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SYSTEMS FOR NUCLEAR AUXILIARY
POWER (SNAP) - ISOTOPIC SNAP
PROGRAM (M-3679, 46th. Ed.)

LARGE MILLIWATT RADIOISOTOPE THERMOELECTRIC GENERATOR PROGRAM

FINAL TECHNICAL REPORT

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May 1966

Aerojet-General Nucleonics
San Ramon, California

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AEC Research and Development Report

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LARGE MILLIWATT, RADIOISOTOPE
THERMOELECTRIC GENERATOR PROGRAM

FINAL TECHNICAL REPORT

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PREFACE

The work in the final study was performed by personnel from Aerojet-General Nucleonics and Monsanto Research Corporation under Contract AT(30-1)-3628. The report represents the contributions of the following individuals from AGN:

Carl Carney

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LARGE MILLIWATT, RADIOISOTOPE
THERMOELECTRIC GENERATOR PROGRAM

FINAL TECHNICAL REPORT*

ABSTRACT

The general characteristics of advanced, large milliwatt, radioisotope thermoelectric generator systems were investigated to determine if such could be constructed from materials available today and in the near future. The power level specified was the range from 150 to 1000 mw(e); three fuel forms were specified; the operating temperature range (ambient) specified was from 28 to 90°F. The study was performed in three phases: liaison, an investigation into the potential applications of such systems; parametric study, a determination of the interplay of parameters on the design of such systems; and the conceptual design of four systems selected by the AEC. This is the final report of the project; it summarizes the liaison and parametric study phases, and reports in detail on the conceptual designs. This study was performed under Contract AT(30-1)-3628 between the New York Operations Office of the AEC and Aerojet-General Nucleonics with Monsanto Research Corporation.

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LARGE MILLIWATT, RADIOISOTOPE
THERMOELECTRIC GENERATOR PROGRAM

FINAL TECHNICAL REPORT

I. INTRODUCTION

This document reports the results of an investigation into radioisotope thermoelectric generators (RTGs) in the large milliwatt (150 to 1000 mw) power range. The study was performed by Aerojet-General Nucleonics (AGN) and Monsanto Research Corporation (MRC) under Contract AT(30-1)-3628 with the New York Operations Office of the U. S. Atomic Energy Commission. The study was performed in three parts: liaison, to establish potential applications; parametric designs, to determine the factors of importance in designing for the application revealed by the liaison work; and the conceptual design of four systems.

The first two phases of the program were reported earlier* and hence are only summarized in this document, although the results of the parametric study are frequently utilized throughout this document. The results of the parametric study indicated that about 16 systems illustrated the interplay of constraints, materials, and design goals within the range of end-uses indicated by the liaison effort. From these systems, the AEC selected four for further study, including a 1000 mw(e), SrTiO₃ system; a 600 mw(e), Pm₂O₃ system; a 300 mw(e), plutonium system; and a 150 mw(e), SrTiO₃ system.

The liaison phase of the program is summarized in Chapter II; and Chapter III summarizes very briefly the results of the parametric study. The general design approach followed during this third phase of the program is discussed in Chapter IV. Each of the designs selected by the AEC is given a chapter of its own (Chapters V, VI, VII and VIII). The final chapter, number IX, is devoted to a discussion of the development program that must precede the reduction of any of these conceptual designs to a final design.

* Letter reports to David Elias, AEC-NYO, from P. E. Underhill, AGN, dated 3 December 1965 and 4 January 1966

Large Milliwatt Radioisotope Thermoelectric Generator Program - Parametric Study Data, March 1966, AGN 8182 (C-RD Report)

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II. LIAISON

The liaison task was organized to obtain definitive information, where available, from potential users of systems based on radioisotope thermoelectric generators (RTGs) in the large milliwatt power range. Candidate organizations for the liaison task activities included those revealed by a pre-contract survey performed by AGN, and letter surveys initiated under this contract. Seven organizations were selected from these lists, including Sandia/Albuquerque; Global Marine; NCEL; ITT; Alpine Geophysics; Woods Hole Oceanographic Institute; and NOL. The meetings were attended by representatives from the AEC and the two contractors working under parallel programs, Hittman Associates and AGN/MRC.

The results of the liaison task revealed a range of markets for the RTGs, and in addition indicated that additional markets were certain to be developed when the devices had been service-tested. The results of the survey are tabulated below: systems selected for further evaluation are shown on p 6.

TABLE 1

SUMMARY OF LIAISON TRIPS

	<u>Power Level, mw</u>	<u>Req'd Life, yr</u>	<u>No. Req'd For Next Five Years</u>
1. NOL	100; 200; 300	10	100 to 1000
2. Sandia	0.5 to 15 15 to 100	10	"Many"
3. Global Marine	1000	5 to 10	500 to 1000
4. NCEL	10 to 1000	5 to 10	56
5. IT&T	1000 to 4000	20	(≈500/cable)
6. Alpine Geophysics	1000	5 to 10	50 to 100
7. Woods Hole Oceanographic Institute	1000	5 to 10	"Few"* "Many"***

* Research

** Harbor markers

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A list of points to be discussed in the liaison meeting was submitted to each of the organizations prior to the actual meeting. This approach minimized the time expended in obtaining the desired information from each organization. The significant factors revealed by each visit are presented below.

A. NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

The discussion at NOL was expedited when that organization distributed a description of their requirements for a SNAP-15C-type power supply. The discussion revealed that a 300 mw supply would cover all of the potential applications insofar as their power requirements were concerned; a 200 mw supply, about 65%; and a 100 mw, about 25%. Each procurement would range from 100 to 1000 units over several years.

NOL's general requirements are within the scope of this program, although the most stringent is for lifetime. NOL desires a 2-yr operational life following 8 to 10 years of storage.

B. SANDIA/ALBUQUERQUE

Although Sandia has no immediate requirement for RTGs in the range being investigated, they need systems in the ranges from 0.5 to 15 and 15 to 100 mw. The meeting was devoted to discussing specifications for such equipment; it is clear that their restrictions make it impractical for anyone save Sandia to design the devices they require.

C. GLOBAL MARINE

The primary application discussed at this meeting was an undersea marking device in the 1000 mw level; however, the organization feels there is a need for a general family of power sources. It needs several hundred such pingers for use in oil well operations on the continental shelf to mark the locations of oil heads and oil pipe lines.

The cost increment related to the RTG can be justified on the basis of the cost of divers and ships in addition to the cost of an oil well if it were to be lost through failure of a pinger.

D. NCEL

The particular interest of this organization in RTGs is for supplying power for Submersible Test Units (STU's). They anticipate the need for more than 50 such power units during the next five years, but they also anticipate that the availability of RTGs with good lifetime, reliability, and minimum procurement problems would lead to numerous other applications. Justification for the RTG cost increment is based on the cost of the STU package (100 k\$); ship cost in retrieval; and the reduction in number of pingers required due to the superior reliability of the RTG power system.

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E. INTERNATIONAL TELEPHONE AND TELEGRAPH

The limited interests of ITT in this field resulted in a round-table discussion of their requirements. These are for amplifiers for use in the submarine communication cable repeaters, and to power microwave repeater stations at remote locations. The availability of the Tel-Star-type of satellite has reduced their requirements for RTG power sources for undersea cables.

F. ALPINE GEOPHYSICS

This organization generally is interested in pingers and in long term recording instruments. A reliable power source with a 5-year-life would be useful in many oceanic instruments. Alpine Geophysics estimated that it could sell 50 to 100 units over the next five years (without regard to the influence the development of deep submersibles might have on the market).

G. WOODS HOLE OCEANOGRAPHIC INSTITUTE

The discussion with representatives of this organization included short-, medium- and long-term pingers, radar beacons, and acoustical and light markers. In common with certain other users, this organization foresaw an expanding market for such power sources once their applications could be realistically explored after service-experience had been accumulated.

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SYSTEM CHARACTERISTICS

EVALUATION

CRITERIA

SYSTEMS	FUEL	POWER LEVEL, mw	DYNAMIC REQUIREMENTS	SHIELD CONFIG.	LOW COST	LONG LIFE	SMALL SIZE & WEIGHT	HIGH RELIABILITY	LOW RADIATION AND HANDLING HAZARD	ADAPTABILITY TO A LARGE NO. OF APPLICATIONS	COMMENTS
1	Sr-90	1000	Low Shock	Full Shield	X	X		X	X	X	Sound pinger applications
2	Sr-90	1000	Low Shock	1/2 Shield*	X	X		X		X	"
3	Pu-238	600	High Shock			X	X	X	X		Intelligence application - non- detectable requirement
4	Pu-238	600	Low Shock			X	X	X	X		"
5	Sr-90	500	Low Shock	Full Shield	X	X		X	X	X	Sound pinger applications
6	Sr-90	500	Low Shock	1/2 Shield*	X	X		X		X	"
7	Pm-147	600	High Shock		X			X			Intelligence application - non- detectable requirement
8	Pm-147	600	Low Shock		X		X				"
9	Pu-238	300	High Shock			X	X	X	X	X	
10	Sr-90	300	High Shock	Full Shield	X	X	X	X	X	X	Ordnance application
11	Sr-90	300	High Shock	1/2 Shield*	X	X	X	X		X	"
12	Pm-147	300	High Shock				X	X	X	X	"
13	Sr-90	150	Low Shock	Full Shield	X	X		X	X	X	Oceanographic instrumentation
14	Sr-90	150	Low Shock	1/2 Shield*	X	X		X	X		"
15	Pu-238	150	High Shock			X	X	X	X		Intelligence application - non- detectable requirement
16	Pu-238	150	Low Shock			X	X	X	X		

* Based on weight of "full" shield required to reduce radiation to 200 mr/hr at surface, 10 mr at 1 meter.

TABLE 2
BRIEF EVALUATION OF 16 SYSTEMS

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III. PARAMETRIC STUDY

A. PURPOSE

The parametric study was performed to investigate the general characteristics of advanced, large milliwatt, radioisotope thermoelectric generator systems that could be constructed from materials available today. The power level specified for such systems ranged from 150 to 1000 mw; the designs incorporated three of several fuel forms investigated; the contract specified an operating ambient temperature range from 28 to 90°F with a storage temperature range from -65 to +160°F; and the operating pressure specified was 10 to 32 in. of mercury. The study included metal as well as semi-conductor elements independently in several configurations.

There are five major components in an RTG system: the thermoelectric module, the isotope heat source, the radiation shielding, the thermal insulation, and the power conditioner. The interactions of the design variables in an RTG system are exceedingly complex, since the type and amount of materials used in each component effect the thermal management and, therefore, system efficiency. Since each component can be fabricated from several materials and in several physical arrangements, the first task of the parametric study was to define environmental constraints. The general characteristics of an RTG coupled to the number of variables led to an unusual analytical approach. The analytical approach and each of the components are discussed below.

B. SYSTEMS ANALYSIS

1. Analytical Approach

The analytical techniques developed in the investigation of these systems were intended to anticipate, in a realistic fashion, any state-of-the-art advances within the limits of the proposed schedule. The analytical techniques employed, particularly well-suited to milliwatt generators, divided the RTG into two subsystems: the electrical system and the thermal system. The electrical system includes the thermoelectric module and, if needed, the power conditioner; the thermal system includes the radioisotope fuel capsule, shielding, insulation and structure. The parametric analysis of each system then proceeded independently of the others. This approach is feasible because the normal interface constraints (surface area of available

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heat source and allowable heat flux) for the radioisotope fuels studied are not restrictive in the milliwatt power range. A bridging procedure is used to couple the results of the two parametric studies.

This technique permits systematic coverage of a large number of variables and makes provision for evaluation of the effects of improvements in technology on the design and performance of a generator.

2. Thermoelectric Module

A survey was conducted to establish the current and projected state-of-the-art in the fabrication of thermoelectric materials. In addition, data on properties, performance, compatibility, test and reliability were reviewed with leading suppliers of such materials. This information was gathered because the characteristics and performance of RTGs in the milliwatt power regime are especially sensitive to the characteristics of the thermoelectric materials used.

Results of the data retrieval showed that bismuth telluride can be fabricated today with the large length-to-area (L/A) ratios required for optimum matching of thermoelectric elements to the electrical load. Furthermore, similar applications of lead telluride 2N/P and 3N/P are promising insofar as fabrication is concerned; on the whole, however, the bismuth telluride modules are the most advanced.

Computer programs were developed at MRC to evaluate non-segmented, segmented, and cascaded configurations of thermoelectric modules. These programs account for losses in the power conditioning unit (where applicable), in parasitic conduction, in electrical contact, and the time-dependent degradation of thermoelectric properties. The primary results of these computer runs are reported in the form of thermoelectric performance maps for the semiconductor and metallic materials. A typical graph relates hot junction temperature, load voltage and power level to module efficiency, number of couples, and L/A ratio. In addition, detailed data on practical dimensions and cost are developed in tabular form or graphical summaries to complete the description of the module. The thermoelectric performance maps, however, provide the basic data required to couple the electrical system to the thermal system, thus completely characterizing the RTG.

3. Isotope Heat Sources

The three radioisotope fuels investigated in the parametric analysis were 90-strontium titanate; 147-promethium oxide, and 238-plutonium oxide. Capsule design was based on the results from a special sub-routine incorporated into a computer program, the subroutine balances the void volume required to accommodate the buildup of helium pressure as the plutonium decays against the thickness of capsule wall. The result is minimum overall capsule weight and near minimum volume.

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4. Radiation Shielding

Where weight and size are determining factors, depleted uranium is the obvious shielding material, and thus was used as input into the computer code. Where cost is the over-riding consideration for systems requiring shielding, lead can be used. Each application thus must be carefully scrutinized before a decision is made on the shielding material.

5. Thermal Insulation

The use of high performance thermal insulation, thus absolutely minimizing the parasitic loss of heat from the generator, is indicated by the cost of radioisotope energy. The thermal insulations useful for milliwatt systems narrow to MIN-K-1301 or MIN-K-503; in both cases the voids are evacuated and back-filled with xenon. In addition to the usual criteria for insulation systems, this application requires radiation damage resistance and non-evolution of gaseous dissociation products. The shock and vibration attenuation characteristics of the final configuration of the insulation system, as well as its ability to maintain integrity after exposure to shock and vibration, are additional criteria of paramount importance.

One other approach was carefully examined for this application (the Super Linde systems), but such systems are not suitable at this time for extended missions due to the cost of maintaining the vacuum required (10^{-3} mm Hg).

6. Power Conditioners

The power conditioner for such systems pose serious reliability programs in addition to the problems inherent in designing a system that will optimize many conflicting parameters. Most of the components required for suitable circuits are available; the selection of circuit design is less difficult than selecting components for maximum reliability.

7. Radioisotope Generator

The radioisotope generator designs were evaluated on the basis of the results of a computer program written for the program. The output overall generation efficiency figure includes compensation for the efficiency of the electrical system as well as heat losses. A cylindrical geometry was used in this analysis, and this study was limited to a configuration using an internal shield.

The capsule L/A ratio was set equal to 1.2 for all fuels used in the study, a value that corresponds closely to the optimum condition for minimum overall system weight and maximum thermal efficiency. A cold junction temperature of 170°F was assumed; this is an average value that is typical for systems in this power range when surrounded by still 70° ambient air at standard atmospheric pressure.

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C. RESULTS

At the conclusion of the parametric study, AGN/MRC submitted brief, preliminary descriptions of 16 systems to the AEC (Table 2, p 6). These systems represented a range of design goals, potential applications and consequent restraints. These technical descriptions represent the first iteration of each design on the basis of this parametric study (Appendix A reproduces the descriptions submitted to the AEC). Four of these systems, ranging in power from 150 through 1000 mw(e) were selected by the AEC for further investigation and refinement.

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IV. SUMMARY OF DESIGN APPROACH

The four designs selected for further investigation included a 1000 mw(e), SrTiO_3 system using either Bi_2Te_3 or PbTe thermoelectrics with a 5-yr life expectancy (System 1 of Appendix A); a 600 mw(e), Pm_2O_3 system with similar thermoelectrics for an 18-month service life (System 8 of Appendix A); a 300 mw(e), plutonium system using Bi_2Te_3 thermoelectrics with a life expectancy of 10-yr (System 9 of Appendix A); and a 150 mw(e), SrTiO_3 system using Bi_2Te_3 thermoelectrics with a life expectancy of 5-yr (System 13 of Appendix A). These designs have certain common characteristics: all of them use a doubly-enclosed source capsule in accordance with current encapsulation practices (Figure 1). (If a single encapsulation proves to be acceptable, the size, weight and cost of each system would be reduced, depending on other characteristics of each system.)

The models used in the parametric analyses were based on the assumption that the thermoelectric module would fit exactly into the volume of thermal insulation it displaced. That has not proven to be true in all cases when the system designs were further refined; some modules are longer than shown in Appendix A and therefore are slightly heavier. Such changes are expected when parametric design details are subjected to additional iterations.

In each of the specific designs discussed in the following chapters, all possible arrangements and material combinations were examined in greater detail, with appropriate results. For example, the 1000 and 150 mw(e) systems proved to be capable of being made smaller without any significant change in weight as a result of the refinements. The more sophisticated designs both use external rather than the internal radiation shielding shown in Appendix A.

The significant advantage in the use of external radiation shielding, other than the design flexibility it affords, is that the resulting proximity of thermal shielding to the heat source improves system efficiency. Thermal conductivity is the controlling physical property of insulation materials for use in RTGs. A low thermal conductivity will not only minimize parasitic heat loss, but will reduce the thickness of insulation required, and hence the amount of radiation shielding necessitated for biological protection. Several thermal insulation materials were considered in these designs (Figure 2); MIN-K-1301 (backfilled with xenon) is representative of the best fibrous insulation. MIN-K-503 is slightly better, but is limited to an operating temperature in the region of 400 to 500°F. Super Linde insulation is superior, but must

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FUEL	A	B	DENSIFICATION PROCESS
SrTiO_3	0	0.010	HOT PRESS
SrF_2	0	0	STEP PRESS
SrO	0.010	0.010	HOT PRESS
Pm	0	0.010	CAST
Pm_2O_3	0	0	STEP PRESS

FIGURE 1. FUEL CAPSULE CONFIGURATION

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FIGURE 2. THERMAL CONDUCTIVITY OF AIR, XENON, ARGON AND SEVERAL HIGH TEMPERATURE INSULATIONS

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operate in a vacuum; it is of little use where the maximum operating temperature capability of the thermoelectric materials (400 to 500°F for Bi_2Te_3), and the associated parasitic losses are not excessive. Its use, however, achieves some improvement in internally shielded configurations which have larger parasitic losses (Figure 3).

The value of Super Linde insulation is increased when it is used with thermoelectric materials that have high temperature capabilities (PbTe, for example), since it permits operation at the optimum temperature while restricting parasitic thermal losses of negligible amounts. The pronounced improvement obtained for the internal shield configuration using PbTe thermoelectrics is plotted in Figure 4. Such insulations can be used for short term applications (12 to 24 months), but gettering systems are required for longer durations to control outgassing and maintain the required vacuum (10^{-3} mm Hg). The development cost of adapting such a system to a 5-yr application has been estimated to be \$50,000 and the subsequent cost per unit, in lots of 10 to 100, is from \$1500 to \$2000.* The development status and cost of such systems thus eliminate them from consideration for use in current RTG systems.

A further consideration in the design of insulation systems for such applications was the need to support the low-weight source and thermoelectric units. A simple test demonstrated that the strength of the MIN-K-1301 insulation is sufficient to support these units. The test was performed with samples of MIN-K-503 which has similar strength characteristics (Figure 5). The tests also showed the need to design each system to have its resonant frequency above 700 to 1000 cps. The use of the insulation as the support for these units increases the requirement for a snug fit of insulation around the thermoelectric module to diminish the force experienced by the Bi_2Te_3 material.

The effect of hot junction temperature EOL is an important cost element in such designs (Figure 6). As a result, AGN and MRC agreed to use the conservative hot junction temperatures tabulated below:

	<u>Hot Junction Temperature, °F</u>			<u>Expected Life, yr.</u>
	<u>BOL</u>	<u>EOL</u>		
Pu	380	350		10
SrTiO_3	425	375		5
Pm_2O_3	450	325		1½

Throughout the rest of this chapter, in discussing aspects of the large milliwatt program, the 1000 mw(e) system is frequently used as an example. That system is discussed in detail, however, in the next chapter.

*Private communication from Union Carbide Corporation-Linde Division, Tonawanda New York, 15 March 1966

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FIGURE 3. EFFECT OF INSULATION MATERIAL ON 1000mw RTG PERFORMANCE FOR INTERNAL SHIELD CONFIGURATION AND A Bi_2Te_3 MODULE

(SrTiO_3 - Full Internal U-Shield - TC 75 - L/D 1.2 - Z 0.90)

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FIGURE 4. EFFECT OF INSULATION MATERIAL ON 1000_{mw} RTG PERFORMANCE FOR INTERNAL SHIELD CONFIGURATION AND A PbTe MODULE
(SrTiO₃ - Full Internal U-Shield - TC 75 - L/D 1.2 - Z 0.55)

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FIGURE 5. VIBRATION TEST RESULTS OF MIN-K-503 THERMAL INSULATION

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FIGURE 6. EFFECT OF HOT JUNCTION TEMPERATURE ON RTG PERFORMANCE
(1000mw - SrTiO₃ - Full External U-Shield - MIN-K-1301 - TC 75 - Z 0.90 - Bi₂Te₃ - L/D 1.2)

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A. STRONTIUM TITANATE AS A HEAT SOURCE

The RTG system basically consists of the radioisotope fuel and its capsule, biological shield, thermal insulation, mechanical support structure, thermoelectric module, container, and power conditioning unit. The system model shown in Figure 7 was used as a basis for the parametric analyses. Although an internal shield configuration is illustrated, analytical techniques permit the evaluation of an external shield, i.e., a shield outside the thermal insulation, as well as split shielding (a partial shield placed in each location).

The analyses were conducted using the AGN Thermoelectric Heater Evaluation (TEHE) IBM-7094 computer program. This system analysis program optimizes the performance of a radioisotope thermoelectric generator and calculates the corresponding physical characteristics and associated costs. A summary of the properties and assumptions used in the TEHE analysis follows: The fuel properties and capsule dimensions are summarized in Table 3. Excess fuel was included at the beginning of life (BOL) to provide for a 5-yr mission.

TABLE 3 - PROPERTIES OF STRONTIUM-90
COMPOUNDS AND FUEL CAPSULES

	<u>SrTiO₃</u>	<u>SrF₂</u>	<u>SrO</u>
Half Life, yr	27.7	27.7	27.7
Densification Process	Hot press	Step Press	Hot Press
Crystalline Density, g/cc	5.11	4.24	4.0
Specific Power - Cryst., w/g	0.217	0.314	0.389
Power Density - Cryst., w/cc	1.11	1.33	1.56
Packing Factor	0.90	0.90	0.90
Bulk Power Density, w/cc	1.00	1.20	1.40

The power conditioning unit efficiency $\eta_{P.C.}$ is assumed to be related to the output voltage from the thermoelectric module V_L by:

$$\eta_{P.C.} = \exp(-0.323 V_L^{-0.533})$$

At 3 v this corresponds to an efficiency of 83.9%.

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NOTE: THIS IS FIGURE I-3 PREVIOUSLY
PUBLISHED IN AGN-8182 (Rev.)

FIGURE 7. SYSTEM ANALYTICAL MODEL - CYLINDRICAL GEOMETRY

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This system electrical efficiency η_E , includes the thermoelectric module $\eta_{T.E.}$ and power conditioning unit efficiency terms,

$$\eta_E = \eta_{T.E.} \cdot \eta_{P.C.}$$

The thermoelectric module efficiency accounts for electrical contact losses (a loss factor of 0.75 was applied), and a degradation of 13% in module performance over the operating lifetime. The system electrical efficiency is approximated by using a pseudo or effective thermoelectric figure of merit Z_E in the basic efficiency equation for matched local conditions:

$$\eta_E = \frac{T_H - T_C}{2 T_H + \frac{4}{Z_E} - \frac{T_H - T_C}{2}}$$

where

T_H = hot junction temperature, $^{\circ}\text{K}$

T_C = cold junction temperature, $^{\circ}\text{K}$

Z_E = effective figure of merit, $^{\circ}\text{C}^{-1}$

This approximation has been shown to accurately characterize the performance of thermoelectric systems. Table 4 shows typical values of Z_E for a number of thermoelectric materials. Values for semiconductor materials correspond to a module output voltage of 3 v and $\eta_{P.C.}$ of 83.9%. The Cupron/Tophel Special module has an output of 18 v and does not require a power conditioning unit.

TABLE 4 - PERFORMANCE PARAMETER FOR
THERMOELECTRIC MODULES

<u>Thermoelectric Material</u>	Effective Figure of Merit
	$Z_E \times 10^3 \text{ } ^{\circ}\text{C}^{-1}$
Cupron/Tophel Special	0.10
MCC-40	0.10
SiGe Alloy	0.30
PbTe (3N/3P)	0.40
SiGe-PbTe (2N/2P) Cascaded	0.40
PbTe (2N/2P)	0.55
PbTe (2N/2P) - Bi_2Te_3 Cascaded	0.69
Bi_2Te_3	0.90

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Shield thickness as a function of strontium-90 thermal power is approximated by the following equations:

$$X_s = \frac{1}{2.95} \ln \frac{Q_F}{0.04849} \text{ (depleted uranium)}$$

$$X_s = \frac{1}{1.535} \ln \frac{Q_F}{0.0536} \text{ (lead)}$$

where

X_s = shield thickness for 200 mr/hr at surface, in.

Q_F = radioisotope thermal power, Btu/hr

Insulation thermal conductivities are related to the temperature by:

$$k_m = 0.0128 e^{2.07 \times 10^{-4} T_H} \text{ (MIN-K-1301-Xenon)}$$

where

k_m = mean thermal conductivity, Btu/hr-ft- $^{\circ}$ F

T_H = hot junction temperature, $^{\circ}$ F

Structural support parasitic heat loss Q_s was estimated by normalizing to values for similar SNAP devices. The following approximation was used:

$$Q_s = 0.00511 (T_H - T_C) D_H^{1.43}$$

where

T_H = hot junction temperature, $^{\circ}$ F

T_C = cold junction temperature, $^{\circ}$ F

D_H = hot surface diameter, in.

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Cost figures used in the parametric analyses were:

	<u>Cost</u>
Strontium-90	
Present	\$32 per watt
Future	\$19 per watt
Depleted Uranium	\$9.40 per lb
Lead	\$0.27 per lb

All other system materials and component costs were assumed to be relatively independent of the variables investigated and were not parametrically evaluated. The RTG outer container was assumed to be stainless steel with a constant thickness of 0.050 in. used throughout the analyses. A detailed description of the TEHE system analysis program was published earlier.*

* Large Milliwatt Generator Program - Parametric Study Data, AGN-8182, Vol. I and II, April 1966, Aerojet-General Nucleonics, San Ramon, California

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B. ANALYTICAL APPROACH TO THERMOELECTRIC MATERIALS

It is evident that the results of the parametric design study for Bi_2Te_3 N/P modules which were based upon two assumptions (i.e., cold junction temperature TC of 170°F and a mission length of 13,000 hr) will have to be adjusted to reflect true operating conditions for a specific system.

For convenience it was decided to investigate the influence of the ambient temperature on system performance independent of the influence of mission length. It was also convenient to investigate the dependency of module performance on ambient temperature and mismatch ratio concurrently. This study was made with the aid of the computer code developed for the parametric design phase (ibid, Appendix II-A). Figure 8 shows module efficiency versus number of couples in series for various hot and cold junction temperatures. Figures 9 through 12 show module efficiency versus mismatch ratio for various hot and cold junction temperatures. Two important conclusions can be drawn from these curves for module efficiency:

- 1) If low ambient temperatures result in cold junction temperatures below 170°F , moderate to large gains can be made in efficiency. This gain (for a given hot junction temperature) results not only from the increased Carnot term in the efficiency equation but also from the increased material efficiency. The latter results from the shape of the figure-of-merit versus temperature curve of Bi_2Te_3 N/P; an extension of the operating temperature range of a Bi_2Te_3 N/P couple to lower cold junction temperatures results in higher average figure-of-merit values.
- 2) A moderate increase of the mismatch ratio beyond $\text{RMIS} = 1$ does not adversely affect the efficiency. Maximum efficiency occurs at $\text{RMIS} = 1.25$ to 1.35 depending on the temperature conditions. At $\text{RMIS} = 1.5$, module efficiencies are 0.1% or less lower than at matched load condition.

Figures 13 through 16 show number of couples in series and L/A ratio for a 1000 mw(e) module versus mismatch ratio. It is evident that a more favorable module design is feasible if a larger mismatch ratio can be accepted.

The plots represented in Figures 8 through 16 were used in the design analysis of the individual systems; however, the L/A ratios are given for a 1000 mw(e) system with zero-fold couple redundancy, a conservative couple degradation rate of 0.005/1,000 hr, and a mission length of 13,000 hr. Similarly, module efficiencies are given for above conditions of degradation rate and mission length. For other conditions of module power level, degradation rate, mission length and couple redundancy, the results represented

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FIGURE 8. MODULE EFFICIENCY VERSUS NUMBER OF COUPLES IN SERIES

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FIGURE 9. MODULE EFFICIENCY VERSUS MISMATCH RATIOS, TH = 450°F

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FIGURE 10. MODULE EFFICIENCY VERSUS MISMATCH RATIO, TH = 425°F

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FIGURE 11. MODULE EFFICIENCY VERSUS MISMATCH RATIO, TH = 400°F

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FIGURE 12. MODULE EFFICIENCY VERSUS MISMATCH RATIO, TH = 375°F

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FIGURE 13. NUMBER OF COUPLES IN SERIES L/A RATIOS VERSUS MISMATCH RATIO, TH = 450°F

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FIGURE 14. NUMBER OF COUPLES IN SERIES, L/A RATIO VERSUS MISMATCH RATIO, TH = 425°F

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FIGURE 15. NUMBER OF COUPLES IN SERIES, L/A RATIO VERSUS MISMATCH RATIO, TH = 400°F

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FIGURE 16. NUMBER OF COUPLES IN SERIES, L/A RATIO VERSUS MISMATCH RATIO, TH = 375°F

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in the plots can be scaled in the following manner:

1) Module Efficiency ETASYS

$$\text{ETASYS DC} = \text{ETASYS RC} \cdot \frac{(1 - \text{EMUC} \cdot \text{TIME}) \text{ RC}}{(1 - \text{EMUC} \cdot \text{TIME}) \text{ DC}}$$

where

ETASYS = module efficiency

EMUC = couple degradation rate/1,000 hr

TIME = mission length in 1,000 hr

DC, RC = indexes referring to design (operating conditions and reference (operating) conditions respectively. The reference value of ETASYS can be taken from Figures 8 through 16.

2) L/A Ratio ELAR

$$\text{ELAR DC} = \text{ELAR RC} \cdot \frac{\text{PSYST RC}}{\text{PSYST DC}} \cdot \frac{\text{M DC}}{\text{M RC}} \cdot \frac{(1 - \text{EMUC} \cdot \text{TIME}) \text{ DC}}{(1 - \text{EMUC} \cdot \text{TIME}) \text{ RC}}$$

where

ELAR = L/A ratio

PSYST = module power level = net electrical power generated at the end of the mission

M = 1 for zero-fold couple redundancy

M = 2 for one-fold couple redundancy

Reference values for ELAR can be taken from Figures 13 through 16.

The formulae for ETASYS DC and ELAR DC can be termed by inspection of the design equations summarized in Appendix II-A of AGN Report No. 8182; however, ETASYS and ELAR can be scaled with above formulae only when designs operate with the same hot and cold junction temperatures.

The performance of various thermoelectric materials, as characterized by their appropriate effective figure of merit Z_E , is shown for the 1000 mw(e) SrTiO_3 system in Figure 17 for an internal full uranium shield (200 mr/hr at surface) and Figure 18 for an external full uranium shield configuration. The metallic Cupron/Tophel Special system ($Z_E = 0.10$) exhibits a relatively large size and weight, and low efficiency compared to the semi-conductor systems and is considered unsuitable for use in these designs. Silicon-germanium alloy ($Z_E = 0.30$) is basically a high temperature material which

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FIGURE 17. SrTiO_3 FULL SHIELD MIN-K-1301 1 w

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FIGURE 18. SYSTEM EFFICIENCY AND WEIGHT VERSUS OUTSIDE DIAMETER - EXTERNAL SHIELD
(1000mw - SrTiO₃ - External Full U-Shield - MIN-K-1301 - TC 75 - L/D 1.2)

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provides relatively poor performance when used by itself in a non-segmented configuration over a temperature range extending to normal ambient conditions. Some improvement is obtained ($Z_E = 0.40$) by cascading Si-Ge with PbTe (2N/2P); however, the net result is approximately the same as if a simpler non-segmented PbTe (3N/3P) module were used. A more dramatic improvement would result at power levels above 100 mw(e) where the high temperature capability of Si-Ge can be fully exploited without being counteracted by excessive parasitic thermal insulation and structural support losses.

The non-segmented (2N/2P) PbTe ($Z_E = 0.55$) and Bi_2Te_3 ($Z_E = 0.90$), and cascaded modules composed of both materials ($Z_E = 0.60$) provide superior performance. The Bi_2Te_3 module is outstanding for the internal shield configuration since:

- 1) optimum hot junction temperatures are limited to about 400°F by the relatively large parasitic heat loss resulting from this configuration, and
- 2) Bi_2Te_3 provides the highest thermoelectric efficiency of any known materials in the low operating temperature region.

Comparative performance of the three T/E modules is quite similar for the external shield configuration, since the thermal insulation is located in a more effective position (next to the radioisotope heat source) thus minimizing parasitic thermal losses, and permitting operation of PbTe at a higher, more appropriate hot junction temperature. The results, however, show that a somewhat smaller and lighter system can be achieved using Bi_2Te_3 . With an external shield, the advantage shifts towards Bi_2Te_3 at lower outputs, as shown in Figure 19 for the 150 mw system, because of the comparative increase in parasitic losses at the higher temperature required to achieve good efficiencies from PbTe.

The overall system performance results show that Bi_2Te_3 is a superior thermoelectric material for the large milliwatt power range. Other advantages offered by Bi_2Te_3 are:

- High system reliability for low temperature operation
- Advanced development status: RTGs and fossil fuel units have been successfully operated
- Large L/A ratio elements have been fabricated into modules which match the electrical characteristics of large milliwatt RTGs and provide a comparatively large output voltage (minimum of 3 volts) and correspondingly high power conditioning efficiency. Similar PbTe module technology does not exist and is more difficult to develop because of higher operating temperature, particularly for the 2N/2P type PbTe materials.

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FIGURE 19. SYSTEM EFFICIENCY AND WEIGHT VERSUS OUTSIDE DIAMETER
(150mw SrTiO_3 - U Shield - MIN-K-1301, Bi_2Te_3)

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- Low materials and module fabrication costs
- Redundancy: cross-connected parallel T/E circuitry can be employed at low power levels because of the large L/A ratio capability of Bi_2Te_3 ; thermoelectric module reliability is thereby greatly improved.

Comparison between Bi_2Te_3 and PbTe are continued throughout the following design studies because they are the most competitive materials available and PbTe becomes increasingly attractive as the power output increases above the 1 watt level.

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C. EFFECTS OF OTHER PARAMETERS

Although cost is the dominant criterion in system optimization, other performance characteristics are important. The effects of the following parameters on cost and performance were investigated to establish the relative trade-off factors:

- 1) Fuel capsule length/diameter ratio
- 2) Fuel chemical compound
- 3) Shield configuration and material

The results provide the basis for selecting reference components, system configuration, and operating conditions for each conceptual design.

1. Fuel Capsule Length/Diameter Ratio

The effect of the fuel capsule aspect ratio (L/D) on system performance was investigated to determine the optimum value for minimum weight and maximum efficiency since variation in this ratio directly affects the shape and weight of the biological shield. Figure 20 shows the effect of L/D on system efficiency and weight as a function of the RTG overall diameter for the internal shield configuration for Bi_2Te_3 . Figures 21 and 22 show a similar comparison for the external shield configuration for Bi_2Te_3 and PbTe . The plots show that the optimum fuel capsule L/D ratio for the above cases is approximately the same (i.e., equal to about 1.2); however, weight and efficiency do not vary appreciably throughout an L/D range of 1.0 to 1.5. Accordingly, a ratio of 1.2 was used in this study.

2. Fuel Chemical Compound

Although SrTiO_3 is the most readily available and common Sr-90 fuel compound, other chemical compounds provide higher power density and therefore a more compact and lighter RTG. Since these compounds (SrF_2 and SrO) can be made available, their effects on system performance and design characteristics were evaluated (Figures 23 and 24). The results show little difference in performance between SrF_2 and SrO and slight improvement over SrTiO_3 (Table 5 compares practical design points). It is concluded that there is no strong incentive for using SrF_2 or SrO in low-power RTGs and that SrTiO_3 is quite satisfactory. The significantly higher power densities of SrF and SrO are obscured at low power levels by the sizeable clearances required in the double encapsulation process, thus the overall capsule power densities do not differ appreciably in this application.

3. Shield Configuration and Material

All of the preceding comparisons have included a consideration of both the internal and external shield configurations using a full (200 mr/hr at the surface), depleted uranium shield. In general, minimum system weight is achieved by placing the biological shield in the closest

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FIGURE 20. EFFECT OF L/D ON SrTiO_3 SYSTEM

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FIGURE 21. OPTIMIZATION CURVE FOR FUEL CAPSULE L/D FOR 1000mw
RTG WITH EXTERNAL SHIELD AND Bi_2Te_3 MODULE
(SrTiO_3 - External Full U-Shield - MIN-K-1301 - Z 0.90 - TC75)

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FIGURE 22. OPTIMIZATION CURVE FOR FUEL CAPSULE L/D FOR 1000 mw RTG WITH EXTERNAL SHIELD AND PbTe MODULE

(SrTiO₃ - External Full U-Shield - MIN-K-1301 - Z 0.55 - TC 75)

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FIGURE 23. EFFECT OF Sr-90 COMPOUNDS ON 1000mw RTG PERFORMANCE FOR EXTERNAL SHIELD CONFIGURATION

(External Full U-Shield - MIN-K-1301 - TC 75 - L/D 1.2)

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FIGURE 24. EFFECT OF Sr-90 COMPOUNDS ON 1000mw RTG PERFORMANCE FOR INTERNAL SHIELD CONFIGURATION
(External Full U-Shield - MIN-K-1301 - TC 75 - L/D 1.2)

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proximity to the radioisotope source (on its surface if possible). For the large milliwatt power range, even with highly effective biological shielding material, the parasitic thermal losses resulting from the internal shield configuration are appreciable. These sizeable losses result from:

- 1) Placing the insulation at a much less effective position where the heat transfer surface is quite large as compared to the surface of the fuel capsule, and
- 2) Increased parasitic structural losses due to the need to support a grossly larger and heavier heat source (weight of fuel capsule plus biological shield).

The lower thermal efficiency requires a larger radioisotope fuel source and thicker biological shield compared with the external shield configuration. The net effect is that the weights of the two systems are approximately the same at 1000 mw but the cost of the external shield system is substantially less because of the lower radioisotope fuel cost. In addition, the internal shield system is considerably larger because of the increased thermal insulation required. These effects are compared for typical design points in Table 5 and the tradeoffs with system diameter shown in Figures 24 and 25.

TABLE 5 - EFFECT OF FUEL COMPOUND ON
PERFORMANCE OF 1000 mw(e) Sr-90 SYSTEM

	External Depleted Uranium Shield					
	Bi ₂ Te ₃			PbTe		
	<u>SrTiO₃</u>	<u>SrF₂</u>	<u>SrO</u>	<u>SrTiO₃</u>	<u>SrF₂</u>	<u>SrO</u>
Diameter, in.	7.90	7.70	7.60	8.50	8.15	8.05
Efficiency, %	3.25	3.25	3.25	3.25	3.25	3.25
Weight, lb	215	198	190	268	235	226
Cost of fuel plus shield, \$	3085	2924	2858	3574	3280	3193

	Internal Depleted Uranium Shield					
	Bi ₂ Te ₃			PbTe		
	<u>SrTiO₃</u>	<u>SrF₂</u>	<u>SrO</u>	<u>SrTiO₃</u>	<u>SrF₂</u>	<u>SrO</u>
Diameter, in.	12.5	12.5	12.5	12.5	12.5	12.5
Efficiency, %	1.74	1.78	1.79	1.33	1.36	1.37
Weight, lb	222	211	206	250	237	231
Cost of fuel plus shield, \$	3931	3785	3724	4840	4657	4574

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FIGURE 25. EFFECT OF Sr-90 COMPOUND ON 1000mw RTG COSTS
(Fuel Plus U-Shield Cost for External and Internal Shield Configurations - MIN-K-1301 - TC 75 - L/D 1.2)

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A split shield configuration was also investigated. In this design, part of the shielding is placed inside of the thermal insulation and part outside. The total effect of both partial shields is equivalent to a full shield, i.e., 200 mr/hr at the surface. Two cases were considered: 1) both shields are depleted uranium, and 2) the internal shield is depleted uranium and the external shield is lead. The results for typical design points are summarized in Figure 26 and show the effect of shield factor on RTG efficiency, diameter, weight, and fuel plus shield cost. Shield factor corresponds to the fractional thickness of an equivalent full shield used in each location (the sum of the two shield factors is always equal to 1.0). It can be concluded that:

- 1) Thermal efficiency decreases as the fraction of internal shield increases, and reaches a minimum for the full internal shield (also the maximum fuel cost).
- 2) Minimum RTG diameter is obtained with a full, external, depleted uranium shield.
- 3) Minimum weight is obtained with either a full external or internal depleted uranium shield (weights are approximately equal). Uranium split shield configurations increase RTG weight. Partial external lead shielding increases system weight, reaching a value about twice that of uranium for the full external shield condition.
- 4) Minimum cost is achieved with a full external shield comprised of inexpensive lead (at the expense of increased RTG size and weight). As noted previously, the full external uranium shield is less costly than the internal configuration, and it is also superior to any combination of uranium split shields.

There is no apparent advantage in split shielding. Although the system analyses show equal weight for the internal and external uranium shield configurations, perturbations resulting from converting the analytical model into hardware will increase the external shield weight while the internal system will be little affected. It is estimated that the real weight of the external shield RTG will be 25 to 50 lb greater, but this does not appreciably alter the comparative results. The characteristics of the two basic shield configurations are summarized in Table 6.

It is concluded that generally the external shield configuration best satisfies the design criteria, particularly in cost, compactness, and adaptability. The ability to fit the shield to a user's budget and operational needs is perhaps the most attractive feature. The small weight penalty (25 to 50 lb) is not considered a significant disadvantage since either system is too heavy for manhandling. Inability to replace the thermoelectric module in the field should create no problem since the complete RTG system

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○ FULL EXTERNAL SHIELD

NOTE: ONLY URANIUM IS USED FOR INTERNAL SHIELD

△ FULL INTERNAL SHIELD

FULL INTERNAL URANIUM SHIELD

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FIGURE 26. OPTIMUM DESIGN POINTS FOR 1000mw RTG'S WITH A SPLIT SHIELD CONFIGURATION

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must operate reliably for long duration. (A Bi₂Te₃ module was tested under accelerated gamma radiation, equal to 10 years²³ operation with SrTiO₃ fuel, without any noticeable deterioration*.)

TABLE 6 - URANIUM SHIELD CONFIGURATION
SUMMARY (1000 mw(e) EXAMPLE)

<u>External Shield</u>	<u>Internal Shield</u>
Moderately low weight (250-275 lb)	Low weight (225-250 lb)
Low cost (about \$500 to \$1000 less than internal shield)	Large (about 11-in. diameter)
High efficiency (about twice that of internal shield)	Provides radiation protection for all system components
Highly adaptable (replacement with low cost shield material requires minimum modifications, and temporary shield can be used if appropriate).	Thermoelectric module can be replaced in field
Simplifies development program, since shielding does not significantly effect thermal management; the support structural requirements are minimal	Must use high cost shield materials, i.e., uranium or tungsten
Provides good heat distribution for waste heat removal	
Thermoelectric module must withstand high radiation	

* P. D. Dunn and F. W. Yeats, Interim Report on the First British Radioactive Isotope Powered Thermoelectric Generators R.I.P.P.L.E. I and II, AERE-M 1594, May 1965

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V. REVIEW OF THE 1000 mw(e), SrTiO₃ SYSTEM

In refining the design of the AEC's System 1, the requirements for the NCEL pinger were used as the goal. The power conditioning equipment for the pinger must supply one 50 m-sec pulse every 10 seconds and draws 62 w. A 24-v d-c system is used in this design to continuously trickle-charge a battery (part of the pinger). The system was optimized on cost, with other considerations that included low* resistance to acceleration shocks, long life, high reliability, and low radiation.

The first step was careful study of the plot of system efficiency (ETA, EOL) against outside diameter (Figure 27) for the PbTe thermoelectric module. This gives a figure of merit (Z) value of 0.55 with an EOL efficiency of 1.04% for a 10.5 in. outside diameter at a system weight of 250 lb. Similar plots for Bi₂Te₃ were consulted (Figure 28) which shows an EOL efficiency of 1.42% for a 10.5 in. outside diameter at a system weight of 230 lb. Obviously, the Bi₂Te₃ system has slight advantages in weight and efficiency. But Figure 29 shows that Z = 0.9 for Bi₂Te₃ and allows a smaller diameter than the Z = 0.55 PbTe system. On the basis of the computer program, and thermoelectric data obtained from Figures 30 and 31, the physical data for this system can be listed. This procedure establishes a 1000 mw(e) SrTiO₃, full internal shield system, using MIN-K-1301 insulation at TC of 170°F, Z of 0.9, and L/D ratio of 1.2 when using a Bi₂Te₃ module. (These values are for a system designed for operation in ambient air.)

The next refinement involved examining a similar system for use in sea water where TC = 75°F with an external uranium shield. Figure 20 shows the lowest weight, 224 lb, smallest outside diameter, 8 in., and highest efficiency, 3.4%, is obtained; therefore the best RTG system is provided by a design incorporating an external shield (i.e., the biological shield is placed outside of the thermal shield to minimize parasitic heat loss).

* That is, those of the transportation environment

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FIGURE 27. SrTiO_3 FULL SHIELD MIN-K-1301 1w

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FIGURE 28. SrTiO_3 - NO SHIELD - MIN-K-1301 - TH 400 Bi_2Te_3

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FIGURE 29. SYSTEM EFFICIENCY AND WEIGHT VERSUS OUTSIDE DIAMETER - EXTERNAL SHIELD
(1000mw - SrTiO_3 - External Full U-Shield - MIN-K-1301 - TC 75 - L/D 1.2)

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FIGURE 30. MODULE EFFICIENCY VERSUS NUMBER OF COUPLES IN SERIES OF MILLIWATT GENERATORS UTILIZING NON-SEGMENTED Bi_2Te_3 N/P THERMOCOUPLES

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FIGURE 31. LOAD VOLTAGE VERSUS L/A RATIO FOR 150 TO 1000_{mw} THERMOELECTRIC GENERATORS UTILIZING NON-SEGMENTED Bi₂Te₃ N/P THERMOCOUPLES

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A. THERMOELECTRIC DESIGN ANALYSIS

The SrTiO_3 fuel decays by about 13% during the 43,000-hr operational life of the system. If the performance at the beginning of life is compared to performance at the end of life, two statements can be made:

- 1) Assuming the thermal conductances of the module and other components do not vary with time, the thermal input to the module at the beginning of life will be about 13% larger.
- 2) Assuming the thermal conductance of the structure connecting the cold junctions of the module with the ambient heat sink (sea water) does not vary with time, the difference between hot and cold junction temperatures will be 13% larger at the beginning of life.

These differences in thermal input at various points during the operational life of the module have several consequences. If the module is designed for optimum operation at the end of life, temperatures at the beginning of life may be too high and not compatible with reliable operation of the module. Conversely, if the module is designed for optimum operation at the beginning of life, performance at the end of life may be seriously impaired. These considerations pertain only to a module operating with an isotope heat source without thermal regulation. If the heat source is thermally regulated (for example, by means of a number of bimetallic strips acting as a time variable thermal shunt), then the module can be designed for optimum performance during the whole of its operational life. It will be assumed in the following that the isotope heat source is not thermally regulated. The most unfavorable ambient temperature to which the system is exposed is 80°F , but the average ambient temperature likely to be encountered is 50°F , resulting in cold junction temperature of $\sim 75^\circ\text{F}$.

As described above, lower ambient temperatures result in increased performance and thus the curves in Figures 32, 33 and 34 represent the lower boundaries of the design parameters shown, since the sea water ambient temperature is likely to be below 80°F resulting in cold junction temperatures below 100°F . To explore the EOL versus BOL design considerations mentioned, an investigation was made of modules operating with an end-of-life hot junction temperature $T_H = 425^\circ\text{F}$. Figure 32 shows hot junction temperature versus time for a 425°F (EOL) module. The design point is designated on the graph at 43,000 hr (5 yr). Operation at a cold junction temperature of 100°F results in a 470°F hot junction temperature (BOL). It can be argued that such a temperature is well within the temperature capability of Bi_2Te_3 N/P, but it is the opinion of the authors that operation at a somewhat lower temperature would be advisable, particularly with regard to the reliability and life requirements. The TC - 80°F curve shows that a decrease in cold junction temperature goes parallel with a decrease in hot junction temperature. The TC - 120°F curve shows the results of exposing the system at BOL to high-temperature ambient air, such as could occur prior to lowering it into the sea.

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FIGURE 32. MODULE HOT JUNCTION TEMPERATURE DURING OPERATIONAL LIFE

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FIGURE 33. LOAD VOLTAGE, NET MODULE POWER OUTPUT, MODULE EFFICIENCY BASED ON EOL POWER OUTPUT; AND MODULE EFFICIENCY BASED ON NET MODULE POWER VERSUS TIME

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FIGURE 34. LOAD VOLTAGE, NET POWER OUTPUT AND MODULE EFFICIENCY VERSUS TIME

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Hot junction temperatures can then get excessive and it is evident that proper cooling of the system must be maintained at all times.

Figure 33 shows load voltage, net electrical power generated (corrected for losses in the power conditioner), module efficiency based on net electrical power generated, module efficiency based on EOL power (1000 mw) for a $T_H = 425^\circ\text{F}$ (EOL) module. The BOL load voltage is about 10% higher than the EOL. It is believed that this is within the capability of the power conditioner. The somewhat higher load voltage at BOL will yield a somewhat higher module efficiency at BOL as compared to EOL module efficiency, since the power conditioner losses will be smaller. This gain in efficiency is rather small and has been neglected in plotting curves for net module efficiency (Figure 33). The net power versus time curve shows that at BOL approximately 56% more power is generated than at EOL to counter electrical degradation of the couples and the decrease of the temperature difference across the couples. The module efficiencies of Figure 33 were calculated for a mismatch ratio of 1.5. The appropriate module efficiency was taken from the curves in Figure 10 and adjusted to account for time-dependent couple degradation and hot junction temperatures. The curves of Figures 32 and 33 are for a conservative estimate of the degradation rate (0.005/1,000 hr). It is felt that such an estimate unduly penalizes a design and the 425°F BOL module was thus designed on the basis of a more realistic estimate of the degradation rate, i.e., 0.003/1,000 hr.

The BOL module efficiency of 425°F (BOL) hot junction temperature and 75°F cold junction temperature module is, as shown in Figure 34, 2.42%.

The design conditions of Figure 34 (including T_H at $BOL = 425^\circ\text{F}$; $T_C = 75^\circ\text{F}$; and load voltage at BOL = 3.4 v; can now be used to determine such module and couple parameters as the number of couples in series, SERJ; the length of thermoelement, ELGTH; and the cross-sectional area of thermoelement, ARCO.

Figure 14 shows that at a mismatch ratio of 1.5, 77 couples in a series are necessary to yield 3 v at constant temperature conditions. The number of couples necessary to yield 3.4 v (BOL) can be found by linear scaling, thus $SERJ = 88$. Also in Figure 14, the L/A ratio for a mismatch ratio of 1.50 is shown to be 52 in.¹. In Appendix II-A of AGN Report 8182, an expression is found for the length of the element ELGTH which (upon substitution of the values of the temperatures, average thermoelectric properties of Bi_2Te_3 N/P and the mismatch ratio) can be written as

$$ELGTH = \frac{1.530}{QH} \text{ in.}$$

where QH = heat flux density at the hot junctions, w/cm^2 . Since $L/A = 52 \text{ in.}^{-1}$ and by definition $L/A = ELGTH/ARCO$, then

$$ARCO = \frac{0.019}{QH} \text{ in.}^2$$

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The following major considerations determine the choice of heat flux density at the hot junctions QH. Large QH values result in large temperature drops in the thermal resistances associated with the structural connection between the cold junctions and the ambient heat sink, which in turn results in a poor utilization of the available operating temperature differences. Large values of QH, however, yield small thermoelements and small modules. Values of both ELGTH and ACRO are shown below for $QH = 5 \text{ w/cm}^2$ and $QH = 7.5 \text{ w/cm}^2$.

	<u>ELGTH,</u> <u>in.</u>	<u>ARCO,</u> <u>in.²</u>
QH at 5 w/cm^2	0.305	0.0057
QH at 7.5 w/cm^2	0.204	0.0025

$QH = 7.5 \text{ w/cm}^2$ yields an element 0.204 by 0.050 by 0.050 in.; a combination of dimensions that is well within the state-of-the-art of Bi_2Te_3 N/P module technology. This heat flux density does not cause excessive temperature drops in the non-thermoelectric components of the module (see Figure 35). A square module fabricated with the technique in which the 176 couples are electrically insulated by thin mica (0.002 to 0.005 in. thick) and use electroplated or sprayed-on nickel contacts of 0.010 in. thickness would be 0.225 in. high and have a cross-section of 1.10 by 1.10 in. For a better definition of the module performance two additional areas must be investigated:

- 1) Thermal bypass losses not yet accounted for: module efficiencies computed above consider the thermal bypass in the thermal (and electrical) insulation between the elements; however, there are additional losses in the thermal insulation of the module package and in the module package wall itself.
- 2) The thermal profile of the module has to be verified to ensure that
 - a) The assumptions with respect to the differences between cold junction and ambient temperatures are correct
 - b) It will operate under the proper temperature conditions with respect to the hot and cold junctions.

Figure 35 shows a physical model of the 1000 mw module for a fully-shielded SrTiO_3 RTG. (A detailed description of the module will be given later.) In this model the thermal properties of the module components are given in terms of thermal conductances C and thermal resistances R. The values for these properties are:

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FIGURE 35. PHYSICAL MODEL AND THERMAL PROFILE OF THE 425°F (BOL) MODULE FOR A FULLY-SHIELDED SrTiO_3 RTG

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C_1 = thermal conductance of the pressure contact between the hot contact plate and the isotope heat source

$$C_1 = 0.5 \text{ w/cm}^2 - ^\circ\text{F}$$

C_2 = thermal conductance of copper hot contact plate

$$C_2 = 2.0 \text{ w/cm}^2 - ^\circ\text{F}$$

C_3 = thermal conductance of pressure contact between the nickel hotshoes of the module and the copper hot contact plate

$$C_3 = 0.15 \text{ w/cm}^2 - ^\circ\text{F}$$

C_4 = thermal conductance of pressure contact between the nickel choldshoes of the module and the copper cold contact plate

$$C_4 = 0.15 \text{ w/cm}^2 - ^\circ\text{F}$$

C_5 = thermal conductance of Eccospheres R: thermal insulation used to fill void between outer and inner bellows

$$C_5 = 1.2 \times 10^{-4} \text{ w/cm}^2 - ^\circ\text{F}$$

C_6 = thermal conductance of pressure contact between the copper conducting ring and stainless steel (Type 316) flange

$$C_6 = 0.15 \text{ w/cm}^2 - ^\circ\text{F}$$

C_7 = thermal conductance of the stainless steel (Type 316) flange

$$C_7 = 2 \text{ w/cm}^2 - ^\circ\text{F}$$

C_8 = thermal conductance of the structure between the stainless steel flange and the sea water ambient

$$C_8 = 0.5 \text{ w/cm}^2 - ^\circ\text{F (estimated)}$$

R_1 = thermal resistance of the stainless steel (Type 316) outer bellows

$$R_1 = 6.4 \times 10^{-3} \text{ w/}^\circ\text{F}$$

R_2 = thermal resistance of the brass inner bellows partially filled with cooper spheres

$$R_2 = 3.5 \text{ w/}^\circ\text{F}$$

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The C_1 , C_3 , C_4 and C_6 values are based upon MRCs experience with pressure contacts¹ operating in vacuum (C_1) and in gas atmospheres (C_3 , C_4 , C_6). In the thermal profile calculations the heat flux was assumed to be one-dimensional. Estimates were made of the cross-sectional areas available for heat flow for the parts associated with C_7 , C_8 . The thermal profile in Figure 35 shows the cold junction temperature to be 75°F at BOL.

The thermal conduction losses in the outer bellows can now be calculated

$$Q_{OB} = 0.122 \text{ w}$$

where

$$Q_{OB} = \text{heat conducted in outer bellows, w.}$$

The thermal conduction losses through the Eccospheres R-filled insulation are:

$$Q_{TI} = 0.370 \text{ w}$$

where

$$Q_{TI} = \text{heat losses in the Eccospheres R insulation, w.}$$

In Figure 34 module efficiency without Q_{OB} and Q_{TI} losses are shown to be 3.01% (EOL). The actual module efficiency corrected for the Q_{OB} and Q_{TI} losses is 2.97%.

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B. DESIGN DESCRIPTION

The conceptual design of the 1000 mw(e), 425°F (BOL), Bi₂Te₃ N/P module for a fully-shielded SrTiO₃ RTG is shown in Figure 36. The various parts are:

- 1) Flange (Mallory 2000)
- 2) Bellows pressure adjustment screw (copper)
- 3) Mounting flange (Type 316 stainless steel)
- 4) Electrical feed-throughs of the ceramic-to-metal seal type
- 5) Outer bellows (Type 316 stainless steel)
- 6) Weld ring (Type 316 stainless steel)
- 7) Hot contact plate (copper)
- 8) Conductance ring (copper)
- 9) Guide rod (Type 316 stainless steel)
- 10) Inner bellows (brass)
- 11) Thermal insulation (Eccospheres R)
- 12) Metal spheres (copper)
- 13) Cold contact plate (copper)
- 14) Thermoelectric module

The Bi₂Te₃ N/P module (14) consists of 88 couples (leg dimensions, 0.204 by 0.050 by 0.050 in.) in series. The module has two cross-connected parallel circuits so that the total number of couples is 176. The legs are electrically insulated from each other by mica separators 0.005-in. thick. The hot and cold shoes are either arc-plasma sprayed or electroplated with nickel, and the surfaces are polished to a high finish to yield low thermal resistance joints with the hot contact plate (7) and the cold contact plate (13). The module is electrically insulated from the contact plates (7,13) by thin boron nitride sheets (0.002-in. thick, not shown). The module is 0.225 in. high; its cross-section is 1.10 by 1.10 in. The module is hermetically enclosed in a package formed by the hot contact plate (7), the outer bellows (5) and the flanges (1 and 3). The package protects the module (14) against oxidation and contamination. It also prevents oxidation of the internal pressure contact areas and thus ensures their continued low thermal resistance during the operational life of the module. A final function of the enclosure is to make the unit interchangeable and shelf-storable. The function of the outer bellows, besides enclosure, is to form a tortuous heat path and to provide the proper contact pressure between the contact plate (7) and the isotope heat source surface. The design contact pressure is 100 psi (BOL). The mating surfaces must have a good surface finish to provide low thermal resistance during operation. Welds between 5 and 7 will be brazed. The joint between 5 and 3 can be either brazed, soldered or welded. The contact pressures between the part combinations 7 and 14, 14 and 13, and 8 and 12, are provided by a bellows (10) partially filled with small copper spheres to improve thermal conductance. Recommended contact

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pressure is 50 psi at BOL. This pressure can be adjusted by the adjustment screw (2). A guide rod (9) prevents the cold contact plate (13) from exerting a shear force on the module during contact pressure adjustments. Joints between 8, 10 and 13 are made by furnace brazing. The pressure contact surfaces of 8 and 13 must have good surface finish to yield low thermal resistance. This also holds for the appropriate surface of part 2. After the adjustment procedure, which must be performed under simulated operating conditions closely resembling BOL operation conditions, flange 1 can be welded in place. The module can subsequently be evacuated, the voids between outer and inner bellows filled with Eccospheres R insulation, backfilled with argon, and sealed (the evacuation tube is not shown). Radiation resistant materials are used throughout the module. The electrical lead wires of the modules can conveniently be electrically insulated with ceramic beads (not shown).

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C. DEVELOPMENT AND FABRICATION PROBLEMS

There are two problem areas related to the development, fabrication and operational qualification of the 425°F (BOL) Bi_2Te_3 module for the 1000 mw(e), fully-shielded SrTiO_3 RTG: the module, and its package and the associated parts that provide a thermal path.

1. Bi_2Te_3 N/P Module

While such modules of a configuration as specified above are not commercially available, it is believed that the design is well within the state-of-the-art and few fabrication problems are anticipated. Modules for power generation are usually built with the so-called "egg crate" technique in which mica, mylar and other materials are assembled in an egg crate arrangement into which the N and P elements are inserted in the correct electrical configuration. The egg crate material forms the electrical insulation between the elements and facilitates the subsequent steps of fabrication, such as forming the electrical contacts. While the fabrication technology of Bi_2Te_3 N/P is complex, it is well established.

One major hurdle must be taken before the module can be regarded as qualified for 5-yr operation under the specified temperature conditions. There is little documentation on long-life tests or reliability tests of such modules at any temperature. Personal communications with researchers investigating Bi_2Te_3 modules yielded scant evidence of prolonged testing, and little reliable test data. Most of the testing appears to have been for periods from hundreds to a few thousand hours. Failures of some modules during these tests were admitted; the results, however, were judged generally favorable and promising.

It is believed that the absence of long-life data for such modules stem from a lack of incentive; for many of the thermoelectric applications investigated, Bi_2Te_3 N/P did not and do not appear to be an attractive material. As shown in this study, however, such a module provides the basis for high-performance large milliwatt systems, and it seems appropriate to qualify it for operational life times of 5 yr or more. It is believed that such modules operating at 425 to 450°F can eventually be qualified for long life with a high level of confidence.

2. Package and Other Components

The design problems of the package are mainly related to proper matching of inner and outer bellows to maintain reliable containment and correct contact pressures under operating conditions, including shock and vibration. It is expected that the package can be fabricated with state-of-the-art techniques. Jigs and fixtures will be required for proper adjustment of contact pressures, for evacuation, and for subsequent introduction of the thermal insulation (Eccospheres R).

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As far as qualification of the package for long life, it appears that while braze joints between stainless steel (Type 316) and copper have not been, to our knowledge, subjected to long-term reliability testing, they can be made with standard techniques. These joints form a hermetic seal between the outer bellows and the hot contact plate. In view of the low operating temperatures (about 425°F), this braze joint qualification problem appears surmountable.

Three different shield configurations are summarized in Table 7. The central thermoelectric module is identical in all three. The flange of the module has been fabricated from Mallory 2000 to eliminate radiation scattering and streaming. The uranium shield of Figure 37 has been clad with Hastelloy C. Since this design has not been intended to serve as a pressure vessel or in direct exposure to sea water, other metals can be used for this outer cladding. The heavy biological shield is lifted through the threaded eye-bolt then through the Mallory cap screws. The electrical leads are brought out to the power conditioner which is mounted in the triangular toroid void directly above the lid. Simplicity, for ease of fabrication and assembly, has been the primary consideration in this design. A minimum number of hot cell operations are required; these are simple placement and screwing operations in mounting the module on top of the fuel capsule.

The 1000 mw(e) system with a Mallory 2000 shield (Figure 38) has been included to show the simplified design associated with this shielding material.

The lead shield for this system (Figure 39) represents the least expensive, but the largest and heaviest design, without sacrificing simplicity. After the thermoelectric module has been placed into position, the MIN-K-1301 insulation is evacuated and back-filled with xenon; the special tube is then pinched and welded shut. No screws are used to fasten the lead lid in place other than those threaded through the top cap after it has been welded in place. The hermetically sealed unit will meet the transportation criteria of the ICC and the Bureau of Explosives.

The designs were analyzed using the 2-DRZ computer program to determine the nominal temperature levels within the system. The thermoelectric modules were simulated by defining the temperature drops across the module and using artificial thermal conductivities to achieve the required temperature drops. The temperatures shown thus are approximate values and will change when more detailed information becomes available. Table 7 completely describes these units, including cost.

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FIGURE 37. 1000mw URANIUM SHIELDED, SrTiO_3 SYSTEM

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FIGURE 38. 1000_{mw} MALLORY 2000 SHIELDED, SrTiO₃ SYSTEM

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FIGURE 39. 1000mw LEAD SHIELDED, SrTiO_3 SYSTEM

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TABLE 7 - SUMMARY OF 1000 mw(e) CHARACTERISTICS

Radioisotope fuel	SrTiO ₃		
Power output EOL	1000 mw(e) at 24 v		
Life expectancy	5 yr		
Thermal power (BOL)	38.3 w		
Thermal efficiency (EOL)	2.55%		
Thermoelectric module efficiency	2.97%		
Power conditioning efficiency	83.9%		
	<u>Uranium</u>	<u>Mallory</u> 2000	<u>Lead</u>
Diameter of system, in.	8.25	9.5	13
Length of main system, in.	11.0	11.5	13
System weight, lb.	300	440	690
Shield (external)			
Thickness, in.	2.73	3.26	4.92
Surface dose rate, mr/hr	200	200	200
Insulation			
Material	MIN-K-1301 (Xenon backfill)		
Thickness	0.47 in.		
Fuel Capsule			
Material	Hastelloy C		
Fuel diameter	1.495 in.		
Fuel length	1,545 in.		
Liner wall thickness	0.030 in.		
Liner end cap thickness	0.40 in.		
Capsule wall thickness	0.080 in.		
Capsule end thickness	0.100 in.		
Capsule diameter	1.76 in.		
Capsule length	2.10 in.		
Capsule L/D	1.20		
Hot junction temperature: EOL	375°F		
BOL	475°F		
Cold junction temperature	75°F		

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Thermoelectric module

Thermoelectric material	Bi_2Te_3
Thermoelectric output voltage (EOL)	3.0 v
Number of couples	88
Degree of couple redundancy	One-fold
Contact loss	25%
Degradation	13%
L/A	80 in. ⁻¹
Module heated area	1.21 in. ²
Heat flux density	7.5 w/cm ²
Element area	0.0025 in. ²
Element dimensions, in.	0.204 long by 0.05 by 0.05
Module dimensions, in.	0.225 high by 1.100 by 1.100

Steady State Operating Temperature Distribution

1.	Ambient sea water temperature	50°F
2.	Nominal shield outer surface temperature	55°F
3.	Nominal shield inner surface temperature	60°F
4.	Thermoelectric coldshoe temperature	75°F
5.	Thermoelectric hotshoe temperature	375°F
6.	Fuel capsule contact surface temperature	400°F
7.	Maximum capsule surface temperature	457°F
8.	Maximum fuel temperature	563°F

System Cost, \$

	<u>Uranium</u>	<u>Mallory</u>	<u>Lead</u>
Fuel Cost*, \$			
Present	1424		
Future	845		
Thermoelectric cost	150		
Power conditioner cost	1050		
Shield cost	Government	6\$/lb	70¢/lb
	Commercial	2590	483
*Does not include encapsulation cost			

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	<u>Uranium</u>	<u>Mallory</u>	<u>Lead</u>
Manufacturing hardware cost	780		
Insulation cost	230		
Total manufacturing cost for lot of 10, per unit			
Present	Government	4990	
Future		4410	
Present	Commercial	5930	6220 4110
Future		5350	5640 3530

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VI. REVIEW OF 600 mw(e), Pm_2O_3 SYSTEM

In refining the design of the second system selected by the AEC (System 8), the design was optimized on size and detectability; less important considerations were resistance to acceleration shocks, low cost, high reliability, and an 18-month lifetime. This again is a submersible application, but operating at depths where the anticipated ambient temperatures range from 30 to 60°F. Examination of Figure 40 reveals that a 600 mw(e) system can be achieved with a diameter of 3.75 in., and a Z of 0.90, using an external uranium shield weighing 7.4 lb.

Reiteration showed that a slight decrease in size could be effected by using an internal uranium shield. The next step was plotting ETA(EOL) versus diameter for both promethium metal and Pm_2O_3 for TC of 75°F (Figure 41). It became obvious that the upper temperature would be 450°F BOL and 325°F EOL, due to the rapid decay of Pm (half-life of 2.62 yr). The plot also shows the increase in system efficiency and decrease in cost obtainable by higher operating temperatures, the limiting factor being the Bi_2Te_3 module; additional investigations are needed to evaluate and test such modules to improve their high temperature capability. Reducing the EOL temperature to 325°F shifted the design point to a system with a 4-in. outside diameter.

A. THERMOELECTRIC DESIGN ANALYSIS

The length of the mission in relation to the half-life of the radioisotope (1.5 vs. 2.62 yr) drops the thermal input by about 29% during the operational life of the module. Such a module obviously cannot be designed to achieve high efficiency at the end of life; and attractive module efficiency can be attained by selecting the maximum hot junction temperature at BOL permissible within the limits of the reliability requirements (18 months). The typical ambient temperatures of this module during service (30 to 60°F) will result in cold junction temperatures from 50 to 80°F. Figure 42 shows the performance characteristics of a 600 mw(e), Bi_2Te_3 N/P module for operation at 450 and 475°F (BOL) hot junction temperatures and at 50 and 75°F cold junction temperatures. The short half-life of the isotope is reflected in the curves for hot junction temperatures, for the net power generated, and for module efficiencies. The sharp drop in hot junction temperature adversely affects the load voltage generated and the module efficiency. As is shown in Figure 42, a higher hot junction temperature at BOL yields a higher average module efficiency during life and a higher efficiency at EOL; however, the choice of hot

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FIGURE 40. Pm_2O_3 FULL SHIELD MIN-K-1301 600mw

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FIGURE 41. SYSTEM EFFICIENCY AND FUTURE FUEL COST VERSUS OUTSIDE DIAMETER Pm_2O_3
 (600mw - MIN-K-1301 - Full U-Shield - Z 0.90 - Bi_2Te_3 - TC 75 - L/D 1.2)

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FIGURE 42. HOT JUNCTION TEMPERATURE, NET MODULE POWER OUTPUT AND MODULE EFFICIENCY VERSUS TIME

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junction temperature is limited by lack of long-life test data at higher hot junction temperatures. A module designed for operation at 475°F BOL would have to operate for 4000 to 4500 hr at temperatures above 450°F; a 450°F (BOL) design would be easier to develop. It is felt that a cold junction temperature of 75°F is a more realistic choice in view of the anticipated ambient temperatures than 50°F which corresponds to a 30°F ambient.

The steep decline of hot junction temperature at a constant cold junction temperature results in an equally steep decline of temperature difference across the couples and thus in the load voltage generated. A 450°F (BOL) hot junction temperature module designed for 3 v at BOL would produce about 2 v at EOL (Figure 43); further decreases in module efficiency at EOL result because of lower power conditioning efficiencies. For example, power conditioning efficiencies drop from 84% at 3 v to about 80% at 2 v; the corresponding efficiency at 3.5 v is 85.5% and at 2.3 v is 81%. A 3.5 v load at BOL was chosen as a compromise between the module efficiency and the reliability related to the necessary increase in number of couples.

The design conditions of Figures 42 and 43 (i.e., $T_H = 450^\circ\text{F}$ at BOL; $T_C = 75^\circ\text{F}$; load voltage at BOL = 3.5 v; and net power at BOL = 1.36 w) can now be used to determine the number of couples in series (SERJ), the element length (ELGTH), the cross-sectional area of the elements (ACRO), and the module dimensions. The important design parameters were determined, using the procedure developed earlier. The module efficiencies of Figure 42 were adjusted for thermal losses in the capsule wall and in the Eccospheres R insulation between the capsule wall and the inner bellows. Figure 44 shows the thermal profile at BOL at a cold junction temperature of about 87°F.

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FIGURE 43. LOAD VOLTAGE VERSUS TIME

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FIGURE 44. THERMAL PROFILE AT BOL OF 450°F FOR 600mw Pm_2O_3 MODULE

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B. DESIGN DESCRIPTION

The conceptual design of the 600 mw(e), 450°F (BOL), Bi_2Te_3 N/P module for a fully-shielded 147-Pm RTG (Figure 45) includes the following parts:

- 1) Flange (Mallory metal)
- 2) Bellows pressure adjustment screws (copper)
- 3) Mounting flange (Type 316 stainless steel)
- 4) Electrical feed-through of the ceramic-to-metal seal type
- 5) Cold contact plate(copper)
- 6) Metal enclosure (Type 316 stainless steel)
- 7) Weld ring (Type 316 stainless steel)
- 8) Hot contact plate (copper)
- 9) Flexible pad (copper)
- 10) Conductance ring (copper)
- 11) Weld ring (brass)
- 12) Inner bellows (brass)
- 13) Thermal insulation (Eccospheres R)
- 14) Guide rod (Type 316 stainless steel)
- 15) Thermoelectric module
- 16) Hot contact plate (copper)

Fabrication and assembly of this module would generally proceed as described for the 1000 mw(e) unit; the main difference relates to the method by which pressure contact is maintained between the module and the isotope heat source. Fabrication tolerances in the axial direction of the 1000 mw(e) module can be adjusted by the spring action of the outer bellows: in other words, the bellows can be designed for a range of axial clearances between the surfaces of the module and the isotope heat source and the mounting surfaces of the flange (3). The compressibility of the copper wool pad (9) is much less, thus reducing the fabrication tolerances on the axial clearance. Contact pressure between the contact hot plate (8) and the copper wool pad should be in the range of 50 to 100 psi. An advantage of using copper wool is that the contact surfaces require less attention. The surfaces must be cleaned, however, to eliminate oxide layers; an appropriate surface treatment will achieve this.

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FIGURE 45. CONCEPTUAL DESIGN OF THE 600mw 450°F (BOL)
Bi₂Te₃ N/P MODULE

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C. DEVELOPMENT AND FABRICATION PROBLEMS

The development and fabrication problems for the 600 mw(e) module resemble those discussed earlier. The necessity of reliability qualification of the module is equally important. While the operational life required of the 600 mw(e) module is only 18 months, the BOL hot junction temperature (450°F) is 25°F higher than for the 1000 mw(e) module. Life and reliability tests on the Bi₂Te₃ N/P module conceivably could prove capability for higher temperatures, perhaps 475 or 500°F, in which case modules are feasible with higher EOL efficiencies (2.75 to 3.5%).

Another development problem is related to the density of the copper wool pad (9); as its density increases, its compressibility and the fabrication tolerances on the axial clearances decrease. Excessive density conceivably could cause problems, since the length of the module shrinks as the temperatures drop during operational life; however, a high density copper wool pad will yield a low thermal resistance path. The optimum density must be determined by experimentation.

The cost, weight and volume of two battery systems are compared to the Pm₂O₃, 600 mw(e) system below:

	<u>600 mw RTG</u>	<u>Lead-Acid</u>	<u>Silver-Zinc</u>
Cost, \$			
Present	26,940	960	9,000
Future	6,440		
Weight, lb	12	1470	300
Volume, in. ³	108	20,740	3,960
ft ³	0.062	12	2.28

The design shown in Figure 46 is smaller in weight and size than either battery system which would permit adaptation to many uses. In addition, the internal shield configuration permits easy and safe transportability in any guise; the thermoelectric unit can be field-installed if necessary.

The shock isolation for this unit can be handled by special finned structures secured directly to the capsule and inner wall of the support case, as shown in Figure 46. Table 8 details the specifics of this 600 mw(e) design.

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FIGURE 46. 600mw Pm₂O₃, SYSTEM

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TABLE 8 - SUMMARY OF 600 mw SYSTEM DESIGN

Radioisotope fuel	Pm_2O_3
Power output	600 mw/ 18 v
Thermal power (BOL)	37 w
Thermal efficiency (EOL)	1.81%
T/E module efficiency	2.41%
Power conditioning efficiency	83.9%
Diameter of system	4 in. (main diameter) 5-1/4 in. flange diameter
Length of main system	8-1/4 in.
System weight	12 lb
Shield (internal)	9.4 lb
Material	Uranium
Thickness	0.594 in.
Surface dose rate	200 mr/hr
Insulation	
Material	MIN-K-1301 (Xenon back-filled)
Thickness	0.68 in.
Fuel Capsule	
Material	Hastelloy C
Fuel diameter	1.367 in.
Fuel length	1.366 in.
Liner wall thickness	0.030 in.
Liner end cap thickness	0.050 in.
Capsule wall thickness	0.080 in.
Capsule end thickness	0.100 in.
Capsule outside diameter	1.597 in.
Capsule length	1.916 in.
Capsule L/D	1.2
Hot junction temperature, EOL	325°F
BOL	450°F
Cold junction temperature	75°F
Thermoelectric module	
Thermoelectric material	Bi_2Te_3 (EOL)

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Thermoelectric output, BOL	3.5 v
EOL	2.5 v
Number of couples	74
Degree of redundancy	one-fold
Contact loss	25%
Total degradation	6.5%
L/A	88 in. ⁻¹
Module heated area	1.04 in. ²
Heat flux density	7.5 w/cm ²
Element area	0.0027 in.
Element dimensions, in.	0.240 long by 0.054 by 0.054
Module dimensions, in.	0.260 high by 1.020 by 1.020

Steady State Operating Temperature
Distribution (EOL)

1.	Ambient sea water	50°F
2.	Thermoelectric coldshoe temperature	75°F
3.	Thermoelectric hotshoe temperature	350°F
4.	Nominal shield outer surface temperature*	370°F
5.	Nominal shield inner surface temperature*	379°F
6.	Fuel capsule contact surface temperature	388°F
7.	Maximum capsule surface temperature	406°F
8.	Maximum fuel temperature	440°F

*Note: This uses an internal shield

System Cost, \$

Fuel Cost,*	
Present	27,700
Future	4,600
Thermoelectric cost,	150
Power conditioner cost,	1,050
Shield cost,	94
Manufacturing hardware cost,	780

*Does not include encapsulation cost

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Insulation cost	230
Total manufacturing cost for lot of 10, per unit	
Present	27,700
Future	6,904

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VII. REVIEW OF THE 300 mw(e) PLUTONIUM SYSTEM

The load and size of this system were designed to meet the NOL's requirements for a SNAP-15C-type power supply. The design was optimized for long life (10 yr) and low cost. Other, lesser, considerations included high resistance to acceleration shocks, compactness, low weight, high reliability, minimum radiation and handling hazards, and adaptability to several systems.

The design activity was begun with a study of the efficiency versus diameter plots (Figure 47) in the light of the cost curves (Figures 48 through 50). It was obvious that the $Z = 0.9$ curve is still in the stable region at low diameters. The initial outside dimension was thus selected as 1.8 in., and incorporated into the data developed initially for the AEC as System 9 (Appendix A).

The first design refinement was accomplished by comparing the system with the NOL envelope; this permitted an increase in outside dimension. The design was analyzed for various hot junction temperatures, a TC temperature of 75°F , and for a different form of fuel (plutonium metal); small gains resulted (Figure 51). A low hot junction temperature was selected to obtain maximum reliability over the 10-yr operational life, for both the Bi_2Te_3 thermoelectric module and the power conditioner components (There still is doubt that the power conditioner components will perform reliably for 10 yr).

The shock and vibration requirements for this module are so severe that the final design will have to be based on the results of a thorough test program. The design embeds the system in elastic shock mount material to isolate the critical components within the envelope specified by NOL. This approach provides for successive shocks over the life of the system; if NOL would accept the concept of only a single, high shock impulse instead, crushable materials that would collapse on seeing a high energy shock could be employed. The mount as shown in Figure 52 will need review by appropriate specialists in complete detail, and several designs perhaps will have to be tested at a site with the 150-g impact capability.

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REF ID: A62110

FIGURE 47. PuO_2 MIN-K-1301 300mw

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FIGURE 48. PuO_2 MIN-K-1301 $Z = 0.55$

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NOTE: THIS IS FIGURE E-5 PREVIOUSLY
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FIGURE 49. PuO_2 MIN-K-1301 $Z = 0.90$

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FIGURE 50. SrTiO₃ - FULL SHIELD - MIN-K-1301 - TH 400 Bi₂Te₃

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FIGURE 51. SYSTEM EFFICIENCY AND FUEL COST VERSUS OUTSIDE DIAMETER FOR VARIOUS HOT JUNCTION TEMPERATURES

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FIGURE 52. 300mw Pu SYSTEM

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A. THERMOELECTRIC DESIGN ANALYSIS

Since the 238-Pu fuel decays only 7.5% during the operational life of the module, the design of a suitable module is much less complex than for the 1000 and 600 mw(e) units described earlier; however, the EOL efficiency of the module will be about the same as for those units because of the lower hot junction temperature required to ensure long life. Figure 14 shows load voltage, net power generated and module efficiency for a 375°F (BOL) and a 400°F (BOL) modules operating at a cold junction temperature that corresponds to 50°F ambient temperature.

The degradation rate is assumed to be constant during operational life and the total degradation is not expected to exceed 15% over 10 yr. There is little published data on the degradation of Bi₂Te₃ N/P modules, but personal communications with users of such modules established that 15% total degradation is reached asymptotically within a few thousand hours of operation.

The module efficiencies were determined for a mismatch ratio of 1.5; values for the hot and cold junction temperature combinations vary considerably (Figure 53). There is a strong incentive to choose a high hot junction temperature, but the long life requirement suggests selection of a lower temperature; the lower temperature (BOL) was chosen (TH= 375°F).

The cold junction temperature was set at 75°F to reflect the average ambient condition likely to be encountered. The EOL efficiency of this module is 2.51%; however, the efficiency is higher over much of its life (BOL is 3.15%) and the module is more efficient at lower ambient temperatures. Table 9 relates BOL and EOL module efficiencies as a function of ambient temperature.

TABLE 9
EOL AND BOL MODULE EFFICIENCIES
FOR VARIOUS AMBIENT TEMPERATURES
(Hot junction temperature BOL: 375°F)

	Ambient Temperature, °F					
	130	100	80	60	30	0
Cold Junction Temperature (est.), °F	150	120	100	80	50	30
BOL Module Efficiency, %	2.42	2.72	2.95	3.11	3.46	3.69
EOL Module Efficiency, %	1.93	2.13	2.35	2.49	2.75	2.92

These module efficiencies were calculated with the aid of the module efficiency curves for TH = 375°F (Figure 12). Thermal losses in the metal module enclosure and in the thermal insulation between the inner compression bellows and the metal enclosure reduce these efficiencies by from 2.5 to 5%. A thermal profile of the 300 mw(e), 375°F (BOL) Bi₂Te₃ N/P module is shown in Figure 54.

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FIGURE 53. LOAD VOLTAGE, NET MODULE POWER, MODULE EFFICIENCY VERSUS TIME

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FIGURE 54. THERMAL PROFILE OF A 375°F (BOL) 300mw MODULE AT BOL

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B. DESIGN DESCRIPTION

The conceptual design (Figure 55) of the 300 mw(e), 375°F (BOL), Bi_2Te_3 N/P module for a 238-Pu RTG includes the following parts:

- 1) Flange (aluminum)
- 2) Mounting flange (aluminum)
- 3) Electrical feed.-throughs of ceramic-to-metal seal type
- 4) Metal enclosure (Type 316 stainless steel)
- 5) Weld ring (Type 316 stainless steel)
- 6) Hot contact plate (aluminum)
- 7) Flexible pad (copper)
- 8) Bellows pressure adjustment screw (copper)
- 9) Conductance ring (copper)
- 10) Guide rod (Type 316 stainless steel)
- 11) Metal spheres (copper)
- 12) Inner bellows (brass)
- 13) Cold contact plate (copper)
- 14) Thermal insulation (Eccospheres R)
- 15) Thermoelectric module

The design of the module is essentially the same as that of the 600 mw(e) module described earlier. For the 300 mw(e) module, the hot contact plate material is aluminum and the thermoelectric module (15) is electrically insulated from the hot contact plate (6). This is achieved by anodizing the mating surfaces (such anodized coatings are stable at the 375°F operating temperature). The stainless steel enclosure (4) is pressure-welded to the hot contact plate (6) and the weld ring (5).

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FIGURE 55. CONCEPTUAL DESIGN OF THE 300mw Bi_2Te_3 THERMOELECTRIC MODULE

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C. DEVELOPMENT AND FABRICATION PROBLEMS

Development and fabrication problems related to this module are not markedly different from the ones described earlier. The elements in the thermoelectric module are somewhat smaller than those for the 1000 and 600 mw(e) modules. The size (0.375 long by 0.040 by 0.040 in.) and the large(230) quantity of elements per module complicate fabrication. The fabrication of N/P modules featuring hundreds of small elements has not been documented; thus this module must be developed. It is evident that there is a greater need to operationally qualify this module than the modules previously described. There is no evidence that semiconductor thermoelectric modules have ever been qualified for operation up to 10 yr.

Another problem that must be resolved is that of the long-life qualification of the pressure weld (or braze joint) between the aluminum hot contact plate (6) and the stainless steel enclosure (4). Such welds have been made routinely without problems; however, weld qualification data are not available and must be generated for the development of the package.

The design performance of the 300 mw(e) system (Figure 52) is summarized in Table 10.

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TABLE 10 - SUMMARY OF 300 mw(e) DESIGN

Radioisotope fuel	Pu metal
Power output	300 mw(e)
Life expectancy	10 yr
Thermal power (BOL)	14.6 w
Thermal efficiency (EOL)	2.22%
Thermoelectric module efficiency	2.51%
Power conditioning efficiency	83.9%
Computer design, O.D.	2 in.
Diameter of system	4-1/2 by 4-1/2 in. (square cross section)
Length of main system	6 in.
System weight	3 lb
Insulation	
Material	MIN-K-1301
Thickness	0.56 in.
Fuel capsule	
Material	Hastelloy C
Fuel diameter	0.5576 in.
Fuel length	0.5229 in.
Axial clearance	0.0577 in.
Liner wall thickness	0.030 in.
Liner end cap thickness	0.050 in.
Capsule wall thickness	0.080 in.
Capsule diameter	.7776 in.
Capsule length	.9330 in.
Capsule L/D	1.20
Hot junction temperature, EOL	350°F
BOL	375°F
Cold junction temperature	75°F
Thermoelectric module	
Thermoelectric material	Bi ₂ Te ₃
Thermoelectric output voltage, BOL	3 v
EOL	2.79 v

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Number of couples	86
Degree of redundancy	One-fold
Contact loss	25%
Degradation	15%
L/A	230 in. ⁻¹
Module heated area	0.74 in. ²
Heat flux density	3.5 w/cm ²
Element area	0.00164 in. ²
Element dimensions	0.375 long by 0.040 by 0.040 in.
Module dimensions	0.400 high by 0.860 by 0.860 in.

Steady State Operating Temperature Distribution

1.	Ambient sea water	50°F
2.	Nominal shield outer surface temperature	57°F
3.	Nominal shield inner surface temperature	60°F
4.	Thermoelectric coldshoe temperature	75°F
5.	Thermoelectric hotshoe temperature (EOL)	350°F
6.	Fuel capsule contact surface temperature	369°F
7.	Maximum capsule surface temperature	434°F
8.	Maximum fuel temperature	490°F

Fuel Cost*

Future	\$8200
Thermoelectric cost	180
Power conditioner cost	1050
Manufacturing hardware cost	450
Insulation cost	230
Total manufacturing cost for lot of 10, per unit	
Future	10,110

*Fuel encapsulation cost not included

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VIII. REVIEW OF 150 mw(e) SrTiO₃ SYSTEM

This system was designed to meet the requirements of the NCEL submerged instrument package, with the primary emphases on low cost and light weight. Since these criteria are incompatible, the light weight feature was given first importance during design. Other considerations included high resistance to shock and vibration*, long life, high reliability, and low radiation; these were met by the resulting design. The system was designed to supply electrical output for 1 minute per operational hour; the package was designed to operate at depths of 20,000 ft.

A. THERMOELECTRIC DESIGN ANALYSIS

After studying the plots in Figure 56, a reasonable first design point was selected, using a system outside dimension of 9.5 in. (These data are summarized under System 13a in Appendix A). Refining this design paralleled that activity for the 1000 mw(e) system. The Bi₂Te₃ has a Z of 0.9 at TH = 387°F; external shielding provided the optimum design. (Figure 57). The lightest unit for this application used uranium shielding clad in Hastelloy C (0.125 in. thick) for protection against salt water corrosion (Figure 58). The design uses a hemispherical dome of Hastelloy C; the mating surface with the body of the design is sealed with an Ethylene-Propylene E515, 88-durometer static O-ring seal. The electrical feed-throughs are Marsh and Marine Type XSA-SBC to fit a special undersea connector.

Since the design conditions are essentially those of the 1000 mw(e) module, the same considerations prevail in regard to selection of temperature values for the hot and cold junctions. The change in hot junction temperature with time (Figure 32) is equally valid for this 150 mw(e) module. The same BOL load voltage was selected, thus the load voltage and module efficiency curves presented in Figure 34 also hold for the 150 mw(e) module. The net module power is plotted against time in Figure 59. Figure 60 shows the thermal profile of the module for the design ambient temperature (120°F). The module efficiencies of Figure 34 must be corrected for the heat losses in the enclosure and in the thermal insulation contained in the void between the inner bellows and the metal enclosure. These heat losses are larger than those in the 1000 mw(e) module; consequently module efficiency at EOL is 2.90% compared to 2.97% for the 1000 mw(e) module.

* That is, the transportation environment

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FIGURE 56. SrTiO_3 FULL SHIELD MIN-K-1301 150mw

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FIGURE 57. SYSTEM EFFICIENCY AND WEIGHT VERSUS OUTSIDE DIAMETER FOR A 150mw SrTiO_3 EXTERNALLY SHIELDED SYSTEM
(External Full U-Shield - MIN-K-1301 - L/D 1.2 - TC 75)

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FIGURE 58. 150mw URANIUM SHIELDED SrTiO_3 SYSTEM
CAPABLE OF 20,000 FOOT DEPTH OPERATION

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FIGURE 59. NET MODULE POWER VERSUS TIME FOR 150mw (EOL) Bi₂Te₃ N/P MODULE

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FIGURE 60. THERMAL PROFILE OF A 425°F (BOL) 150mw MODULE

B. DESIGN DESCRIPTION

The conceptual design of the 150 mw(e), 425°F (BOL), Bi_2Te_3 N/P module for a fully-shielded SrTiO_3 RTG (Figure 61) has the following parts:

- 1) Flange (Mallory 2000)
- 2) Bellows pressure adjustment screw (copper)
- 3) Mounting flange (Mallory 2000)
- 4) Electrical feed-throughs of a ceramic-to-metal seal type
- 5) Metal enclosure (Type 316 stainless steel)
- 6) Weld ring (brass)
- 7) Hot contact plate (copper)
- 8) Conductance ring (copper)
- 9) Metal spheres (copper)
- 10) Inner bellows (brass)
- 11) Guide rod (Type 316 stainless steel)
- 12) Cold contact plate (copper)
- 13) Thermoelectric module
- 14) Thermal insulation (Eccospheres R)
- 15) Flexible pad (copper)

The module is similar to the 1000 mw(e) module described in Chapter V. A metal enclosure (5) is used instead of an outer bellows, and a flexible pad of copper felt provides the thermal contact between the hot contact plate and the heat source.

FIGURE 61. CONCEPTUAL DESIGN OF THE 150mw Bi_2Te_3 N/P THERMOELECTRIC MODULE

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C. DEVELOPMENT AND FABRICATION PROBLEMS

The problems anticipated in the development of this module are similar to those described for the other modules; however, development of the Bi_2Te_3 module will be more difficult, since the L/A ratio of this module is much higher. Bismuth telluride N/P modules with L/A ratios of 150 in.^{-1} are commercially available, but modules featuring L/A ratios of 262 in.^{-1} and a large number of couples are not. It is felt, however, that such designs can be developed to achieve a high degree of reliability.

The design features are summarized in Table 11.

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TABLE 11 - IMPORTANT PARAMETERS
OF THE 150 mw(e) SrTiO₃ SYSTEM

Radioisotope fuel	SrTiO ₃
Power output	150 mw
Thermal power (BOL)	9.1 w
Thermal efficiency (EOL)	1.86%
Thermoelectric module efficiency	2.90%
Power conditioning efficiency	83.9%
Diameter of system	6.75 in.
Length of main system	14 in.
System weight	177 lb
Shield	
Material	Uranium
Thickness	2.91 in.
Surface dose rate mr/hr	200
Insulation	
Material	MIN-K-1301
Thickness	0.55 in.
Fuel capsule	
Material	Hastelloy C
Fuel diameter	0.914 in.
Fuel length	0.847 in.
Liner wall thickness	0.030 in.
Liner end cap thickness	0.050 in.
Capsule wall thickness	0.080 in.
Capsule end thickness	0.100 in.
Capsule diameter	1.164 in.
Capsule length	1.400 in.
Capsule L/D	1.2
Hot junction temperature, EOL	375°F
BOL	425°F
Cold junction temperature	75°F

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Thermoelectric module

Thermoelectric material	Bi_2Te_3
Thermoelectric output voltage, BOL	3.4 v
EOL	3.0 v
Number of couples	88
Contact loss	25%
Degradation	13%
L/A	262 in.^{-1}
Module heated area	0.64 in.^2
Heat flux density	3 w/cm^2
Element area	0.0018 in.^2
Element dimensions	0.510 long by 0.0424 by 0.424 in.
Module dimensions	0.530 high by 0.800 by 0.800 in.

Steady State Temperature Distribution

1.	Ambient sea	50°F
2.	Nominal shield outer surface temperature	58°F
3.	Nominal shield inner surface temperature	60°F
4.	Thermoelectric coldshoe temperature	75°F
5.	Thermoelectric hotshoe temperature (EOL)	375°F
6.	Fuel capsule contact surface temperature	385°F
6.	Maximum capsule surface temperature	416°F
8.	Maximum fuel temperature	426°F

System Cost, \$

Fuel Cost, *

Present	292
Future	173
Thermoelectric cost	200
Power conditioner cost	1050
Shield cost	
Government	1040
Commercial	1680

*Does not include fuel encapsulation cost

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Manufacturing hardware cost	780
Insulation cost	230
Total manufacturing cost for lot of 10 , per unit	
Commercial	
Present	4230
Future	4110
Government	
Present	3600
Future	3470

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IX. DEVELOPMENT PROGRAM

The development program includes the engineering tasks, the scheduling, and the costs related to the reduction of any of the four prototype designs into the production hardware stage. All experimental testing, and the development of special fabrication techniques, will be completed during the development phase of the program. Since the expected system lifetimes range up to 10 yr, the full lifetime reliability tests will continue well into the production phase. The accelerated reliability tests, however, will also be initiated during this period, and some of them completed.

This schedule requires that the production run will be initiated without the benefit of data derived from completed reliability tests. It is anticipated that only minor changes will be required, and that these will be incorporated into the second and third production runs. The initial production is scheduled to start within six months after the development program is begun.

Much importance has been placed on the reliability of RTG systems, but an economical test program to demonstrate 5-yr reliability for a thermonuclear power supply cannot proceed until component operational and environmental stress limits are defined and system compatibility is proved. The proposed reliability demonstration program is based on sound technical considerations in which confidence in the reliability prediction is balanced against the number of tests and their duration. Statistical analysis techniques are used to obtain a maximum amount of useful information from a minimum of test data and test time.

The limits of component operational and environmental stresses will be determined by screening tests; system compatibility will be demonstrated by extensive instrumentation, and by periodic disassembly and inspection of prototype sub-systems and systems.

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A. ENVIRONMENTAL AND OPERATIONAL STRESS SCREENING TESTS

Components susceptible to degradation from environmental and operating stresses will be tested individually and sequentially under conditions more severe than expected during service. Tests under combined environmental conditions are not considered necessary as no synergistic mechanisms are predicted; however, any combinational degradation factors will be uncovered during later system tests.

The environmental conditions to be simulated include:

- External pressure (applied to 150 mw system only)
- Vibration and shock
- Temperature
- Radiation

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B. LONG-LIFETIME RELIABILITY DEMONSTRATION

There are several approaches to demonstrating system long-life reliability: three approaches are based on firm statistical considerations but require many test items, or very long duration tests; the suggested approach is based on an intuitive procedure in which increasing confidence is gained from the careful monitoring of a few systems tested with simulated operating loads and environmental conditions.

1. Tests to Design Lifetime

The approach to reliability testing in which the system is tested under operating conditions for a duration equal to service requirements is commonly used in testing such relatively inexpensive devices as electronic components.

The number of systems which must be tested to the design lifetime to achieve a given reliability at several confidence levels has been statistically assessed (Figure 62). To demonstrate 95% reliability at the 90% confidence level, 45 tests without a failure are required, but a 60% confidence level is sufficiently demonstrated with only 18 tests. If a 70% reliability is acceptable, 7 tests are required at the 90% confidence level, or 3 tests for the 60% confidence level.

The dependence of confidence level on the number of items tested for 95 and 80% reliability is plotted in Figures 63 and 64. The number of tests required is increased severely if one failure occurs: for 95% reliability at the 90% confidence level, the number of successful tests required is increased from 45 to 76 if one failure occurs in the test series. For 80% reliability at the 90% confidence level, the number of successful tests required is increased from 11 to 18 if a single failure occurs.

2. Time-testing to Failure

In implementing the test-to-failure philosophy, several components are placed on test under simulated operating conditions, and the distribution of the failures is then utilized to predict the reliability achievable during the design lifetime. This test approach requires fewer components than the above, but requires much longer test durations. Figure 65 indicates the total ratio of component test hours to mission hours to achieve several reliability goals as a function of the number of test failures.

Theoretically, a large number of components could be tested for a short time to achieve the total component test hours required; however, this test approach is only valid when it has been previously demonstrated that the component lifetime is not limited to less than the desired lifetime by wear-out mechanisms.

FIGURE 62. NUMBER OF FAILURE FREE TEST REQUIRED TO ESTABLISH RELIABILITY AT SEVERAL CONFIDENCE LEVELS (CL)

FIGURE 63. CONFIDENCE LEVEL DEPENDENCE ON NUMBER OF ITEMS TESTED FOR 95% RELIABILITY

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FIGURE 64. CONFIDENCE LEVEL DEPENDENCE ON NUMBER OF ITEMS TESTED FOR 80% RELIABILITY

FIGURE 65. TEST HOURS REQUIRED FOR PROOF OF RELIABILITY 90%
CONFIDENCE LEVEL

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The correct use of this test approach would be the successful testing of ten components for 45,000 hr; a 95% reliability of 10,000 hr of successful mission operation at the 90% confidence level could then be predicted.

3. Over-testing

An approach to testing in which the test operational conditions are made more severe than the actual operating conditions can be used to shorten the time required on-test and minimize the number of components to be tested. The overstress conditions must be applied, however, so the spurious failure modes are not developed and the amount of overstress must be known, carefully controlled, and accurately related to its effect on component life. Unfortunately these conditions cannot be met until an extensive test history has been acquired.

An alternate approach concept consists of submitting a test component to an increasing stress until failure. By observing the statistical behavior of the stresses at which failure occurs, a lower limit of stress below which the probability of failure is very small can be selected by using the mean and standard deviation of these data. This test procedure therefore firmly establishes design safety margins. For a thermo-nuclear power supply, this test approach would involve electrical, thermal, environmental and mechanical over-stressing to divulge incipient weaknesses in the design.

4. System Compatibility Demonstration

The proposed reliability demonstration program is based on the careful monitoring of the performance of previously qualified parts in prototype system and subsystem tests. Extensive instrumentation will be used to monitor the continuing performance of components and subassemblies. Periodic dis-assembly and inspection will verify the condition of parts which cannot be instrumented.

A comprehensive failure mode and cause analysis will be performed on each component that indicates off-design performance. Corrected units will be immediately installed and testing resumed. This approach leads to the development of long-term reliability by an evolutionary process and avoids the great expense of conducting an extensive reliability testing program on units which have not been fully developed and qualified for the application. The development program schedule is presented in Table 12. The six-months schedule is tight, but allows an extra month for unforeseen delays.

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TABLE 12 DEVELOPMENT PROGRAM SCHEDULE

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C. PROGRAM MANAGEMENT

A program manager will be assigned the responsibility for planning, scheduling, budgeting and direction the program. He also will be responsible for meeting the requirements revealed by the liaison phase as well as for advising potential users in complying with the radiation requirements.

1. System Analysis

The prototype design will be examined and modified as need be to meet the specific requirements of the users. The complete mission will be discussed with the customer to assure that the best, most appropriate RTG system has been selected.

2. Engineering Design and Development

Each major component and function of the RTG system (fuel, heat transfer, shielding, mechanical design, thermoelectric module, and power conditioner) will be optimized to meet each specific mission.

3. Manufacturing

Fabrication of the parts for component testing will start as soon as the specifications are defined. The electrical prototype and final RTG system fabrication will begin after the results of component tests have been factored into the drawings. These are scheduled for completion at the end of the fourth month.

4. System Test Operations

The extent of the test operations, including functional and reliability testing, will depend on the demands of the specific RTG system.

5. Final Design Review

The compilation of test data on both the electrical and fueled RTG system constitutes the final design review.

Any of the four designs could be made into a working RTG system by following the above plan. Reliability will be improved as these systems are on test and placed in operation.

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APPENDIX A

TECHNICAL CHARACTERISTICS
OF LARGE MILLIWATT POWER SYSTEMS

The following systems were selected by the AEC as candidates for further investigation on the basis of being suitable for application in the near future. The need for such systems was revealed by surveys and liaison with organizations who utilized power systems with characteristics that emphasized the unusual qualities associated with radioisotope thermoelectric generators.

The characteristics reproduced in the following pages were developed by AGN and MRC from the power requirements of the potential users and the results of a parametric study performed by these two organizations. These characteristics are first iterations, and thus only represent possible designs.

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APPENDIX A

Technical Characteristics of Large Milliwatt Power Systems

AEC System No.	1a	1b
Radioisotope Fuel	SrTiO ₃	SrTiO ₃
Power Output, mw(e)	1000	1000
Thermal Power (BOL)	80.0	47.3
Thermal Efficiency, %	1.42	2.39
Thermoelectric Module Efficiency, %	2.24	3.95
Power Conditioning Efficiency, %	83.9	83.9
Diameter of System, in.	10.50	8.50
Weight, lb.	230	175
Shield	Full	Full
Material	U	U
Thickness, in.	2.93	2.75
Surface Dose Rate, mr/hr	200	200
Insulation		
Type	Min-K	Linde
Thickness, in.	1.29	0.61
Hot Junction Temperature, °F	400	800
Cold Junction Temperature, °F	170	170
Thermoelectric Material	Bi ₂ Te ₃	PbTe
Thermoelectric Output Voltage, v	3.0	3.0
Number of Couples	136	2 x 42
Contact Loss, %	25	25
Degradation, %	6.5	6.5
L/A, in. ⁻¹	46	138
Length of Elements, in.	0.206	0.330
Module Heated Area, in. ²	2.45	0.81
Heat Flux Density, w/cm ²	5	10
Element Area, in. ²	0.0045	0.0024
Element Dimensions, in.	0.206x0.067x0.067	0.330x0.048x0.048
Module Dimensions, in.	1.56x1.560	0.9 x 0.9
Life Expectancy, yr.	5	5

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AEC System No.	1a	1b
Fuel Cost, \$		
Present	2,560	1,520
Future	1,520	900
Thermoelectric Cost, \$	150	650
Power Conditioning Cost, \$	1,050	1,050
Shield Cost, \$	3,300	3,080
Manufacturing Hardware Cost, \$	780	780
Fuel Encapsulation Cost, \$	100	100
Insulation Cost, \$	50	1,000
Total Cost, \$		
Present	7,990	8,180
Future	6,950	7,560

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AEC System No.	2a	2b
Radioisotope Fuel	SrTiO ₃	SrTiO ₃
Power Output, mw(e)	1000	1000
Thermal Power (BOL)	72.5	36.6
Thermal Efficiency, %	1.57	3.09
Thermoelectric Module Efficiency, %	2.24	4.65
Power Conditioning Efficiency, %	83.9	83.9
Diameter of System, in.	6.0	5.0
Weight, lb.	60	40
Shield	1/2 shield	1/2 shield
Material	U	U
Thickness, in.	1.45	1.32
Surface Dose Rate, R/hr	22	16
Insulation		
Type	Min-K	Linde
Thickness, in.	0.55	0.37
Hot Junction Temperature, °F	400	1000
Cold Junction Temperature, °F	170	170
Thermoelectric Material	Bi ₂ Te ₃	PbTe
Thermoelectric Output Voltage, v	3.0	3.0
Number of Couples	2 x 136	31
Contact Loss, %	25	25
Degradation, %	6.5	6.5
L/A, in. ⁻¹	92	82
Length of Elements, in.	0.205	0.858
Module Heated Areas, in. ²	2.45	1.32
Heat Flux Density, w/cm ²	5	5
Element Area, in. ²	0.0023	0.0106
Element Dimensions, in.	0.205x0.048x0.048	0.858x0.106.x0.106
Module Dimensions, in.	1.560x1.560	1.15x1.15
Life Expectancy, yr.	5	5
Fuel Cost, \$		
Present	2,320	1,170
Future	1,380	695

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<u>AEC System No.</u>	<u>2a</u>	<u>2b</u>
Thermoelectric Cost, \$	150	650
Power Conditioning Cost, \$	1,050	1,050
Shield Cost, \$	1,440	980
Manufacturing Hardware Cost, \$	780	780
Fuel Encapsulation Cost, \$	100	100
Insulation Cost, \$	50	1,000
Total Cost, \$		
Present	6,390	5,730
Future	5,450	5,260

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AEC System No. _____		3 & 4
Radioisotope Fuel		PuO ₂
Power Output, mw(e)		600
Thermal Power (BOL)		20.8
Thermal Efficiency, %		3.11
Thermoelectric Module Efficiency, %		4.65
Power Conditioning Efficiency, %		83.9
Diameter of System, in.		2.50
Weight, lb.		1.7
Insulation		
Type		Min-K
Thickness, in.		0.67
Hot Junction Temperature, °F		1000
Cold Junction Temperature, °F		170
Thermoelectric Material		PbTe
Thermoelectric Output Voltage, v		3.0
Number of Couples		31.0
Contact Loss, %		25
Degradation, %		6.5
L/A, in. ⁻¹		134
Length of Elements, in.		0.858
Module Heated Areas, in. ²		0.79
Heat Flux Density, w/cm ²		5
Element Area, in. ²		0.0064
Element Dimensions, in.		0.858x0.080x0.080
Module Dimensions, in.		0.89x0.89
Life Expectancy, yr		10
Fuel Cost, \$		
Future		11,050
Thermoelectric Cost, \$		650
Power Conditioning Cost, \$		1,050
Shield Cost, \$		--
Manufacturing Hardware Cost, \$		450
Fuel Encapsulation Cost, \$		100

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AEC System No.

3 & 4

Insulation Cost, \$

50

Total Cost, \$

Future

13,950

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AEC System No.	5a	5b
Radioisotope Fuel	SrTiO ₃	SrTiO ₃
Power Output, mw(e)	600	600
Thermal Power (BOL)	58.8	34.9
Thermal Efficiency, %	1.15	1.95
Thermoelectric Module Efficiency, %	2.24	2.24
Power Conditioning Efficiency, %	83.9	83.9
Diameter of System, in.	10.0	8.0
Weight, lb.	200	150
Shield	Full	Full
Material	U	U
Thickness, in.	2.82	2.65
Surface Dose Rate, mr/hr	200	200
Insulation		
Type	Min-K	Linde
Thickness, in.	1.23	0.54
Hot Junction Temperature, °F	400	400
Cold Junction Temperature, °F	170	170
Thermoelectric Material	Bi ₂ Te ₃	Bi ₂ Te ₃
Thermoelectric Output Voltage, v	3.0	3.0
Number of Couples	136	136
Contact Loss, %	25	25
Degradation, %	6.5	6.5
L/A, in. ⁻¹	78	78
Length of Elements, in.	0.206	0.206
Module Heated Area, in. ²	1.42	1.42
Heat Flux Density, w/cm ²	5	5
Element Area, in. ²	0.00264	0.00264
Element Dimensions, in.	0.206x0.052x0.052	0.206x0.052x0.052
Module Dimensions, in.	1.19x1.19	1.19x1.19
Life Expectancy, yr.	5	5
Fuel Cost, \$		
Present	1,880	1.120
Future	1,120	663
Thermoelectric Cost, \$	150	150

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AEC System No.	5a	5b
Power Conditioning Cost, \$	1,050	1,050
Shield Cost, \$	3,240	2,980
Manufacturing Hardware Cost, \$	780	780
Fuel Encapsulation Cost, \$	100	100
Insulation Cost, \$	50	1,000
Total Cost, \$		
Present	7,250	7,180
Future	6,130	6,400

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AEC System No.	6a	6b
Radioisotope Fuel	SrTiO ₃	SrTiO ₃
Power Output, mw(e)	600	600
Thermal Power (BOL)	50.0	24.5
Thermal Efficiency, %	1.36	2.78
Thermoelectric Module Efficiency, %	2.24	4.35
Power Conditioning Efficiency, %	83.9	83.9
Diameter of System, in.	5.70	4.75
Weight, lb.	50	35
Shield	Half	Half
Material	U	U
Thickness, in.	1.38	1.26
Surface Dose Rate, R/hr	20	15
Insulation		
Type	Min-K	Linde
Thickness, in.	0.57	0.38
Hot Junction Temperature, °F	400	900
Cold Junction Temperature, °F	170	170
Thermoelectric Material	Bi ₂ Te ₃	PbTe
Thermoelectric Output Voltage, v	3.0	3.0
Number of Couples	136	35
Contact Loss, %	25	25
Degradation, %	6.5	6.5
L/A, in. ⁻¹	78	132
Length of Elements, in.	0.206	0.760
Module Heated Area, in. ²	1.42	0.8
Heat Flux Density, w/cm ²	5	5
Element Area, in. ²	0.00264	0.0057
Element Dimensions, in.	0.206x0.052x0.052	0.760x0.075x0.075
Module Dimensions, in.	1.19x1.19	0.895x0.895
Life Expectancy, yr.	5	5
Fuel Cost, \$		
Present	1,600	780
Future	950	470

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AEC System No.	6a	6b
Thermoelectric Cost, \$	150	650
Power Conditioning Cost, \$	1,050	1,050
Shield Cost, \$	1,760	850
Manufacturing Hardware Cost, \$	780	780
Fuel Encapsulation Cost, \$	100	100
Insulation Cost, \$	50	1,000
Total Cost, \$		
Present	5,490	5,210
Future	4,540	4,900

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AEC System No.	7 & 8a	7 & 8b
Radioisotope Fuel	Pm ₂ O ₃	Pm ₂ O ₃
Power Output, mw(e)	600	600
Thermal Power (BOL)	48.0	22.0
Thermal Efficiency, %	1.86	4.404
Thermoelectric Module Efficiency, %	2.24	4.65
Power Conditioning Efficiency, %	83.9	83.9
Diameter of System, in.	3.75	3.10
Weight, lb.	10	6
Shield	Full	Full
Material	U	U
Thickness, in.	0.59	0.43
Surface Dose Rate, mr/hr	200	200
Insulation		
Type	Min-K	Linde
Thickness, in.	0.56	0.53
Hot Junction Temperature, °F	400	1000
Cold Junction Temperature, °F	170	170
Thermoelectric Material	Bi ₂ Te ₃	PbTe
Thermoelectric Output Voltage, v	3.0	3.0
Number of Couples	136	31
Contact Loss, %	25	25
Degradation, %	6.5	6.5
L/A, in. ⁻¹	78	134
Length of Elements, in.	0.206	0.858
Module Heated Area, in. ²	1.42	0.79
Heat Flux Density, w/cm ²	5	5
Element Area, in. ²	0.00264	0.0064
Element Dimensions, in.	0.206x0.052x0.052	0.858x0.080x0.080
Module Dimensions, in.	1.19x1.19	0.89x0.89
Life Expectancy, yr.	1-1/2	1-1/2
Fuel Cost, \$		
Present	24,600	12,400
Future	4,100	2,050

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AEC System No.	7 & 8a	7 & 8b
Thermoelectric Cost, \$	150	650
Power Conditioning Cost, \$	1,050	1,050
Shield Cost, \$	210	110
Manufacturing Hardware Cost, \$	780	780
Fuel Encapsulation Cost	100	100
Insulation Cost, \$	50	1,000
Total Cost, \$		
Present	26,940	16,090
Future	6,440	5,740

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AEC System No.

9a

Radioisotope Fuel	PuO ₂
Power Output, mw(e)	300
Thermal Power (BOL)	15.6
Thermal Efficiency, %	2.07
Thermoelectric Module Efficiency, %	2.24
Power Conditioning Efficiency, %	83.9
Diameter of System, in.	1.80
Weight, lb.	1.25
Insulation	
Type	Min-K
Thickness, in.	0.37
Hot Junction Temperature, °F	400
Cold Junction Temperature, °F	170
Thermoelectric Material	Bi ₂ Te ₃
Thermoelectric Output Voltage, v	3.0
Number of Couples	136
Contact Loss, %	25
Degradation, %	6.5
L/A, in. ⁻¹	140
Length of Elements, in.	0.255
Module Heated Area, in. ²	1.0
Heat Flux Density, w/cm ²	4
Element Area, in. ²	0.00184
Element Dimensions, in.	0.255x0.043x0.043
Module Dimensions, in.	1.0x1.0
Life Expectancy, yr.	10
Fuel Cost, \$	
Future	8,750
Thermoelectric Cost, \$	1,050
Shield Cost, %	--
Manufacturing Hardware Cost, %	450
Fuel Encapsulation Cost	100
Insulation Cost	50
Total Cost, \$	
Future	10,580

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AEC System No.	10a	10b
Radioisotope Fuel	SrTiO ₃	SrTiO ₃
Power Output, mw(e)	300	300
Thermal Power (BOL)	40.0	19.8
Thermal Efficiency, %	.85	1.72
Thermoelectric Module Efficiency, %	1.47	2.24
Power Conditioning Efficiency, %	83.9	83.9
Diameter of System, in.	9.5	7.5
Weight, lb.	165	112
Shield	Full	Full
Material	U	U
Thickness, in.	2.69	2.45
Surface Dose Rate, mr/hr	200	200
Insulation		
Type	Min-K	Linde
Thickness, in.	1.21	0.60
Hot Junction Temperature, °F	300	400
Cold Junction Temperature, °F	170	170
Thermoelectric Material	Bi ₂ Te ₃	Bi ₂ Te ₃
Thermoelectric Output Voltage, v	3.0	3.0
Number of Couples	242	136
Contact Loss, %	25	25
Degradation, %	6.5	6.5
L/A, in. ⁻¹	86	140
Length of Elements, in.	0.290	0.510
Module Heated Area, in. ²	3.26	1.8
Heat Flux Density, w/cm ²	2	2
Area of Leg, in. ²	0.0034	0.0036
Element Dimensions, in.	0.290x0.058x0.058	0.510x0.060x0.060
Module Dimensions, in.	1.8x1.8	1.34x1.34
Life Expectancy, yr.	5	5
Fuel Cost, \$		
Present	1,280	630
Future	760	380
Thermoelectric Cost	180	180

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AEC System No.	10a	10b
Power Conditioning Cost, \$	1,050	1,050
Shield Cost, \$	3,070	2,500
Manufacturing Hardware Cost, \$	780	780
Fuel Encapsulation Cost, \$	100	100
Insulation Cost, \$	50	1,000
Total Cost, \$		
Present	6,510	6,240
Future	5,990	5,990

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AEC System No.	11a	11b
Radioisotope Fuel	SrTi ₃	SrTi ₃
Power Output, mw(e)	300	300
Thermal Power (BOL)	30.3	15.9
Thermal Efficiency, %	1.12	2.14
Thermoelectric Module Efficiency, %	2.24	3.95
Power Conditioning Efficiency, %	83.9	83.9
Diameter of System, in.	5.50	4.30
Weight, lb.	39	28
Shield	Half	Half
Material	U	U
Thickness, in.	1.30	1.19
Surface Dose Rate, R/hr	16	13
Insulation		
Type	Min-K	Linde
Thickness, in.	0.67	0.30
Hot Junction Temperature, °F	400	800
Cold Junction Temperature, °F	170	170
Thermoelectric Material	Bi ₂ Te ₃	PbTe
Thermoelectric Output Voltage, v	3.0	3.0
Number of Couples	136	42
Contact Loss, %	25	25
Degradation, %	6.5	6.5
L/A, in. ⁻¹	140	230
Length of Elements, in.	0.510	0.660
Module Heated Area, in. ²	1.8	0.48
Heat Flux Density, w/cm ²	2	5
Element Area, in. ²	0.0036	0.00236
Element Dimensions, in.	0.510x0.060x0.060	0.660x0.053x0.053
Module Dimensions, in.	1.34x1.34	0.69x0.69
Life Expectancy, yr.	5	5
Fuel Cost, \$		
Present	970	510
Future	580	302
Thermoelectric Cost, \$	180	650

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AEC System No.	11a	11b
Power Conditioning Cost, \$	1,050	1,050
Shield Cost, \$	630	450
Manufacturing Hardware Cost, \$	780	780
Fuel Encapsulation Cost, \$	100	100
Insulation Cost, \$	50	1,000
Total Cost, \$		
Present	3,760	4,540
Future	3,350	4,332

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AEC System No.	12
Radioisotope Fuel	Pm ₂ O ₃
Power Output, mw(e)	300
Thermal Power (BOL)	26.3
Thermal Efficiency, %	1.70
Thermoelectric Module Efficiency, %	83.9
Power Conditioning Efficiency, %	83.9
Diameter of System, in.	3.25
Weight, lb.	6.0
Shield	Full
Material	U
Thickness, in.	0.46
Surface Dose Rate, mr/hr	200
Insulation	
Type	Min-K
Thickness, in.	0.55
Hot Junction Temperature, °F	400
Cold Junction Temperature, °F	170'
Thermoelectric Material	Bi ₂ Te ₃
Thermoelectric Output Voltage, v	3.0
Number of Couples	136
Contact Loss, %	25
Degradation, %	6.5
L/A, in. ⁻¹	140
Length of Elements, in.	0.255
Module Heated Area, in. ²	1.0
Heat Flux Density, w/cm ²	4
Element Area, in. ²	0.00184
Element Dimensions, in.	0.255x0.043x0.043
Module Dimensions, in.	1.0x1.0
Life Expectancy, yr.	1-1/2
Fuel Cost, \$	
Present	14,470
Future	2,450

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AEC System No.

12

Thermoelectric Cost, \$	180
Power Conditioning Cost, \$	1,050
Shield Cost, \$	160
Manufacturing Hardware Cost	780
Fuel Encapsulation Cost, \$	100
Insulation Cost, \$	50
Total Cost, \$	
Present	17,060
Future	4,750

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AEC System No.	13a	13b
Radioisotope Fuel	SrTi ₃	SrTi ₃
Power Output, mw(e)	150	150
Thermal Power (BOL)	24.2	12.0
Thermal Efficiency, %	0.70	1.42
Thermoelectric Module Efficiency, %	1.47	2.24
Power Conditioning Efficiency, %	83.9	83.9
Diameter of System, in.	9.5	7.0
Weight, lb.	130	87
Shield	Full	Full
Material	U	U
Thickness, in.	2.52	2.28
Surface Dose Rate, mr/hr	200	200
Insulation		
Type	Min-K	Linde
Thickness, in.	1.49	0.61
Hot Junction Temperature, °F	300	400
Cold Junction Temperature, °F	170	170
Thermoelectric Material	Bi ₂ Te ₃	Bi ₂ Te ₃
Thermoelectric Output Voltage, v	3.0	3.0
Number of Couples	242	136
Contact Loss, %	25	25
Degradation, %	6.5	6.5
L/A, in. ⁻¹	168	280
Length of Elements, in.	0.290	0.510
Module Heated Area, in. ²	1.66	1.0
Heat Flux Density, w/cm ²	2	2
Area of Leg, in. ²	0.00172	0.00182
Element Dimensions, in.	0.290x0.042x0.042	0.510x0.043x0.043
Module Dimensions, in.	1.29x1.29	1.0x1.0
Life Expectancy, yr.	5	5
Fuel Cost, \$		
Present	770	380
Future	460	230

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AEC System No.	13a	13b
Thermoelectric Cost, \$	200	200
Power Conditioning Cost, \$	1,050	1,050
Shield Cost, \$	2,740	2,180
Manufacturing Hardware Cost, \$	780	780
Fuel Encapsulation Cost, \$	100	100
Insulation Cost	50	1,000
Total Cost, \$		
Present	5,690	5,690
Future	5,380	5,540

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AEC System No.	14a
Radioisotope Fuel	SrTi ₃
Power Output, mw(e)	150
Thermal Power (BOL)	20.8
Thermal Efficiency, %	0.81
Thermoelectric Module Efficiency, %	2.24
Diameter of System, in.	5.30
Weight, lb.	33
Shield	Half
Material	U
Thickness, in.	1.22
Surface Dose Rate, R/hr	15
Insulation	
Type	Min-K
Thickness, in.	0.70
Hot Junction Temperature, °F	400
Cold Junction Temperature, °F	170
Thermoelectric Material	Bi ₂ Te ₃
Thermoelectric Output Voltage, v	3.0
Number of Couples	136
Contact Loss, %	25
L/A, in. ⁻¹	280
Length of Elements, in.	0.510
Module Heated Area, in. ²	1.0
Heat Flux Density, w/cm ²	2
Element Area, in. ²	0.00182
Element Dimensions, in.	0.510x0.043x0.043
Module Dimensions, in.	1.0x1.0
Life Expectancy, yr.	5
Fuel Cost, \$	
Present	670
Future	400
Thermoelectric Cost, \$	200
Power Conditioning Cost, \$	1,050

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AEC System No.

14a

Shield Cost, \$	800
Manufacturing Hardware Cost, \$	780
Fuel Encapsulation Cost, \$	100
Insulation Cost	50
Total Cost, \$	
Present	3,650
Future	3,380

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AEC System No.	15 & 16
Radioisotope Fuel	PuO_2
Power Output, mw(e)	150
Thermal Power (BOL)	8.3
Thermal Efficiency, %	1.96
Thermoelectric Module Efficiency, %	2.24
Power Conditioning Efficiency, %	83.9
Diameter of System, in.	1.50
Weight, lb.	1.0
Insulation	
Type	Min-K
Thickness, in.	0.32
Hot Junction Temperature, $^{\circ}\text{F}$	400
Cold Junction Temperature, $^{\circ}\text{F}$	170
Thermoelectric Material	Bi_2Te_3
Thermoelectric Output Voltage, v	3.0
Number of Couples	136
Contact Loss, %	25
Degradation, %	6.5
L/A , in. ⁻¹	280
Length of Elements, in.	0.510
Module Heated Area, in. ²	1.0
Heated Flux Density, w/cm ²	2
Element Area, in. ²	0.0018
Element Dimensions, in.	0.510x0.043x0.043
Module Dimensions, in.	1.0x1.0
Life Expectancy, yr.	10
Fuel Cost, \$	
Future	4,660
Thermoelectric Cost, \$	200
Power Conditioning Cost, \$	1,050
Shield Cost, \$	--
Manufacturing Hardware Cost, \$	450
Fuel Encapsulation Cost, \$	100

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AEC System No.	15 & 16
Insulation Cost, \$	50
Total Cost, \$	
Future	6,510

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AEC System No.	17a	17b
Radioisotope Fuel	Pm ₂ O ₃	Pm ₂ O ₃
Power Output, mw(e)	1000	1000
Thermal Power (BOL)	75.1	37.6
Thermal Efficiency, %	1.97	3.95
Thermoelectric Module Efficiency, %	2.24	4.65
Power Conditioning Efficiency, %	83.9	83.9
Diameter of System, in.	4.25	3.25
Weight, lb.	15	7.5
Shield	Full	Full
Material	U	U
Thickness, in.	0.70	0.52
Surface Dose Rate, mr/hr	200	200
Insulation		
Type	Min-K	Linde
Thickness, in.	0.60	0.44
Hot Junction Temperature, °F	400	1000
Cold Junction Temperature, °F	170	170
Thermoelectric Material	Bi ₂ Te ₃	PbTe
Thermoelectric Output Voltage, v	3.0	3.0
Number of Couples	2 x 136	31
Contact Loss, %	25	25
Degradation, %	6.5	6.5
L/A, in. ⁻¹	92	82
Length of Elements, in.	0.205	0.858
Module Heated Area, in. ²	2.45	1.32
Heat Flux Density, w/cm ²	5	5
Element Area, in. ²	0.0023	0.0106
Element Dimensions, in.	0.205x0.048x0.048	0.858x0.106x0.106
Module Dimensions, in.	1.560x1.560	1.15x1.15
Life Expectancy, yr.	1-1/2	1-1/2
Fuel Cost, \$		
Present	42,100	21,050
Future	6,990	3,500

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AEC System No.	17a	17b
Thermoelectric Cost, \$	150	650
Power Conditioning Cost, \$	1,050	1,050
Shield Cost, \$	420	210
Manufacturing Hardware Cost, \$	780	780
Fuel Encapsulation Cost, \$	100	100
Insulation Cost, \$	50	1,000
Total Cost, \$		
Present	44,650	24,840
Future	9,540	7,290

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