactions with the system were considered to be negligible.

Further details concerning the computer program and calculation techniques are given in Reference 24.

4. Shielding Requirements

Shielding calculations for the various isotopes and various power levels for each isotope are all made for a length to diameter of one. Further, in each case, an inner capsule of tantalum, 0.127 cm thick, and an outer capsule of Haynes-25, 0.127 cm thick, is used to surround the source. In each calculation, the surface of the generator system is assumed to be on the outer surface of either the shield or insulation, whichever is on the outside.

Due to the small size of the generator system, it was found that if a dose rate requirement of 200 mrem/hr is met, the dose rate at 100 cm from the generator is well below 10 mrem/hr. On the other hand, if the dose rate at 100 cm is 10 mrem/hr, the dose rate on the generator surface is well above 200 mrem/hr. Consequently, all shielding requirements are given for a 200 mrem/hr surface dose rate since this also means the dose rate at 100 cm is below the upper limit.

a. PuO₂. Figures III-20 through III-22 show the depleted uranium, lead and iron shielding requirements as a function of insulation thickness and power level to give gamma dose rates of 200 mrem/hr and 100 mrem/hr on the surface of the generator system. Shield thicknesses are given for 10, 20 and 50 w thermal power levels for insulation thicknesses of from 0 to 3.0 cm.

Figure III-23 gives the shield thickness and insulation thickness requirements for neutron dose rates of 200 mrem/hr and 100 mrem/hr on the surface of the generator system if the O-18 has been removed from the oxygen in the PuO₂ fuel. If the O-18 is not removed, the neutron generation rate from (α , n) reactions is large enough that the dose rate from neutrons is higher than 200 mrem/hr on the surface of the maximum size generator system allowed for this study.

To arrive at shield and insulation thicknesses to give a total dose rate of 200 mrem/hr on the surface of the generator system requires that the dose rate distribution between gammas and neutrons be specified. From the 100 mrem/hr dose rate lines in Figures III-20 to III-23 some idea of the shielding requirements for an even dose rate distribution between gammas and neutrons can be obtained. For example, for a 50 w source with 0.3 cm of depleted uranium shielding an insulation thickness of 3.2 cm is required for a 200 mrem/hr surface dose rate. For the same source with 0.6 cm of lead approximately 2.9 cm of insulation is needed. For the same source with an iron shield the gamma dose rate requirements for 100 mrem/hr on the surface insure a neutron dose rate of less than 100 mrem/hr on the surface.

Figure III-20. Shield and Insulation Thickness for 100 and 200 mrem/hr Gamma Surface Dose - PuO_2 Fuel, Depleted Uranium Shield

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Figure III-21. Shield and Insulation Thickness for 100 and 200 mrem/hr Gamma Surface Dose - PuO₂ Fuel, Lead Shield

Figure III-22. Shield and Insulation Thickness for 100 and 200 mrem/hr Gamma Surface Dose, PuO_2 Fuel, Iron Shield

Figure III-23. Shield and Insulation Thickness for Neutron Surface Doses of 200 and 100 mrem/hr PuO_2 Fuel

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b. Pu and Pu-Zr. Gamma dose rate calculations were performed for both plutonium metal and plutonium-20 percent (a/o) zirconium. In both cases, the results of the calculations were essentially identical to the results obtained for PuO_2 so that Figures III-20, III-21 and III-22 apply to these two sources as well as the PuO_2 source fuel form.

With the O-18 removed from the oxygen impurities in both the Pu metal and Pu-Zr fuel forms, the neutron dose rate is the same as that given in Figure III-23 for PuO_2 with O-18 removed from the oxygen. Figure III-24 gives the shield and insulation thickness requirements for neutron dose rates of 200 mrem/hr and 100 mrem/hr on the surface of the generator system for the Pu-metal and Pu-Zr fuel forms.

c. SrTiO_3 . Dose rate calculations for strontium sources are divided into three categories. First the shielding requirements as a function of power level and insulation thickness for a dose rate of 200 mrem/hr on the surface, second the dose rate on the surface of the generator system if the shield mass is changed and third the dose rate with no shielding. The first two items may be evaluated by use of nomograph number one. The dose rate on the generator surface for an unshielded strontium source is given in Figure III-25 as a function of insulation thickness and power level.

d. Pm_2O_3 . The shielding requirements for 200 mrem/hr gamma dose rates on the generator surface as a function of insulation thickness and power level are given in Figures III-26, III-27, and III-28 for depleted uranium, lead and iron shields.

5. Comparison of Calculated Results

Comparison of the computed results with those of E. D. Arnold (Reference 23) is made in Figure III-29. The comparison is made for a 100 watt SrTiO_3 source with a dose point 100 cm from the center of the source and various thicknesses of depleted uranium shielding between the source and dose point. The same source spectrum was used by Arnold, and since the same basic equations were used, the comparison is really one of material input data, especially those for the buildup factor. The comparison is favorable with these calculations giving slightly more conservative results. While our calculation technique can be used very close to the source, Arnold does not give results in this region so no comparison can be made.

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Figure III-24. Shield and Insulation Thickness for Neutron Surface Dose Rates of 200 and 100 mrem/hr - Pu Metal and Pu-Zr Fuel

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Figure III-25. Dose Rate From Unshielded SrTiO₃ Source

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Figure III-26. Shield and Insulation Thickness for 200 mrem/hr Surface Dose - Pm_2O_3 Fuel, Depleted Uranium Shield

Figure III-27. Shield and Insulation Thickness for 200 mrem/hr Surface Dose - Pm_2O_3 Fuel, Lead Shield

Figure III-28. Shield and Insulation Thickness for 200 mrem/hr Surface Dose - Pm_2O_3 Fuel, Iron Shield

Figure III-29. Comparison of Dose Rates 100 cm from Center of Source Versus Depleted Uranium Shielding Thickness

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K. Radiological Safety

It is unnecessary to pursue an extensive safety study as part of this program since the subject has been thoroughly investigated for larger generator designs with greater fuel content than will be realized with a milliwatt design. However, because of potential hazards associated with the use of nuclear material of any quantity, a basic safety philosophy and design criterion should be established.

The basic safety philosophy behind the use of any nuclear device is the assurance that the general populace will not be subjected to undue radiation hazards, internally or externally, resulting from an accident or system malfunction during any phase of system operation. To be more specific, fuel containment must be maintained under all conditions except when release does not constitute a health hazard as defined by the International Committee for Radiation Protection (ICRP). Emphasis must also be directed toward providing sufficient shielding to maintain safe radiobiological levels in the vicinity of the nuclear device. Control and accountability of the device and its fuel form represent one final segment in the overall nuclear safety philosophy.

To conform to the primary goals of the nuclear safety philosophy, the following criteria were established: (References 25 and 26)

- (1) Complete fuel containment under all conditions of intended use and credible accidents whether during normal operation, storage, or transportation phases. The fuel capsule must retain its integrity under the following conditions:
 - (a) Internal pressure resulting from the formation of helium gas due to alpha emitting fuel form (when applicable).
 - (b) External pressure due to hydrostatic forces which may reach 10,000 psi.
 - (c) High temperature and possible thermal shock (2000°F to 50°F).
 - (d) Impact at a velocity of approximately 100 ft/sec.
 - (e) A crushing force of 1000 pounds that may occur in transit.
 - (f) Normal shock and vibration experienced during transportation and installation.
- (2) The fuel form must be compatible with the containment material.
- (3) Containment material corrosion due to the effects of seawater, whether galvanic in nature or otherwise, should be minimized.

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- (4) ~~The radiation level must not exceed 200 mr/hr at the surface of the generator and 10 mr/hr at one meter from the generator centerline. A shipping cask may be used for handling purposes.~~
- (5) Because milliwatt generators are basically terrestrial or oceanographic in application, desirable fuel form properties should be included in the design criteria. Aside from the usual requirements of high melting point and good thermal conductivity, low solubility in fresh and salt water should be a design feature.
- (6) Fuel accountability and control from encapsulation through utilization and deposition should be maintained.

1. Containment

The first and foremost safety criterion is containment. Preliminary design studies indicate that the fuel should be doubly encapsulated with capsule materials chosen from Rene'41, tantalum, tantalum-10 tungsten, Haynes-25, hastelloy, and molybdenum. Capsule thicknesses will be approximately 0.050 inch. Generator housing material will be fabricated from either aluminum, stainless steel, or a superalloy. In addition to these materials, shielding and thermal insulation can also be considered as part of the containment.

a. External and Internal Pressure. Milliwatt generators are highly applicable to oceanographic uses. Therefore, the containment structure must be able to withstand hydrostatic pressures on the order of 10,000 psi that are experienced near the ocean floor. In addition to external pressure, the use of an alpha emitting fuel such as plutonium presents an additional internal pressure problem.

Realizing the significance of these pressure considerations, Larson-Miller data and stress-temperature curves were used as the starting point for the capsule design study. Consequently, every capsule design insured no loss of structural integrity due to either internal or external pressure. However, these calculations were carried out assuming a normal operating temperature of approximately 500°F.

During the transportation phase, fires represent a credible accident. The high temperatures typical of burning gasoline must be considered a distinct (but infrequent) possibility. Reference 25 shows the following accident frequency table.

TABLE III-12. ACCIDENT FREQUENCY RATE FOR GENERATOR SHIPMENT

<u>Type of Carrier</u>	<u>Probability of Accident per 1000 Miles</u>	
	<u>Minor</u>	<u>Major</u>
Air Cargo	1/5550	1/42,000
Truck	1/230	1/115,000
Rail Freight	1/3300	1/82,000

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The worst condition resulting from a transportation accident (aircraft) is expected to be on the order of 2000°F for a 30 minute period. (Reference 25)

If a quantity of helium gas is suddenly exposed to temperatures reaching 2000°F, the internal pressure of the gas may prove to be too great for containment. From the ideal gas relationship, $PV = nRT$, it is obvious that the gas pressure, P , varies directly as the temperature, T (all other factors being constant). Thus, if the temperature increases by a factor of four, so does the internal pressure. In order to maintain capsule integrity under these high temperatures, a safety factor of at least four or preferably, due to other capsule weakening forces such as corrosion and impact, five or six should be used in the capsule design.

b. Corrosion*. Since the generator housing material would be directly acted upon by a potential ocean environment, the effects of seawater corrosion were investigated for several of the proposed materials. Aluminum and stainless steel both react to seawater by pitting. Aluminum was investigated over a four year period and showed a 0-5 percent tensile strength loss due to corrosion. Galvanic corrosion must also be considered when using aluminum as housing material since a cathodic reaction can take place between the aluminum and other structural materials.

There are many grades of stainless steel. Those grades which are of primary consideration in housing fabrication, 310 and 316, show a pitting rate of approximately 7 mils per year. Other stainless steel grades, such as 304, pitted approximately 70 mils per year. In all cases of pitting, regardless of material used, the pitting rate is greatest in still water which is representative of conditions at the ocean floor.

Corrosion of the fuel capsule containment materials must also be considered. If a generator is either lost or deliberately not retrieved, the generator containment shell can be expected to be breached in a period of a few years under many circumstances, and the fuel capsule would be immediately exposed to the sea water environment if this were to occur. A number of suitable materials which are nominally considered for fuel capsule containment are listed in Table III-13. As may be seen, the corrosion resistance of the materials selected for use in the Milliwatt conceptual designs is excellent.

c. Thermal Considerations. It has been mentioned earlier that a high temperature fire represents a credible accident that may occur during transport or storage. Table III-14 shows the approximate melting temperature of several generator and capsule structural materials. In the event of a prolonged high-intensity fire in the range of 2000°F, the only material that will melt is aluminum. With the exception of tantalum and, to an excellent degree, molybdenum, the other materials will retain a reasonable degree of integrity although, of course, there will be considerable loss of tensile strength. This should not constitute a significant problem except in the case of an alpha emitting fuel, which may have caused a significant helium pressure to have been built up within the capsule. Retention of considerable wall strength would be very important in this

*Some portions have been taken from Reference 27.

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TABLE III-13. CORROSION CHARACTERISTICS OF TYPICAL
FUEL CAPSULE MATERIALS EXPOSED TO
SEA WATER

<u>Item</u>	<u>Corrosion Characteristics</u>
Rene'-41	No specific data are available, but corrosion characteristics are believed to be similar to Haynes-25.
Tantalum-10 Tungsten	Welded: 1.97×10^{-4} inches per year; Nonwelded: 1.19×10^{-4} inches per year.
Tungsten	No specific data are immediately available for sea water corrosion. However, it would be expected that tungsten would be very resistant to sea water because of similar behavior with the highly refractory materials. It is quite resistant to the action of acids.
Haynes-25	Welded: 4.71×10^{-4} inches per year; Nonwelded: 3.82×10^{-4} inches per year.
Hastelloy-C	Should be highly resistant to salt and fresh water corrosion. It is highly resistant to the action of acids, but no specific data of long term effects are available for sea water.
Molybdenum	Welded: 9.01×10^{-4} inches per year; Nonwelded: 3.06×10^{-4} inches per year.
Tungsten-25 Uranium	Welded: 1.65×10^{-3} inches per year; Nonwelded: 2.5×10^{-3} inches per year.

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case. This immediately implies that one of the refractory metals such as tantalum or molybdenum, would be desirable. These materials retain a significant degree of structural strength at elevated temperatures. However, the refractory materials are notorious for oxidizing in an air atmosphere at elevated temperatures. Further, molybdenum is difficult to fabricate and is quite brittle at lower temperatures. Tantalum, however, can be readily fabricated into fuel capsules and remains tensile under virtually all conditions.

TABLE III-14. STRUCTURAL MATERIAL MELT POINTS
(References 27 and 28)

<u>Material</u>	<u>Melt Point (°F)</u>
Aluminum	~ 1220
Stainless Steel	2500-2550
Hastelloy	2400-2800
Tantalum	~ 5400
Molybdenum	~ 3200
Rene'-41	2400-2500

As a result, a refractory type material is recommended for use as the primary containment vessel for the alpha emitting fuel forms. It is also recommended that it be retained for use in the nonalpha emitting generators because of the increased degree of safety which is realized.

The material selected for the designs presented in this study was tantalum-10 tungsten. This material has roughly the strength properties of tungsten, which are considerably greater than those of pure tantalum, and retains the fabricability characteristics of tantalum. Its melting point is considerably above that of pure tantalum, and its corrosion characteristics are excellent.

Since the refractory materials oxidize at high temperature, a second layer of material is added to provide protection against an oxidizing atmosphere. This material can be made of either Hastelloy or Haynes-25, or of Rene'-41. The fabricability of Rene'-41 is not as straightforward as that of the other two materials, which are very similar. The corrosion characteristics and degree of protection provided in oxidation-type atmospheres are excellent for all three.

The size of the milliwatt range generator and the structural materials utilized result in a negligible thermal shock problem for transportation type accidents. Although it is possible that thermal shock could seriously perturb the thermoelements and cause degradation of the generator output, this is not a safety consideration. It is concluded that, insofar as safety is concerned, there is no thermal shock problem.

d. Fuel Form Compatibility with Encapsulation Material. Compatibility between the fuel form and the encapsulation material has been discussed in Section III-A and will not be repeated here.

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2. Radiation Hazards

Biological hazards due to radiation can be divided into those due to direct radiation from the generator itself, and into those due to radiation resulting from fuel form release.

a. External Radiation Levels. Maximum acceptable radiation levels of 200 mr/hr at the generator surface and 10 mr/hr at one meter provided the initial design point for the radiation shielding effort. That is to say, the milliwatt generator will be designed and shielded so as to meet the prescribed nuclear safety limits with little or no overdesign. This shielding design criterion is primarily due to the intended oceanographic uses of milliwatt generators where water and distance both provide additional radiation shielding. In all cases studied, which ranged from fuel loadings of one thermal watt to 100 thermal watts, the 200 mr/hr generator surface dose rate was the dominant characteristic. Satisfaction of this value always resulted in a value at one meter of less than 10 mr/hr. These data may be compared to the body limits which are shown in Table III-15.

This comparison shows that a person would have to remain within one meter of the generator of the order of 10 to 20 hours per week before the most critical organs would have received the maximum permissible dose. This is considered to be unlikely and ordinary handling of the generators should cause no problems. If a person were required to remain close to the generator for extended periods auxiliary shielding could be provided to eliminate the radiation problem. Once the generator is installed in the ocean, a completely negligible external radiation hazard will exist.

TABLE III-15. RADIATION LIMITS FOR
EXTERNAL EXPOSURE
(Reference 29)

<u>Body Part</u>	<u>Maximum Permissible Dose</u>
Gonads	0.1 rem/wk
Blood forming organs	0.1 rem/wk
Lens of the eye	0.1 rem/wk
Hands and forearms	1.5 rem/wk
Skin	0.6 rem/wk

b. Radiation Release Hazards (Reference 30). If a fuel form release is to occur, either due to corrosion or an impact force, most probably it will be in water or such time as the generator is removed from its shipping container. In order to evaluate the degree of hazard, assume a typical two thermal watt Sr-90 fuel loading release to the ocean surface. This means that 300 curies of activity will begin to diffuse through the water. Horizontal diffusion rates in the ocean are high, but vertical diffusion rates decrease and become negligible below a depth of approximately 100 meters. Immediately after a release, before the activity has been diffused over more than a one square mile area, the strontium activity concentration can be calculated to be $1.17 \mu\text{c}/\text{m}^3$ which is greater than

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the maximum permissible concentration of $1 \mu\text{e}/\text{m}^3$. However, horizontal diffusion rates are high in the ocean due to currents and up-swirls and will quickly reduce any significant radiation concentrations to safe permissible levels. Deep down on the ocean floor the generators are completely safe, even in event of fuel release via corrosion.

Strontium titanate is virtually insoluble in fresh water and is soluble to approximately 10 parts per billion in sea water (Reference 31). Since the titanate fuel form is virtually insoluble, the activity will remain concentrated in the fuel capsule itself for a long period of time, even though the capsule containment is breached. This means that the maximum concentration which may be reached in sea water is far below the value previously mentioned (above) because those values were based upon an instantaneous release of the soluble fuel. It is concluded that release of the fuel in an ocean environment is not a serious problem provided the fuel capsule remains intact and is not physically crushed to a small size which may be dispersed.

It is also possible that milliwatt range generators may be used on land. Here, the insoluble fuel form is also an important consideration since, if the capsule containment is breached, the fuel form again will not dissolve in water and as a result cannot contaminate the watershed area. The only dispersal technique that need be considered for surface-type contamination is physical scattering of particles of the fuel due to wind or water action.

The plutonium dioxide fuel form is normally considered to be insoluble in any media encountered in the natural environment, subject to the restriction that it is not presently known whether the radioactive decay of the plutonium-238 has an accelerating effect on solubility (Reference 32). The water solubility rates of plutonium dioxide are shown in Table III-16. These data, taken from the Monsanto Plutonium-238 Fuel Data Sheets (Reference 3), indicate that release rates of the order of $10^{-3} \text{ gm}/\text{mm}^2$ per day for periods of 13 to 175 days will occur. The material is not identified in the reference as to whether it is in pellet form or microsphere form.

This reference also gives information pertaining to the solubility in other chemicals. It is stated that the dioxide powder dissolves slowly in mineral acids at elevated temperatures and, further, the solubility is affected by the previous history of the oxide.

Other information available in the literature indicates that plutonium dioxide is stable in oxidizing and neutral atmospheres. No volatile higher oxides exist (see Reference 33).

No specific data are available for the solubility of promethium. However, sintered pellets of other lanthanon sesquioxides disintegrate in boiling water tests and there results an alkaline solution which indicates the formation of a soluble lanthanon hydroxide (Reference 7).

Promethium is reported to have only one valence state, the +3 state. It is therefore expected that only the one oxide, Pm_2O_3 , will be formed and that if formed, it will be stable in an oxidizing atmosphere (Reference 6).

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TABLE III-16. SOLUBILITY OF Pu-238 O₂ IN WATER

(Reference 1)

<u>Sea Water</u>					
<u>Sample</u>	<u>Area mm²</u>	<u>Slope*</u> <u>μgm/day x 10²</u>	<u>For Days</u>	<u>Release Rate</u> <u>μgm/day-mm² x 10³</u>	<u>y-axis*</u> <u>Intercept</u>
1-F 17	35.81	3.53	13 - 175	1.19	+1.07
2-F 17	42.58	5.56	13 - 175	1.31	+2.08
3-F 17	54.69	4.57	13 - 175	0.84	+2.89
<u>Distilled Water</u>					
1-F 17D	82.69	11.3	13 - 175	1.37	+2.47
2-F 17D	46.32	5.89	13 - 175	1.27	+1.19
3-F 17D	76.79	10.3	13 - 175	1.34	+1.95

* All data determined by the least squares method.

As with water, the solubility of this fuel form in various chemicals is not known. About the only information that is available is that the similar form, the lanthanon sesquioxide, dissolves rapidly in acid solutions (Reference 8).

It is considered probable that insoluble promethium compounds, such as the titanates, can be produced and if this is done, then the solubility problem of this fuel form will be considerably reduced or made entirely negligible. However, this will result in a dilution of the fuel form with a lower power density resulting. This, in turn, will produce a less attractive fuel form.

Maximum permissible concentrations of the three fuels are given in Table III-17. The behavior of fuel release into the air may be compared with these permissible concentrations by considering the Seale and Couchman modification of the Sutton equations (Reference 34).

TABLE III-17. MAXIMUM PERMISSIBLE CONCENTRATIONS
(Reference 35)

	(μ curies/cc)			
	<u>40 hr week</u>		<u>168 hr week</u>	
	<u>Water</u>	<u>Air</u>	<u>Water</u>	<u>Air</u>
<u>Pm-147</u>				
Soluble	6×10^{-3}	6×10^{-8}	2×10^{-4}	2×10^{-9}
Insoluble	6×10^{-3}	10^{-7}	2×10^{-4}	3×10^{-9}
<u>Pu-238</u>				
Soluble	10^{-4}	2×10^{-12}	5×10^{-6}	7×10^{-14}
Insoluble	8×10^{-4}	3×10^{-11}	3×10^{-5}	10^{-12}
<u>Sr-90</u>				
Soluble	4×10^{-6}	3×10^{-10}	10^{-7}	10^{-11}
Insoluble	10^{-3}	5×10^{-9}	4×10^{-5}	2×10^{-10}

*Reference 35

These are:

$$\bar{X} = \frac{2 \bar{Q} \exp(-h^2 / C_z^2 x^{2m_z})}{\mu C_z C_y x^{(m_y + m_z)}} \quad (\text{III-109})$$

for inversion conditions:

C_y	=	0.44	diffusion coefficients
m_y	=	0.69	
C_z	=	0.20	stability parameters
m_z	=	0.73	
μ	=	3 m/sec, mean wind speed	
$\bar{Q}$	=	source strength, curies	
x	=	point downwind, m	
$\bar{X}$	=	concentration at x, curies-sec/m ³	
h	=	height of release, m = 2m	
$\bar{X}$	=	$\frac{2 \bar{Q} \exp \left[-4 / (0.04) (x^{1.46}) \right]}{(3)(0.20)(0.44)(x^{1.42})}$	
$\bar{X}$	=	$\frac{2 \bar{Q} \exp \left[-10^2 x^{-1.46} \right]}{0.83 x^{1.42}}$	

Assume: 30 watt(th) x 0.033 = 1 watt(e)

Sr, 30 watt x $\frac{150 \text{ curies}}{\text{watt}}$ = 4500 curies

Pu, 30 watt x $\frac{30 \text{ curies}}{\text{watt}}$ = 900 curies

Pm, 30 watt x $\frac{2770 \text{ curies}}{\text{watt}}$ = 83100 curies

The results of applying these equations with the corresponding data are shown in Figure III-30. Here, a fuel release occurring at a steady-state rate over a specified period of time is considered at a two meter altitude. With a wind speed of 3 meters per second, the activity concentrations at ground level are presented as a function of distance measured downwind from the release point.

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Figure III-30. Downwind Activity Concentration Subsequent to Fuel Release

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A similar calculation may be made for seawater activity concentration as a function of position. Again, an equation from Eisenbud may be utilized:

$$C_m = \frac{Q}{2D} \frac{1}{2} \frac{1}{k u x} \quad * \quad \text{(III-110)}$$

where:

Q = source strength, curies/sec

D = depth, meters - (30 m)

u = current velocity, m/sec - (1 m/sec)

k = diffusion constant, m²/sec - (10⁻⁴ m²/sec)

x = distance from source, m

C_m = activity concentration, curies/m³ or $\mu\text{c/cc}$

$$30 \text{ watts(th)} \times 0.033 = 1 \text{ watt(e)}$$

$$\text{Sr, } 30 \text{ watts} \times 150 \frac{\text{curies}}{\text{watt}} = 4500 \text{ curies}$$

$$\text{Pm, } 30 \text{ watts} \times 2770 \frac{\text{curies}}{\text{watt}} = 83,100 \text{ curies}$$

$$\text{Pu, } 30 \text{ watts} \times 30 \frac{\text{curies}}{\text{watt}} = 900 \text{ curies}$$

$$1 \text{ wk} = 6.04 \times 10^5 \text{ sec}$$

$$1 \text{ mo.} = 2.59 \times 10^6 \text{ sec}$$

$$1 \text{ yr.} = 3.11 \times 10^7 \text{ sec}$$

$$4500 \frac{\text{curies}}{\text{wk}} = 7.45 \times 10^{-3} \frac{\text{curies}}{\text{sec}}$$

$$83,100 \frac{\text{curies}}{\text{wk}} = 1.38 \times 10^{-1} \frac{\text{curies}}{\text{sec}}$$

$$900 \frac{\text{curies}}{\text{wk}} = 1.49 \times 10^{-3} \frac{\text{curies}}{\text{sec}}$$

These data are presented in Figure III-31, which shows the activity concentration as a function of distance downstream from the source for an ocean depth of 30 meters and a current velocity of one meter per second.

*Reference 34

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Figure III-31. Downstream Activity Concentration Subsequent to Fuel Release

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3. Accountability and Control

The Atomic Energy Commission has placed a 10 cm minimum external dimension on any packages which contain radioisotopes. This size has been defined because it has been felt that smaller sizes could be misplaced, which might result in a potentially dangerous situation. It is quite possible that radioisotope fuel generators in the large milliwatt range could violate this restriction, and in that case special shipping containers would have to be used.

During transportation and storage, it is presently felt that fuel accountability and control should be maintained. This will assure that quantities of radioisotope fuel are not misplaced and forgotten in situations where fuel release due to gross mishandling could occur.* Many of the generators installed in deep ocean will be considered as disposable devices. Once such an installation has been made, it appears reasonable that there will be no potential safety problems, and fuel accountability and control may be relaxed.

*For example, someone could discover a generator, and, not realizing what it is, decide to take it apart to find out what is inside. Although fuel capsules are exceedingly strong, it is possible that they could be deliberately opened.

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IV. DATA PRESENTATION

A. Introduction

A careful consideration was given, at the beginning of this program, to the quantity of data which had to be presented if the entire parametric study results were presented directly. It was immediately determined that this was infeasible in all forms. The alternatives were to either present a portion of the results of the study or to present the study results in such a way that accurate and concise calculations could be performed as needed. Investigation of the former approach immediately showed that the quantity of information was still prohibitive insofar as a concise presentation was concerned. At best, it appeared that of the order of 100 to 300 graphs would be required or a large amount of tabular information would have to be presented. The usability of this information was considered to be of limited value, and this approach was excluded. This left a concise and relatively rapid calculation of the large milliwatt generator behavior as the most desirable technique.

This technique has been followed in the presentation of most of the results of this program. The overall result has been the generation of four nomographs (located in Appendix B), a coined word taken from the use of nomogram as well as graphs in combination. The first, and most useful, of the nomographs presents overall design characteristics of the generator system. The second nomograph gives the surface temperature of a particular generator when operating in air, and enables the cooling fins to be designed so that it will operate in air at a specified temperature. The third nomograph presents cost information in terms of the applicable design characteristics, and the fourth enables detailed thermoelement characteristics to be defined, if desired. This last nomograph will probably be used the least since this amount of detail is seldom required in the determination of overall generator characteristics.

The use of all nomographs is similar, and it is intended that each nomograph be completely self-explanatory. A sample problem is included, printed in red, to illustrate the steps involved in performing the calculations. Further, there is generally reproduced a list of typical values which may be used as the starting point of the investigation. Therefore, nomograph use involves the selection of the necessary dependent variables, and then paralleling the sample problem, which is numbered from step to step, to obtain the desired dependent characteristics. Once this has been done for one design, the effect of perturbations may, in many instances, be readily investigated by utilizing only a small portion of a nomograph to evaluate the effect of changes. This has the additional attractiveness of yielding a quick "engineering feel" for the problem which is many times lost in other approaches. This engineering feel in turn leads to the development of an intuitive feeling for the effects of perturbations on a particular design and also can result in the more rapid generation of the best design for a particular application.

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B. Use of Nomograph #1

It is best to prepare a list of the independent variables which must be selected prior to beginning work with the nomograph until the calculations technique has become completely familiar. This will prevent becoming "lost" in the construction process. The following variables will be necessary in Nomograph #1:

- (1) Hot junction temperature
- (2) Thermoelement material
- (3) Cold junction temperature
- (4) Power conditioner input voltage
- (5) Insulation efficiency
- (6) System power output
- (7) Design life
- (8) Fuel
- (9) Void fraction if the fuel is plutonium and of the low power density form
- (10) Fuel capsule length-to-diameter ratio (for both the inside and the outside of the fuel capsule)
- (11) Temperature drop between the heat source and the hot junction
- (12) Temperature drop between the cold junction and the generator case
- (13) Insulation thermal conductivity

In addition, if strontium-90 is used as the fuel form and it is decided to obtain shielding characteristics, the shield material must be selected. Other variables required will have been previously calculated.

The calculation process in Nomograph #1 is begun by locating the number "1" near the righthand side of the nomograph roughly one-third of the way from the top. The large arrowhead at the circled number indicates that the initial direction is upward. The note beside the number "1" indicates that the hot junction temperature is to be selected. (Note the list of typical values presented in red to the left of this point.) The sample problem is based on an initial selection of 550°F.

The indicated direction of travel leads to point 2 where the cold junction temperature and the material are to be selected. Note that the direction of travel between points 1 and 2 is vertical. The light blue background on the nomograph is provided as an aid in this process.

The next move is horizontal to point 3 where the thermoelectric efficiency of 0.5 is determined. The large arrowhead above the number "3" indicates the direction to number "4". Here, the power conditioner input voltage is to be selected, and travel to point 5 indicates that the end-of-life power output is to be selected. Horizontal movement to point 6 then determines the power con-

ditioner efficiency. Point 7 is then determined by connecting points 3 and 6 by a straight line. A horizontal line from point 7 to the intersection of the sloped line gives point 8.

A vertical line constructed downward from point 8 leads to point 9 where the insulation efficiency is to be selected. This, by definition of the ratio of the insulation heat loss to the heat generated within the heat source, is ordinarily taken at the end-of-life conditions. Typical values will range from 0.6 or 0.7 for small generators to 0.8 or 0.85 for the larger generators. A perturbation of the order of 50 percent may additionally be expected due to the thermal insulation. The use of Min-K is strongly recommended for all systems and, if an air-filled Min-K is used, the thermal conductivity is almost twice that of xenon-filled.

A horizontal line constructed from point 9 determines the end-of-life efficiency at point 10. By this time, it is quite reasonable that certain selections of parameters could have resulted in the horizontal line failing to intersect with the end-of-life efficiency line. If this occurs, in virtually all situations it will indicate that the selection of previous independent variables has been taken in either an unattractive or an unrealistically optimistic manner, and new selections should be made.

The intersection of the extension of the straight line between point 9 and point 10 to the line representing the previously selected power output defines point 11. The horizontal dashed line located between point 11 and point 12 illustrates the calculation technique to obtain the end-of-life heat flow through the thermoelements if this is desired. As may be seen, the intersection of line 11-12 was the end-of-life power line (defined as 1 watt) determines the beginning of the horizontal dashed line. This is followed to the indicated 45 degree line, then projected downward to the previously selected insulation efficiency, and then "bounced" horizontally, and end-of-life heat flow through the thermoelements of 5.6 watts is immediately determined.

The vertical line from point 11 intersecting with the previously defined insulation efficiency of point 6 defines point 12. A horizontal line constructed from this to the insulation efficiency line of 1 defines point 13, and a vertical line downward immediately determines the end-of-life insulation heat loss. Illustrated is 3.6 watts. Continuation of this line to the intersection with the sloped reference line as shown defines point 15, and a horizontal line constructed from this point to the illustrated vertical reference line defines point 16. This point will be required later in the construction process and should be noted for future reference. The large arrowhead shows the direction of travel back to point 17, where another large arrowhead indicates the downward direction. Traveling in the direction as illustrated determines the end-of-life fuel requirements, shown as point 18. Selection of the type of fuel to be used and the design life at point 19 immediately determines the beginning-of-life fuel which must be provided at point 20. Continuation of this line will determine point 21.

The determination of point 21 for promethium-147 and strontium-90 is straightforward. It is only necessary to define the fuel. However, a number of selections are possible if plutonium-238 is to be used. Two fuels are illustrated, and the information presented in the nomograph in relation to these fuels is necessarily limited for classification reasons. The low power density fuel is

the oxide [REDACTED] This is presented as a function of void fraction ranging from 0 to 0.9. Ordinarily, a void fraction of 0.5 should be selected, and the resulting design will be completely sufficient for virtually all uses. The high density fuel illustrated is not presented as a function of the void fraction because this could immediately lead to supposition concerning what the fuel was and could lead to a determination of its properties. The high density fuel form is the metallic form, and it is presented only for a fifty percent void fraction. The behavior for other void fractions may be immediately determined by using the same spacing as shown for the low density form and progressing as for the void fractions that are illustrated.

The vertical line constructed downward from point 21 immediately leads to point 22. The steps between point 22 and point 30 are somewhat complex. In virtually all cases, the most attractive fuel capsule will be one in which the length and diameter of the capsule are equal. In this case, it is only necessary to continue on downward using the same straight line as determined from point 21 to point 22 to determine the capsule length and diameter at point 30-C. This dashed line is also continued onward to illustrate the calculation procedure where the capsule length and diameter are considered the same. Both calculations would follow this approach. It is recommended because it is simpler and more rapid than for an unequal length-to-diameter ratio, and further, it will generally result in a more attractive design.

If the length and diameter are not to be considered equal for some reason, then the direction of travel from point 22 to point 23 is illustrated by the large arrowhead. At point 23, the desired inside capsule length-to-diameter ratio is to be selected. A straight line should be constructed downward from point 23 to point 24, a permanent point illustrated by the large black dot. The intersection of this line with the straight horizontal reference line specifies point 25. A vertical line upward to the original fuel capsule length-to-diameter ratio line defines point 26. Point 22 should then be connected to point 26 to define point 27. The construction of a straight line between point 27 through point 28-A, another permanent point, will determine point 29-A. A straight line from point 27 through the selected length-to-diameter ratio will define point 29-B. Vertical lines constructed downward from points 29-A and 29-B will determine the diameter at point 30-A, and the length at point 30-B, respectively. The diameter that has been determined, shown at point 30-A, can now be connected to the capsule side wall thickness to determine point 31. A horizontal line immediately determines the outside diameter of the capsule at point 32. A similar construction using the capsule end thickness, normally twice the side wall thickness, will determine the capsule outside length, also illustrated as point 32. If the inside diameter and length are equal, and, as an approximation, the end and side wall thicknesses are also considered to be equal, then the dashed line may be followed to determine the capsule outside diameter and length which are both the same. The selection of a wall thickness roughly halfway between the side wall and the end cap thickness for this equal length and diameter situation will approximately compensate for the realistic situation where the end wall thickness is greater. This yields a more realistic number.

At this point the discussion will be restricted to the unequal capsule outside diameter and length situation. The equal length and diameter will be discussed later.

After the outside diameter and length have been obtained at points 32, both of the lines 31 to 32 should be extended in a horizontal manner as shown. The intersection of the diameter line with the 45 degree reference line defines point 33, and a vertical line constructed downward from the slope intersection will define point 34. This point will be needed later in the construction process, and should be noted. Further extension of the diameter line will define point 35, and extension of the length line parallel to it will define point 36. A line should now be connected between point 36 and the permanent point, indicated as 37. The intersection of this line with the vertical reference line located between these points defines point 38. A straight line is then constructed from point 35 through point 38 and extended until it intersects the vertical reference line. This intersection defines point 39. A horizontal extension from point 39 toward the left as indicated defines point 40 at the intersection with the sloped reference line. A vertical line should be constructed through this point so that it covers the parameter Z graph. This line should be saved.

Construction next begins at point 41, which is identical to point 1. In this case, the direction is downward to point 42 where the temperature difference between the hot junction and the heat source is to be determined. The heat source temperature that should be used in this determination is the average heat source surface temperature. This parameter will be used to determine the insulation heat loss. The horizontal construction from point 42 will determine point 43 when the temperature drop between the cold junction and the average case temperature has been defined. A vertical line constructed downward from point 43 will intersect the previously selected cold junction temperature at point 44, and a horizontal extension of this point to the curved line will define point 45. A downward extension from point 45 to the thermal conductivity of the insulation determines point 46, and the intersection of a horizontal extension of this with the vertical line defining the edge of the graph will determine point 47. A construction may now be made by connecting a straight line from point 47 through the previously determined point 16 to define point 48, a horizontal construction to the sloped reference line as shown gives point 49, and a vertical construction to the horizontal line will define point 50. The previously determined point 34 may now be connected to point 50. The intersection of this line with the horizontal reference line defines point 51. (The point indicated on the nomograph is for a length and diameter equal situation, the dash line. The point 51 for this situation is right beside it, and is connected to the solid lines.) A vertical construction from point 51 to the vertical reference line indicates point 53. Continuation of line 52-53 will give an intersection in the graph with the previously extended point 40. This defines the parameter "C." This parameter may then be used to determine point 55 on the parameter Z coordinates, located in the center at the bottom of the nomograph. Connection of this point 55 to the previously determined outside diameter, point 32, immediately defines the insulation thickness at point 56.

If an equal capsule outside diameter and length were to be used, indicated by the dashed lines, an extension from point 32 may be made to the sloped reference line as indicated (essentially point 33), and a downward vertical line may be constructed to define point 34. At this junction, the construction should proceed directly to point 41 and points 41 through 53 should be followed as previously discussed. An extension to the right of the now-constructed line 52-53 will intersect the red line which is indicated by a 40 with the note, "40 will determine this line if length and diameter are equal," and hence the parameter Z will be immediately determined.

The parametric studies conducted under this program indicated that for practical purposes there would be no shielding problems with the promethium and plutonium fuel forms. As a result, no shielding information for these materials is presented on the nomograph. This is not the case with strontium-90. A complete presentation of the shielding characteristics for this fuel would require a fairly complex nomograph. However, virtually all generators designed for strontium-90 for the milliwatt series would be designed with a shield outside length to diameter ratio of 1 to minimize the shield weight, as well as in some cases to maximize the conversion efficiency. A relatively concise presentation of shield information for a length to diameter ratio of 1 is possible, and this has been incorporated into the nomograph. Point 57 refers to a graph of the shield thickness required as a function of shield material, quantity of radioisotope to be shielded, and insulation thickness. The quantity of material to be shielded is presented in watts, and the value to be used is the beginning of life or maximum fuel loading. The insulation thickness referred to is the insulation inside of the shield. For a generator with a total quantity of insulation outside of the shield, and no void within the shield, this would be zero. Three shield materials are listed: iron, lead and depleted uranium. The shield thickness resulting from this presentation is the value which will give 200 mr/hr at the surface. The value at 1 meter will always be less than 10 mr/hr when the specified thickness is used.

The remainder of the nomograph, points 58 through 69, are used if further shield information is required.

Item 58 refers to a graph from which an input of shield thickness, the shield material and the inside shield radius will yield the shield weight. The inside radius will be immediately available from the dimensions which have been obtained through previous use of the nomograph. Item 59 refers to a technique for working "backwards" to obtain a new shield thickness which corresponds to a different shield weight. Illustrated is the technique for obtaining the shield thickness corresponding to a design which weighs half of the 200 mr/hr design. If a different weight or thickness shield is desired than that obtained for 200 mr/hr, the dose rate at the surface may be evaluated by locating both the new and 200 mr/hr shield outside radii at point 60 as illustrated (the shield outside radius will be readily determined since the inside radius is known, as is the shield thickness).

The new value selected for the shield thickness is first connected to the permanent point A, indicated by the X, to define point 61. The 200 mr/hr shield outside radius, indicated also at point 60, is then connected by a straight line through point 61 to determine point 62. The new and old shield thicknesses are next located on the graph on the upper right hand side of nomograph number 1 as indicated by point 63. The 200 mr/hr thickness immediately will determine point 64 as shown. The new value of shield thickness will determine point 65. The intersection of the line constructed from connection of point 65 to the permanent point C and the vertical reference line located between these points defines point 66. Point 64 is then connected to point 66 by a straight line to define point 67 as shown and connection of the point 67 to the previously determined point 62 immediately defines 68. A line may now be constructed between the permanent point B and point 68 to define the dose rate corresponding to the new shield thickness at point 69.

Once familiarity with the nomograph has been obtained it is relatively easy to use small portions to perform selected variations in the parametric performance. For example, if the required insulation thickness for several different insulations were to be evaluated for a particular selection of temperatures and insulation efficiency, points 16, 34, and 45 could be considered as fixed and the insulation type could be varied by simply changing the thermal conductivity which perturbs point 46. Immediately, then, points 47, 48, 49 and 50 will follow. Connection of 50 to 34 will determine 51, and hence 52, 53, and 54. This leads directly to the point 55 and connection of 55 to the previously defined 32 will give the new insulation thickness for the different insulation at point 56. A number of similar variations and the perturbation upon selected parameters may also be performed.

C. Use of Nomograph Number 2

Nomograph number 1 utilized as one independent variable the cold junction temperature and as well the temperature difference between the cold junction and the average case temperature. This essentially implied that the generator operational surface temperature is known. If the intended use of the generator is for an oceanographic application, then the temperature drop between the ocean water and the generator surface will be negligible and the generator surface temperature will actually be known. However, if the generator is to be used in air, the surface temperature may be considerably above the ambient air temperature. In this case it will be necessary to show that the assumed surface temperature (and the resulting cold junction temperature) has been realistically selected. Nomograph number 2 provides for this calculation. Further, if the assumed temperature is insufficient to reject the unconverted heat, the nomograph will enable fins to be added to the generator. A selected surface temperature higher than shown to be the case in nomograph number 1 will introduce no problem because the generator performance will be essentially as previously calculated, and the only perturbation will, for practical purposes be a reduction in operating temperatures.

The following items will be required for the determination of surface temperature in nomograph number 2:

- (1) Generator outside length
- (2) Generator outside diameter
- (3) Generator heat rejection rate

In addition, if fins are to be sized, the following independent variables must be selected:

- (1) Fin Thermal conductivity
- (2) Number of fins
- (3) Fin thickness
- (4) Desired surface temperature (for air operation with the ambient air at 72°F)

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The initial point 1 (number 1) is located approximately in the center of this nomograph. Here, the case length is to be selected. A horizontal line constructed from this point and intersecting with the selected case diameter will define point 2, a vertical line immediately defines point 3, and connection through the selected heat rejection rate, point 4, will define point 5. Point 5 may now be extended vertically to the case diameter line to define point 6, and a horizontal extension to the right of point 6 will define point 7, the surface temperature of the generator in 72°F air if there are no fins. If this temperature is equal to or less than the previously assumed temperature that was used in nomograph number 1, no fins are necessary, and there is no need to work further with nomograph number 2. However, if it is determined that the generator surface temperature will be higher than assumed, then either fins must be added to the generator, or its characteristics must be changed. The remainder of nomograph number 2 will allow fins to be added to the generator and will predict the characteristics of those fins.

At point 8, located on the left hand side of the nomograph, the desired surface temperature is selected. A vertical line then is constructed to intersect with the previously determined case diameter, and a horizontal extension of this line will define point 10. At point 11, the fin thermal conductivity is to be selected. Connection of point 11 through point 10 with a straight line will define point 12. At point 13 the number of fins is to be selected (when this is done, care should be taken that there is actually room on the generator surface for the number of fins selected, and that there is sufficient space between the fins for air to circulate in a relatively unimpeded manner). Connection of points 13 and 12 will define point 14, the intersection with the indicated vertical line. At point 15 the fin thickness is to be selected (the same comments as applied in the determination of point 13 are applicable here as well). A straight line may now be constructed between points 15 and 14 to determine point 16. This point should be recorded for future use. Point 17, the case diameter previously selected, should be used and at point 18 the number of fins should be determined as previously selected. A straight line connected between points 17 and 18 will determine point 19. This point should be recorded for future reference. A vertical line constructed from point 19 to the desired surface temperature defines point 20. A projection of this point to the vertical reference line defines point 21. A straight line may now be connected between point 21 and the permanent point, P, to determine point 22. The previously recorded point 16 may now be connected to point 22 to define point 23, and a horizontal extension of point 23 will define points 24 and 25. The line connecting these two points should be recorded for future reference. At point 26 the surface temperature is to be referenced. A horizontal projection to the reference case diameter defines point 27, and a vertical line extended downward to the horizontal reference line specifies point 28. The case length, and diameter are referenced at point 29, and point 30 respectively. From these, point 31 is immediately determined. Points 28 and 31 may now be connected to determine point 32, and immediately the parameter "A" is defined by the scale. Point A should be recorded as indicated at point 33. The previously selected fin thickness should be referenced on the scale to define point 34, and a construction between this and the previously recorded point 19 will define point 35. A vertical line constructed downward from point 35 and intersecting with the previously selected surface temperature will define point 36, and a horizontal line from this intersection will lead to point 37, which is defined as B. This value of B should be recorded as indicated at point 38. The case length is again referenced at point 39, and the amount of heat which

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must be rejected is referenced at point 40. Connection of points 39 and 40 will define point 41. A vertical to the surface temperature which has been previously selected will determine point 42, and a horizontal line projection defines parameter C. C should be recorded as shown at point 44. Step 45 indicates that B is to be subtracted from A, and step 46 indicates that C should be subtracted from the previously determined number to obtain the parameter D. Point 47 is merely an indication that the previously determined point 16 should be extended horizontally to point 48, the intersection of the indicated sloped line. Point 49 is then determined by a vertical line as shown, and point 50 is the negative value of the previously determined parameter D. Connection of points 49 and 50 will then lead to point 51, which gives the negative value of E. This negative value of E may then be used to determine point 52, located at the intersection of the parametric lines representing E, and the previously determined horizontal connecting line points 24 and 25. A line constructed downward from this intersection point will determine the fin height which is necessary as indicated at point 53.

If the determined fin height is not as desired, further calculations may be performed to determine how it may be changed by making various selections of independent variables. As was the case in nomograph number 1, many of these changes may be investigated by using only a small portion of a nomograph. The techniques whereby this can be done will become obvious as experience is gained in using the nomograph for calculations.

D. Generator Cost Analysis

Nomograph number 3 presents a calculational technique for estimating the cost of a generator. To utilize the nomograph will require the following items:

- (1) Power conditioner efficiency
- (2) System power level
- (3) Insulation efficiency
- (4) Fuel
- (5) Thermoelectric efficiency
- (6) Generator life time
- (7) Fuel cost/watt
- (8) Shield weight
- (9) Shield cost/lb
- (10) Interest rate

The starting point for this nomograph is located in the upper left hand corner. To begin, the power conditioner efficiency is to be selected at point 1 and the power desired from the system at point 2. Connection of points 1 and 2 by a straight line will immediately determine point 3, and a vertical line constructed downward from point 3 will determine point 4 at the intersection with the curved line. A horizontal extension of this line will give point 5, the cost of the generator exclusive of the shield, fuel, and fuel encapsulation charges.

Selection of the previously determined insulation efficiency at point 6, and connection of point 3 and point 6 will yield point 7. At point 8, the thermoelectric efficiency is to be selected, and a straight line connected between points 7 and 8 will yield point 9, the intersection with the indicated horizontal line. A vertical extension of point 9 to the intersection of the fuel and operational life will define point 10, and a horizontal extension of this line will yield point 11 as shown. Point 12 may be determined by selecting the fuel cost/unit of fuel, and connection of points 11 and 12 will define the purchase price of the fuel at point 13.

If it is desired to determine the lease cost of the fuel rather than the purchase price, the lifetime may be referenced at point 14, and points 15 and 17 will be immediately determined by selecting the interest rate (which defines 15) and referencing the fuel. A vertical extension of point 15 to the indicated horizontal line will define point 16 and a vertical movement of point 17 will define point 18. Connection of points 16 and 18 will yield point 19, which then may be extended vertically to define point 20, and horizontally to define point 21. Connection of point 21 with the previously determined fuel purchase price, point 13, will determine the total cost of the fuel on a leased basis, point 22.

The use of the nomogram for determining shield cost is very straightforward and has not been numbered. This nomogram is located just to the right of the starting point. It may be used by selecting the shield weight on the indicated scale, and selecting the shield cost/unit weight on the other indicated scale. A straight line connected between these two selected points will immediately determine the shield cost in dollars.

E. Nomograph Number 4, Calculation of Thermoelement Characteristics

If desired, nomograph number 4 may be used to determine the open circuit voltage per couple, the generator load voltage, the P and N element shape factors, the element cross sectional areas, and the element diameters. To perform these calculations will require the following items:

- (1) Power conditioner efficiency
- (2) System power output
- (3) Hot junction temperature
- (4) Cold junction temperature
- (5) Generator load voltage
- (6) Number of couples
- (7) Thermoelectric material
- (8) Thermoelement length

The starting point for this nomograph is located at the center top, where the power conditioner efficiency is to be selected at item number 1. The output power from the system is to be defined at point number 2, and the generator output power is immediately determined by connecting points 1 and 2 as shown at point 3. Point 3 should next be connected to the permanent point 5, which defines point 4 by the intersection as shown. A vertical line constructed from

point 4 will define point 6 which should be recorded for future reference. At point 7, the hot junction temperature is to be selected, and at point 8 the material and cold junction temperature must be selected. This will lead to point 9, which should be noted for future reference. This will also be the open circuit voltage per couple if it is desired to record this value. At point 10, the previously selected hot junction temperature should be used, and at point 11 the cold junction temperature and material should be referenced. Points 10 and 11 will yield point 12, which should also be recorded for future reference. A horizontal extension of point 12 to an intersection with the curved line will define point 13 as shown, and a vertical extension of point 13 will define point 14 at the horizontal line. This point should also be recorded for future reference. Point 15 may now be determined by connecting the previously found points 9 and 12. Point 16 will be determined by the horizontal extension from point 15 to the indicated slant line. A vertical projection downward of point 16 will define point 17, which should also be recorded for future reference. An upward extension of point 16 will lead to definition of point 18. At point 19, the generator load voltage desired should be selected. Point 20 may now be determined by connecting points 18 and 19 with a straight line. This point indicates the number of couples required in the generator if all couples are to be series connected. The number of couples for series-parallel connection or for simple parallel is simply the number of parallel paths times the number of couples indicated at this point.

Point 20 may now be connected through the previously determined point 6 to define point 21. Connection of point 21 with the previously determined point 17 will yield point 22, and connection of point 22 with the previously defined point 14 will yield point 23. This point may be extended vertically to the slant line as indicated at point 24, and horizontally to the vertical line at point 25. Point 26 is defined by the intersection of the hot junction temperature coordinate with the thermoelectric material and the cold junction temperature lines. A horizontal extension immediately determines point 27, and connection of points 27 and 25 will yield point 28, the shape factor for the P type thermoelement. This point should be noted for future reference in the construction process.

A horizontal extension of point 28 to the slant line will define point 29, and a vertical extension of this point will yield point 30, which should be noted. The thermoelement length may be selected to define point 31, and connection of points 30 and 31 yields the thermoelement cross sectional area and diameter as shown at point 32 for the P type thermoelement. The characteristics of the N type thermoelement may be determined by referencing the hot junction temperature at point 33, and the cold junction and material at point 34. Point 35 will result. Point 35 and the previously determined point 28 may now be connected to define point 36, the negative type thermoelement shape factor. Horizontal extension of point 36 to the slant line will define point 37, and a vertical projection of this will define point 38. Connection of point 38 to the previously selected thermoelement length at point 31 will define point 39, the negative type thermoelement cross sectional area and diameter.

F. Further Design Considerations

These four nomographs may be used to obtain additional information which has not been previously discussed, but which can be important in designing of a milliwatt range thermoelectric generator for a particular application.

One of the biggest problems is to assure an adequately low temperature at the beginning of life when an excess of fuel is provided. As an example, the use of bismuth telluride as the thermoelectric material will be attractive in many of the large milliwatt designs. Bismuth telluride can be operated for extended periods to approximately 550°F. Temperatures in excess of this will cause rapid degradation of the material, with a corresponding decrease in the electrical output of the generator. If a generator is designed to operate at a hot junction temperature of 550°F at the end of life, the excess fuel at the beginning of life will cause this value to be exceeded, and generator degradation will result. Similarly, if a generator is designed to operate in air at 72°F with a hot junction temperature of 550°F, its exposure to air at 125°F will cause overheating and generator degradation. This must obviously be avoided.

One of the easiest corrections to make involves the variation of the generator case temperature with changes in the surrounding ambient temperature. In this case, it may be assumed that the temperature difference between the generator case and the surroundings remains constant. Since nomograph number 2 is based on 72°F air, the difference is easily determined. Changes in the ambient air temperature may then be converted to changes in the generator case temperature.

The effect of the amount of heat that is rejected is similarly straight forward. In this case, the temperature difference between the generator case and the surrounding ambient air may be ratioed directly with the quantity of heat involved. This means that if the quantity of heat which must be rejected increases by a factor of 1.2, the temperature difference between the case and the surrounding ambient air will also increase by approximately the same factor of 1.2.

As a first approximation, similar behavior may be assumed within the generator. This would mean that if the generator case temperature were to increase by 50 degrees, for example, then the cold junction temperature would increase by 50 degrees and the hot junction temperature would increase by 50 degrees. If the quantity of heat produced within the generator were to be increased by 15 percent at the beginning of life as compared with the end of life, then the temperature drop at all portions within the generator would also be increased by 15 percent.

These simple ratio techniques provide an approximation for evaluating the behavior of the generator under a large number of conditions. It is important that this type of consideration be applied so that generator internal overheating may be avoided.

In many cases, a generator may be designed for use under water, and it may not be desirable to put cooling fins on the generator so that it may be operated in air (for example, if the overall dimensions of the proposed underwater use were limited). In this case, the use of a finned shipping case may be indicated which can reduce the generator temperature during shipment. Nomograph number 2 may be used to size the shipping case, since the overall dimensions of the shipping case may be determined from the outside dimensions of the generator, and the quantity of heat which must be rejected is the same as is to be rejected from the generator.

A reduction in the hot junction temperature may be obtained through use of the Peltier effect during shipment when it is not necessary that a useful power output be obtained. Roughly 20 percent of the energy transferred through the thermoelements is due to Peltier cooling at the hot junction. The Peltier cooling effect is directly proportional to the current that flows. If the generator is short-circuited, the current increases, and immediately the Peltier cooling increases proportionally. Sufficient information may be obtained from nomograph number 4 so that the effect may be evaluated. Nomograph number 4 will yield the design power output, the load voltage, and the open circuit voltage. The current at the design point may also be determined. The short-circuit current may be established by constructing a straight line extrapolation from zero current at the open circuit voltage condition through the design current at the design point to short circuit current at the zero voltage condition. The change in current may be directly ratioed to the 20 percent Peltier cooling to determine how much the effect is increased. This specifies the quantity of heat which is removed by conduction through the thermal elements. This quantity of heat may now be ratioed to the previous quantity of heat and multiplied by the previous temperature difference to determine the new temperature difference between the hot and cold junctions. This permits evaluation of the effect of short circuiting the generator in the steady-state condition.

V. DESIGN STUDY

The market survey performed under this program indicated sixteen possible applications for RTGs in the 100 milliwatt(e) to 1 watt(e) power range. Of these sixteen possible concepts, four were selected to be designed conceptually. These designs are primarily intended to indicate the versatility and adaptability of RTGs to various applications. They are not intended to present solutions to attendant design problems nor to indicate design detail.

The four concepts selected for the design study are:

- (1) 1 watt(e), strontium-90 fueled, fully-shielded oceanographic system
- (2) 1 watt(e), strontium-90 fueled, removable shield oceanographic system
- (3) 300 milliwatt(e), strontium-90 fueled, fully shielded ordnance system
- (4) 1 watt(e), plutonium-238 fueled, oceanographic system

A. 1 Watt(e), Strontium-90 Fueled, Fully-Shielded Oceanographic System

The first of the four design concepts is intended primarily for deep ocean ($\sim$ 18,000 feet) operation applications. It is a low cost strontium-90 powered system, fully shielded, which will produce one watt(e) output at 18 volts. In operation, the strontium-90 capsule produces heat through isotopic decay to drive a bismuth-telluride semiconductor thermopile. Johns-Manville, Min-K 1301 insulation provides heat containment of all fuel capsule surfaces not in contact with the thermopile, and depleted uranium is placed completely around the generator to provide nuclear radiation shielding. The low voltage, high current thermopile output is put through a dc-dc converter to produce the required 18 volt, one watt output. The arrangement of the generator is shown in Figure V-1 (SK 427), the generator specifications are listed in Table V-1, and the details of each component are described below.

1. Component Description

Figure V-1 can be used to aid in the comprehension of the details as described in each of the following components.

a. Fuel Capsule. The fuel is SrTiO_3 . The required amount at the beginning of life is 44 watts yielding 191 grams or 6.9 kuries at a volume of 3.3 in^3 . The inner capsule liner is Ta-10W, 0.02 inch thick and the outer capsule liner is Haynes-25, 0.08 inch thick. Welds will be made at the capsule top and bottom as indicated in the exploded view of Figure V-1. The

Figure V-1. 1 Watt(e), Strontium-90 Powered RTG Oceanographic Application (Fully Shielded)

TABLE V-1. ADVANCED LARGE MILLIWATT(e) RTG DESIGN
SPECIFICATION SHEET

Contractor: Hittman Associates, Inc. Contract No.: AT(30-1)-3627

Use and Application: Oceanographic - 1 Watt(e) "Pinger" Power Supply,
18,000 Feet Maximum Depth

Status: Conceptual Design

Power Supply Subsystem

Fuel: Strontium-90

Concept: Radioisotope Thermoelectric Generator

Major Assemblies: Fuel, Capsule, Thermopile, Insulation, Casing,
dc - dc Converter, Radiation Shield

	<u>Specification</u>
Power (End of Life) - Watts	1.0
Voltage (End of Life) - Volts	18.0
Weight - Pounds	315.6
Length - Inches	10.45
Diameter - Inches	9.20
Pressure Vessel Flange - Inches	12.00
Volume - Cubic Inches	400
Operational Environment	Undersea - to 18,000 feet
Dynamic Environment	Low Shock
Reliability	High
Radiation Level	Fully Shielded (200 mrem/hr surface)

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TABLE V-1 (CONTINUED)

<u>Thermoelectric Generator</u>			
<u>Parameter</u>	<u>Storage 125° Air</u>	<u>Beginning of Life</u>	<u>End of Life</u>
Electrical Output - Watts			1.0
Thermal Input - Watts		44	34
Efficiency - %			2.96
Open Circuit Voltage			0.864
Output Voltage			
RTG			0.5
dc-dc Converter		18.0	18.0
Resistance - Ohms			0.2
Temperatures - °F			
Fuel Capsule Surface	612	519	420
Hot Junction	560	467	380
Cold Junction	195	105	100
Heat Distribution - Watts			
Thermopile		32.5	25.1
Insulation		9.4	7.3
Miscellaneous		2.1	1.6

Fuel: Isotope - Strontium-90

Chemical Form: SrTiO_3

Design Data:

Compound Density - 5.11 gm/cm^3

Power Density - 1.24 watts/cc (theoretical)

Melting Point - 1910°C

Thermal Conductivity = $0.0132 \text{ cal/sec-cm}^\circ\text{C}$ at room temperature

Cost - \$19/watt(t)

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TABLE V-1 (CONTINUED)

Capsule:

Overall Length: 1.8 inches Overall Diameter: 1.8 inches
 Fuel Loading (Beginning of Life): 44 watts(t), 191 grams (0.42 lb),
 6.9 kcuries
 Internal Volume (Fuel Region): Fuel 3.37 in³, Void: None
 Capsule Closing Mechanism: TIG Weld

<u>Parameter</u>	<u>Capsule</u>	
	<u>Inner</u>	<u>Outer</u>
Material	Ta-10W	Haynes-25
Inside Diameter - Inches	1.60	1.64
Inside Length - Inches	1.60	1.64
Wall Thickness - Sides - Inches	0.02	0.08
Wall Thickness - Ends - Inches	0.02	0.08
Total Weight - Pounds	0.064	0.408
Melting Point - °F	5522	2425
Thermal Conductivity - Btu/hr-ft-°F	32.7	8.1
Linear Expansion Coefficient, 10 ⁻⁶ in/in/°F	5.510	7.57
Density - lb/in ³	0.608	0.33
Strength		
Tensile - psi	80,600	127,500
Yield - psi (0.2% offset)	71,000	40,400
Elongation - %	27	72

Insulation

Type: Min-K 1301

Manufacturer: Johns-Manville, Inc.

Thickness - Inches:

Sides: 0.5

Ends: 0.5

Weight - Pounds: 0.162

Thermal Conductivity - Btu/ft-hr-°F: 0.018

Fill Gas: 90% Argon, 10% Hydrogen

Pressure - Atm: 1.3

Maximum Operational Temperature - °F: 1300

TABLE V-1 (CONTINUED)

Thermopile

Total Thermocouples: 32

Arrangement: Rectangular

Electrical Connection: Series/Parallel

Efficiency - End of Life: 5.0 percent

Thermoelement Data:

<u>Parameter</u>	<u>P</u>		<u>N</u>	
Material	Bi ₂ Te ₃		Bi ₂ Te ₃	
Manufacturers	General Instruments Corp. / Asarco Corp.			
Length - Inches	0.5		0.5	
Sides - Inches	0.14 x 0.14 sq.		0.14 x 0.14 sq.	
Temperature - °F	BOL	EOL	BOL	EOL
Hot Junction	467	380	467	380
Cold Junction	105	100	105	100

Electrical Contact: Tinned copper leads, soldered at cold junction

Materials:

<u>Component</u>	<u>Materials</u>	<u>Dimensions</u>
Hot Shoe	Nickel Plated Copper Lengths	0.10 x 0.20
Cold Shoe	Nickel Plated Copper Lengths	0.10 x 0.20

Casing

Material: Depleted Uranium with Hastelloy-C corrosion shield

Outside Diameter - Inches: 9.20 including corrosion shield

Outside Length - Inches: 2.75 Depleted uranium; 0.125 Hastelloy C
(1.2 Hastelloy connection flange)Volume - in³: 37.5 - uranium; 43.4 - Hastelloy

Weight - lb: 252.7 - uranium; 14.15 - Hastelloy = 266.85 pounds

Case Temperature: Maximum Storage - 195°F at 125°F air temperature
Normal - 100°F at 80°F seawater temperature

Casing Closure Method: Bolted Flange (O-ring)

1. Uranium Shield Plug and Uranium Pressure Vessel:
Bolt and "O" Ring, ceramic to metal seal at wire port
2. Hastelloy-C Corrosion Shield: Weld

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TABLE V-1 (CONTINUED)

Radiation Shield

Material: Depleted uranium

Thickness:

Sides - Inches: 2.75

Ends - Inches: 2.75

Weight: 252.7 pounds

Dose Rate:

Surface - mrem/hr: 200

1 Meter - mrem/hr: 4

dc-dc Converter

Type: Transistorized

Shape: Cylindrical

Dimensions:

Length - Inches: 1.75

Diameter - Inches: 2.0

Weight - Pounds: 3.5

Input:

Voltage: 0.5

Current - amps: 2.5

Output:

Voltage: 18

Current - amps: 0.0555

Efficiency - %: 80

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inner containment in the configuration is welded by a stepped press joint method, as well as the bottom plate of the outer liner. Final closure at the top lid of the Haynes-25 outer liner is welded vertically (trepan method) by providing a 0.125 inch high lip on the top lid. Weld specifications are 100 percent penetration, and can be provided by electron beam or TIG weld. All operations must be performed in a hot cell.

The fuel surface operating temperature is calculated to be 519°F at beginning of life in a seawater ambient temperature of 80°F.

b. Thermopile. At the fuel surface and seawater temperatures stated above, the hot shoe temperature of the thermopile is 467°F, the cold side is 105°F.

The thermopile will form a rectangular module approximately 0.5 inch high, 0.75 inch wide, and 1.37 inches in length, and located at the seaward end of the fuel capsule. The thermopile material is bismuth telluride containing n and p elements. The thermoelement legs are arranged electrically in series/parallel and thermally in parallel. The elements are rectangular in shape, have cross sectional dimensions of 0.14 by 0.14 inch and are 0.5 inch long. Thirty-two thermocouples are used in the module arranged in two parallel chains of 16 couples in series. Each couple is connected to its companion in the other parallel chain in order to provide a grid matrix. The grid matrix arrangement prevents the breakdown of a series chain through the loss of only one couple and with the grid configuration complete, module open circuit failure is only possible with the failure of two companion couples.

Nickel plated copper links approximately 0.005 inch thick are placed on each side of the couples and form the hot and cold shoes. Beryllium oxide wafers provide electrical insulation while maintaining thermal conduction between the hot shoe, the fuel capsule surface, and between the cold shoe and the shielding. Tinned copper leads are soldered to the cold shoe links at the corners of the module as shown in Figure V-1, Section B-B. A plastic encapsulating material provides individual insulation as well as perimeter support and strength to the contact leads. The entire module, without the BeO₂ wafers is inserted into the generator at final assembly as an integral unit. Configuration of the thermopile module is shown in Section B-B of Figure V-1.

c. Insulation. The selected insulation material is Johns-Manville Min-K 1301. The thickness is nominally 0.5 inch after preload, and is placed around all surfaces of the fuel capsule excluding that portion in contact with the thermopile. The insulation blanket will be fabricated in three parts, a bottom disk, a top ring, and an open-ended cylinder for the fuel capsule sides. Each component is machined from a solid block to close tolerances and has interlocking grooves and tapers at the ends. All machined dimensions are those calculated to yield the final dimensions required after outgassing and preload. Outgassing is accomplished by baking the machined parts at 1000°F in a vacuum chamber for several hours. Preload on the assembled insulation is required to sustain dynamic load conditions and will be applied through a preload force from the shield plug bolts. The preload force per bolt is limited to 156.3 pounds to avoid crushing components during assembly.

d. Shielding and Pressure Vessel. A shield consisting of 2.75 inches of depleted uranium is required around the RTG to reduce the surface radiation to 200 mrem/hr at the beginning of life fuel quantity, 191 grams. The shield is bell jar shaped with a bolted notched plug at the flat end of the bell for assembly and insulation preload. Since a 2.75 inch thick uranium bell jar yields a fairly rugged chamber, it is also used as the pressure vessel container required to survive the pressure at an 18,000 foot ocean depth. A corrosion cladding of 0.125 inch thick Hastelloy-C will surround the uranium pressure vessel to avoid seawater reaction with uranium. Hastelloy-C is also used to form the flange for attachment of the RTG to the pinger or the electronic package it is powering. Each flange thickness is 1.2 inches with eight 3/8 inch diameter bolts. The bearing load of the Hastelloy-C flange is dumped into the pressure vessel through a 0.312 inch high collar on the inside of the flange protruding into the uranium material.

Presently the uranium pressure vessel is anticipated as being fabricated by first, a rough casting to the approximate external dimensions. Then the draw in the casting is machined to form the internal cavity for the fuel capsule, insulation and plug. Four T-bolt holes are then machined into the second ledge of the plug cavity, the hole ends widened by an offset fly cutting operation, and the T-bolt insertion slots cut. T-bolts are then inserted, and turned and locked by driving in the two uranium wedges. A detail of the T-bolt assembly is shown in Figure V-2. The uranium plug is then machined from separate stock, and a final close tolerance machining of the external surface is performed before the pressure vessel/shield is inserted into the Hastelloy-C cladding. An alternate method of fabrication may be to cast the uranium directly into its cladding thereby reducing the final machining operation. However, the cladding material must be Zircaloy and its seawater corrosion characteristics are not as well known as those of Hastelloy-C. Therefore, the first method is recommended.

e. Cladding. As stated previously, a cladding is required around the uranium pressure vessel to protect it from seawater reaction and corrosion. Hastelloy-C alloy was selected as the case or clad because of its very low corrosion rate in seawater (approximately 5.44×10^{-4} inches per year) yielding a thickness requirement of 5.44×10^{-3} inches for 10 years. Thickness was increased to 1/8 inch, however, primarily to avoid penetration of the cladding through handling impacts or scratching. Fabrication of the 1/8 inch thick can can be accomplished by either a deep draw or spinning operation. The attachment flange is also of Hastelloy-C, 1.20 inches thick and 12.00 inches in outside diameter. An "O" ring groove is machined 0.30 inch from the bolt circle diameter for the watertight seal. Eight 1/2 inch diameter bolt holes spaced 45 degrees apart are also machined into this flange.

f. Seals

(1) Shield Plug. A washer-shaped plate is used to contain the inert atmosphere within the Min-K insulation by means of an "O" ring seal on either side of the circular seam between the removable depleted uranium shielding. Smaller "O" rings are also placed around each of the four T-bolts to provide a seal around the plug bolt hole.

Step I

Step II

Step III

Figure V-2. T-Bolt Assembly

(2) Attachment Flange. The watertight seal between the main attachment flange is accomplished through a solid metal heavy cross section "O" ring. Monel is used for the "O" ring since it is compatible with Hastelloy-C. The principle advantage of the solid metal "O" ring technique is that the high pressure sealing needed at the 18,000 foot depths can be obtained at relatively moderate bolt loads. In addition, the moderate bolt loading insures a seal at surface conditions where the sea pressure is not aiding flange closure. Grooves machined on the inside diameters of the flanges insure accurate radial location of seal, reduce the amount of surface area requiring high tolerance machining and aid in initial alignment during assembly.

g. dc - dc Converter. The circuit used in the dc-dc converter is shown in Figure III-10 and consists of a chopper, rectifier-filter, and shunt regulator. The exact component values of the shunt regulator need not be specified in a conceptual design. The chopper transistors, Q_1 and Q_2 , are very low saturation resistance type MHT 2205, manufactured by Solitron Devices, Inc. The operation of the converter is described in Section III (Part F, Power Conditioner).

The use of MHT 2205 transistors will result in $V_{CE(sat)}$ voltage drop of only about 0.03 volt, thus permitting an overall circuit efficiency of about 80 percent.

With this efficiency, the input and output characteristics become:

P_{in}	= 1.25 W	P_o	= 1 W
V_{in}	= 0.5 V	V_o	= 18 V
I_{in}	= 2.50 A	I_o	= 0.056 A

Although a slight advantage could be gained by using the collector to base junction of the MHT 2205 transistor (or any other similar low saturation transistor) as a rectifier, size and weight considerations dictate the use of a conventional diode such as the germanium 1N91. The transformer core material will be 2 mil Square Permalloy-80 (a Magnetics, Inc. brand name).

Packaging of the above components is accomplished in a 1.5 inch length by 2.0 inch diameter right circular cylinder mounted on the bottom of the bell jar shield plug and inside the Hastelloy-C flange. The components are arranged in "cordwood" style between and on either side of two circular printed circuit boards. The two large transistors are mounted to the front and back of the top printed circuit board. The torroidal transformer is mounted at the bottom side of the second printed circuit board, and the remaining components interspersed between. Two terminal posts are provided at the bottom (unattached) end for the 18 volt output. Two large posts are provided at the top end of the can for the input power leads. Fabrication is state-of-the-art G-10 epoxy double-sided copper foil circuit boards, etched, and then silver braze dipped with components premounted in grooves

in the boards. The singular exception is the transformer which has its leads manually brazed to the land areas on the circuit board and is bolted to the bottom printed circuit board.

h. Leads. Output power leads are taken off from the thermopile module at the cold shoe links as previously described to avoid parasitic heat loss through the wires. From this point, they are run in a spiral groove along the interface between the insulation and the shielding and along the interface between the plug and shield until it reaches the surface (bottom of the bell jar) near the dc-dc converter. Here a ceramic-to-metal seal penetrates the seal washer.

2. Stress Analysis

a. Pressure Vessel. This RTG system is designed for an external overpressure of 10,000 psi, which is the pressure at an 18,000 foot ocean depth with a safety factor for density variation, engineering design, etc. In addition, only the strength of the depleted uranium shell is considered. Therefore, the added strength due to the external Hastelloy shell is also an inherent factor of safety in the design.

The RTG transition section from the cylindrical section of the generator to the spherical dome is gradual, thereby eliminating stress discontinuities in the transition region.

The material properties of the depleted uranium are shown in Table V-2.

TABLE V-2. DEPLETED URANIUM PROPERTIES

S_{YP} (Compressive Yield Strength)	= 33,000 psi
E (Young's Modulus)	= 25.5×10^6 psi
G (Shear Modulus)	= 10.6×10^6 psi

The RTG spherical dome is a solid cap. The compressive stresses produced in the cylindrical section of the generator due to reaction of the pressure acting on this dome is:

$$S_C = \frac{PD_2^2}{D_2^2 - D_1^2} \quad (\text{longitudinal compressive stress in cylinder})$$

where: P = 10,000 psi
 D_2 = 8.25 inches (O.D. of Depleted Uranium)
 D_1 = 2.875 inches (I.D. of Depleted Uranium)

$$\therefore S_C = 11,400 \text{ psi}$$

The maximum hoop stress in the cylinder due to the external pressure is at the inner surface of the cylinder.

$$S_H (\text{max}) = \frac{2 P b^2}{b^2 - a^2} \text{ (compressive hoop stress in cylinder)}$$

where: $P = 10,000$ psi
 $b = 4.13$ inches (outer radius of depleted uranium)
 $a = 1.44$ inches (inner radius of depleted uranium)

$$\therefore S_H (\text{max}) = 22,800 \text{ psi}$$

At point (f) shown in Figure V-3, a reduction in the wall thickness of the cylinder results in a certain degree of stress discontinuity.

Figure V-3. Analytical Stress Model

Here the longitudinal stress may be considered as constant over the thickness of the shell, since intimate contact is maintained at point (g) due to the preload bolts. However, due to manufacturing tolerance a small gap will exist between the preload plug wall and the cylinder wall. Therefore, the stresses acting at point (f) are analyzed with respect to the point (e), immediately above the reduced wall thickness, and point (h) immediately below point (e) and in the reduced wall area. The hoop stress at point (e) is:

$$S_{He} = \frac{Pb^2}{R^2} \frac{(a^2 + R^2)}{(b^2 - a^2)}$$

where: $R = 2.375$ inches

a and b are the same as before

$$\therefore S_{He} = 15,600 \text{ psi}$$

The hoop stress at point (h) is therefore

$$S_{Hh} = \frac{2 Pb^2}{b^2 - R^2} = 30,000 \text{ psi}$$

The strain acting on the above points around the cylinder is

$$\epsilon_e = \frac{S_{He}}{E}$$

where: $S_{He} = 15,600 \text{ psi}$
 $E = 25.5 \times 10^6 \text{ psi}$

$$\therefore \epsilon_e = 612 \times 10^{-6}$$

and therefore

$$\epsilon_h = \frac{S_{Hh}}{E} = 1178 \times 10^{-6}$$

The shear stress acting between the interfaces of the locus of points (e) and (h) around the cylinder is

$$S_S = G (\Delta \epsilon)$$

Solving for the shear stress from the value given

$$S_S = 6,000 \text{ psi}$$

At this point Mohr's circle was used to determine the principle stresses acting on the higher stressed point (h).

Figure V-4. Stresses on Point (h) of Figure V-3

Constructing Mohr's circle from the above stress model yields the maximum or principal stresses acting in the region of the reduced wall thickness.

Figure V-5. Mohr's Circle

The maximum shear stress in the cylinder acts at an angle of 45° from the principal stress. The value of the maximum shear stress is then

$$S_S (\text{max}) = |Z| = \sqrt{9300^2 + 6000^2} = 11,060 \text{ psi}$$

The maximum principal stress determined also from Mohr's circle is

$$S_n = 20,700 + 11,060 = 31,760 \text{ psi}$$

The above maximum principal stress of 31,760 psi is below the yield strength of the depleted uranium. Therefore, the design is acceptable for pressures of 10,000 psi and greater.

At the severe depth and pressures, deflections of the vessel must also be investigated. The worst case is assumed below by using a long thick walled cylindrical model and ignoring the reinforcing effect of the end plug and dome.

$$\Delta a = -p \frac{a}{E} \left(\frac{2b^2}{b^2 - a^2} \right)$$

where: a, b, p and E are as before.

$$\Delta a = -1.283 \times 10^{-3} \text{ inch}$$

The considered design is readily amenable to such slight deflection.

b. Hastelloy-C Flange. The capability of designing a flange-seal arrangement to insure a leak-free system at pressures of 10,000 psi is within the state-of-the-art, and the type of seal selected for the generator has been used in oil drilling production equipment at pressures to 15,000 psi. Flange size will therefore not be determined since any final selection of thickness will not affect the design concept. However, the number and size of bolts may be a size limitation and will be calculated through the total joint contact-surface compression load method.

If H_p = total joint contact-surface compression load
 and b = $\frac{0.25}{8}$ gasket sealing width
 G = 8.9 diameter at location of gasket reaction load
 p = 10,000 design pressure
 m = 6, gasket factor (monel gasket)

Then $H_p = 2b \times \pi GmP = 105,000 \text{ pounds}$

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The total bolt area required to obtain the 105,000 pounds compressive load is

$$A_{bt} = \frac{H_p}{S_b}$$

where: $S_b = 180,000$ psi (tensile yield for Hastelloy bolts)

$$\therefore A_{bt} = 0.584 \text{ (total bolt area)}$$

As shown in Figure V-1 or V-2, eight bolts are equally spaced around the bolt circle of the flange. The required size is

$$A_b = \frac{A_{bt}}{8} = 0.073 \text{ in}^2 \text{ (required cross-sectional area at root of bolt)}$$

The bolts selected are 3/8 inch, each having a root area of 0.0878 in^2 .

The stress acting on each of the 3/8 inch diameter bolts produced by applying the compressive H_p is

$$S_{b1} = 150,000 \text{ psi}$$

The acting stress (S_{b1}) is below the tensile yield stress (S_b). Therefore, the bolts selected will not be overstressed by obtaining the desired joint contact-surface compressive load.

c. Handling and Shipping

(1) "G" Loads. The maximum "g" load acting on the system is 5 "g's" as specified by the normal vibration loads by common carrier per MIL STD 810A.

(2) Min-K Preload. In order to eliminate the effects of the above shock and vibration load, tending to cause damage to the thermoelectric elements, the Min-K insulation will be compressively preloaded to 5 times the weight of the fuel container and the thermoelectric elements. The compressive stress on the Min-K from part (4) below is 1.67 psi.

(3) Thermopile Load. By preloading the Min-K as discussed above, the contact pressure between the shoes of the thermoelectric elements and the depleted uranium is

$$P = \frac{W_e}{A_C} \text{ (contact pressure)}$$

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where:

$$W_e = 5 W \text{ (equivalent weight)}$$

$$W = 0.8 \text{ lbs (composite weight of fuel block and T/E elements)}$$

$$A_C = 0.16 \text{ in}^2 \text{ (contact area of T/E shoes)}$$

$$\therefore P = 25 \text{ psi}$$

The model of each couple is shown below in Figure V-6. The contact area of one shoe is 0.01 in^2 and the cross sectional area of one element of 0.0196 in^2 . The combined stress due to compression and bending from eccentric loading is:

Figure V-6. Load Diagram Thermopile

$$S_c = \frac{P}{A} + \frac{P_e C}{I}$$

where:

$$S_c = \text{total compressive stress, psi}$$

$$P = \text{load on one element, lbs} = \frac{p A_s}{2}$$

$$p = \text{uniform load} = 25 \text{ psi}$$

$$I = \text{moment of inertia for one element} = 1.46 \times 10^{-3} \text{ in}^4$$

$$C = \text{maximum distance from neutral stress areas to outer edge of element} = 0.07 \text{ inch}$$

$$e = \text{eccentricity of loading} = 0.02 \text{ inch}$$

$$A_s = \text{area of one shoe} = 0.01 \text{ in}^2$$

$$A = \text{cross sectional area of one element} = 0.0196 \text{ in}^2$$

$$\therefore S_c = 0.261 p$$

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The compressive stress acting on each element of the thermopile is therefore:

$$S_C = 6.5 \text{ psi}$$

(4) Plug and Plug Bolt Load. The load acting on the plug and plug bolt is that force which is necessary to preload the Min-K to the equivalent weight shown above.

$$P_{bt} = \text{total bolt load} = W_e$$

Four bolts are used to preload the Min-K in this design. The preload on each bolt is

$$P_b = \frac{P_{bt}}{4} = 1 \text{ pound}$$

The stresses acting on the bolt and plug due to the small bolt preload are negligible. The compressive stress on the Min-K is

$$S_C = \frac{W_e}{A_{\text{Min-K}}}$$

where: $A_{\text{Min-K}} = 2.4 \text{ in}^2$

so $S_C = 1.67 \text{ psi}$

(5) Limiting Load. Since the preload required to withstand shipping is small the limiting condition is the specification of a maximum load on each of the plug bolts. This is to avoid crushing during assembly.

$$S_C \text{ allowable} = 2000 \text{ psi for bismuth telluride}$$

from (3)

$$2000 \text{ psi} = 0.261 P; P = 7650 \text{ psi}$$

$$W_e = 7650 \times 0.16 = 1250 \text{ lb}$$

$$P_b = \frac{1250}{4} = 312 \text{ psi}$$

With a safety factor of 2

$$P_b \text{ limit} = 156 \text{ lbs/bolt}$$

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and the Min-K stress at this bolt load is

$$S_C = \frac{1250}{2.4} = 520 \text{ psi}$$

3. Assembly

The components will be brought to the assembly area in the final configuration. The assembly will then be in three stages:

- (1) Initial checkout.
- (2) Hot cell assembly.
- (3) Final assembly.

Particular emphasis was placed on the design concept for reducing assembly time in the hot cell.

a. Initial Checkout. All components will have incoming inspection. Items to be assembled in the hot cell will also have a preassembly performed to insure fit once the components are inside the cell. The dc-dc converter can be checked out with a standard power supply. The thermopile will be checked out as part of the pre-hot cell assembly. Here the thermopile with its surrounding insulation ring is placed into the pressure vessel radiation shield, a previously calibrated electrical heater is then inserted into the fuel capsule and insulation cavity, insulation is added to fill the plug, and a pre-determined "standard" power level applied to the heater. Thermopile performance is then monitored at a "standard" load. After the thermopile has qualified, it remains in the pressure vessel, a shield plug is selected and tested for fit, the internal cavity measured, and the dimensions matched to premachined insulation parts. The matched set is then placed into the hot cell.

b. Hot Cell Assembly. In the hot cell, the fuel block has already been placed into its open-ended cylinder of insulation and a compression ring clamp placed over the insulation cylinder. Once the pressure vessel and thermopile is placed into the hot cell, the compression ring is tightened to a predetermined amount, centered into the open plug hole, and then pressed into a cavity with a small hydraulic press. The bottom insulation plug is pressed in over the fuel block, the uranium plug slipped onto its bolts and into place. The nuts are then attached and tightened until the plug is level with the bell jar bottom. At this point, the entire assembly is fully shielded and can be removed from the hot cell.

c. Final Assembly. At final assembly, the shield is slipped into the cladding can, the flange is then press fit onto the uranium shield, and the flange and cladding seam welded at the joint. The final assembly step is the attachment of the converter package to the RTG through the small lag-type mounting bolts provided in the uranium shielding at the bottom of the generator.

B. 1 Watt(e), Strontium-90 Fueled, Removable Shield
Oceanographic System

The second design concept is identical in purpose, system design, and environment with the exception of a removable radiation shield. The object is to reduce system cost by allowing reuse of the considerable amount of shielding required. Generator specifications are shown in Table V-3, the unshielded generator interior in Figure V-7 (SK-450) and the removable shield details in Figure V-8 (SK-430).

1. Components

Since the generator is similar to the first design discussed, the details of the fuel capsule, insulation, thermopile, converter and watertight seals will not be repeated here. Only the internal uranium shieldplug, plug tiedown, pressure vessel, and, of course, the removable external shielding are different and will be discussed below.

a. Pressure Vessel. The pressure vessel is again bell jar shaped for high strength, is made of Hastelloy-C and is 0.375 inch thick. A 1.25 inch thick flange with four 1/2 inch bolts is used for attachment. Stress in the pressure vessel at 18,000 foot depth is determined from the following analysis.

(1) Maximum Stress

$$\text{Max } S_H = p \frac{2b^2}{b^2 - a^2}$$

where: p = 10,000 psi
 b = 1.875 inch outside diameter
 a = 1.5 inch inside diameter

$$\therefore S_H = 55,000 \text{ psi}$$

Yield stress for investment cost and aged at 1475°F for 25 hours is 76,200 psi resulting in a safety factor of approximately 1.4.

(2) Check for Effect of Dome - from paragraph V-A-2-a

$$S_C = \frac{pD_2^2}{D_2^2 - D_1^2}$$

where: p = 10,000 psi
 D₂ = 3.75 inch outside diameter
 D₁ = 3.00 inch inside diameter

$$\therefore S_C = 27,700 \text{ psi}$$

TABLE V-3. ADVANCED LARGE MILLIWATT(e) RTG DESIGN
SPECIFICATION SHEET

Contractor: Hittman Associates, Inc.

Contract No.: AT(30-1)-3627

Use and Application: Oceanographic Instrumentation Power Supply

Power Supply Subsystem

Fuel: Strontium-90

Concept: Low Cost Production, Long Lived with Removable Radiation Shield

Major Assemblies: Fuel Capsule, Thermopile, Insulation, Casing, Radiation
Shield, dc-dc Converter

	<u>Specification</u>
Power (End of Life) - Watts	1.0
Voltage (End of Life) - Volts	18
Weight - Pounds*	61.50
Length - Inches	8.50
Volume - Cubic Inches	125.8
Operational Environment	Deep Ocean (18,000 feet)
Dynamic Environment	Low Shock
Reliability	High
Radiation Level **	Shielded - 200 mrem/hr at surface 4 mrem/hr at 1 meter Unshielded - 1.2×10^7 mrem/hr at surface 2.2×10^4 mrem/hr at 1 meter in water

* Removable shield weight is an additional 690 pounds

** Removable shield concept

TABLE V-3 (CONTINUED)

<u>Thermoelectric Generator</u>			
<u>Parameter</u>	<u>Storage 125° Air</u>	<u>Beginning of Life</u>	<u>End of Life</u>
Electrical Output - Watts			1.0
Thermal Input- Watts		44	34
Efficiency - %			2.96
Open Circuit Voltage			0.864
Output Voltage			
RTG			0.5
dc-dc Converter		18.0	18.0
Resistance - Ohms			0.2
Temperatures - °F			
Fuel Capsule Surface	612	519	420
Hot Junction	560	467	380
Cold Junction	195	105	100
Heat Distribution - Watts			
Thermopile		32.5	25.1
Insulation		9.4	7.3
Miscellaneous		2.1	1.6

Heat Source

Fuel: Isotope - Strontium-90

Chemical Form: SrTiO_3

Design Data:

Compound Density: 5.11 gm/cm^3

Power Density: 1.24 watts/cc (theoretical)

Melting Point: 1910°C

Thermal Conductivity: $0.0132 \text{ cal/sec-cm}^\circ\text{C}$ (at room temperature)

Estimated Cost: *~\$100/watt(t)

* Unencapsulated

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TABLE V-3 (CONTINUED)

Capsule:

Overall Length: 1.80 inches Overall Diameter: 1.80 inches
Fuel Loading (Beginning of Life): 44 watts(t), 191 grams (0.42 lbs),
6.9 curies
Internal Volume (Fuel Region): Fuel 3.3 in³; Void: None
Capsule Closing Mechanism: Weld

<u>Parameter</u>	<u>Capsule</u>	
	<u>Inner</u>	<u>Outer</u>
Material	Ta-10W	Haynes-25
Inside Diameter - Inches	1.60	1.64
Inside Length - Inches	1.60	1.64
Wall Thickness - Sides - Inches	0.02	0.08
Wall Thickness - Ends - Inches	0.02	0.08
Total Weight - Pounds	0.064	0.408
Melting Point - °F	5522	2425
Thermal Conductivity	32.7	8.1
Linear Expansion Coefficient, 10 ⁻⁶ in/in/°F	5.510	7.57
Density - lb/in ³	0.608	0.33
Strength		
Tensile - psi	80,600	127,500
Yield - psi (0.2% offset)	71,000	40,400
Elongation - %	27	72

Thermopile

Total Thermocouples - 32
Arrangement: Rectangular
Electrical Connection: Series/Parallel
Efficiency: End of Life - 5.0%

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TABLE V-3 (CONTINUED)

Thermoelement Data

<u>Parameter</u>	<u>P</u>		<u>N</u>	
Material	Bi ₂ Te ₃		Bi ₂ Te ₃	
Manufacturer	General Instrument Corporation or Asarco Corporation			
Length - Inches	0.50		0.50	
Diameter - Inches	0.14 x 0.14 sq.		0.14 x 0.14 sq.	
Temperature - °F	BOL	EOL	BOL	EOL
Hot Junction	476	380	467	380
Cold Junction	105	100	105	100

Electrical Contact: Tinned copper leads soldered at cold junction

Materials:

<u>Component</u>	<u>Materials</u>	<u>Dimensions</u>
Hot Shoe	Nickel Plated Copper Lengths	0.10 x 0.20
Cold Shoe	Nickel Plated Copper Lengths	0.10 x 0.20

Insulation

Type: Min-K 1301

Manufacturer: Johns-Manville, Inc.

Thickness - Inches:

Sides: 0.50

Ends: 0.50

Weight - Pounds: 0.162

Thermal Conductivity: Btu/ft-hr-°F: 0.018

Fill Gas: 90% Argon, 10% Hydrogen Pressure Atm: 1.3

Maximum Operating Temperature - °F: 1300

Casing

Material: Hastelloy-C

Outside Diameter - Inches: 3.55

Outside Length - Inches: 8.50

Thickness - Inches: 0.375

Volume - in³: 130.8

Weight - Pounds: 45.9

Casing Closure Method: Bolted Flange

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TABLE V-3 (CONTINUED)

Radiation Shield*

Material: Depleted uranium

Thickness: 2.84 Inches

End Plug Diameter: 2.80 Inches

Weight: 13.5 Pounds

Dose Rate:	<u>Shielded</u>	<u>Unshielded</u>
Surface - mrem/hr	200	1.2×10^7
1 Meter - mrem/hr	4	2.2×10^4

* Removable for reuse

dc - dc Converter

Type: Transistorized

Shape: Cylindrical

Dimensions:

Length - Inches: 1.50

Diameter - Inches: 1.50

Weight: 3.5

Input:

Voltage: 0.5

Current - amps: 2.5

Output:

Voltage: 18

Current - amps: 0.0555

Efficiency - %: 80

Figure V-7. 1 Watt(e), Strontium-90 Powered RTG Oceanographic Application (Removable Shield)

Figure V-8. Handling Fixture/Shipping Cask, 1 Watt(e), Strontium-90 Powered RTG Oceanographic Application (Removable Shield)

(3) Bolt Load: from paragraph V-A-2-b

$$H_p = 2 b \pi G m p$$

$$p = 10,000 \text{ psi}$$

$$b = 0.0312 = \text{gasket sealing width } \left(\frac{0.25}{8} \right)$$

$$m = 6 \text{ gasket factor}$$

$$G = \text{mean diameter of gasket} = 4.8 \text{ inches}$$

$$H_p = A_{bt} S_b = 5.65 \times 10^4$$

$$S_b = 180,000$$

Total bolt area required is:

$$\frac{H_p}{S_b} = 3.14 \times 10^{-1} \text{ in}^2$$

The total stress area of four 3/8 inch bolts is 0.3512 in^2 .
The resulting stress on each bolt is

$$S_{b1} = \frac{H_p}{0.3512} = 161,000 \text{ psi}.$$

b. Internal Uranium Shadow Shield. An internal shield consisting of a 2.84 inch thick, 2.80 inch diameter uranium plug is used as a shadow shield to prevent radiation damage to the electronic components of the pinger and the dc-dc converter attached to the generator. In addition, the plug provides an assembly access hole and a preload on the Min-K insulation. The preload is obtained by turning the large Hastelloy-C threaded lock ring below the uranium plug until it has obtained the same level as the external shielding. Total force on the nut is 625 pounds or equal to the same force required of the four bolts in the first design presented.

c. Removable Shield. The removable shield is bell jar shaped, made of lead, nominally 4.80 inches thick, and weighs 690 pounds not including ancillary floats and float support structure. The various components of this shield shown in Figure V-8 will be described in detail in the handling system description. Fabrication will be simply casting the various lead components directly into a carbon steel cladding.

2. Handling System

As previously indicated in the 1 watt(e) fully shielded concept, the shield required to limit the dose rate to 200 mr/hr is approximately 265 pounds of depleted uranium. At a very minimum cost of \$2.50/lb of depleted uranium, this represents \$663. The cost could reach \$1590 at \$6.00 per pound with machining and casting included. Since in deep ocean systems recovery is often difficult or impossible, this material cost is often lost with the device. Furthermore, since shielding is only required for surface op-

eration, storage aboard ship, or shallow water operation, the nonremovable shield loss is often unnecessary. The obvious alternative is to develop a removable shield concept which would allow reuse.

Hittman Associates, Inc. has taken the low cost strontium-90 one watt system and built around it a unique removable shield and corresponding handling system. The system is designed for use with the often limited facilities aboard small oceanographic ships. In fact, in its most simplified form, the generator and pinger can be swung overboard, released and the shield recovered through the use of only a single boom. The versatility of the system will be described below.

a. Design Requirements. Prior to conception of the existing handling system, a series of design requirements or goals were established in order to insure a system of maximum application, ease of operation, simplicity and of lowest cost. These requirements are:

- (1) Maintain a 200 mr/hr at surface (or less than 10 mr/hr at one meter).
- (2) Require no powered operations other than crane lifting.
- (3) Provide a configuration which allows convenient hot cell assembly, a rugged shipping cask and a good method of shipboard storage.
- (4) Provide a system adaptable to the varying devices to which the generator or generator and pinger may be attached and allow maximum option in method of delivery to ocean floor.
- (5) Provide recoverability.
- (6) Maintain a low cost.

b. System Description. The removable shield and handling system meets all the requirements described above. How it accomplishes this is best described through a detailed description of each step experienced by the generator from assembly in the hot cell to recovery from the ocean floor.

(1) Hot Cell Assembly. In the hot cell, the generator has been assembled into the configuration shown in Figure V-7. The pinger is not, of course, attached. The assembled removable shield as shown cross-hatched in Figure V-8 is placed in the hot cell without the release plug. The recovery float wire has been prewound into the spiral grooves in the shielding sleeve and wound and taped into place in the flange well. The recovery float is not attached, and the release plug is also placed in the hot cell separately.

Assembly into the shield is started by threading the stud bolt into the hole at the top of the generator pressure vessel. The release plug is then threaded onto this bolt, and the generator and release plug assembly is inserted into the shield. A bottom cover plate is bolted

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into place which locks the RTG into the shield. At this point the assembly can be removed from the hot cell, the float attachment bolts can be attached, and the assembly readied for shipment.

(2) Shipping Configuration. Figure V-9 shows the shipping configuration. It is basically the assembly as removed from the hot cell turned upside down (the cover plate facing up) and attached to a framed supporting stand.

(3) On Board Storage. Onboard storage can be identical to the shipping configuration or, if space is at a premium, the supporting stand can be removed.

(4) Pinger Installation. When the pinger is attached to the generator, the shipping configuration of Figure V-9 results. To install the pinger the cover plate is removed, exposing the RTG flange, power conditioner and "O" ring. Then the flange of the pinger is set over the RTG flange, bolts inserted into the holes and threaded into the welded-in-place nuts on the shield side of the RTG flange. The bolts are then tightened, the RTG latch mechanism safety cotter pin is removed, and the recovery float attached to the other end of the wire which is wound inside the shield flange well.

Another support frame is mounted to the shipping frame, the device is then turned right side up and is supported by the new frame. A buoy, shown in Figure V-8 is then attached to the ring member of the shipping stand. The system now assumes the configuration of Figure V-10 and is ready for attachment to the crane. Also in this configuration, several options of unloading methods can be taken.

(5) Option 1 - Lowered with RTG and Pinger Attached to a Larger System

Figure V-11 shows an option which can be used if the RTG and pinger are to be attached to a larger item, and the system is to be lowered by this larger item. Here the configuration of Figure V-10 has been placed on the larger device and bolted to the pinger's lower flange.

The entire system is lifted and swung over the side by the cargo boom. Recovery lines have been attached to the eye bolts on the large float. The large float has a displacement volume of 25,000 in³ and is designed to float just at the surface level with the generator locked in the shield. With the large float at this level, the shield is 5.0 feet under water which will yield a 3 mrem/hr radiation value at the surface. Consequently, with this float concept, the RTG is released only after sufficient water depth has been reached to provide adequate shielding. Release of the RTG in this first option is accomplished by pulling the lanyard of the RTG latch (release) mechanism after the float has reached buoyancy (just at the surface level). Once released, the RTG sinks, pulling with the small recovery float and its connecting wire.

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Figure V-9. Shipping Configuration - On Board Storage

Figure V-10. Crane Attachment Configuration

Figure V-11. Descent of RTG and Pinger Attached to Large System

(6) Option 2 - Recovery with Option 1. Figure V-12 shows the system of Option 1 as it is being brought to the surface after recovery from the depths. The small RTG recovery float bobs to the surface some 10 - 20 feet ahead of the system. It is fished from the water by a hook, the float removed and the float cable fed through the center hole in the shield and in the buoy. The buoy and shield is then lowered over the side, again with lines attached to the eye bolts for added safety. Recovery by crane lifting of the large device, is restarted and the recovery float wire is pulled up through the center holes in the shield and buoy.

At this point, the adjustable parts built into the shield come into play. It is expected that after a period of time at the sea bottom, the surfaces of the generator will become encrusted or covered with silt to such an extent that it would not slide back into the shield cavity. For this reason, the shield has adjustable segments, which, prior to recovery, are moved radially outward by turning the three adjustable bolts. This adjustment leaves a 1/2 radial clearance between the shield and the nominal RTG outer diameter. In addition, the release plug may also have acquired a layer of dirt, etc., and the shielding sleeve can be loosened by removing the screws from the sleeve flange, shown in Figure V-8. Once loose, the sleeve by seeking its own position on the taper of the release plug will adjust to any amount of crud accumulation up to 1/2 inch in depth. Therefore, with the two components being adjustable in the shield, the RTG can be recovered even laden with dirt or scale. Streaming, however, is unavoidable in this situation and care in handling is required. However, the streaming will only be either vertically upward or downward, and once aboard can be stopped by simple bottom plates and top cover plates. The distinct advantage of the recovery system is the self-alignment and self-adjustment allowed by the "pull through the center" of the shield concept as shown in Figure V-13.

(7) Option 3 - Lowering Through the Buoy and Shield. In Figure V-14, the third option can be exercised by lowering the RTG, pinger and attached device through the center of the shield and float. Release is again assured only after the release pin has been pulled which in turn is activated only after the float has become level with the water. Thus a safe depth of water for separation is assured. Once released, the recovery float and attached wire unwind from the shield cavity as the RTG and system is lowered. Recovery is the reverse of the operation with the small recovery float yielding sufficient advanced warning of the arrival of the RTG. Again, the pull through the center concept aids in alignment.

(8) Option 4 - Nonrecovery. It is anticipated that there will be times when no attempt will be expended to recover the device, RTG or pinger, and that this procedure will be known in advance. Under such a condition, the release plug of Figure V-8 is simply unthreaded from the stud bolt and attached to the generator pressure vessel. The system is then swung overboard by attaching the crane to the eyebolts on the large float. When buoyancy is obtained, the safe water depth is reached and the RTG latch (release) lanyard is pulled. The RTG, pinger and device then sink of their own accord, and the small recovery float wire

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Figure V-12. RTG and Pinger Recovery When Attached to Large System

Figure V-13. "Pull Through" Recovery of RTG

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Figure V-14. Lowering Through the Buoy and Shield

and release plug can be saved for use with a recoverable system. This last option is shown in Figure V-15.

c. Summary - Removable Shield Handling System. In summary, the removable shield and handling system described in detail above offers a low cost, simple device by not requiring any powered operations other than the use of the ship's cargo boom. Enough versatility is built in to allow almost any handling option and also allow recovery even under conditions of large surface dirt buildup or encrustment. Finally, the system is safe by having an inherent separation of water at the time of release and by having a self-aligning capability.

3. Fabrication and Assembly

Fabrication and assembly is very similar to the 1 watt(e) fully shielded design. It is fabricated in three phases, pre-hot cell checkout, hot cell assembly, and final assembly, has the uranium shield inserted into the cladding, and has the same T-bolt slot assembly. The only major difference is the tightening of only one nut for shield plug tiedown and Min-K preloading, which actually represents a simplification in the shield process.

C. 300 Milliwatt(e), Strontium-90 Fueled, Fully Shielded Terrestrial System

As the third design concept, another strontium-90 fueled RTG was selected. Here the similarity to the other two Sr-90 fueled designs ends, for this concept is developed for a high shock load environment, lower power (300 milliwatt), and in air as well as in water operation. Specifically, the generator is designed to meet as closely as possible Naval Ordnance Laboratory specified requirements. The generator configuration is shown in Figure V-16 and its specifications are given in Table V-5.

1. Components

Figure V-16 should be referred to in the following discussions of component design.

a. Fuel Capsule. Twenty-three watts of SrTiO_3 is required at the beginning of life yielding a volume 1.55 in^3 , or 130 grams. The wall thickness of the Ta-10W inner lining is 20 mils; the outer Haynes-25 liner is 80 mils. Fabrication is identical to that in the previously described fully shielded Sr-90 fueled RTG. The maximum fuel operating temperature is calculated at 540°F in 120°F ambient air.

b. Thermopile. The thermopile material is again bismuth telluride. The maximum hot shoe temperature is restricted to 487°F in order to reduce thermoelectric material degradation to a minimum and attain the long life requirement. The cold side temperature with an ambient of 70°F is 154°F at beginning of life and is 120°F at end of life. A total of 38 couples are used consisting of two parallel chains of 19 couples each and connected in a grid

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Figure V-15. Nonrecovery System

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Figure V-16. 300 Milliwatt(e), Strontium-90 Powered RTG Ordnance Application

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Heat Source

Fuel: Isotope - Strontium-90

Chemical Form: SrTiO_3

Design Data:

Compound Density: 5.11 gm/cm^3

Power Density: 1.24 Watts/cm^3 (theoretical)

Melting Point: 1910°C

Thermal Conductivity: $0.0132 \text{ cal/sec-cm-}^\circ\text{C}$ at room temperature

Estimated Cost*~\$100/watt(t)

* Unencapsulated

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Capsule:

Overall Length: 1.49

Overall Diameter: 1.49

Fuel Loading (Beginning of Life): 23 watts(t), 130 gms (0.286 lbs),
3420 curies

Internal Volume (Fuel Region): Fuel: 1.55 in³; Void: None

Capsule Closing Mechanism: Weld

Fabrication:

<u>Parameter</u>	<u>Capsule</u>	
	<u>Inner</u>	<u>Outer</u>
Material	Ta-10W	Haynes-25
Inside Diameter - Inches	1.89	1.33
Inside Length - Inches	1.20	1.33
Wall Thickness -Sides - Inches	0.02	0.08
Wall Thickness - Ends - Inches	0.02	0.08
Total Weight - Pounds	0.064	0.408
Melting Point - °F	5522	2425
Thermal Conductivity	32.7	8.1
Linear Expansion Coefficient, 10^{-5} in/in/°F	0.510	7.57
Density - lb/in ³	0.608	0.33
Strength:		
Tensile - psi	80,600	127,500
Yield - psi (0.2% offset)	71,000	40,400
Elongation - %	27	72

Thermopile

Total Thermocouples: 38

Arrangement: Rectangular

Electrical Connection: Series/Parallel

Efficiency: End of Life - 3.15%

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TABLE V-4 (CONTINUED)

Thermoelement Data

<u>Parameter</u>	<u>P</u>		<u>N</u>	
Material	BiTe		BiTe	
Manufacturer	General Instruments Corporation/ Asarco Corporation			
Length - Inches	0.50		0.50	
Diameter - Inches	0.14 x 0.14 sq.		0.14 x 0.14 sq.	
Shape Factor (L/A) in ⁻¹				
Temperature - °F	BOL	EOL	BOL	EOL
Hot Junction	487	380	487	380
Cold Junction	154	120	154	120

Electrical Contact

Materials:

<u>Component</u>	<u>Materials</u>	<u>Dimensions</u>
Hot Shoe	Nickel Plated Copper Length	0.10 x 0.20
Cold Shoe	Nickel Plated Copper Length	0.10 x 0.20

Insulation

Type: Min-K 1301

Manufacturer: Johns-Manville, Inc.

Thickness - Inches:

Sides: 0.50

Ends: 0.50

Weight - Pounds: 0.122

Thermal Conductivity - Btu/ft-hr-°F: 0.088

Fill Gas: 90% Argon, 10% Hydrogen Pressure Atm.: 1.3

Maximum Operating Temperature - °F: 600°F

Casing

Material: Hastelloy-C

Casing Closure Method:
Bolted flange ("O" Ring)

Outside Diameter - Inches: 8.07

Outside Length - Inches: 8.90

Thickness - Inches: 0.125 shell

Volume - in³: 43.51

Weight - lb: 14.1

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TABLE V-4 (CONTINUED)

Material: Depleted uranium

Thickness - Inches:

Sides: 2.58

Ends: 2.58

Weight - Pounds: 220

Dose Rate:

Surface - mrem/hr: 200

1 Meter - mrem/hr: 4

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matrix. The thermoelements are 0.139 square inch and all 38 couples form a module 1.1 by 1.2 inches and approximately 0.5 inch high. All other design features are identical to those previously presented.

c. Insulation. The selected insulation is also Min-K 1301, nominally 0.5 inch thick and with an assembly identical to that of the other Sr-90 designs. The high "g" impact conditions require a greater preload on the insulation which in turn requires a different shield plug assembly. This plug is described in more detail later.

d. Shielding. 2.58 inches of depleted uranium is required to meet the 200 mrem/hr surface radiation dose requirement. Again, the basic shape of the shield can is that of a bell jar with a tapered and notched plug at the bottom end for assembly purposes. The end plug is secured by tightening the large lock nut shown above the plug in Figure V-16. A 1/8 inch thick Hastelloy-C corrosion cladding is used around the outside of the shielding to protect the uranium. The entire generator is held to the interfacing container by bolting onto a Hastelloy-C internal flange. Six 1/2 inch diameter bolts are used to attach the flange and generator and are imbedded directly into the uranium shield in the same T-bolt method of the 1 watt Sr-90 design (Figure V-3).

e. Seals. The shield plug is sealed primarily by pouring epoxy sealant over the large nut after assembly, and secondly through the tapered metal-to-metal contact of the shield plug. An attachment flange seal is achieved through the use of a solid metal, heavy cross section, Monel "O" ring method.

f. dc - dc Converter. Figure V-16 shows a one tap 18 volt, 300 milliwatt converter setting in the flange well below the generator for illustration purposes only. It is to serve as a reminder that the converter must be considered.

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2. Design for High "G" Load

The single outstanding difference between the third Sr-90 design and the first two described is the severe shock survival requirement. The shock profile as described in Figure V-19 is typical of the loads expected of a fairly blunt-ended cylindrical shaped object impacting perpendicular to the water surface.

Water impact is the prime reason for the smooth external appearance of the generator. In particular, the attachment flange is placed internally to avoid any external projection which would expose a larger profile to the water and thereby increase the entry "g" loads. Further, the rounded nose allows a smoother transition from the compressive phase to the drag phase and also reduces impact loads. Generator survival is also enhanced by using the mass strength of the uranium shield. Use of this mass is achieved by the bolt and flange attachment method shown in Figure V-16 which serves to tie together as a unit the uranium shield bell jar, the Hastelloy-C internal flange, and the flange on the remaining "device". Homogeneity of structure is also provided by the large nut behind the assembly plug by dumping the Min-K and thermopile preload directly into the Hastelloy-C flange which is in turn tied to the uranium shield as just described. The total effect of the structural arrangement is to make it impossible for one component to move independent of any other component and therefore be able to take advantage of the strength of the whole structure/generator.

3. Stress Analysis

a. Water Impact. A great deal of effort has been concentrated on various shaped bodies experiencing water impact at high velocities. One of the better references for this subject is a book published by Spartan Books, Inc. and authored by M. Kornhauser entitled "Structural Effects of Impact". The analysis made below has been accomplished through Kornhauser's approach and serves to verify the capability of the generator and its components to survive water impact. The analysis is divided into two phases, the compressive phase and the drag phase.

(1) Compressive Phase. The change in velocity of a blunt-nosed object due to the compressive shock wave experienced at vertical entry into water is

$$v = v_0 (1 - \exp \frac{-1}{4\gamma})$$

The nomenclature for the above equation is:

$$\begin{aligned} \Delta v &= \text{velocity change} \\ v_0 &= \text{velocity immediately prior to water impact} \\ \gamma &= \frac{W}{\frac{4}{3} \pi R^3 \rho_w} \text{ (referred to as ballistic density)} \end{aligned}$$

Figure V-19. Water Impact - Shock Profile

W = weight of generator

R = radius of generator

ρ_w = density of water

Solving for the ballistic density where

W = 255 pounds

R = 4.2 inches

$$\gamma = 22.2$$

The specification pertaining to severe shock and vibration call out a maximum velocity change (Δv) of 5.5 FPS. Solving for the above equation for v_o

$$v_o = \frac{\Delta v}{1 - e^{-\frac{1}{4\gamma}}} = 420 \text{ FPS}$$

where v_o is the velocity prior to impact required to produce a change in velocity of 5.5 FPS during the compressive phase of vertical water entry.

(a) Shield. Figure V-20 is a curve for the theoretical damage limits for steel shells upon entry into the water. The curve was obtained from the previously mentioned publication and is apparently somewhat conservative with respect to obtained empirical data as explained by Kornhausser. On the curve shown, the value $\frac{h}{r}$ is the shell thickness to radius of curvature ratio of the object entering the water. The ordinate $\frac{V}{C_o}$ is the ratio of the impacting velocity to the velocity of sound in water. For values above the curve, shell damage occurs due to local buckling, therefore the curve represents the upper safe limits for the drag criteria of the entering body.

Considering the outer Hastelloy shell, with no support due to the thick depleted uranium shell, the $\frac{h}{r}$ ratio is 0.043. Entering Figure V-20 at $\frac{h}{r}$ equal to 0.043, the limiting damaging velocity is

$$v_D = 0.1 C_o$$

where C_o = 5000 FPS
 v_D = damaging velocity
 v_D = 500 FPS

Figure V-20. Theoretical Damage Limits for Steel Shells

From previous calculations, the entering velocity to meet a velocity change (Δv) of 5.5 FPS was found to be approximately 420 FPS, which is below the damaging velocity of 600 FPS. Therefore, damage due to buckling of just the cladding shell during the compressive phase of vertical impact will not occur.

The above curve for steel is a function of Young's modulus. Since Young's modulus for steel, Hastelloy and uranium are all approximately the same, the above curve may be used interchangeably. A large factor of safety is also included in the design, since the depleted uranium immediately behind the Hastelloy will add greatly to the strength of the generator. With added strength, impact velocities much higher than 500 FPS are required before damage to the shell will occur in the compression phase of water entry.

(b) Components. The compressive phase occurs over a very short period of time -- specified as 0.1 to 0.3 millisecond. A component to be in resonance to this duration of impulse would have to have a frequency of $\frac{1}{t}$ or 10,000 to 3,000 cps respectively.

Since most components are far below this frequency, they will not have time to react to the compressive phase before the effect of the longer duration drag phase becomes overriding. In reference to the shock and vibration writeup in Section III and Appendix A, this reaction time phenomena can be explained by noting the ratio of natural frequency of component to the input pulse frequency is very low in the compressive phase leading to the less than 1 amplification factor. Therefore, component analysis is under the drag phase loads.

(2) Drag Phase. The decelerations of a projectile during the drag phase of water entry are much lower than the decelerations experienced in the compressive phase. The peak decelerations of the drag phase may be calculated by:

$$\ddot{y} = \frac{3}{8} C_p \frac{v_o^2}{R \gamma}$$

However, the maximum acceleration $\ddot{y}$ is given as 150 "g" peak by specification. From Figure A-4 of Appendix A of the shock and vibration writeup the maximum amplification is 2. Therefore a "g" value of 2 x 150 or 300 will be used on the components.

The deceleration during the drag phase of water entry is reduced to the following equation when the generator has fully penetrated the water.

$$\ddot{y} = \frac{3}{8} C_D \frac{v^2}{R \gamma}$$

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In the above equations the term $\frac{3}{3 R \delta}$ is the same. However, C_p is variable and is a function of the depth of penetration, radius of curvature and the ballistic density. The value of C_p reaches higher values than the constant C_D term of the latter equation. Also v_o in the first equation is the maximum velocity of the projectile, whereas v in the latter equation is constantly diminishing. The net result of the above explanation is to show that the projectile experiences larger deceleration rates in the first phase and that the factor of 300 is the worst case.

Greater damaging effects on the shell of the projectile will be experienced during the initial impact or compressive phase as explained above.

b. Min-K Preload. In order to eliminate the effects of the above shock and vibration load, tending to cause damage to the T/E elements, the Min-K insulation will be preloaded to a compressive load 300 times the weight of the fuel container and the T/E elements. The compressive stress on the Min-K from part d below is 100 psi.

c. Thermopile Load. By preloading the Min-K as discussed above, the contact pressure between the shoes of the T/E elements and the depleted uranium is

$$P = \frac{W_e}{A_C} \quad (\text{contact pressure})$$

where: $W_e = 300 W$ (equivalent weight)
 $W = 0.8 \text{ lbs}$ (composite weight of fuel block and T/E elements)
 $A_C = 0.16 \text{ in}^2$ (contact area of T/E shoes)

$$\therefore P = 1500 \text{ psi}$$

The compressive stress acting on each element of the thermopile is

$$S_C = 0.261 P = 392 \text{ psi (see section V-A-2-c-(3))}$$

d. Plug and Plug Bolt Load. The load acting on the plug and plug bolt is that force which is necessary to preload the Min-K to the equivalent weight shown above.

$$P_{bt} = \text{total bolt load}$$
$$P_{bt} = W_e$$

As shown in drawing SK-451 six bolts are used to preload the Min-K. The preload on each bolt is then

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$$P_b = \frac{P_{bt}}{6} = 40 \text{ lbs}$$

The stresses acting on the bolt and plug due to the small bolt preload are negligible. The compressive stress on the Min-K is

$$S_C = \frac{W_e}{A_{\text{Min-K}}}$$

where: $A_{\text{Min-K}} = 2.4 \text{ in}^2$

$$S_C = 100 \text{ psi}$$

e. Pressure Vessel. The maximum compressive hoop stress from paragraph V-A-2-a is:

$$\text{Max } S_H = p \frac{2 b^2}{b^2 - a^2}$$

where: $p = 10,000 \text{ psi}$
 $b = 4.094 \text{ inches}$
 $a = 1.38 \text{ inches}$

$$\therefore S_H = 22,550 \text{ psi}$$

The maximum stress at the thinnest portion of the pressure vessel shell is found by substituting $a = 1.88 \text{ inches}$ in the above equation. The calculated maximum stress is $25,300 \text{ psi}$.

$$S'_H = 25,300 \text{ psi}$$

Stress from the dome load is (from paragraph V-A-2-a):

$$S_C = \frac{p D_2^2}{D_2^2 - D_1^2}$$

where: $D_2 = 8.188 \text{ inches}$
 $D_1 = 2.76 \text{ inches}$
 $p = 10,000 \text{ psi}$

and:

$$S_C = 11,300 \text{ psi}$$

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f. Bolt Loads. From paragraph V-A-2-b

$$\begin{aligned}H_p &= 2 b \pi G m p \\p &= 10,000 \text{ psia} \\b &= 0.0312 \\m &= 6 \\G &= 4.18\end{aligned}$$

$$\therefore H_p = 4.92 \times 10^4 \text{ pounds}$$

and

$$H_p = A_{bt} S_b$$

$$\begin{aligned}\text{where: } S_b &= 180,000 \text{ psi} \\A_{bt} &= 2.73 \times 10^{-1} \text{ in}^2 \\A_b &= \frac{A_{bt}}{6} = 4.55 \times 10^{-2} \text{ in}^2\end{aligned}$$

5/16 - 18 bolt permissible

$$\begin{aligned}A_{b1} &= 6 \times 0.524 \\&= 0.3144 \text{ in}^2 \\S_{b1} &= \frac{H_p}{A_{b1}} = 156,500 \text{ psi}\end{aligned}$$

D. 1 Watt(e), Plutonium-238 Fueled, Oceanographic System

This generator configuration represents the most radical departure from state-of-the-art design, the most stringent of environmental requirements, and the longest lifetime requirement. It is designed for use in an undersea repeater station system. Its environment includes seawater at great depth and pressure, surface handling, and in air storage. Its requirements are the survival after high "g" load water impact, 20 year life, high reliability, and low radiation and handling hazard. To meet the combined effects of all these requirements, an entirely different configuration had to be developed. It is shown in Figure V-21 and is basically that of a hemisphere.

The fuel capsule is hemispherical with the plutonium-238 fuel located on the inside surface of the flat end of the hemisphere and the thermopile at the outside of this flat surface. Surrounding the fuel capsule is a hemisphere of Min-K insulation which is itself contained by a hemispherical pressure vessel. A flange at the flat end of the vessel forms the attachment point to the repeater station. Operating specifications for this generator are shown in Table V-6.

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Figure V-21. 1 Watt(e) Plutonium-238 Powered RTG Oceanographic Application

TABLE V-5. ADVANCED LARGE MILLIWATT(e) RTG DESIGN
SPECIFICATION SHEET

Contractor: Hittman Associates, Inc.

Contract No.: AT(30-1)-3627

Use and Application: Repeater Station Power Supply

Status: Conceptual Design

Power Supply Subsystem

Fuel: Plutonium-238

Concept: Low Production Cost, Long Life

Major Assemblies: Fuel, Fuel Capsule, Thermopile, Insulation, Casing

	<u>Specification</u>
Power (End of Life) - Watts	1.0
Voltage (End of Life) - Volts	18.0
Weight - Pounds	9.93
Length - Inches	2.72
Volume - Cubic Inches	32.2
Operations Environment	Deep Ocean
Dynamic Environment	High "g" water impact
Reliability	High
Radiation Level	Low

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TABLE V-5 (CONTINUED)

<u>Parameter</u>	<u>Beginning of Life</u>	<u>End of Life</u>
Electrical Output - Watts		1.0
Thermal Input - Watts	33	30
Efficiency - %		3.4
Open Circuit Voltage		0.864
Output Voltage		
RTG		0.5
dc-dc Converter		18
Resistance - Ohms		0.2
Temperatures - °F		
Maximum Fuel		
Fuel Capsule Surface	462	420
Hot Junction	418	380
Cold Junction	110	100
Heat Distribution - Watts		
Thermopile	28.0	25.5
Insulation	4.1	3.7
Miscellaneous	0.9	0.8

Heat Source

Fuel: Isotope - Plutonium-238

Chemical Form: PuO₂

Design Data:

Compound Density: 10 gm/cm³

Power Density: 3.9 watts/cm³

Melting Point: 2300°C

Thermal Conductivity: 0.14 cal/sec-cm-°C (at 400°C)

Estimated Cost*: ~\$894/watt

* Unencapsulated

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TABLE V-5 (CONTINUED)

Capsule:

Overall Length: 1.00 in Overall Diameter: 1.70 in
Fuel Loading (Beginning of Life): 33 watts(t)
Internal Volume (Fuel Region): Total: 0.88 in^3 , Fuel: 0.44 in^3 ,
Void: 0.44 in^3

Capsule Closing Mechanism: Weld

Fabrication:

1. Flat plate spun of hydroformed hemisphere
2. Top: flat plate
3. Machine and tolerances

<u>Parameter</u>	<u>Capsule</u>	
	<u>Inner</u>	<u>Outer</u>
Material	Ta-10W	Haynes-25
Inside Diameter - Inches	1.50	1.60
Inside Length - Inches	0.75	0.85
Wall Thickness - Sides - Inches	0.05	0.05
Wall Thickness - Ends - Inches	0.05	0.1
Total Weight - Pounds	0.18	0.145
Melting Point - $^{\circ}\text{F}$	5522	2425
Thermal Conductivity	32.7	8.1
Linear Expansion Coefficient, 10^{-6} in/in/ $^{\circ}\text{F}$	5.510	7.57
Density - lb/in 3	0.608	0.330
Strength (Room Temperature) Recrystallized	600 $^{\circ}\text{F}$	
Tensile - psi	80,600	127,500
Yield - psi (0.2 % offset)	71,000	40,400
Elongation - %	27	72

Thermopile

Total Thermocouples: 32
Arrangement: Rectangular
Electrical Connection: Series/Parallel
Efficiency: End of Life - 5.0%

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TABLE V-5 (CONTINUED)

Thermoelement Data:

<u>Parameter</u>	<u>P</u>		<u>N</u>	
Material	Bi ₂ Te ₃		Bi ₂ Te ₃	
Manufacturer	General Instrument Corporation/ Asarco Corporation			
Length - Inches	0.5		0.5	
Diameter - Inches	0.179		0.169	
Shape Factor (L/A) in ⁻¹	0.095		0.1	
Temperature - °F	BOL	EOL	BOL	EOL
Hot Junction	467	380	467	380
Cold Junction	105	100	105	100

Electrical Contact: Tinned copper leads soldered to cold side

Materials:

<u>Component</u>	<u>Materials</u>	<u>Diameter</u>
Hot Shoe	Nickel Plated Copper Lengths	0.10 x 0.20
Cold Shoe	Nickel Plated Copper Lengths	0.10 x 0.20

Insulation

Type: Min-K 1301

Manufacturer: Johns-Manville, Inc.

Thickness - Inches:

Sides: 0.06

Ends: 0.06

Weight - Pounds: 0.084

Thermal Conductivity - $\text{Btu/ft-hr-}^{\circ}\text{F}$: 0.018

Fill Gas: Xenon Pressure Atm: 1/2

Maximum Operating Temperature - $^{\circ}\text{F}$: 612

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TABLE V-5 (CONTINUED)

Casing

Material: Hastelloy-C

Outside Diameter - Inches: Hemisphere 1.72 R; Flange 7

Outside Length - Inches: 2.72 (excluding power conditioner package)

Thickness - Inches: 1/4 Hemisphere; Flange 0.54

Volume - in³: 20.6

Weight - lb: 6.65

Finned Surface: Operating in Seawater - None

dc - dc Converters

Type: Transistorized

Shape: Cylinder

Dimensions:

Length - Inches: 1.5

Diameter - Inches: 2.0

Weight - Pounds: 3.5

Input:

Voltage: 0.5

Current - Amps: 2.4

Output:

Voltage: 18

Current - Amps: 0.0555

Efficiency - %: 80

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The selection of the casing hemispherical shape will yield a maximum surface strength for water impact and sea pressure, yet retain a minimum size, and distribute all loads uniformly. The shape will also result in the simplest assembly methods, fewest parts, most reliable seals, and a simple storage method which will insure against overheating. Thus the hemisphere found to be the best overall solution for all the requirements.

1. Components

a. Fuel Capsule. With a beginning of life fuel requirement of 33 watts of $\text{Pu}^{238}\text{O}_2$ [REDACTED] a fuel volume of 0.44 in^3 is required. To contain internal pressure buildup and to retain a reasonable size, a void fraction of 0.5 is used. The wall thickness of the Ta-10W inner lining is an easily weldable 50 mils all around. The Haynes-25 liner thickness at the hemisphere portion is 0.05 and 0.15 at the flat end. The stress due to helium pressure buildup after 20 years is 2560 psi. The fuel is placed at the top of the hemisphere for maximum heat transfer, and is held there by the roundness of the walls and a Ta-10W spacer. Fabrication of the hemispherical portions of the fuel capsule is accomplished by hydroforming and final machining for weld preparation. Welding is identical to the end closures of the cylindrical capsules.

b. Thermopile. The thermopile is identical to the one watt Sr-90 RTGs previously described. The maximum temperature of the hot shoe side of the thermopile, 467°F , is assured against storage condition by the fluid filled storage is shown in Figure V-21. Here the storage can is attached to the housing by simply screwing it into the threads located on the generator just below the flange. If the storage ambient climbs above 80°F for a long period of time, water must be continually circulated through the storage container by pumping or natural convection. The primary purpose of maintaining the thermopile temperature at 467°F or less is to reduce degrading of the thermoelements and element poisoning by component outgassing.

c. Insulation. The insulation is 0.6 inch thick Min-K 1301. It is fabricated in two sections, a hollow hemisphere, and a flat disk with the cutout for the thermopile. Here, at the insulation, the greatest gain in the hemispherical shape is obtained. Not only are there only two pieces, but an assembly for high preload conditions is simplified. Recall that in the one watt(e) Sr-90 designs, the side insulation in the shape of a cylinder had to be slipped over the fuel capsule, carefully located over the fuel capsule cavity, and a preload applied to it and the fuel capsule through the tightening of an enclosing ring clamp around the entire assembly. The entire assembly then had to be pushed while under this clamp load into the cavity. The result for insulation that must be heavily loaded for high "g" load conditions is a large possibility of insulation failure. Especially critical would be partial failures not detected in assembly. The hemispherical shape eliminates this problem. In addition, a uniform radial compressive load is guaranteed. Finally, preload can be easily obtained by bolting down the cover plate. High insulation efficiency is obtained by using a Xenon gas backfill and a positive seal is maintained to avoid leakage by the cover plate.

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d. Pressure Vessel and Shield. The advantage of Pu-238 fuel is that little shielding is required and the outer container need act only as a pressure vessel. The pressure vessel is a 0.25 inch thick, 3.58 inch diameter Hastelloy-C hemisphere. It is designed to withstand pressures at 18,000 foot ocean depths. It is also designed to withstand high "g" water impact from an air drop. Stress calculations for these conditions are discussed on the next several pages. In both of these conditions, the hemispherical structure aids in obtaining the required structural strength.

An external flange is shown in Figure V-21, although an internal flange system similar to that of the 300 milliwatt strontium-90 fueled RTG previously discussed could be used to reduce water impact loads. However, external flanges are more universal, and the internal flange may be too restrictive on the components of the repeater station due to the small diameter of the generator. Therefore, the large external flange is shown but should not be taken as a limiting size requirement.

Fabrication of the pressure vessel is accomplished by investment casting and aging Hastelloy-C into the hemispherical shape. A subsequent grind and polish operation will provide the finish and final tolerances required. Both "O" ring grooves, one for the interface flange and one for the cover plate, are machined from the flange. The eight cover plate bolt holes are also tapped and drilled; 0.25 inch diameter by 0.375 inch deep threads. Seals for the inner cover plate and for the interface flange will be the solid metal copper "O" rings.

e. dc - dc Converter. The dc-dc converter is identical to the one previously described in the 1 watt Sr-90 systems.

2. Stress Analysis

a. Water Impact. The water impact analysis is in two phases, as discussed for the 300 milliwatt generator system in Section V-C-3-a, compressive and drag, and the shell is designed to the compressive phase conditions and the components to the drag loads.

(1) Compressive Phase

$$v = v_o (1 - \exp \frac{-1}{4\gamma})$$

where:

$$\begin{aligned} \Delta v &= 5.5 \text{ ft/sec velocity change} \\ v_o &= \text{velocity immediately prior to water impact} \\ \gamma &= \frac{W}{\frac{4}{3} \pi R^3 \rho_w} \quad \text{ballistic density} \end{aligned}$$

$$W = \text{weight of generator} = 9.93 \text{ lbs}$$

$$R = \text{radius of generator} = 1.72 \text{ lbs}$$

$$\rho_w = \text{density of water} = 3.59 \times 10^{-2} \text{ lb}_m/\text{in}^3$$

$$\therefore \gamma = 12.95$$

$$v_o = \frac{\Delta v}{(1 - e^{-\frac{1}{4\gamma}})} = 288 \text{ ft/sec}$$

$$h = 0.25 = \text{pressure vessel thickness so } h/R = 0.1454$$

From curve, Figure V-20:

$$\frac{v_D}{C_O} = 0.427$$

$$C_O = 5000 \text{ ft/sec}$$

$$v_D = 2135 \text{ ft/sec (damage velocity)}$$

Since v_D , the damage velocity, is much greater than the actual velocity v_o (288 ft/sec), a safe margin for the shell during water impact is indicated. This margin of safety shows the benefit of the small size and the hemispherical shape.

(2) Drag Phase. Maximum load to the components is as before, 300 "g's" (see Section V-C-3-a).

(3) Thermopile Load

$$P = \frac{W_e}{A_c} \quad (\text{contact pressure between shoe and cover plate})$$

where:

$$W_e = 300 W \text{ (equivalent weight)}$$

$$W = 1.41 \text{ lbs (composite weight of fuel block and T/E elements)}$$

$$A_c = 0.192 \text{ in}^2$$

$$P = 2200 \text{ psi}$$

The compressive stress on each element of the thermopile is:

$$S_c = 0.261 P = 522 \text{ psi}$$

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(4) Cover Bolt Load for Min-K Preload

$$P_{bt} = W_e = 423 \text{ lbs}$$

There are 6 bolts so

$$P_b = \frac{P_{bt}}{6} = 70.5 \text{ lbs/bolt preload required}$$

(5) Min-K Preload Stress

$$S_c = \frac{W_e}{A_{\text{Min-K}}} = \frac{423}{(1.46)^2} = 63.2 \text{ psi}$$

b. Pressure Vessel

(1) Internal Pressure and Resulting Stress. Internal pressure from between buildup due to PuO_2 decay is:

$$V = 0.44 \text{ in}^3 \text{ void volume}$$

$$T = 880^\circ \text{R surface temperature}$$

$$\text{PuO}_2 \text{ beginning of life power} = 33 \text{ watts power density of}$$

$$\text{PuO}_2 = 0.55 \text{ watts/gm.}$$

$$\text{Initial PuO}_2 \text{ mass} = \frac{33 \text{ watts}}{0.55 \text{ watts/gm}}$$

$$= 60 \text{ gm}$$

$$= 0.132 \text{ lb}$$

$$1 \text{ lb - mole of PuO}_2 = 278 \text{ lb}$$

$$\text{Initial moles of PuO}_2 = n_o = 4.75 \times 10^{-4}$$

$$\text{End of life} = 20 \text{ years} = t$$

$$t_{1/2} = 89.4 \text{ for PuO}_2$$

$$\lambda = \frac{0.693}{t_{1/2}} = 0.00775 \text{ Yrs.}^{-1}$$

$$n' = n_o e^{-\lambda t}$$

$$n' = 4.06 \times 10^{-4} \text{ lb-moles}$$

$$n = \text{moles of helium}$$

$$n = n_o - n'$$

$$n = 6.9 \times 10^{-5} \text{ moles}$$

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$\bar{R} = 1545$ Universal Gas Constant (consistent units)

$$P_i = \frac{n \bar{R} T}{\bar{V}}$$

$$P_i = 3.68 \times 10^5 \text{ lb/ft}^2 = 2560 \text{ psi}$$

$$S_2 = \frac{P_i R}{t}$$

$$R = 1.72 \text{ inches}$$

$$t = 0.25 \text{ inch}$$

$$\therefore S_2 = 17,600 \text{ psi}$$

(2) External Pressure. Stress resulting from crushing pressure of seawater at 18,000 foot depth is:

$$\text{Max } S_2 = p \frac{3 R^3}{2 (R^3 - a^3)}$$

$$p = 10,000 \text{ psi}$$

$$R = 1.72 \text{ inches}$$

$$a = 1.47 \text{ inches}$$

$$S_2 = 39,800 \text{ psi}$$

(The external pressure would tend to counterbalance internal pressure resulting in a much lower stress than either calculated or 39,800 - 17,600 = $S_2 = 22,200$ psi).

(3) Bolt Load (External Pressure) From Paragraph V-A-2-b

$$H_p = 2 \pi G m p b$$

$$p = 10,000 \text{ psi}$$

$$b = 0.312$$

$$m = 6$$

$$G = 2.5$$

$$H_p = 2.94 \times 10^4 \text{ lb}_f$$

$$A_{bt} = \frac{H_p}{S_b} = \frac{2.94 \times 10^4}{1.8 \times 10^5} = 1.63 \times 10^{-1} \text{ in}^2$$

$$A_b = \frac{1.63 \times 10^{-1}}{6} = 2.72 \times 10^{-2} \text{ in}^2$$

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$S_o \frac{1}{4} - 20$ bolt is permissible

$$S_{bl} = 0.191 \text{ in}^2$$

$$S_{bl} = \frac{H_p}{A_{bl}} = 154,000 \text{ psi}$$

The effect of the internal pressure of the system reduces the net hydrostatic end force acting on the seal. This effect on the bolts will be ignored. Therefore, an additional factor of safety is realized in the selection of the flange bolt size.

3. Final Assembly

Final assembly is the simple operation of laying the Min-K hemisphere into the pressure vessel, setting the fuel capsule in it, placing the thermopile on the capsule and the top Min-K over the thermopile, and then just bolt on the top. The dc-dc converter is then added at convenience.

E. Design Summary

Four conceptual designs have been presented. These concepts are maintained within state-of-the-art wherever possible, although some slight advancements are postulated. The fuel capsule interior liners are recommended to be Ta-10W in all cases. Previous SNAP-7 and [REDACTED] systems utilized inconel [REDACTED]. Ta-10W is an easily fabricable and weldable material and it represents a significant increase in strength and radiological safety.

Min-K thermal insulation is also a "standard" SNAP system component but in its present form, it does not represent the panacea of such materials. Outgassing problems have continually existed and its pre-conditioning preparation is still expensive. Johns-Manville is attempting to make this material more suitable for use in these type generators under another USAEC contract.

The thermoelements recommended are off-the-shelf components from either General Instrument Corporation or Asarco, Inc. Again, while these materials suffice, they are of low efficiency and structurally weak. Lower cost and more stable systems could be produced if improved thermopiles were available.

The pressure vessels recommended are also as standard as may be currently postulated. No attempt has been made to utilize high compressive strength, low weight materials such as titanium and its alloys or glass composite substances. Rather, the brute force approach of using super-alloys with "O" ring seals is taken. Although this approach is less developmental, it is obvious that pressure vessels to withstand an 18,000 foot ocean depth, of any sort are not completely "standard".

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Therefore, while the designs presented are within laboratory or limited use state-of-the-art, none are completely development free. To produce these systems, a development program, which covers the points listed and is heavily reliability and production oriented, will be required.

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APPENDIX A

DYNAMIC AND STRUCTURAL MODEL

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APPENDIX AI. DYNAMIC LOADS - EQUIVALENT STATIC LOAD METHOD

Dynamic models, using as a basic tool differential equations of motion, are the most desirable methods of analyzing structural responses of a system to dynamic loads. However, models made descriptive of the actual system are often extremely complex, can only be described by three to six degrees of freedom systems, and are non-linear. Consequently, an alternative method of analysis is often used consisting of the "g" load factor multiplier and static stress analysis combination. It uses as a basic tool, the great amount of theory, data and empirical formulas gathered in the theory of structures. It converts the dynamic load to a dimensionless factor by which the static weights are then multiplied. The converted loads are treated as static loads and the system is analyzed in the classic manner of structural analysis.

The advantages of the method are ease of analysis and confidence in the results. Disadvantages are the determination of the exact value of the "g" multiplier and the selection of accurate structural models. Nevertheless, it is the method followed in this program.

A. Severe Shock Pulse Derivation

The severe shock is defined as "both axial directions and along selected radial directions (if a body of revolution)". Otherwise, along the three principal orthogonal axes of the system. There are two phases: (a) a "g" versus time diagram which depicts a triangular area with a Δv of 5.5 FPS over a time period of 0.1 - 0.3 milliseconds; (b) an average loading for a 10 - 50 millisecond duration of 90 - 100 "g" with a 125 - 150 "g" peak.

The graph of this impulse is shown in Figure A-1. It is typical of water entry shock of a right circular cylinder in which there are two phases, compressive phase and drag phase. The compressive wave consists of a very high "g", low duration impulse which occurs upon initial contact. It is caused by a sonic compressive wave forming at the center of the flat contact end of the cylinder and spreading to the outer edge of the cylinder. An actual example of this phenomena is the well known stinging slap felt when the hand is swung open palm into water. The force of this phase can be described as a local pressure felt on the end of the cylinder for the duration taken for the wave to traverse the distance, at the speed of sound in water, from the center to the outside radius.

When the shock wave has passed the outer edge of the cylinder, the object begins to sink and the system enters the drag phase. It is lower and of longer duration force impulse than the compressive phase and contains most of the energy of the combined shock. Simply described, it is the rapid deceleration of the cylinder due to the water drag forces. Its equation for acceleration is a function of entry velocity and the drag factor and is shown below (Reference 2).

Impact phase is triangular area with V of 5.5 - 7 FPS.
Drag phase is 90 - 110 g average with 125 - 150 g peak.

Figure A-1. Shock Impact

$$\ddot{a} = \frac{3}{8} C_D v^2 / rz \quad (A-1)$$

where z = ratio of device weight to equal volume of water

The drag coefficient C_D indicates the dependence of the acceleration (shock pulse) on the geometry, size and construction of the device. If the device is dense, smooth sided and has a streamlined nose, it will have a much lower deceleration than a larger less dense blunt nosed device. What is the design in the specified severe shock? It cannot be determined. However, it can be taken as an indication of the "type" of loading and the magnitude of the shock load.

The magnitude of each shock phase is given by the area under the curve of Figure A-1. Consequently, from total energy considerations, it can be expected that the effect upon the RTG of the phase (b) shock will be very much greater than the phase (a) shock. For the parametric study, phase (a) will, therefore, be ignored.

B. Dynamic Model

The prediction of RTG response to this shock pulse was determined by first selecting a simplified model and then selecting a worst case and a best case shock load. Each shock load having the equivalent energy of the specified pulse. The actual response was then bracketed, enabling the prediction of a maximum and minimum equivalent static load.

The most simple dynamic model is shown in Figure A-2. It represents a simple degree of freedom system. It is undamped and linear. Such a system could be the equivalent of spring loaded thermoelectric couples a retaining cap spring clip system or a fuel capsule supported through the exterior RTG case. The model, although simple, has the capability for presenting typical response characteristics of frequency affected dynamic systems. The basic differential equation of motion is:

$$m_r \ddot{\delta} = F_s(\delta) = -m\ddot{u} \quad (A-2)$$

where:

$\ddot{\delta}$	=	acceleration of spring deflection
m_r	=	rigid mass
$\ddot{u}$	=	acceleration of support (condition of shock)
F_s	=	force on spring due to deflection

1. Basic Shock Pulse Shapes

Two basic shock pulses are presented in Figure A-3 along with their describing equations. The rectangular pulse is representative of a most severe case, one of instantaneous rise and fall times and a log effective pulse duration which is not usually found under actual operating conditions.

Figure A-2. Undamped Linear Single Degree of Freedom Dynamic Model

Figure A-3. Basic Pulse Shapes

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The 1/2 versed sine wave is of the opposite extreme having the ability to depart into any structure the more favorable conditions of slow rise and fall times at a constantly changing slope.

2. Shock Spectra

The shock response of system to the various pulse shapes is shown in Figure A-4. It shows that for the 1/2 versed sine shape, the maximum transmitted acceleration is between 1.6 and 1.8 times the impact acceleration (Reference 36). Also, that at high natural frequencies the transmitted value reduces to the maximum input acceleration. The rectangular curve shows the worst transmitted acceleration of twice the peak input shock (Reference 37). Therefore, the maximum static equivalent load or "worst" case is 2 times the maximum input "g" and a best case is equal to the maximum input "g". From the specified shock curve of Figure A-1, the maximum static equivalent load is 300 "g", the minimum is 150 "g".

C. Equivalent Static Load - Severe and Normal Vibration

Severe and normal vibration is specified as follows:

1. Severe Vibration

- (1) 2 "g" low frequency 10-60 cps (0.1 inch peak to peak max)
- (2) 3 "g" high frequency 60-500 cps (no peak to peak max)
- (3) 5 "g" special 10-2000 cps (0.15 inch peak to peak max)

This severe vibration is typical of missile launching loads.

2. Normal Vibration

Test required for equipment transported by common carrier according to MIL-STD-810A, 23 June 1964.

The vibrations in the above conditions are assumed to be harmonic and the equations describing the motion are:

$$\text{displacement: } x = x_0 \sin (2 \pi f t) = x_0 \sin \omega t \quad (\text{A-3})$$

$$\text{velocity: } \dot{x} = x_0 (2 \pi f) \cos (2 \pi f t) = x_0 \omega \cos \omega t \quad (\text{A-4})$$

$$\text{acceleration: } \ddot{x} = x_0 (2 \pi f)^2 \sin (2 \pi f t) = x_0 \omega^2 \sin \omega t \quad (\text{A-5})$$

The maximum values of each parameter occurs when the temperature functions are equal to unity and are as follows:

$$x = x_0 \quad (\text{A-6})$$

$$\dot{x} = \omega x_0 \quad (\text{A-7})$$

$$\ddot{x} = \omega^2 x_0 \quad (\text{A-8})$$

Figure A-4. Shock Spectrum Curves

By placing the specified severe vibration conditions into these equations, it shows that the 0.1 peak to peak limit at a 2 "g" level will be met at 20 cps and above. For the 0.15 inch peak to peak limit the 5 "g" level will be 26 cps and above. Below these respective frequencies, the required "g" level cannot be reached with the double amplitude peak limitations as specified.

3. Dynamic Model

The dynamic model used to obtain response levels to the above harmonic equation is shown in Figure A-5. It is similar to the shock model except for the addition of a dashpot in parallel with the spring. Its equation of motion is:

$$m \ddot{x} + c \dot{x} + k x = 0 \quad (A-9)$$

When the harmonic forcing functions are placed on the system of Figure A-5, the complete equation of motions becomes Equation (A-10).

$$m \ddot{x} + c \dot{x} + k x = x_0 \sin \omega t \quad (A-10)$$

Figure A-5. Vibration Dynamic Model

Curves of Equation (A-10) for various damping ratios are shown in Figure A-6. The curves like those for shock (Figure A-4) indicate the transmitted acceleration can be magnified to peak values. Unlike shock, the point of maximum amplification always occurs at resonance (point where the period of the systems natural frequency is equal to the period of vibration). Also unlike shock, the controlling factor in the amount of amplification at resonance is at the critical damping value and is equal to one. The maximum is infinity with no damping. Since neither case is actually obtainable, the expected "worst" and "best" case amplification can be determined from experimental data on normal damping ratios in structures. With normal ranges of damping being between 0.1 C and 0.5 C (Reference 36), amplification factors will be from 12 to 20 times the maximum input acceleration. The "best" case loading was then selected as a static multiplier of 12 times 5 "g" or 60 "g" and "worst" case as twenty times the 5 "g" special case input for severe vibration, or 100 "g".

D. Equivalent Static Load - Normal Shock

Normal shock is defined as "two 3 "g" shocks having a 6 millisecond half sine wave pulses in each of the three principal orthogonal axes". If the time between the first and second pulse is sufficient to allow the RTG to come to rest between pulses, the maximum equivalent "g" load will be that of the 1/2 sine wave shock spectra of Figure A-6 or 1.8 times 3 "g" or 5.4 "g". If the two shocks are in rapid succession, the generator's motion in response to the first shock may collide with the second shock wave. The resulting collision may cause a very great increase in shock loading. However, since the time between shock pulses is not known at this time, it will be assumed that even the worst case will not exceed the severe shock equivalent static loading range of 150 to 300 "g".

E. Shock and Vibration Incompatibility

A very soft or low frequency shock absorbing system can be developed which will attenuate the long duration high energy shock pulse. It will also, however, provide large excursions and allow resonance with low frequency vibration. The danger is evident, to design the optimum configuration to shock may provide a mode of failure under vibration. This is also true in reverse, a vibration absorber may amplify shock loads. Evidently, if the system is designed "soft" (see Figure A-4 where the period of response is large (low frequency) compared to the dynamic input pulse duration), this danger of amplification will always be possible. If the systems are designed "hard", where the period of response is small (high frequency) compared to the dynamic input period, the amplification is no greater than unity. Consequently, a stiff (hard) structural system is the safer approach if both shock and vibration are present. Since both are to be present, a stiff system will be assumed for the parametric study and the greatest static load will then be 150 "g" -- equal to a gain of unity or equal to the peak acceleration of the severe shock load.

Figure A-6 Vibration Responsive Curves

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F. Other Dynamic Loads

Since the purpose of the milliwatt generator is to provide a useful device to many using agencies, shock and vibration loads other than specified will be encountered. Such loads would have to be evaluated in a similar manner as those just mentioned and checked against the structural models. However, since the system is assumed hard or stiff, it has the best chance of surviving the widest range in types of dynamic loads. Only the peak "g" load or total energy will be important in these new loads. If the new "g" loads are above those allowed by the RTG or its weakest component, then a carrying case type of exterior absorbing structure could be developed for this special purpose only. This assumes that the new dynamic environment could be clearly defined and the new "g" loads are within a reasonably attenuable value.

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II. SIMPLIFIED STRUCTURAL MODELS

Some of the structural models for checking the RTG and components ability to survive the previously established loads are presented in this section. It includes the attenuation versus case deflection, a thermoelectric model, and a case model. As the parametric designs become evident, more structural models will be developed and used in a similar manner.

A. Shock and Vibration Attenuation Model

The free falling mass shown in Figure A-7 is a simplified model of the severe shock. The mass m is considered to be the RTG in a shipping case free falling a distance h . The distance h is sufficient to obtain the energy in the specified shock impulse. After impact the carrying case deflects a distance h_a and, in deflecting, absorbs some portion of the impact energy. The energy not absorbed in case deflection is transmitted to the contained RTG. If a carrying case is not used the model is still valid for h_a can be taken as the RTG case deflection. In addition, it will be shown from the equations developed that if the case is not allowed to deflect past its yield point, h_a will be very small and almost all of the impact energy will be transmitted to the RTG components. (See graph of Figure A-8).

A general energy equation for the model of Figure A-7 is given as

$$E_I = E_a + E_{TR} \quad (A-11)$$

where:

E_I	=	energy impact
E_a	=	energy absorbed
E_{TR}	=	energy transmitted

In free fall

$$E = 1/2 m v^2 \quad (A-12)$$

but $v = \sqrt{2 g h}$

or $E = m g h$

The ratio of impact energy to absorbed energy is

$$\frac{E_I}{E_a} = \frac{m g h}{m g h_a} = \frac{h}{h_a} = \gamma \quad (A-13)$$

where γ can be considered an attenuation factor.

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Figure A-8. "g" Load Versus Height of Fall, Deflection and Duration of Impact

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Figure A-7. Severe Shock Model

Rewriting Equation (A-13)

$$E_I - \frac{E_I}{\gamma} = E_{TR}$$

or

$$E_I \left(1 - \frac{1}{\gamma} \right) = E_{TR} \quad (A-14)$$

The impulse curve of severe shock is defined in Figure A-1 can be approximated by a rectangular impulse of magnitude equal to the average "g" load of 150 versus the time duration of 50 milliseconds. The new impulse curve is shown in Figure A-9. The momentum in this impulse is defined as:

$$\alpha w \Delta t = \text{momentum} = mv \quad (A-15)$$

w = weight of RTG (or RTG + case) ($w = g m$)

m = mass of RTG (of RTG and case)

α = "g" load (average "g" load of 150)

Δt = impulse time duration (50 milliseconds)

Figure A-9. Rectangular Impulse

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The change of momentum of RTG is equal to the momentum of the RTG just prior to impact

$$\alpha W \Delta t = m v \quad (A-16)$$

$$\text{from } v = \sqrt{2 g h} \text{ and } m = w/g$$

$$h = \frac{\alpha^2 (\Delta t)^2 g}{2} \quad (A-17)$$

Substituting Equation (A-4) into Equation (A-4) yields

$$1/2 m v^2 (1 - \frac{1}{\alpha}) = 1/2 m v^2 \quad (A-18)$$

and $v = \alpha (\Delta t) g$ from Equation (A-16) yields

$$\alpha (\Delta t)^2 g^2 (1 - \frac{1}{\alpha}) = v^2 \quad (A-19)$$

If the duration of the response pulse form is assumed to be equal to the input impulse duration, then Equation (A-9) becomes

$$\alpha \sqrt{1 - \frac{1}{\alpha}} = g \text{ transmitted} \quad (A-20)$$

$$\text{since } = \frac{h}{h_a}$$

$$\alpha \sqrt{1 - \frac{h_a}{h}} = g \text{ (transmitted)} \quad (A-21)$$

$$\text{since } h = \frac{\alpha^2 (\Delta t)^2 g}{2}$$

$$\alpha \sqrt{1 - \frac{2 h_a}{(\alpha \Delta t)^2 g}} = g \text{ (transmitted)} \quad (A-22)$$

The equivalent free fall h for the specified impulse is approximately 400 feet. Unless h_a is on the order of many feet, "g" transmitted will be approximately equal to average "g" load α or 150 "g". Attenuation for other impulse values is shown in Figure A-8.

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B. Thermoelectric Model

Worst case: The worst case for lead telluride thermoelectric elements would be loaded as a cantilever which would put the upper surface in tensile stress, its weakest condition. The configuration is shown in Figure A-10.

$$S_{yp} = \frac{M}{Z} \quad (A-23)$$

$$Z = \frac{\pi D^3}{32} \quad (A-24)$$

$$M_{max} = \frac{0.281 \pi D^2 L^2}{8} \quad (\text{Reference 4}) \quad (A-25)$$

$$S_{yp} = 1000 \text{ psi}$$

then

$$\frac{L^2}{D} = \frac{874}{\alpha} \quad (A-26)$$

This equation for various lengths is shown in Figure A-10.

Best case: Since the lead telluride elements are strongest in compression, the best configuration would be for complete compressive loading. The model for this case is shown in Figure A-11.

$$S_{max} = 2 P_o \quad (S_{max} = 10,000 \text{ psi}) \quad (A-27)$$

$$P_o = \frac{F}{A} = \frac{F}{\pi D L} \quad (\text{Reference 4}) \quad (A-28)$$

$$F = \alpha W$$

$$W = \frac{\rho \pi D^2 L}{4} \text{ lbs}$$

$$\rho = 0.281 \text{ lb/in}^2$$

$$L = 1 \text{ inch}$$

$$F = \frac{\alpha \rho \pi D^2}{4}$$

$$2 P_o = \frac{\alpha \rho D}{2}$$

$$2 P_o = S_{max} = 10,000$$

$$\frac{D}{2} = \frac{3.56 \times 10^6}{\alpha} = R \quad (A-30)$$

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Figure A-10. "G" Load Versus Diameter for Lead Telluride - Worst Case

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$S_{\text{compression}} = 10,000 \text{ psi}$
 Material = Lead Telluride

Figure A-11. "g" Loading Factor Versus Radius Required for Failure - Best Case

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This equation is plotted in Figure A-11.

C. Case Model

Worst case: The worst loading configuration for the RTG container is the side load (or side impact) condition of Figure A-12.

Best case: The best loading condition for the container would be a uniform external pressure producing hoop stress. The equations for the side loading (longitudinal - worst case) and the best case, hoop stress, is as follows:

Maximum Longitudinal Stress

$$S_1 = -0.1188 A^{3/8} p R^{1/4} t^{1/2} \quad (A-31)$$

Maximum Hoop Stress

$$S_h = -0.492 A^{1/8} p R^{3/4} t^{-1/2} \quad (A-32)$$

$$A = 12 (1 - r^2)$$

Weight of cylinder = W

For purposes of analysis $P = \alpha W, lb$

where α = loading factor

ρ = density, lb/in³

Haynes Alloy No. 25, $\rho = 0.330$ lb/in³

R = 0.288 inch

E = 32.64×10^6 psi

Room Temperature $S_{yp} = 55,000$ psi

$S_t = 130,000$ psi

Elongation = 45%

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$p = \beta W$
where β is "g" loading factor
See page 272, Reference 4

Figure A-12. Worst Loading for Container (Side Load)

Figure A-13. Best Loading for Container (Hoop Load)

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$$A = 12 (1 - 0.288^2) = 11$$

$$A^{3/8} = A^{0.375} = 2.456$$

$$S_1 = 0.2905 p R^{1/4} t^{1/2} - 7/4$$

$$A^{1/8} = A^{0.125} = 1.349$$

$$S_h = 0.578 p R^{3/4} t^{-1/2} - 5/4$$

$$S_1 = 0.2905 W R^{0.25} t^{0.5} - 1.75 \quad (A-33)$$

$$S_h = 0.578 W R^{0.75} t^{-0.5} - 1.25 \quad (A-34)$$

$$\text{Longitudinal} \quad t^{1.75} = \frac{W R^{0.25} t^{0.5}}{447,000} \quad (A-35)$$

$$\text{Hoop} \quad t^{1.25} = \frac{W R^{0.75}}{225,000 t^{0.5}} \quad (A-36)$$

Figure A-12 and Figure A-13 show the worst and best case models to the above equations with an assumed system weight of 10 pounds.

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APPENDIX B

NOMOGRAPHS

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NOMOGRAPH NO. 1 LARGE MILLIWATT GENERATOR DESIGN CHARACTERISTICS

NOMOGRAPH NO.2 LARGE MILLIWATT GENERATOR CASE DESIGN

NOMOGRAPH NO. 3 LARGE MILLIWATT GENERATOR COST ANALYSIS

Produced for the United States
ATOMIC ENERGY COMMISSION
by HITTMAN ASSOCIATES Inc. Under
Contract No. AT(30-1) 3627, MAY, 1966