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MND-P-2901
C-92A, M3679,
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CLASSIFICATION CANCELLED
A 250-Watt(e) Isotope-Fueled ~~CONFIDENTIAL~~ **UNCLASSIFIED**
Thermionic Generator Study
BY AUTHORITY OF D. G. C.
BY L. Tupper DATE 11/2/71

FINAL REPORT

MND-P-2901

June 1963

SPECIAL REVIEW FOUO DETERMINATION Class: <u>U</u>	Reviewers	Class.	Date
	<u>TR</u>	<u>U</u>	<u>3-9-82</u>

This report has been prepared under Contract AT(30-1)-3021 with the
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GROUP 1

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FOREWORD

This report, prepared by the Martin Company, covers the work performed under Contract AT(30-1)-3021 for the U.S. Atomic Energy Commission. The objective of the work was to perform a design study of a 500-watt(e) isotope-fueled thermionic generator. To gain reliability by redundancy and lessen fuel handling problems, a 250-watt(e) generator system was selected for the basis of the design. This study is the result of a technical effort which was performed the first quarter of fiscal year 1963.

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SUMMARY

This report presents the conceptual design of a cerium-144-fueled, 250-watt, thermionic space power plant. The design is modular in character so that two units may be assembled to provide a power level of 500 watts. The basic 250-watt unit weighs only 153 pounds, including power conditioning equipment.

The specific power of 1.6 watts/lb makes this generator attractive for many scientific and military, unmanned space missions, such as weather and communication satellites, space probes and surveillance satellites. The generator is also insensitive to orientation, solar flux and other components of the space environment.

Some significant generator characteristics are (see Figure 1):

(1)	Power to load	250 watts
(2)	Total generator weight	153 pounds
(3)	Specific power	1.6 watts/lb
(4)	Design lifetime (including ground time)	13 months
(5)	Estimated operational date	1967
(6)	Estimated fuel cost	\$61,000.00
(7)	Overall generator efficiency, including control requirements and lead losses	6.0%
(8)	Output voltage to load	28 volts dc
(9)	Fuel inventory - beginning of life	1.5×10^6 curies
(10)	Fuel inventory - end of life	$.58 \times 10^6$ curies
(11)	Fuel thermal power - beginning of life	12,200 watts
(12)	Fuel thermal power - end of life	4690 watts

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(13)	Number of thermionic diodes	6
(14)	Thermionic emitter material	Iridium
(15)	Generator electrical power output	294 watts
(16)	Voltage into power conditioning equipment	3.9 volts
(17)	Power conditioning equipment weight	10 pounds
(18)	Conversion efficiency of power conditioning equipment	89%
(19)	Generator weight without power conditioning	143 pounds
(20)	Overall system efficiency	5.3%

Significant features of the design are:

- (1) Fueling with isotope is accomplished by inserting fuel into the generator and making one seal weld.
- (2) Thermionic diodes are replaceable by removing the generator cap.
- (3) A diode is utilized that requires minimum development. The diode is designed for 150-g loads.
- (4) The diode seal is not required for structural support. It is designed for minimum stress and is located in a low-temperature region.

The generator is designed for complete fuel containment in the event of a launch or ascent abort. In the case of re-entry from orbit, complete burnup of the generator by aerodynamic heating will occur. A four-meter boom isolates the generator from the space vehicle and reduces the radiation flux at the vehicle to 100 r/hr for the beginning-of-life condition.

A 37-pound drag fin is required to reduce the terminal velocity and orient the generator in case of a low-altitude abort. This weight has been charged to the satellite since the skirt serves as the generator launch vehicle structural support and as a satellite

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Figure 1. 250-Watt(e) Thermionic Generator, Cerium Fueled

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skin during the launch. The skirt has been optimized for minimum total weight.

Two modified generator designs were examined to determine the applicability of alpha-emitting fuels to this system. Curium and polonium fuels yield a 250-watt generator with a weight of 88 pounds and an efficiency of 10.2%, but with design lifetime of six months. Plutonium fuel will produce a generator lifetime of from 1-5 years, with a corresponding weight of 111.5 pounds and efficiency of 8.6%. The use of any of these three alpha-emitter fuels or curium 244 would significantly reduce shield-weight requirements on the vehicle.

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I. INTRODUCTION

This report contains the results of a feasibility and design study for a 500-watt(e) isotope-fueled space power system. The 500-watt system consists of two generator subsystems, each of which produces 250 watts at 28 volts dc. MIDAS was used as the postulated mission where mission requirements had to be considered.

The objectives of this report are:

- (1) To prove the technical feasibility of 250-500-watt thermionic space power plants.
- (2) To determine the state-of-the-art for such systems, especially in the areas of isotope fuel production and thermionic technology.
- (3) To determine the performance parameters of such isotopic space generators.
- (4) To design conceptually a space generator system using current technology insofar as possible.
- (5) To define the development and testing areas necessary for a reliable design.
- (6) To define a reasonable reliability study to assure generator performance.

Section IV of this report summarizes the generator system. Since detailed discussion of the problems, possible solution techniques and development areas are omitted, this section provides the reader with a resume of the generator design.

Sections II and III contain descriptions of background information and approaches used to develop the conceptual design. Section II contains the data utilized as a design basis and presents the calculation techniques of specific interest in thermionic systems. Section III contains a detailed discussion of the starting point in the study, the problems, and the progress toward a workable conceptual design.

Section V presents a brief study of the use of different fuels in the cerium-144 conceptual design. Only minor changes in the design were permitted to modify the generator for other fuels.

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Section VI contains the reliability approach, and a discussion of the testing and development necessary to produce a useful design.

This report was based upon principal contributions by M. E. Talaat, W. C. Lyon, W. E. Kortier, J. L. Kane, A. Lieberman and R. Stankiewicz of the Nuclear Division, Martin Company, of the Martin-Marietta Corporation.

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II. DESIGN INFORMATION

A. THERMIONIC DATA

1. Introduction

Two requirements must be satisfied for thermionic energy conversion to succeed as an auxiliary power source. First, the power density and efficiency must be on the order of 3-10 watts/cm² and 10%, respectively, at emitter temperatures in the range of 1500-1800° K. Second, the thermionic module design must be such that the finished generator will have a high reliability. The second requirement dictates among other things coarse tolerances in fabrication (large interelectrode spacing in the diode). Experiments with many different emitter materials have demonstrated that these two requirements can be met more readily using cesium vapor-filled thermionic conversion devices with high-vacuum work function emitters such as iridium and rhenium.

2. Background Tests

The emitter materials iridium, rhenium, platinum and rhodium have been studied at the Martin Company using filament-type, metal-envelope devices.¹

A sketch of a metal-envelope thermionic energy converter with a directly heated emitter is shown in Figure 2. The emitter consists of the central 0.500-inch portion of a 0.020-inch-diameter wire which has a total length of 1.500 inches. The emitter consists of the central 0.500-inch portion of a 0.020-inch-diameter wire which has a total length of 1.500 inches. The emitter area facing the nickel collector is 0.203 cm². The interelectrode gap is 0.030 inch. End effects are minimized in this design by enlarging the gap beyond the central 0.5-inch portion of the wire to 0.300 inch. Thus, the current collected tends to be restricted to that coming from the central 0.203 cm² of the emitter, and this figure is taken as the nominal emitter area to be used in data analysis. The lower temperatures at the ends of the wire emitter also tend to minimize end effects.

Prior to tests with cesium vapor, the emitter was outgassed at

1. Contract (NONR-3639(00)). The major emphasis has been on iridium.

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Figure 2. Scale Drawing of a Filament Device with 0.020" Filament as Emitter. The emitter is positioned between a molybdenum tensioning spring and a Kovar electrode so that there is a uniform temperature in the portion of the emitter which faces the collector. Not shown are ceramic-to-metal seals on both ends of the device and side-arms for evacuation and for the cesium reservoir.

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temperatures in excess of 2000° K. The entire device was baked at temperatures of about 650° K until ionization gage measurements indicated that there was no further evolution of gases from any part of the device.

The testing procedure consisted of using a half-wave rectified power supply to heat the emitter. The output current and voltage were measured using an oscilloscope to observe these quantities during the "off" part of the cycle when no voltage gradients are present on the emitter. At large output currents, a voltage gradient exists due to the flow of this current in the emitter; however, analysis of the results shows that any uncertainty in the output voltage due to such gradient is no greater than 0.030 volt.

The liquid cesium and the collector temperatures were recorded using chromel-alumel thermocouples. An environmental oven was used to control the cesium vapor pressure. The oven holds the liquid cesium temperature to within $\pm 1^\circ$ C throughout a run.

A Shawmeter (two-color optical pyrometer) was used to observe the emitter temperature. With this instrument monitoring the emitter temperature, the input power was adjusted to maintain a constant emitter temperature throughout the measurement of a characteristic curve. There is a limit to the input power which can safely be supplied to the emitter to overcome electron cooling, and for this reason the output current of the device was not allowed to exceed 5-6 amperes (25-30 amp/cm²). Thus, some of the characteristics do not show a saturation current, and the optimum output power density, reported in the summary curves, may fall somewhat short of the true optimum value.

Characteristic current versus voltage curves measured with the iridium emitter are shown in Figures 3 through 6. The figures give families of characteristic curves, showing several emitter temperatures at given cesium temperatures.

Figures 7 and 8 are plots of the experimental power density versus cesium temperature, parametric in the emitter temperature. These curves show a comparison of iridium and rhenium.

Figures 9 and 10 show the iridium power density and efficiency,

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Figure 3. Iridium Output Current vs Voltage

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Figure 4. Iridium Output Current vs Voltage, Cesium Temperature 556° K.

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Figure 5. Iridium Output Current vs Voltage, Cesium Temperature 575° K.

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Figure 6. Iridium Output Current vs Voltage, Cesium Temperature 596° K.

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Figure 7. Rhenium Output Power vs Cesium Temperature
(Volume Ionization Mode)

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Figure 8. Iridium Output Power vs Cesium Temperature.
(Volume Ionization Mode)

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Figure 9. Iridium Output Power vs Emitter Temperature.
(Volume Ionization Mode)

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Figure 10. Iridium Efficiency vs Emitter Temperature.
(Volume Ionization Mode)

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Figure 11. Assembly Drawing of Parallel Plate Thermionic Module.

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respectively, versus emitter temperature for several values of cesium temperature. The data were obtained with the device operating in the volume ionization mode.

3. Data Comparison

A comparison of tantalum, molybdenum, rhenium and iridium has been made. The data for tantalum and molybdenum were taken from the literature², the data for rhenium from literature² and from work carried out at Martin, and the data for iridium from work carried out at Martin. Power density and thermionic efficiency versus emitter temperature were compared in all cases.

It is particularly noteworthy that the iridium and the Martin rhenium data were taken on identical devices, indicating the superiority of iridium as shown in Figures 7 and 8. The power density and efficiency data are also corroborated by the data on emission characteristics³ and data taken at University of California⁴. Available iridium data are presented for only one relatively large spacing, 30 mils.

4. Test Results, Flat Plate Devices

A flat plate device with a 1-inch-diameter iridium emitter has been designed and fabricated (see Figures 11 and 12).

Preliminary data obtained with this device tend to corroborate the data of the filament device. Though this device is different from the filament device in interelectrode spacing, collector material and collector temperatures, the power densities obtained were of the same

2. First Quarterly Progress Report for the Thermionic Emitter Materials Research Program, submitted by Thermo Electron Engineering Corporation to the Office of Naval Research.

3. Kennedy, A. J., "Cesium Adsorption on Refractory Metals," Symposium on Thermionic Power Conversion, Paper VI-2, Colorado Springs, Colorado, May 14, 1962.

4. "Emission Characteristics of Tantalum, Tungsten, Rhenium and Iridium in Plasma Diodes," UCRL 6809, Ernest O. Lawrence Radiation Laboratory, Livermore, California, 1962.

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Figure 12. Photograph of Parallel Plate Thermionic Module.

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magnitude (and in some instances almost identical) to the power densities obtained with the filament device.

5. Conclusions Regarding Data

The iridium data used in this report were obtained from a device which has been tested over a full range of emitter temperatures and cesium pressure. Prior to the testing of this device, three other iridium devices were built and tested by the Martin Company. The data obtained on all devices are consistent and show the superior performance of iridium.

The test of filament-type devices has provided a verification of the premise that emitter materials having high-vacuum work functions lead to superior performance in cesium vapor-filled thermionic energy converter devices. This is of particular importance at the low emitter temperature range where output power densities in the range of 5-19 watts/cm² have been obtained with an iridium emitter in the temperature range of 1580-1900° K. Energy conversion efficiencies evaluated on the basis of these measurements were in the range of 9-17%. It is significant that these results have been obtained with relatively large interelectrode spacing of 30 mils.

Measurements on the emission properties of iridium and other materials in cesium vapor corroborate the trends shown by Martin Marietta data*. These experiments provide, essentially, a measure of the effective work function of several materials as a function of cesium pressure and emitter temperature; iridium is shown to have the lowest effective work function. The low effective work function of iridium in cesium vapor plays the primary role in its effectiveness as the emitter in an energy conversion device⁵.

5. Talaat, M. E., "The Surface Ionization and Volume Ionization Modes of Operation in the Thermionic Plasma Energy Converters," Paper II-6 in Symposium on Thermionic Power Conversion, Colorado Springs, Colorado, May 14, 1962.

* Reference 4 on page 19.

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The available data show that iridium is a superior emitter material when operated in cesium. There has been no problem with the compatibility of iridium and the other materials in the diode. Therefore, the generator has been designed with this emitter material.

6. Selection of Emitter Temperature

Useful thermionic emission begins at approximately 1500 to 1600° K and usually becomes more attractive with increasing temperature. However, it is desirable to keep the operating temperatures as low as possible in a thermionic generator that must withstand ground handling and launch vibrations so that material problems are minimized. For example, there are few metals that are useful at these temperatures, and their strength decreases rapidly with increasing temperature in this range. In addition, it is necessary to enclose the radioisotope fuel in a material that resists air oxidization at high temperature. Rhodium is used which melts at 2239° K. Since portions of the fuel block will be hotter than the emitter surface, it is necessary that the emitter temperature be considerably below 2239° K so that the oxidization-resistant coating of the fuel will remain intact.

An emitter temperature of 1738° K was chosen because it is sufficiently high that good emission characteristics occur, but is low enough that the material problems can be solved. The exact value, 1738° K, is used since there is considerable iridium data for this temperature and it is not necessary to interpolate between emitter temperatures to use these data.

B. CALCULATION TECHNIQUES

1. Thermal Shields

No fibrous insulation is available that will operate at 1700-2000° K, that has a low thermal conductivity, and that causes no contamination problems due to outgassing, decomposition, etc. Therefore, layers of thermal shields will be used in the generator wherever it is necessary to insulate the high-temperature components.

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A theoretical calculation for 40 tantalum shields in series results in a heat loss of $0.0862 \text{ watts/cm}^2$ of shield surface. However, in practice the heat loss is greater than this because of radiation streaming and heat conduction. Heat losses of 2 watts/cm^2 have been measured in small experimental generators⁶ and this value has been used throughout the design of the 250-watt system. This value is highly conservative since the larger generator considered in this study will have fewer heat "leaks" which occur at the cleavages of the shields per unit of surface area. The conservative approach is reflected throughout the system with the result that temperature drops are increased, structural requirements are more difficult to meet, and volumes and weights figures become maximum design values.

2. Thermionic Calculations

a. Introduction

The thermionic analysis was performed by utilizing an IBM 7090 digital computer program titled "Thermionic Results Achieved with Statistical Help" (TRASH). Required input information consists of the chosen emitter temperature, thermionic data, and the required electrical output characteristics. Output from the code consists of the required number of diodes, the emitter area, the thermal input, the thermionic efficiency, and values of the independent parameters voltage, cesium temperature, collector temperature and interelectrode spacing which result in the maximum efficiency.

b. Description of Code

Proven analytical theories exist for thermoelectric conversion that predict performance with a high degree of accuracy. However, an adequate theory has not yet been developed for thermionic conversion. It is therefore necessary that experimental data be utilized in the design of thermionic generators.

The basic purpose of the code is to use experimentally determined current density data which have been gathered for various combinations

6. Thermionic Development Program, Contract Number AT(30-2)-3060.

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of the independent parameters and to select the parameter combination which gives maximum thermionic efficiency. This is done by a digital computer to eliminate the time-consuming and repetitive manual calculations involved in thermionic analyses when only one or two of the independent parameters are considered, and to make possible the optimization of a thermionic diode when all the independent parameters are considered.

Only the thermal and electrical aspects of the diode are considered because the generator geometrical characteristics (which determine the thermal losses for a system) vary from one generator concept to another. Thus the code can be used as a tool for all thermionic generator designs, and the nondiode portions analyzed separately.

Two basic computations are available:

- (1) Efficiency calculation.
- (2) Independent parameter optimization.

An efficiency calculation is performed by selecting the voltage, emitter temperature, cesium temperature, collector temperature and interelectrode spacing and using the code to compute the efficiency. For an optimization, only the emitter temperature need be selected. The code can be used to determine other characteristics that will result in the optimum efficiency. If experimental data are not available for one or more independent parameters, only those parameters for which data are available will be considered.

The input parameters are:

- (1) Initial values of the independent parameters which are diode voltage, emitter temperature, cesium temperature, collector temperature and interelectrode spacing. (In the case of no optimization these will be the given values for which the thermionic efficiency is to be calculated. In the case of optimization, they are used as starting values for an iteration procedure and will be changed to produce the highest efficiency.)
- (2) The physical properties of the electrical lead, emitter

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and collector:

- (a) electrical resistivity of the lead
 - (b) thermal conductivity of the lead
 - (c) emissivities of emitter and collector
 - (d) collector work function
- (3) Electrical characteristics:
- (a) the total desired external power
 - (b) the total output voltage under load

(4) A complete mapping of the diode characteristics. These are the experimentally determined values of current density as a function of the five independent variables diode voltage, emitter temperature, cesium temperature, collector temperature and interelectrode spacing.

In addition to supplying the code with experimental values of current density, it is also possible to supply experimentally determined values of the electron cooling voltage. If such data are unavailable, an approximate relation is used for the electron cooling term.

3. Thermal and Design Calculation Techniques

Relatively standard techniques have been used in the design of the generator except those previously discussed. The remainder of the analysis work is reported in the specific area investigated or in the appendixes.

C. FUEL SELECTION

1. Introduction

This section presents the results of a fuel study for application to a 250-watt thermionic generator. The fuels investigated for availability were curium 242, polonium 210, plutonium 238, uranium 232 and cerium 144.

The selection of any radioisotope fuel for use as a heat source in a thermionic generator is predicated upon availability, half-life, thermal power per unit volume and general radiological characteristics. The five fuels chosen do not show favorable characteristics in all four areas, and, indeed, a compromise must be made in any fuel selection.

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Figure 13. Kilowatts of Isotope Power Required vs System Efficiency, Curium 242.

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2. Curium 242

Cm 242 is an alpha emitter which decays to Pu 238. It has a half life of 162.5 days and a specific activity of 3.3×10^3 curies/gram. In addition, some neutrons and gamma radiation are produced by spontaneous fission (half-life - 7.2×10^6 yr) of the curium and (α , n) reactions with light elements. Approximately 2×10^5 curies are required for a 250-watt system.

The oxide is the most suitable fuel form since it has a high melting point and is the most chemically stable form. Curium, because of its high specific activity, must be diluted with an inert matrix material such as rhodium or platinum to facilitate handling.

The fuel offers the advantages of high power density (150 watts/cc) and a high melting point in the oxide form (2240°C). Its thermal conductivity is essentially that of the metal matrix and thus can be taken to be approximately 0.865.

The fuel has marked disadvantages. It is produced by the irradiation of Am-241 which necessitates the use of a high flux reactor such as the MTR or ETR. It has a short half-life (~ 163 days) and poor availability. Estimates as shown in Table 1 indicate approximately 1.5 kilowatts/yr available in 1964, with anticipation of 9.5 kilowatts/yr by 1965. Reference to Figure 13, a plot of kilowatts of isotope power required as a function of system efficiency and mission time, indicates that present quantities are insufficient.

3. Polonium 210

Po 210 is an alpha emitter having a high power density (150 watts/cc), a half-life of 138 days and a specific activity of 4.5×10^3 curies/gram. The very low incidence of gamma radiation along with the absence of beta decay results in extremely low shielding requirements.

At the high temperatures required for thermionic applications, polonium in the elemental form would not be suitable because of extremely high vapor pressure and chemical reaction rates. A development program is presently under way at Mound Laboratory to investigate high

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TABLE 1
CURRENT AND FUTURE SUPPLY OF RADIOISOTOPES*
 (Kilowatts/Year at Fuel Fabrication Time)

<u>Isotopes</u>	<u>Fiscal Years</u>									
	<u>1963</u>	<u>1964</u>	<u>1965</u>	<u>1966</u>	<u>1967</u>	<u>1968</u>	<u>1969</u>	<u>1970</u>	<u>1971</u>	<u>1972</u>
Ce 144	25	25	25	25	700	700	700	700	700	700
Pu 238	1.5	3.0	6.0	0.5	11.5	15	17	20	23	25
Cm 244	---	0.1	0.2	14	41	92	129	129	134	134
Cm 242	---	1.5	9.5	120	120	120	120	120	120	120
Po 210	3.0	7.0	14	14	140	140	140	140	140	140

* Communication, Division of Isotope Development, AEC; February, 1963.

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melting temperature polonides of lanthanum and similar rare earth metals⁷.

Po 210 can be produced artificially by irradiating Bi 209 with neutrons. This reaction, however, has a relatively low cross section and thus a large quantity of bismuth must be processed to obtain adequate quantities of polonium. The fuel therefore is inherently costly (\$26,500.00/gm).*

Other disadvantages of this isotope include short half-life (~138 days) and limited availability. Table 1 indicates that at present 3.0 kilowatts/yr would be available, but that by 1965 the production capacity could be increased to 14 kilowatts/yr. According to Figure 14, this amount would be sufficient to produce a 5- to 6-month mission generator.

4. Plutonium 238

Pu 238 has a half life of 89.6 years and decays by alpha emission to U 234. The alphas are accompanied by a small amount of low energy gammas and an almost negligible neutron flux due to spontaneous fission (half-life - 3.8×10^{10} yr). The specific activity of the isotope is 16.8 curies/gram and approximately 10^5 curies are required for a 250-watt system.

The advantages of this fuel are its small shielding requirements and long half-life. The oxide form of the fuel has a high (~2000° C) melting point. A thermal power decrease of only 0.5% per year eliminates the requirement for dumping excess heat at beginning of life and makes the fuel suitable for long mission applications. The disadvantages include low power density (~5 watts/cc), low thermal conductivity (.034 watts/cm °C), and limited availability. Figure 15 indicates the isotope requirement.

7. Quarterly Report on Isotope Development at Mound Laboratory, MLM 1143, July-September 1962, Classified Conf., Restricted Data

* Same Reference as on Table 1, page 28.

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Figure 14. Kilowatts of Isotope Power Required vs System Efficiency, Polonium 210.

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5. Uranium 232

An unusual fuel in that it combines a long half-life (~70 years) with a good power density (~38 watts/cc for the oxide form), U 232 seems particularly attractive as a fuel source. The melting point of the oxide form is above 2000° C.

Its major disadvantage is its complete unavailability. At the present, only minute quantities have been produced for experimental purposes. Due to its unusual decay chain, a considerable amount of hard and soft gammas are released. Shielding requirements are essentially identical to that required for cerium. Its thermal conductivity (0.034 watts/cm °C) is also unattractive. Figure 15 indicates the isotope requirement.

6. Cerium 144

Ce 144 has a half-life of 290 days and decays by beta emission to Pr 144. The daughter is in turn radioactive, decaying by beta emission to stable Nd 144 with a 17.5-minute half-life. Some gamma emission during the decay (plus bremsstrahlung associated with beta particle slowing) causes a serious radiation hazard. Approximately 1.5×10^6 curies of Ce 144 are required for a 250-watt system. The radiation dose rate from unshielded sources of this general size is 1.7×10^4 r/hr at 1 meter.

Ce 144 is a low-cost isotope and combines the advantages of high availability and a fair half-life to make it usable for applications of one-year missions or less. According to Table 1 and Figure 16, the current production capability of 25 kilowatts/yr is sufficient to produce two generators per year. By 1967 more than 60 generators per year could be produced. Other attractive features are the high oxide melting point (>2000° C) and its well-advanced state-of-the-art. A fission product isotope, it is found to be easily separated in large quantities.

Ce 144 has serious disadvantages, the most detrimental being the very hard (2.9 Mev) gamma radiation in its decay chain. Heavy shielding is therefore required during all handling operations.

The power density of Ce 144 is theoretically high. However, the

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Figure 15. Kilowatts of Isotope Power Required vs System Efficiency,
Uranium 232 or Plutonium 238

Figure 16. Kilowatts of Isotope Power Required vs System Efficiency,
Cerium 144.

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impurities and stable cerium associated with Ce 144 in the presently available concentration reduce the power density (6-8 watts/cc) to slightly more than the Pu 238 power density. The relatively short half-life means that the end-of-life power density for missions of one-year duration is very low.

Several fuel forms are possible, including the oxide, carbide, sulphide and the metal. The oxide is not desirable because of possible O₂ release during the decay process and the change of valence associated with the decay. The other three forms are more difficult to make.

Since Ce 144 is the only fuel available in the quantity necessary for a multiple 250-watt generator program, it was decided that major emphasis would be placed on Ce 144 during this study.⁸

a. Cerium-144 Fuel Forms

(1) Introduction

The choice of the cerium fuel form is governed by:

- (a) Cerium density in the fuel form.
- (b) Melting point.
- (c) Compatibility with the container.
- (d) Absence of gaseous products.
- (e) Burnup capability.
- (f) Ability to be manufactured.

Each of the possible fuel forms will be compared to these criteria in the following sections.

(2) Oxide Form

The oxide CeO₂ is the easiest fuel form to manufacture. Oxygen could be released during the decay to praseodymium according to the following equation:

Therefore, a getter material would have to be provided to absorb the oxygen. Typically, niobium could be used and approximately three pounds

8. Meeting at the Martin Company, July 3, 1962. AEC Representatives, J. Cline, NYOO, R. Carpenter, Germantown.

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would be required to getter the liberated O_2 . The getter (niobium) oxide has a much greater volume than the pure metal and a void volume would have to be provided. These additions reduce the available power density, although not seriously, and increase the fuel weight.

The Ce_2O_3 has a melting point of $1963^\circ K$ and would be molten in some areas of the fuel block.

Since Ce_2O_3 is pyrophoric, no burnup problem would exist and the fuel would burn rapidly once the outside container was burned off during re-entry from orbit.

(3) Carbide Form

The density of cerium carbide, either as CeC_2 or Ce_2C_3 , is lower than the oxide, although still acceptable. The Martin Company has made both of these carbides.⁹ The CeC_2 was manufactured utilizing the oxide and Ce_2C_3 using the metal.

The Ce_2C_3 is easier to prepare. A mixture of the oxide and carbon is reacted in a vacuum or an inert atmosphere for four hours at $1900^\circ K$. This is followed by crushing, pressing into pellet form, and resintering at $1900^\circ K$ for eight hours. The pellets have 90% of the theoretical density. The Ce_2C_3 can also be made by the reaction of the metal or hydride with carbon. Pyrometallurgical means as described by Schneider¹⁰ are also applicable.

The carbide melting point appears to be about $1970^\circ K$ according to Brawshaw.¹¹ Both carbides are pyrophoric and hence no burnup problem would exist. However, they must be handled in extremely

9. Bowes, W., MND-P-3014-III, Snap Quarterly Progress Report No. 6, Fuel Technology Development Program.

10. Schneider, A., Burris, L., Jr., and Lamroski, F., "The Synthesis of Refractory Nuclear Feed Materials in Liquid Metal Media," Trans. ANS, Vol. 4, No. 2 P 345 (1961).

11. Brawshaw, W. G., and Matthews, C. D., "Properties of Refractory Materials - Collected Data and References," LMSD 2466.

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pure inert atmosphere.

(4) Sulphide Forms

Three cerium sulphides have been reported, but only two, CeS and Ce_3S_4 , appear to have a reasonable density. Both of these have melting points above 2270°K .¹² Since they must be handled in an inert atmosphere during manufacture, they should meet burnup requirements.

Although the sulphides have been used as containers for melting active metals,¹³ the fuel form is difficult to manufacture, particularly in a hot cell. They are formed by first forming Ce_2S_3 by passing H_2S over CeO_2 in a carbon furnace at $1200\text{--}1400^\circ\text{C}$. The Ce_2S_3 is then reacted with CeH_3 in a molybdenum crucible at 2200°C with a vacuum of 10^{-4} mm Hg.¹² An excess of CeH_3 is usually desired to remove the oxygen in the form of CeO . The hydride for the reaction must be formed from the metal.

The sulphides are unattractive unless a simpler manufacturing technique can be formulated.

(5) Cerium Metal

Cerium metal is a possible fuel form. Although it melts at 1043°K , it boils at greater than 2690°K (one atm pressure, absolute). Thus the pressures are insignificant at the generator operating temperatures. The cerium density in the metallic form is the highest of any of the possible fuel forms.

The metal can be prepared in atmospheres identical to those required for sulphide preparation. The required temperatures, however, are considerably lower than for the other fuel forms. The metal can be

12. Eastman, E. D., Brewer, L., Bramley, L. A., Gilles, P. W., and Lofgren, N. L., "Preparation and Properties of Refractory Sulphides," J. Am. Chem. Soc. 72, 2248-50 (1950).

13. Eastman, E. D., Brewer, L., Bremley, L. A., Gilles, P. W., and Lofgren, N. L., "Preparation and Tests of Refractory Sulphide Crucibles," KJ. Am. Ceramic Soc. 34, 128-134 (1951).

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prepared by the bomb reduction of the chloride with calcium or iodine,¹⁴ by bomb reduction from the fluoride,¹⁵ or by pyrometallurgical methods.* Impurities can be removed by vacuum remelting at 1300-1400° C.

The molten metal can be contained in tantalum. No reaction occurs at 1700° C, although at 1800° C some reaction has been noted. Since this work was done in 1950, higher temperatures may be possible with the improved technology of tantalum since that time. This fuel form is an attractive possibility, and could have considerable effect on generator performance (see Section IV A).

(6) Recommended Fuel Form

No firm recommendation concerning a fuel form will be made at this time. The final selection will depend upon further work in the area. Consequently, the generator has been designed so that any of the possible fuel forms could be utilized. The generator efficiency and weight would become more attractive if the metal fuel form were used. If the sulphide were to be used, the fuel block volume would have to be increased slightly.

(7) Physical Properties

The physical properties of the cerium fuel forms are summarized in Table 2.

7. Conclusions

Although several of the other isotopes present more attractive advantages from the standpoint of thermal and radiological considerations, Ce 144 suggests itself as the best fuel form from the standpoint of availability. Sufficient quantities of the fuel are available at the present to produce a 250-watt thermionic generator, and by 1967 more

14. Ahmann, L. H., "Metallurgy of the Rare Earths with Particular Emphasis on Cerium," ISC-68 (1950).

15. Spedding, F. H., and Daane, A. H., "The Preparation and Properties of Rare Earth Metals," Prog. Nucl. Energy (V), 413-32 (1956).

* Reference 10 on page 34.

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than 60 generators per year could be produced. This is not true of the other fuels, and, as can be seen from Table 1, it would require several years before sufficient quantities of the other fuels were available for even one generator.

TABLE 2
PHYSICAL PROPERTIES OF CERIUM FUEL COMPOUNDS

Cerium Metal

Melting Point	770 $\pm$ 10 to 804° C
Boiling Point	2417 $\pm$ 70 to 3600° C
Density of Ce, gm/cc	6.69
Vapor Pressure, mm Hg	1 @ 1748° C
	1 x 10 ⁻³ @ 1331-1580° C
	1 x 10 ⁻⁶ @ 1180° C

Oxide

	CeO ₂	Ce ₂ O ₃
Melting Point	2600° C	1690° C
Density (theo) gm/cc	7.13	6.86
Ce density (theo) gm/cc	5.77	5.85
Thermal conductivity, Btu/ft hr °F	@ 92° C - 2.71	
	@ 280° C - 2.54	
	@ 495° C - 2.24	
	@ 757° C - 1.94	
	@ 2000° C - 1.22 (est.)	
Vapor pressure, mm Hg	@ 1580° C - 10 ⁻³	
	@ 1180° C - 10 ⁻⁶	

Carbides

	CeC ₂	Ce ₂ C ₃
Melting Point	1700° C	1700° C
Density (theo), gm/cc	5.23	---
Ce Density (theo), gm/cc	4.47	---

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TABLE 2 (Continued)

Sulphides

	CeS	Ce ₃ S ₄	Ce ₂ S ₃
Melting Point	2450 + 100° C	2050 + 75° C	1980 + 50° C*
Density (theo), gm/cc	5.93	5.3	5.2*
Ce Density (theo), gm/cc	4.85	4.0	2.68
Thermal conductivity, Btu/ ft hr °F		4.3* at room temp	2.78 at 500° C (Ref 16) 2.42 at 1100° C
Vapor pressure, mm Hg	10 ⁻³ 10 ⁻⁴	@ 1700° C @ 1570° C	

16. Carter, F. L., "Preparation and Properties of Some Rare Earth Semiconductions," Metallurgy of Semiconductor Material, edited by J. B. Schroeder, Interscience Publishers (1961).

* Reference 11 on page 34.

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III. DEVELOPMENT OF THE CONCEPTUAL DESIGN

A. APPROACH

1. Introduction

The initial program objective was to design a 500-watt thermionic generator system. The design effort evolved into consideration of two 250-watt systems. This increases reliability in that, if one generator fails, the total system electrical output is not completely lost. It also results in a 250-watt electrical generation system that can be used in satellites with power requirements in that range. Therefore, the majority of the study has emphasized 250-watt electrical generation systems consistent with the 500-watt objective.

The 250-watt system is to supply electricity at 28 volts. Since this is considerably above the voltage output expected from thermionic conversion, a high-current low-voltage dc-dc converter is necessary. The dc-dc converter efficiency is a function of the generator output characteristics. Since the generator and converter studies were performed simultaneously, assumptions were made concerning the characteristics of each at the beginning of the program.

2. Thermionic Generator

A major consideration in the generator design was the amount of development required to deliver a working generator. An attempt has been made to keep the development effort to a minimum. Therefore, areas that could cause difficulty were first considered to determine which would have a major effect on the generator characteristics. One major area was immediately recognized, the problem of attaching a thermionic diode to a fuel capsule when the operating temperature is approximately 1700 to 1800° K. Considering generators consisting of one diode, or several diodes operating in parallel, a "simple" braze can be used and the fuel capsule is operated at the emitter potential. It is desirable that the voltage from the thermionic generator be as high as possible so that the lead losses and dc-dc converter losses be minimized. This implies

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operation of diodes in series.

The high heat fluxes required to maintain the necessary emitter temperatures cause problems with connecting the isotope heat source to the diode. A good thermal connection must be made or the emitter temperature cannot be maintained. Developing an electrical insulator that is also a good heat conductor to electrically isolate the diodes from the heat source represents a major development area. The operating temperature of such a member is 1700-1800° K and, of necessity, it must be large (one-inch diameter, for example) to transmit heat between the diode and the heat source. Due to the major development involved using an electrical insulating — thermally conducting braze, this scheme was abandoned.

The immediate solution was to braze a diode to a heat source in the manner used for previous isotope-fueled thermionic generators, and to make up a generator composed of a number of heat sources, each running at different electrical potentials and connected in series. This offered the additional advantage of a system in which components could be replaced if one diode were lost prior to launch. This concept was chosen as the starting point for the study.

Each fuel capsule with the attached diode (or diodes if operated in parallel) was essentially a small generator by itself. The expected generator characteristics for a system of this type are shown in Figure 17, a graph indicating the output voltage and efficiency dependence. This behavior occurs because a greater voltage requires a larger number of diodes and, hence, more fuel capsules. As the number of fuel capsules is increased, the surface area per unit volume and hence the heat loss increases. This causes the efficiency to decrease.

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Figure 17. Characteristic Efficiency vs Output Voltage for Multicapsule Diode Concept Generator.

3. DC-DC Converter

The problems in designing an efficient dc-dc converter increase as the operating current is increased and the input voltage decreased. A typical converter behaves as indicated in Figure 18. Therefore, it is desirable that the converter input voltage be as high as possible.

4. Electrical Generation System

A combination of the thermionic generator and dc-dc converter was expected to have a maximum efficiency as shown in Figure 19. The initial design was started on this basis. The following dc-dc converter characteristics were assumed:

Input Voltage	Present	<u>Efficiency</u>	Estimated Results of Study
1	.6		.75
2	-		-
3	-		-
5	.7		.85

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Figure 18. DC-DC Converter Characteristics.

Linear interpolation was assumed between the end points. The estimated efficiencies represent the results expected from the dc-dc converter study.

Figure 19. Characteristic Generator System Efficiency.

The estimated efficiencies were used to compute the following thermionic generator characteristics:

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<u>Output Voltage</u>	<u>Electrical Power Required, Watts</u>	<u>Current Flow, Amps</u>
1	333	333
2	324	162
3	312	104
5	290	58

These data were used to begin work on the thermionic generator and dc-dc converter.

5. Isotope Fuel to Be Used

Four fuels were to be considered during the initial phases of the program:

- a. Polonium 210
- b. Curium 242
- c. Plutonium 238
- d. Cerium 144

Initial studies were to be concentrated on generator designs that were best for each individual fuel with no regard for availability, and fuel availability studied separately. When good concepts were available for all fuels, availability was to be considered and a choice made of a generator where the major design emphasis was to be placed.

B. GENERATOR SYSTEM DESIGN CHARACTERISTICS

The following characteristics constitute the design criteria for this study:

- (1) Power to Load: 250 watts (from converter)
- (2) Output Voltage: 28 volts dc
- (3) Minimum Efficiency: 7%
- (4) Minimum Radiation Dose Rate at One Meter during
Ground Handling: 100 mr/hr
- (5) Maximum Radiation Dose Rate in Space: 1000 r/hr
at one meter.*
- (6) Maximum Weight: 100 pounds

* Later modified to 1000 r/hr maximum dose rate to satellite.

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- (7) Launch Vehicle: Atlas-Agena
- (8) Generator Life:
 - (a) Po 210, Cm 242: 6 months
 - (b) Ce 144: 1 year
 - (c) Pu 238: 5 years

C. TYPE OF DIODE

Two basic types of thermionic diodes were considered for this study, cylindrical and flat plate. Both of these types have been built, although none has operated for the lifetimes required for this generator.

1. Cylindrical Diode

Cylindrical diode work has been concentrated on designs suitable for use in nuclear reactors. These concepts have a cylindrical emitter surrounding a central heat-producing zone that contains the uranium fuel. A cylindrical collector is built outside the emitter.

The adaptation of this type diode for isotope-fueled thermionic conversion is feasible for the high power density fuels Po 210, Cm 242 and perhaps U 232. However, the usual cylindrical diode will not work with low power density fuels such as Ce 144 and Pu 238. The available heat is insufficient to maintain a reasonable emitter temperature for practical size diodes.

An "inside-out" cylindrical diode was considered that removed this objection. This concept is shown in Figures 20 and 21. The emitter and collector surfaces are reversed from the usual concept. The bottom end of the diode is surrounded by the isotope heat source (not shown) which allows the necessary quantity of fuel to be attached to the emitter. Heat from the inside collector flows axially past the seal and into the generator case (not shown, but the case would be in the portion of the diode where the break is shown). The cesium reservoir extends outside of the case.

There are a number of development problems associated with this type diode. It has a large-diameter seal that has not been developed for long life. Since heat is transferred from the outside toward the center

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Figure 20. Cylindrical Diode Assembly.

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Figure 21. Cylindrical Diode Assembly.

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and a temperature gradient exists with the hottest temperature on the outside, differential thermal expansion could cause a considerable problem. As the various portions of the diode are heated, the parts would tend to loosen rather than tighten. Significant problems exist in keeping temperature drops along the collector to reasonable values. For these reasons, the cylindrical diode was rejected in favor of a flat plate diode that is closer to present state-of-the-art.

2. Flat Plate Diode

Several flat plate diodes have been built suitable for use with isotope heat sources, but none of them has lasted under test for the time considered in this study. One major objective was to improve the flat plate concept and eliminate the problems that caused failure on previous electrically heated generators.

A major problem is the cesium seal. In several previous flat plate designs, the seal has suffered stress failure because of differential thermal expansion of its components. Experimental evidence indicates that smaller-diameter seals are more reliable -- indicating increased material stresses with greater diameters. The solution to the cesium seal problem was to change the flat plate diode design to utilize a developed seal of proven capability.* The concept, shown in Figure 22, uses a seal of small diameter, which should make it very reliable. In addition, it operates in a comparatively cool temperature region and has to carry no structural loads except for slight differential expansion in the electrical leads. This expansion is allowed for in the design by an expansion member. Differential expansion within the seal is minimized by using niobium for all parts which closely matches the thermal expansion of the alumina electrical insulation member.

The use of the small highly reliable seal was made possible by carrying the cylindrical emitter lead down along the collector and passing it beneath the collector, as shown in Figure 22. The lead is insulated

* Developed under Martin Company sponsored Direct Conversion Reactor Program.

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Figure 22. Flat Plate Diode Concept No. 1.

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electrically from the collector by alumina and heat from the collector flows through the alumina-emitter lead-alumina assembly and into the heat sink block. The alumina in this design is required to transmit heat, but not to carry tension loads or form a cesium seal. Thus, if cracking were to occur, as long as the cracks were parallel to the heat flow, no problem would exist. This can be assured by "precracking" the alumina ring prior to brazing. Cracking is minimized by making all components of niobium, which closely matches the alumina thermal expansion characteristics. A high-temperature vanadium braze is used to join the components. The same braze material is used in the Martin-developed seal. Thus the seal problem appears to be minimized, but at the expense of a relatively smaller development problem in the insulator assembly area.

Another problem in diode design was the emitter lead-emitter support structure. In the initial concept (Figure 22) extra strength was provided by using a ceramic member to help support the emitter. The ceramic has relatively high strength under compression and a low thermal conductivity to minimize heat losses. By locating it outside of the emitter lead, the problem of cesium attack at high temperature is completely eliminated.

The use of Ce 144 or Pu 238 fuels results in both sizable and heavy fuel sources. Launch vibrational loads of 100 g's can be expected, and a diode constructed to support a heavy heat source under these conditions would have a very heavy emitter support. Such a support would result in large heat losses and poor efficiency. Therefore an early flat plate conceptual design (Figure 22) was supported from the heat source since it is prohibitive to support the heat source from the diode.

The connection from the heat sink on the diode to the generator case had to be flexible so that differential movement can occur between the heat source and the case. An early concept (Figure 22) used stranded copper wires to transmit the heat and allow flexibility.

The use of the ceramic structural members means that the diode must

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be operated in compression. In tension or shear, the diode would fail. This problem was not considered in the concept shown in Figure 22.

The first major change in the flat plate concept is shown in Figure 23. The stranded copper was replaced with intermeshing fins to provide the necessary heat transfer and flexibility. The copper wires probably would not be flexible in the large number that were required. Since the heat sink was electrically isolated from the generator case it was possible to eliminate one of the alumina emitter lead insulation rings used on the first concept.

This concept also has a spring to keep the ceramic diode members in compression. However, the problem of shear on the diode structural members had not been eliminated. In addition, the temperature drop between the intermeshing fins is greater than desirable, which increases the fin area required to cool the collector.

A number of modifications were made to this concept to eliminate the problems, but none of them was completely satisfactory as long as the necessary movement between the heat source and the diode took place at the collector end.

The possibility of allowing movement at the emitter end was then considered. This had not been considered previously because of the heat source temperature required. Temperature drops on the collector end cause an increase in the required heat removal area (heat is rejected by radiation); however, no technical problems result except the weight increase. A temperature drop on the emitter end of the diode forces the heat source temperature higher to obtain proper diode operation. Since high temperature creates a material problem on the heat source design, it was preferred not to raise the temperature. A study of intermeshing fins on the emitter end of the diode led to the somewhat unexpected result that temperature differentials between the diode and heat source could be kept low without physical contact. This led to the final configuration between the heat source and the diode, shown in Figure 24.

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Figure 23. Flat Plate Diode Concept No. 2.

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Figure 24. Flat Plate Diode Concept No. 3.

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Further investigation of the emitter spacer using tantalum -- 10% tungsten in place of the previously considered tantalum showed that the ceramic could be eliminated in this area, and that the emitter could be adequately supported from the collector end.

There now existed a diode design that would withstand launch vibrations. The next consideration was that of diode replacement. A study of various techniques for attaching the diode to the generator case led to a threaded connection, with the necessary heat transfer taking place across the threads.

D. REJECTION OF EXCESS HEAT AT THE BEGINNING OF LIFE

1. Introduction

The use of polonium, curium or cerium fuels requires provision for the excess heat production that occurs at the beginning of life. The heat source temperatures that result if no provision is made are incompatible with available construction materials. Several techniques are available to cool the generator when the heat production rate is high:

- a. Electron cooling.
- b. Movable shutters.
- c. Gas leak.
- d. Conduction techniques.
- e. Sublimable solids.

2. Electron Cooling

Electron cooling refers to the energy transmitted from the emitter to the collector by electron flow. As the current passing through a diode is increased, the electron flow and hence the electron cooling is also increased. The current can be increased by changing the load on the generator or increasing the emitter temperature. Changes in cesium pressure can be made to increase the maximum current that will flow at a sacrifice in conversion efficiency. All of these techniques can be used to cool the generator. This is attractive since no moving parts are involved. However, the amount of heat that can be transmitted by electron cooling is limited. For generators in which the operational

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life is considerably less than the half-life of the isotope fuel, electron cooling is completely adequate. However, in the generators considered in this study, it is inadequate. For example, in the Ce-144 generator only 10% to 15% of the heat that must be dumped can be transmitted by electron cooling.

3. Movable Shutters

The usual technique used to cool isotope-heated generators at the beginning of life is to expose a portion of the heat source to the environment by opening a shutter. This method is objectionable because it involves moving parts. However, it can be used to dump the heat in the designs considered in this study. It has the additional advantage of excellent controllability.

4. Gas Leak

In a generator of this type where the heat source is insulated by thermal shields with a one-mil spacing between each shield, it is possible to change drastically the heat transfer characteristics of the thermal shields by using a high thermal conductivity gas such as helium. Again using the Ce-144 generator as an example, the necessary 8000 watts of heat that must be dumped can be "leaked" through the thermal shields at the beginning of life if the shields are filled with helium.

The most feasible technique for this type of heat dump would be to fill the entire generator with helium and let it leak from the generator to space at a controlled rate during the generator life. The calibrated leak must be designed so that no air or other contaminants enter the generator, or the generator will be destroyed. Another disadvantage is the lack of control, in that the leak must be programmed to compensate approximately for the decrease in the heat production rate in the source as time increases. An error in the programming could cause the generator to operate off optimum or become inoperative.

Some control can be gained by using electron cooling with the gas leak, but this complicates the dc-dc converter design over what occurs if the current to the converter is relatively constant.

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If a technique could be found to control the fill gas pressure as required, this heat dump method would work well under all conditions. However, no suitable technique was obtained for high thermal conductivity gases. It is possible to control the pressure for some gases by utilizing their vapor pressure. The gases suitable for that purpose have low thermal conductivities and are not suitable as a heat dump medium in the thermal shields.

This technique was discarded in favor of the movable thermal shutters for this study.

5. Conduction Techniques

This type of heat dump operates by mechanically changing the heat conduction path between the heat source and surroundings. Several methods were considered, but found unsuitable for the large quantities of heat that must be conducted. The mechanical linkages had no advantage over the movable shutters and this technique was discarded.

6. Sublimable Solids

A solid that sublimates in the vacuum of space is attractive as a heat control medium. This can be applied in two different ways: to a fin that slowly sublimates during generator life, and to changing the heat leakage through the thermal shields.

The first technique could be utilized by attaching a sublimable fin to the heat source. As the fin sublimed it would remove less heat from the block. This scheme has the disadvantage in that, at end of life, the penetration to the heat source remains and heat is lost through the hole.

The sublimable solid could be placed between the thermal shields to cause high heat leakage. As the solid sublimed, less heat would leak through the shields.

A major disadvantage is the lack of control. The leakage must be programmed to fit the isotope decay rate, and hence decrease the heat production rate. In addition, the system could be unstable. If the solid sublimed more rapidly than anticipated, the heat source temperature would increase. This would increase the sublimation rate, and over-

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heating could promptly result. The opposite situation could occur if the solid sublimed too slowly.

Sublimable solids were rejected for these reasons and because of the development problems involved.

E. ISOTOPE CONTAINMENT DURING IMPACT

1. Introduction

One of the most difficult problems in the design of the Ce-144-fueled thermionic generator involved the situation where a rocket abort occurs during launch. There is a finite probability that this could occur during the initial launch phase and the generator would fall back onto the launch pad or in the immediate vicinity. It is necessary that the isotope fuel remain contained if this occurs, since a breach in the fuel container will cause release of the fuel, and in addition to the radioactive release it is known that available cerium fuel forms are pyrophoric.

2. Fuel Containment Materials

a. Introduction

The number of materials available to operate at 1800-2000° K is extremely limited. The number that have any impact strength at these temperatures is even more limited.

The following refractory metals were considered for fuel containment vessels:

- (1) Tungsten
- (2) Tantalum
- (3) Molybdenum
- (4) 90% Tantalum, 10% Tungsten
- (5) 85% Tantalum, 5% Tungsten, 10% Hafnium
- (6) 90% Tantalum, 8% Tungsten, 2% Hafnium

b. Oxidization

All of these materials will oxidize rapidly if exposed to air at the operating temperature of the thermionic generator. At the fuel capsule equilibrium temperature outside of the generator, the reaction

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is less rapid, but the containment vessel will eventually oxidize sufficiently to allow fuel escape. Therefore, an additional container must be provided that resists attack by oxygen. This container has to be inside the strong refractory metal container so that it is protected during the impact. After impact, if the refractory metal is exposed and oxidized, the inner oxidization-resistant container will remain to contain the fuel.

The only suitable materials for use as the oxidization-resistant liner are the platinum group metals. Of these, rhodium was most suitable and is utilized in the 250-watt generator design. A major problem is the melting point of rhodium, 2239° K. This temperature cannot be exceeded at any time in the generator life prior to orbiting since, if the rhodium melts, the fuel containment is lost in the event of an abort that results in land impact. An impact of this type will break the generator case (in the final design) exposing the refractory metal-clad fuel.

c. Comparison of Refractory Metals

Each of the refractory metals considered for the fuel case will be discussed in the order considered.

Tungsten

Martin-Nuclear has had considerable success with tungsten for small fuel containers. These have been fabricated and pressure tested under high-temperature conditions. They met all design criteria. However, the fabrication of a large container suitable for containing all the fuel appears beyond present technology. Therefore, tungsten can be considered only for small-diameter fuel.

Tantalum

Tantalum is one of the easier refractory metals to fabricate and is suitable for high-temperature use in a vacuum. It is relatively weak and therefore not conducive for use as a high-strength impact material for the fuel container vessel except in prohibitive thicknesses.

Molybdenum

Molybdenum is not as strong as tungsten even when compared on a

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weight-to-yield strength basis. Moreover, its high vapor pressure at the fuel temperatures involved make its use marginal unless clad. Therefore it was considered only when clad with tantalum. Its fabricability is comparable to tungsten, which makes it unattractive.

90% Tantalum, 10% Tungsten

This alloy is very promising for high-temperature use. The components have low vapor pressure and high melting points. The alloy strength is comparable to tungsten, but the fabricability compares to that of tantalum. This alloy could be used in fuel capsules.

85% Tantalum, 5% Tungsten, 10% Hafnium

This alloy was promising when first developed several years ago. However, problems with long-term effects at high temperature have been encountered.

90% Tantalum, 8% Tungsten, 2% Hafnium

This alloy appears to be the best high-strength material for this use that is presently available. Its fabricability is similar to tantalum, it is apparently free of the long-term effects that caused 85% Ta — 5% W — 10% Hf to be discarded, and its strength is better than tungsten. There is a question of hafnium vaporization from the alloy at the fuel-clad operating temperatures but, if this occurs to a slight extent, the effect should not be serious. If significant, a change to Ta — 10% W could be made. The present design is based on use of this alloy for fuel containment.

Summary

Listed below in the order of decreasing strength (at temperature) are the available refractory materials considered for the fuel containment:

<u>Substance</u>	<u>Ultimate Strength as % of Best Substance</u>
(1) Ta — 8W — 2Hf	100
(2) W	98
(3) Ta — 10W	60

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<u>Substance</u>	<u>Ultimate Strength as % of Best Substance</u>
(4) Mo	39
(5) Ta	18

Of more interest is a comparison on a weight basis rather than the usual volume basis. Listed below in order of decreasing strength per unit weight are the same alloys:

<u>Substance</u>	<u>Ultimate Strength as % of Best Substance</u>
(1) Ta — 8W — 2Hf	100
(2) W	82
(3) Mo	65
(4) Ta — 10W	58
(5) Ta	18

The alloy 90% Ta — 8% W — 2% Hf was chosen because of favorable strength and fabricability.

3. Design for Impact

a. Introduction

A number of investigations were performed to find a technique for protecting the fuel capsule during impact. An acceptable design method for accomplishing this purpose has been established. It unfortunately adds considerable weight to the generator.

Each design investigation conducted is briefly summarized in the following sections for the final fuel capsule configuration. The problem is less severe for other fuels, provided gas containment is not necessary, and the conclusions established for cerium do not apply to other fuels in general.

b. Containment within Individual Fuel Capsules

The Ce-144 fuel is divided into a number of small-diameter (<one inch) capsules to limit radial temperature gradients. The initial impact analysis work was conducted by investigating the clad thickness necessary to protect the fuel. A weight of approximately 100 pounds was obtained for clad material alone, and this method was abandoned. No

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attempt was made to investigate this type of containment with slow impact velocities, but it is doubtful that significant weight savings could be obtained over the design chosen for this report.

c. Containment within the Heat Source Block

Since the initial containment study resulted in a prohibitively heavy generator, an investigation of containing the fuel within the fuel block was made. In this model, the fuel is also in a capsule form. However, in this model the fuel is clad with a thin rhodium coating to facilitate hot cell handling. The containment was provided by rhodium surrounding the fuel block, which was in turn protected by a refractory metal case. Preliminary analysis resulted in clad weights similar to the initial study and the effort was terminated.

d. Containment by the Generator Case

An investigation was made of containment just outside of the thermal shields. Theoretically, such a containment vessel would be only slightly larger than the fuel block since the thermal shields take up little space, and would operate at temperatures of 1150° K or less. Since the fuel block containment vessel must withstand 2100° K temperatures, the high-density refractory metals had to be used. Thus, the relaxation to 1150° K represented a considerable improvement in strength of suitable materials and metal density.

The first investigation of this type utilized inconel X at a temperature of 810° K. The containment vessel weighed 56 pounds with an assumed generator weight of 90 pounds (the latter determined the impact velocity). A change to René 41 would be suitable for use at 1150° K, and some weight reduction would result. Such a containment structure would have a number of penetrations for diodes and actuators which were neglected in the inconel X calculation. Thus, it would give incomplete protection. Therefore, the containment vessel was moved outside of the diodes to eliminate the major penetrations. Since the cylindrical containment vessel with hemispherical ends was more attractive from an impact viewpoint, these were added and utilized to contain the actuator and cesium reservoir. Thus the containment vessel became, in effect,

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the generator case. The first investigation of this concept using an impact velocity corresponding to a 100-pound generator resulted in a case weight of 100 pounds, and no further investigations of this shape case for total impact protection were made.

A spherical outside case was considered with a 38-cm diameter. The material was inconel X operating at 810° K, a reasonable value because of the increased surface area. The case weight for this situation was 28-1/2 pounds, which is quite attractive. The weight could be decreased further by the use of René 41. However, this calculation was based on an impact velocity corresponding to a 100-pound system and completely neglected the impact of the fuel capsule inside of the generator case. These problems would cause a considerable increase in the weight. Nevertheless, this was the most attractive system and should be used if a nonrandom impact is considered. It also deserves further consideration for random impact utilizing the techniques developed for the random impact analysis.

A number of other features were considered to protect the case. The more attractive ones were:

<u>Item</u>	<u>Weight of Item</u>
(1) Crushable splines covering case to absorb impact energy	80 pounds
(2) Hastelloy C spike to stick into surface impacted	80 pounds each spike, several required
(3) Honeycomb structure to protect case -- not feasible with standard thin honeycomb; prohibitively heavy with thick honeycomb.	

e. Containment for Several Vessels in Series

The use of the generator case to absorb some energy, the fuel block vessel to absorb some, and the fuel capsules to absorb the remaining energy was investigated. There appeared to be a relatively even trade in weight for each combination considered, and all weights for the impact structure alone were 80 to 100 pounds.

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f. Crushable Structure to Protect the Fuel

The use of crushable honeycomb inside the generator case was considered to protect the fuel block. The preliminary work indicated no advantage over other previously considered techniques.

g. Oriented Impact

The next analysis considered was based on an oriented impact, where the generator would be designed to impact on one end, and the fuel block protected accordingly. The initial analysis indicated a "cushion" (impact pad to protect fuel block) weight of 20 to 25 pounds not including the structure to orient the generator. This was chosen as the best technique of having reasonable success with a comparatively low weight.

h. Conclusion

No lightweight impact system was achieved. This is basically due to the large fuel block mass and volume associated with the Ce-144 fuel and the lack of suitable high-strength low-density materials.

The final configuration of the fuel block designed is discussed in Section IV B 6.

F. SHIELDING

The shielding analysis for a 250-watt cerium-144-fueled generator was made for the analytical model shown in Figure 25. Twenty-two fuel capsules 1.04 inches in diameter clad with 20 mils of rhodium are enclosed in a graphite block 6-3/4 inches in diameter by 6-3/8 inches long. The graphite block is clad with 40 mils of rhodium and 80 mils of tungsten. The shielding effect of the thermal shields and a layer of crushable material were not considered in the analysis. The entire assembly was housed in 80 mils of inconel X.

Dose rates from this model were found by means of the equations and curves for cylinders given in Rockwell:¹⁷

17. Rockwell, T., ed., "Reactor Shielding Design Manual," TTD-7004.

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Figure 25. Generator Shielding Model.

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$$\text{Flux} = \phi = \frac{B S_v R_o^2}{2 (a + z)} F(\theta, b) \quad \text{Eq. (III-1)}$$

where:

B = buildup factor

S_v = volumetric source

R_o = radius of source

a = distance from source surface to dose point

z = effective self-absorption distance

$F(\theta, b)$ = attenuation function

and:

Dose rate = $\phi \times$ conversion factor

These relations apply to monoenergetic radiation. However the nuclear radiation from the decay of Ce 144 and its daughter consists of direct gammas of different energies and bremsstrahlung from the 3-Mev beta associated with the daughter praseodymium 144. This radiation was split into ten energy groups and the above equation evaluated for each group.

The fuel, its cladding and the graphite block were treated as a homogeneous mixture and an effective cross section found.

Shield thicknesses were found by applying the following relation for tenth value thicknesses

$$t = t_{.1} \times \log_{10} n$$

where t = shield thickness

$t_{.1}$ = tenth value thickness

n = ratio of existing dose rate to dose rate required

The results are summarized as follows:

- (1) Dose rate at one meter - no shielding = 16,760 r/hr
- (2) Ground handling-shielding required to give dose rate of 100 mr/hour at one meter - 10.25 inches lead or 6.5 inches uranium
- (3) Mission requirement of 1000 r/hour at one meter needs 2.4 inches of lead or 1.5 inches of uranium

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- (4) Separation distance required to reduce 16,760 r/hour to
1000 r/hour = 4.1 meters

G. CESIUM TEMPERATURE CONTROL

Control of the cesium pressure in the diode is accomplished by causing the vapor-liquid interface to form at the coldest point of the cesium system. The system cesium pressure is therefore the cesium vapor pressure corresponding to the controlled temperature. The terms pressure and temperature are usually applied interchangeably when speaking of cesium pressure in the diode. Temperature used in this way refers to the temperature of the liquid-vapor interface and not the actual cesium vapor temperature in the diode.

The interface is made to form in a reservoir so that there is an excess of liquid cesium over that actually required for system control. This assures that sufficient cesium is available as well as aiding control of the liquid-vapor interface position.

Several temperature control schemes are available for an isotope-heated thermionic generator. The simplest is a completely static system, shown on the cylindrical diode concept in Figures 20 and 21. This is desirable because no other control is necessary. It requires careful analysis and complete testing to be assured of proper operation.

The temperature is maintained by a balance between heat flow into the bulb from the generator and heat flow out of the tube and bulb due to radiation to space. Since the temperature is relatively high (500-600° K), variations in space ambient (i.e., sun, shade) will have little effect on the bulb temperature.

Since the cesium temperature is critical for proper diode operation, and is determined in part by the generator surface temperature, the latter must be known within 5°C. This implies careful testing of the generator case under simulated space conditions.

In an isotope-fueled generator of the Ce-144 type where required operation is longer than the isotope half-life, some portions of the generator surface temperature will change since the amount of heat

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rejected to space is a variable. Thus, it is probable that some change in the temperature of the generator skin, and hence the cesium reservoir temperature, will occur, although the latter can be minimized by careful design. However, it will have some effect on the generator output and conversion efficiency.

In an isotope-fueled generator there exists a potential for more electrical output at the beginning of life than at the end of life. Therefore, variations in the cesium temperature can be compensated by the increased output potential. Design at the end of life would be for a reservoir temperature corresponding to the maximum conversion efficiency. At other times in the generator life, the cesium temperature may be off-optimum, but the electrical output could probably be maintained by the increased power potential that corresponds to the increased heat output of the heat source.

A careful analysis of behavior of a statically controlled cesium temperature was not possible under this program. However, static cesium temperature control will work with the Ce-144 generator design. The generator is shown with a more complicated (mechanically) electrically heated system that has been designed within the scope of this program. A completely static system is recommended, provided adequate design and experimental development effort can be expended.

The "nonstatic" systems referred to can be of two types, those with moving heat transfer members and those with controlled electric heaters. Control with moving parts would be accomplished by mechanically controlling the amount of heat either entering or leaving the cesium reservoir to control the temperature. This type of system was not seriously considered since the system with no moving parts appears more attractive.

The system chosen for this design is controlled by a one-to three-watt electric heater. It is based on thermally isolating the cesium reservoir from the rest of the generator by surrounding it with thermal insulation. The generator in the vicinity of the reservoir is designed to operate with a temperature lower than desired for the cesium reser-

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voir. Electrical heat is used to increase the reservoir temperature to the desired level. Since the reservoir is thermally isolated from its surroundings, this requires little power.

This type of system can be accurately controlled and the generator output maintained under the most efficient conditions, if desired.

H. CHRONOLOGICAL DEVELOPMENT OF CONCEPTUAL DESIGN

1. Introduction

Conceptual design work has been done on 250-watt and 500-watt isotope-powered thermionic generators prior to this study.¹⁸ Part 2 of this section consists of a brief review of those designs since they represent the starting point for this study. The changes necessary to design a working system, and a progression to the final design achieved in this study, are discussed.

2. Previous Design Concepts

The previous design work on isotope-fueled thermionic generators has utilized the alpha-emitting fuels Cm 242 and Pu 238. Conceptual designs shown in Figures 26 and 27 have been made. These designs are based on the diode configuration shown in Figure 28.

The fuel in these designs is contained in a spherical case and coated with graphite ablative material.

An ablative material must be added to the pressure container walls to permit intact orbital re-entry. Graphite appears to be a suitable material for this application. The graphite may be made anisotropic (pyrolytic graphite) so as to promote heat flow to the conversion device while impeding the flow to "inactive" portions of the generator assembly. A minimum-weight ablative body with desirable characteristics could be achieved in this manner.

In the case of Cm 242, the power density is so high that a significant void could be incorporated in the capsule and still maintain an adequate heat flux to the conversion device. However, this causes a

18. "Preliminary Study of Radioisotope Thermionic Space Powerplants for Space Use," MND-2648, Martin Company, Nuclear Division.

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Figure 26. 250-Watt(e) Thermionic Generator Pu_2C_3 Fuel with Post Launch Gas Vent, Previous Design Concept.

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Figure 27. 250-Watt(e) Thermionic Generator, Curium-242 Fuel; Gas Contained. Previous Design Concept.

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Figure 28. Cesium Thermionic Diode, Previous Design Concept.

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decrease in the efficiency.

The encapsulation of Pu 238 produced different problems. The low thermal power density and large fuel volume leave little or no void volume within the capsule proper. A pressure buildup which is virtually noncontainable might be produced. The quantitative amount of pressure buildup is unknown at this time. Obvious compromise solutions are to vent the helium to the environment or to a secondary helium containment, either within or external to the generator. A porous plug of sintered metal theoretically could be used as a filter to prevent the loss of the active plutonium fuel. Again, as in the case of curium containment, the entire fuel capsule could be enclosed in the ablative graphite or an equivalent.

The conversion device is a group of thermionic diodes arranged around the fuel capsule and connected in series to give adequate output voltage. A flat plate, cesium plasma diode appears to be the most appropriate for this application because of its high performance.

At present, research devices are being built with interelectrode spacings of 5 mils and less. However, for the transition from research devices to the lightweight, highly reliable thermionic system required for this application, a coarse tolerance on spacing is extremely desirable. From this viewpoint, the results with iridium devices of spacings 0.030 inch and 0.058 inch are most significant. It seems clear that a reliable module in the region of 0.030-inch spacing can be developed much sooner than one of lesser spacing. Furthermore, the sensitivity of the output to small variations in spacing is more critical in close-spaced rather than in wide-spaced diodes. For example, two devices with the widely different spacings of 0.030 inch and 0.058 inch showed little difference in performance. Thus, the large-spaced device greatly facilitates the problem of constructing devices sufficiently well matched for the series connection and will not be seriously affected by changes in spacing due, for example, to metal creep. In this conceptual study an interelectrode spacing of 0.030 inch was used.

A ceramic can be conveniently flame-sprayed to the metal or graphite wall of the fuel capsule and will keep the emitters electrically insulated

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from one another. The emitter is placed on the ceramic in good thermal contact through the use of a braze.

The series connection is made by small extensions on emitters and collectors so that each collector effectively overlaps the next emitter. Each connector will probably be an integral part of the emitter which, on assembly, is welded to the collector.

The collector assembly will be similar to that of the emitter, the metal collector in good thermal contact with an insulator which has been flame sprayed on the outer surface of the generator.

Many existing thermionic energy converter designs utilize a high-vacuum, metal-to-insulator seal which maintains electrical insulation between emitter and collector. This is considered a major problem in high-temperature, long-life service. Through the use of a single cesium reservoir, common to all diodes, the problem of requiring leakproof ceramic-to-metal seals as part of each diode is avoided. A single leakproof seal may be used for the electrical lead-through which can be placed in a region where the temperatures are considerably lower than those in other parts of the system.

The generator outer shell serves as the radiator for dissipating the unconverted thermal energy. The collector of the diode may be operated at high temperatures (700-800° C) without any significant performance penalty. An adequate radiator at these low power levels can easily be contained within a small envelope. Assuming a device efficiency of 7%, the required radiator must have an area of 1.0 ft² with an emissivity of 0.75. This requirement is a very easy one to meet in the system design.

To achieve maximum thermal efficiency, heat leakage from the fuel capsule is minimized by providing fifty 0.001-inch-thick thermal foil reflectors at the capsule and surfaces. Close-fitting formed ceramic insulation sections reduce radial leakage between diodes.

Preliminary data for these designs are indicated in Tables 3 through 5.

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TABLE 3

250-WATT GENERATOR DATA SUMMARY PREVIOUS DESIGN CONCEPT

	<u>Pu₂C₃-Fueled</u>	<u>Cm₂O₃-Fueled</u>
	<u>Generator</u>	<u>Generator</u>
System Efficiency (%)	7.0	7.0
Diode Efficiency (%)	10.0	10.0
Fuel Required - Beginning of Life (gm)	7870	80.2 + 1560 (tungsten)
Fuel Remaining - End of Life (gm)	~7840	32.8 + 1561 (tungsten)
Emitter Temperature (°C)	1600	1600
Collector Temperature (°C)	700 → 800	700 → 800
System Weight (lb)	67	61
Generator Skin Temperature (°C)	700	700

TABLE 4

WEIGHT SUMMARY

TYPICAL 250-WATT Pu₂C₃ FUEL GENERATOR PREVIOUS DESIGN CONCEPT

(Figure 26)

Fuel	17.5 lb
Fuel Cladding	7.0
Ablative Coating	8.0
Diode Heat Collector Ring	7.0
Diodes (30)	10.0
Thermal Reflectors and Insulation	3.0
Radiator Case	9.0
Cesium Reservoir	2.0
Miscellaneous Hardware	<u>3.5</u>
	67.0 lb

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~~CONFIDENTIAL~~TABLE 5WEIGHT SUMMARYTYPICAL 250-WATT CURIUM-FUELED GENERATOR PREVIOUS DESIGN CONCEPT

(Figure 27)

Fuel	3.7 lb
Fuel Cladding	16.0
Ablative Coating	7.0
Diode Heat Collector Ring	7.0
Diodes (30)	10.0
Thermal Reflectors and Insulation	3.0
Radiator Case	9.0
Cesium Reservoir	2.0
Miscellaneous Hardware	<u>3.3</u>
	61.0 lb

3. Problem Areas Associated with Previous Design Concepts

The following are significant problems associated with the preliminary designs (an asterisk indicates significant development would be required):

- a. Spherical fuel*
- b. Brazes between diode and fuel block*
- c. Brazes between diode and radiator
- d. One cesium reservoir
- e. Spherical construction
- f. Lack of consideration for differential thermal expansion
- g. Poor efficiency with ablative material inside the thermal shields
- h. Fuel block supported from diode*
- i. Generator fueling*

Therefore, the first work done on this contract represented an attempt to eliminate as many of the potential problems as possible.

Isotope fuel in a hemispherical form is not feasible with present hot cell techniques. It is doubtful if it could be manufactured without a major development program unless a liquid fuel form were used. There-

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fore, all fuel was considered in a cylindrical shape that is compatible with present technology. This has the disadvantage of greater surface area per unit volume, and hence more heat leakage through nonuseful generator components for the low power density isotope fuels.

High-temperature brazes with an electrical insulation between the diode and fuel block do not appear feasible with present technology.

Brazes with electrical insulation between the collector and generator case are feasible if properly designed. However, a development program is required.

One cesium reservoir for a number of diodes might lead to interaction between the diodes. It is preferred to use individual reservoirs until such time that the use of a common reservoir has been demonstrated. A design objective was set in this study that the concept should be usable with either single or multiple reservoirs unless undue problems resulted from the objective.

The objective of using as little fuel as possible consistent with a reasonable design was established. For this reason, it was preferred to put the ablative material outside the thermal shields so that heat leakage is reduced.

With the exception of curium and polonium, the fuel will weigh 15-25 pounds for a 250-watt generator. When properly contained, the block weight is 30-50 pounds. It appears unreasonable to support this weight from the diodes and expect the generator to survive launch vibrations. Therefore, the heavy fuel blocks were considered with separate supporting structure.

A major consideration for an isotope-fueled generator is the fueling operation. It should be simple and straightforward to be consistent with remote handling in a hot cell.

These considerations led to a new conceptual design suitable for use with any of the proposed fuels.

4. Conceptual Design No. 2

One of the conceptual designs generated as a result of the consider-

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ations discussed in the previous section is shown in Figure 29 for curium or polonium fuel. The design for plutonium or cerium is similar, except that the fuel capsules are considerably larger. This is the "back-to-back" concept. The other concept is similar, except only one fuel capsule and one diode is used (i.e., two of that concept, connected back-to-back with the ends removed where connected, form a "back-to-back" concept).

In the back-to-back design, the diodes are brazed to the fuel capsules and electrically connected in series. The capsules run at the emitter potential and are electrically insulated by a ceramic spacer. A ceramic cylinder (not shown) separates the thermal shields, which are also at emitter potential, from the generator case. The use of a diode on each end increases the efficiency over a single diode generator since heat is lost only through the sides of the fuel capsule. Fueling is relatively easy since the generator would come in two identical parts. Fueling would consist of dropping a fuel capsule into each of the generator positions and brazing it to the diode. The ceramic spacer between the capsules would be added, and the generator halves either welded or brazed together.

Several of these generators would ordinarily combine to form 250-watt or 500-watt systems. In these cases, the ablative coating would probably be put outside of all the generators to reduce the coating weight.

Many of the necessary details are not shown in the sketch, such as the fuel support, movement of diodes relative to fuel and generator case, electrical leads, etc. However, the concept lends itself to all of the innovations in the final conceptual design for Ce 144 and hence is attractive for the high power density fuels.

The conversion characteristics of this concept with one diode per generator are presented in Table 6, for curium and polonium fuels. Two efficiencies are presented, one based on containing the theoretical amount of helium produced, and the other based on leaking the helium to space. These efficiencies would increase slightly for the back-to-back concept.

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Figure 29. Conceptual Generator Design No. 2 for Curium 242 or Polonium 210.

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TABLE 6
CONVERSION CHARACTERISTICS OF GENERATOR CONCEPT NO. 2

<u>Fuel</u>	<u>Output Power per Diode, Watts</u>	<u>Generator Life, Days</u>	<u>Overall Efficiency, %</u>	
			<u>Gas Leaked</u>	<u>Gas Contained</u>
Cm 242	111	120	13.3	10.3
Cm 242	83.3	120	13.0	9.8
Cm 242	66.7	120	12.7	9.4
Cm 242	55.5	120	12.4	9.0
Po 210	111	120	13.2	7.4
Po 210	83.3	120	12.9	6.8
Po 210	66.7	120	12.6	6.4
Po 210	55.5	120	12.3	5.9

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Table 7 shows data for the generator fueled with cerium. This table also contains a comparison of the efficiencies for the single diode and back-to-back concepts. Further investigation of this concept for cerium showed it to be impractical because of high center line fuel temperatures. In addition, a generator life of 390 days requires a mechanical heat dump that is not shown on the conceptual design.

5. Cerium-144 Generator Design

The program was examined after the initial effort described in Sections 1-4 to determine a fuel or fuels for concentrated study. Since Ce 144 was the only fuel available in the quantities necessary for this generator, it was decided that most of the further effort would be devoted to this fuel.*

A further investigation of the conceptual design for Ce 144 showed that fuel temperatures were prohibitive and containment could not be maintained. It was necessary, therefore, to add graphite, the only light high thermal conductivity material capable of high-temperature operation in the fuel, to the fuel capsule. This increased the fuel capsule size and consequently the heat leakage. The conversion efficiency therefore decreased. It was also desirable to keep the diode diameter to what appears to be present state-of-the-art, about one inch. When these effects were considered, the Ce-144 generator design for one-year life had less than 5% efficiency. Since it was known this would decrease further when a more detailed investigation was begun, the conceptual design was changed to increase the efficiency consistent with what could be built. An efficiency of much less than 5% appeared to be an unreasonable design.

It was found that if all the fuel were placed in one block of cylindrical shape with a one-to-one length to diameter ratio to minimize the heat losses, and sufficient graphite added to give reasonable temperature gradients, the overall generator efficiency approached 7%. The conceptual design was changed to include this effect. The good thermal contact between diode and heat source was retained by brazing. The heat source was

* Reference 8 on page 33.

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TABLE 7
CERIUM 144 GENERATOR CHARACTERISTICS CONCEPT NO. 2

<u>Output Power per Diode, Watts</u>	<u>Generator Life, Days</u>	<u>Conversion Efficiency, %</u>	
		<u>Single Diode</u>	<u>Back to Back</u>
111	210	8.6	9.4
83.3	210	8.0	8.8
66.7	210	7.5	8.4
55.5	210	7.1	7.9
111	390	7.2	8.1
83.3	390	6.6	7.5
66.7	390	6.0	7.0
55.5	390	5.7	6.6

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separated into six segments. Each of these segments was attached to a diode, and electrically insulated from the other segments. The fuel block concept is illustrated in Figure 30. When the mechanical contact between the fuel and the diode was eliminated, it was a simple step to the single block design that represents the final conceptual configuration. The progression to this concept has been presented in Section C of this chapter.

Final analysis and design of the concept resulted in a decrease in overall efficiency from about 7% to 5.8%. This occurred because of an increase in fuel block size due to the addition of mating fins for the diodes and to the addition of more fuel block structural material.

I. DC-DC CONVERTER AND VOLTAGE REGULATOR

1. DC-DC Converter

a. Introduction

This section deals with the design of the high-efficiency converter for changing low-d-c voltage to a higher value by means of static circuitry. The analysis is based on state-of-the-art conversion methods. The inherent losses are calculated and data tabulated to show maximum efficiencies versus operating voltage for presently available hardware. An analysis is made of the efficiency versus volume and weight of a practical inverter.

Since the thermal power of the isotope changes, and the heat dump on the generator probably will not exactly compensate for this, a device is included to regulate the current output from the generator.

b. Conversion Methods

The highest efficiency conversion methods use switching devices to alternately switch the input voltage to a transformer and hence to a suitable load. The switching device yielding the lowest overall losses provides the highest efficiency system. The three solid-state devices having the desired characteristics for converters are the germanium transistor, the silicon controlled rectifier and the tunnel diode. Of these three devices, the transistor is the only unit yielding high con-

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Figure 30. Segmented Fuel Block.

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version efficiencies. The silicon controlled rectifier, while requiring little driving power, is characterized by a voltage drop of one to two volts. Hence it must be disregarded for applications having low input voltages. The tunnel diode shows great promise for static conversion since forward voltage drops of 0.050 to 0.090 volt are possible. However, the present high current devices have peak-to-valley current ratios of 3 to 6, which yields conversion efficiencies of 25 to 50%. However, if these devices are improved, they could replace transistors for high-efficiency converters.

c. Circuit Configurations

The basic transistor converter circuits are all quite similar and differ only because of optimization of different parameters. Two basic circuits yielding high efficiency are shown in Figures 31 and 32. Figure 31 shows the conventional two-transformer converter using a small saturating transformer to provide the switching and a large nonsaturating transformer for the main power transformer. The circuit of Figure 32 is similar except the output rectification is accomplished by using the switching transistors. It can be noted that the load current is in series with the emitter base and hence is used to provide the base drive for the switching transistors. Some restrictions exist for the circuit of Figure 32, however, which may make it prohibitive for certain applications. Since the output is connected to the input there is no isolation, and grounding must be consistent for input and output. The optimum efficiency of the system is dependent on the voltage output or ratio of transformation. The transformation ratio cannot be higher than the transistor beta, and some efficiency is lost if the transformation ratio is less than the transistor gain. The present germanium units have a gain of approximately 20, and for 28-volt output the optimum input would be 1.4 volts. Calculations of the two circuit configurations are given in Appendix B for an input voltage of 2.0 volts to show the results of nonoptimization of the transformer ratio of Figure 32.

Refinements on Figures 31 and 32 are made to optimize the effi-

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Figure 31. Conventional Converter Circuit.

Figure 32. Self-Rectifying Converter Circuit.

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ciency, but no basic change is made in the circuits. The remainder of this section will give figures of efficiency and other parameters based on the circuit configurations of Figures 31 and 32.

d. Conversion Efficiency

In the design of dc to dc converters operating from low input voltages a compromise exists between efficiency, size, weight and relative cost. To determine the maximum efficiencies possible with the present state-of-the-art devices and the variation of this efficiency by changes in the weight and size, it is necessary to investigate the factors affecting the efficiency and procedures for optimization of these factors.

The losses in a conventional transistor converter of the type shown in Figure 32 can be listed as follows:

- (1) Transistor Losses
 - (a) Switching losses
 - (b) Saturated switch losses
 - (c) Leakage current losses
 - (d) Base drive losses
- (2) Transformer Losses
 - (a) Core loss
 - (b) Copper loss
- (3) Rectifier Losses
- (4) Filter Circuit Losses
- (5) Other Circuit Losses

Transistor Losses

The primary losses in the switching transistor consist of the switching loss and the saturated switch losses. A second order loss is the leakage current loss which at low input voltages is generally insignificant. The switching loss is the time averaged value of the instantaneous power dissipated during the "turn on" (t_R) and "turn off" (t_F) time of the transistor. This switching loss can be calculated with a reasonable accuracy using Equation III-2:

$$P_S = 1/6 \left[2 V_S I_C f (t_R + t_F) \right] \quad \text{Eq. (III-2)}$$

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where P_S = average power during time transistor is switching on and switching off

V_S = supply voltage

I_C = maximum value of collector current

f = operating frequency

t_R = rise time for transistor to switch on

t_F = fall time for transistor to turn off

With present available devices, switching times t_R and t_F are in the order of 40 to 50 microseconds. Improvement in switching losses can only be made when devices are available with high emitter cutoff frequencies.

The saturated switch loss of the transistor is the average loss of the transistor during the time it is saturated or turned on. This loss is the product of the average voltage across the transistor when saturated and the average current through the device. Equation III-3 is suitable for calculating these losses:

$$P_C = R_S I_C^2 \left[\frac{1}{2} - f (t_R + t_F) \right] \quad \text{Eq. (III-3)}$$

where P_C = average power dissipated during "on" period

R_S = effective saturation resistance

$$= \frac{V_{CE} \text{ (SAT)}}{I_C}$$

I_C = maximum collector current

$V_{CE} \text{ (SAT)}$ = voltage from collector to emitter in the saturated condition

This loss is again dependent primarily on the available transistors and at the present time the best value of R_S is in the order of 0.002 ohm. The situation is somewhat more complex since the saturated voltage drop is dependent upon the base drive current, decreasing for increasing current drive. Hence, suitable choices must be made as to base drive versus saturated switch losses.

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Leakage current losses are those losses occurring as a result of the transistor being a finite resistance when switched off. These losses are usually negligible. However, they may be computed from Equation III-4:

$$P_B = 2 V_S I_{CO} \left[1/2 - f (t_R + t_F) \right] \quad \text{Eq. (III-4)}$$

where P_B = average power when transistor is off

I_{CO} = leakage current at maximum temperature of operation

Base drive loss, while not intrinsically a transistor loss but a circuit loss, is a result of the transistor having a finite current gain, usually in the order of 20 for the higher current germanium devices. Adequate circuit design is required to keep these losses to a minimum and, as mentioned previously, is a compromise with the saturated drop.

Thus, after selection of a given transistor, the frequency of operation must be chosen to give minimum switching and saturation losses and, in addition, the base drive must be selected to give minimum saturation and base drive losses.

Transformer Losses

The transformer or transformers used in the converter have two losses which are predominant, the core loss and copper loss. The transformer losses can be theoretically made as small as desired but only at the cost of larger volume and weight. Higher operating frequency will yield smaller transformers of the same loss; however, the operating frequency is more critically determined by transistor losses rather than transformer losses. Exotic core material and sophistications such as silver conductors, etc., yield some gain in size versus weight of the transformer, but will result in a cost increase with a gain in efficiency of perhaps 1/2 to 1% for the same weight unit. These sophistications were not included in this study.

Rectifier Losses

The rectifier is defined in this report as any device causing

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unilateral load current. The use of diodes as rectifiers will add losses as a result of the voltage drop across the device during conduction. The lowest voltage drop units are germanium diodes with selected units having drops of approximately 0.3 volt. A better approach to rectification is the use of the low drop germanium transistor with a circuit configuration as shown in Figure 33. With this system rectification losses may be compared to the standard diode system. This comparison is given in Appendix B and shows a net decrease of the transistor system losses of approximately 700%.

Filter Losses

The output of the converter is an approximate square wave and requires filtering. In general, filtering will be done by a single capacitor filter for maximum efficiency. Since the leakage current on available electrolytic-type capacitors is about 1 ma per 10,000 micro-microfarads of capacity at the voltage levels in question, the filter losses will be negligible and are not included in the converter calculations.

Other Circuit Losses

A starting circuit is generally included because of problems encountered in starting the converter under full load conditions. This circuit can be automatically disconnected during the steady-state operation of the converter; hence the losses in this section of the circuit are also quite negligible.

In analyzing the losses predominant in the converter circuitry and factors affecting these losses, one finds the selection of the switching transistor (and the state-of-the-art in development of such devices) to be of paramount importance in the final efficiency of the system. In investigating the various semiconductor manufacturers, a tentative specification for a suitable switching transistor was written, the important parameters of which are:

$$V_{CE}(\text{SAT}) = 0.1 \text{ volt max}$$

$$V_{BE} = 1.0 \text{ volt max @ 2 A (base to emitter voltage)}$$

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Figure 33. Circuit for 4.14-Volt Converter and Regulator.

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$$\begin{aligned}
 I_C &= 65 \text{ amps max} \\
 H_{FE} &= 25 @ I_C = 50 \text{ A (static gain)} \\
 f_{ae} &= 2 \text{ kc min (cutoff frequency)}
 \end{aligned}$$

Recent information released by Minneapolis-Honeywell shows possibilities of increasing the specified current gain to 50 and the f_{ae} to 10 kc. This would yield improvements in efficiency and weight of the converter over those presented in this report. From the selection of the transistor, the optimum operating frequency is determined and converter designs and efficiencies may be determined. The design techniques and conversion efficiencies can now be shown.

e. Circuit Design

The design of a converter for 1-, 2-, 3- and 5-volt inputs is covered in this section and in Appendix B. These designs yield high conversion efficiencies with present state-of-the-art. Procedures for the calculations given in Appendix B are discussed.

The initial converter work was based upon the following generator electrical characteristics:

System Voltage (Volts)	Design Current (Amps)
1	333.33
2	161.50
3	104.11
5	58.82

These data were obtained from a preliminary analysis of the back-to-back generator concept in which the conversion efficiency is a strong function of the output voltage.

The circuits of Figures 31 and 32 are compared with respect to efficiency. A crossover point is shown to exist between the Royer conventional circuit of Figure 31 and the self-rectifying system of Figure 32. In both cases design calculations of the final efficiencies are made by using Equations III-2, 3 and 4 to determine total transistor

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dissipation. The transformer losses are computed by making three sample design transformers suitable for each converter. Rectifier losses are included with the above losses to yield the total power dissipation of the converters. These figures are compared to the approximate weights and volumes of the converters and plotted graphically.

f. Circuit Design Considerations

Problems are encountered in paralleling transistors and in changes in parameters with operating temperature. Since these have a tendency to lower the theoretical maximum efficiencies, it is necessary to show the proposed methods of keeping the efficiency constant.

Paralleling Power Transistors

In paralleling power transistors, there are two important points to be considered to maintain high efficiencies. The collector currents must be reasonably close to assure satisfactory operation and the emitter base of the transistors must not be overdriven. Equal collector currents depend on each transistor having equal current gain and equal transconductance. In the specified parameters of the transistors, it must be considered that units somewhat better than the maximums will be distributed randomly in a given lot of transistors. Paralleling of the transistors for maximum efficiency would be done as shown in Figure 34.

Figure 34. Circuit for Paralleling Transistors.

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In this system Q_1 would be the unit on the maximum end of the specification while Q_2 is somewhat better than the maximum unit. R_1 tends to equalize collector currents I_1 and I_2 . R_2 tends to also equalize collector currents and keep base drive currents to within required values.

Parameter Changes with Temperature

The changes in transistor parameters with temperature can have a large effect on the efficiency of the system at high operating temperatures. Since base drive losses represent an appreciable part of the transistor losses, the drive current for the transistor must be held reasonably constant. It will be found that the drive voltage required to produce a given current is a function of temperature. Since the base drive voltage is produced by a transformer winding which will remain relatively constant, it is necessary to insert a temperature compensating device in the emitter base as shown in Figure 35.

Figure 35. Temperature Compensation Circuit

The characteristics of Z with temperature must be such as to keep the current I_B essentially constant and yet have very low resistance at nominal conditions. A thermistor can be used to accomplish this with little change in efficiency and these devices are available with either positive or negative temperature coefficients.

Transistor gain changes will affect the efficiency to a small degree as will changes in saturation resistance. With these parameters it is simply a matter of knowing what the manufacturer of the device will specify at the maximum operating ambient temperatures.

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g. Results of DC-DC Converter Study

The results of the calculated efficiencies at various input voltages with respect to volume and weight are plotted in Figures 36 through 41.

Figure 36 shows the small gain in efficiency in using the self-rectifying circuit in lieu of the conventional circuit when operating between 1.35 and 1.5 volts. This curve is based on a transformer efficiency of approximately 95%.

Figure 37 shows the efficiency possible at various input voltages for the three calculated volumes and weights considered.

Figures 38 and 39 give the converter efficiency as a function of volume and weight of transformers used, while Figure 40 gives an approximate loss versus weight for a suitable transformer.

Figure 41 is a useful curve for grading the size or weight of a converter for a given efficiency. This curve gives a plot of converter power output per pound of converter weight and the efficiencies obtainable for this parameter.

These data were utilized in making a selection of an optimum system in regard to input voltage.

2. Voltage Regulator

In isotope-heated thermionic generators, the beginning-of-life electrical power production is usually greater than the end-of-life output. However, in this generator it has been necessary to include a heat dump to compensate for the excess heat produced by the Ce-144 fuel at the beginning of life, and the heat source temperature is relatively constant. Thus, a large excess of electricity is not produced at the beginning of life and the voltage to the dc-dc converter can be regulated with a small current voltage regulator.

The Ce-144-fueled generator output power will be roughly regulated to less than 20 watts above the required power. At a voltage of 4.14 volts (actual design point^{*}), this represents approximately 4.8 amps of

^{*} 4.14 v for converter. The generator design value is 3.94 v. The slight discrepancy will cause no significant variance in conclusions.

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Figure 36. Converter Efficiency vs Input Voltage for Conventional and Self-Rectifying Circuit. (Transformer Efficiency of 95%)

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Figure 37. Converter Efficiency vs Input Voltage for Various Volumes and Weights.

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Figure 38. Converter Efficiency vs Transformer Volume.

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Figure 39. Converter Efficiency vs Transformer Weight.

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Figure 40. Transformer Loss vs Transformer Weight.

Figure 41. Converter Efficiency vs Watts per Pound of Converter Weight.
(Cased, Unpotted Assembly)~~CONFIDENTIAL~~

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excess current. This current could be easily drawn by using an input regulator. However, the circuitry becomes slightly more complicated because of the voltage levels. By referencing the regulator to a higher level of voltage, a high degree of regulation can be achieved without undue complexity.

Results of voltage regulator study: the proposed regulator is shown schematically with the 4.14-volt converter in Figure 33. A reference diode, CR1, is used to provide a stable reference which is compared to the input voltage (actually a voltage proportional to the input). Any difference in these two voltages is amplified by a differential amplifier and subsequent stages of d-c amplification. The amplification is such as to have Q14 and Q15 draw a current to very nearly keep the input at 4.14 volts. To provide suitable threshold and operating range, the simplifier stages are returned to a +10-volt output on the converter.

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Figure 1. 250-Watt(e) Thermionic Generator, Cerium Fueled

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IV. CERIUM-144 GENERATOR DESIGN

A. INTRODUCTION

This section of the report contains a design description of the Cerium-144 generator concept. A description of the components and their operation, with references to appendixes for the design calculations and a discussion of the assembly of the major components of the generator that require explanation, is given. A presentation of the handling techniques for fueling, repairing, transportation and launch site handling and the safety aspects of the design are discussed.

The design output of the thermionic generator for a 250-watt(e) system is 294 watts. This takes into account the dc-dc converter losses (31 watts), electrical heat for the cesium reservoir and heat dump actuator (2-6 watts), and allows for some electrical lead loss between the diodes and the dc-dc converter.

Figure 1 is a view of the generator showing the major components. This generator weighs 143 pounds. The dc-dc converter weight is 9.5 pounds, giving a total system weight of 152.5 pounds or 1.6 watts/lb at 28 volts dc. The generator end-of-life efficiency is 6.0% and the dc-dc converter efficiency is 89%. Overall efficiency of the 250-watt system is 5.3% (includes electrical lead losses, dc-dc converter losses and electricity losses in the generator controls).

A sketch of the generator attached to the payload is shown in Figure 42. The conical payload shape is necessary for proper generator behavior during a launch abort, as discussed in Section IV D. However, once the proper cone area has been provided for generator behavior, no other restrictions exist with regard to payload shape.

A sketch of a 500-watt installation is shown in Figure 43. The generators are connected in parallel since each generator uses ground as one of the electrical leads. This also increases the reliability of the entire power output since, if one generator failed, the output of the other would continue.

Sketches of the satellite and generator system in orbit and the

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Figure 42. 250-Watt Generator Installation.

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Figure 43. 500-Watt Generator Installation.

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generator in the event of a low-altitude launch abort are shown in Figure 44. The use of an extension system eliminates the need of heavy shielding to reduce the dose rate to the package. This arrangement can also be used to stabilize the satellite, with the heavy satellite package always oriented toward the earth. This eliminates the weight of orientation apparatus on the satellite, effectively reducing the generator weight by the orientation device weight (with suitable allowance for the extension boom). The probability of successful orientation for the satellite should be increased considerably since, once extended, the device becomes completely static. An additional advantage of satellite-generator separation is to thermally separate the generator (1500°F on some surfaces at beginning of life) from the rest of the satellite system.

In the event of a low-altitude abort the generator is separated from the satellite and, using part of the satellite skin to orient and slow it down, the generator will impact on the earth's surface. This arrangement results in a considerable decrease in generator weight over that required if the generator impacts at high velocity in a random manner.

A detailed drawing of the generator is presented in Figure 45, pages 107-110.

Each of the major components of the generator is discussed in the following sections.

B. DESIGN DESCRIPTION

1. Diodes

a. Introduction

The most important component of a thermionic generator is the diode. As previously discussed, a major emphasis was placed upon the following characteristics:

- (1) As close to "state-of-the art" as possible
- (2) Reliability
- (3) Rugged seal (small diameter)
- (4) Strength

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Figure 44. Generator Extension System and Re-Entry Drag Cone.

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- (5) Efficiency
- (6) Replacement
- (7) Manufacturing ease

The diode discussed in this section has been designed to meet all requirements. This diode has not been built, and a device of this type must be produced and tested before firm conclusions can be made.

A flat plate diode design was chosen because this geometry has an advanced state-of-the-art over other configurations applicable to low power density fuels. The diode diameter has been limited to about one inch since diodes of this diameter have been developed. Construction of larger-diameter diodes could lead to additional development.

The diode designed for this generator is shown in Figure 24. Close examination shows that it meets the listed requirements.

b. State-of-the-Art

The diode is approximately one inch in diameter which represents present "state-of-the-art." A number of diodes of this size have been built and most of the design problems recognized. * Development areas have been minimized in the design.

c. Cesium Seal and Electrical Lead-Through

The small-diameter seal is a major advantage. A number of seals of this identical design have been constructed and have performed satisfactorily. The seal, as used in other applications, provides structural support and operates at higher temperatures than anticipated in this diode design. These requirements have been eliminated in this diode, providing additional reliability.

The metal components of the seal are niobium (columbium), which is resistant to cesium vapor and closely matches the thermal expansion characteristics of the ceramic. The ceramic is alumina, which is easy to shape, is strong, and is compatible with the intended use. The alumina is joined to the niobium using a high-temperature vanadium braze.

Mechanical stresses on the seal have been reduced. An expansion

*Reference 2 on page 19.

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Figure 45a. 250-Watt Thermionic Generator, Cerium Fueled.

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Section **BB**

Diode Cesium Reservoir
(Typ. 6 Plcs.)

Section **AA**

Figure 45b. 250-Watt Thermionic Generator, Cerium Fueled.

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Figure 45c. 250-Watt Thermionic Generator, Cerium Fueled.

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Crushable Structure
(See Figure 43)

Figure 45d. 250-Watt Thermionic Generator, Cerium Fueled.

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joint is provided to compensate for differential thermal expansion and manufacturing tolerances. Niobium is used throughout the collector-seal portion of the diode to minimize differential expansion.

d. Strength

The diode is designed for long life and resistance to launch vibrational loads. The emitter backup plate (with fins) is constructed of tantalum (tantalum-10% tungsten may be used) and is adequately thick to provide high-temperature strength and eliminate deformation. The collector, constructed of niobium, has the same characteristics.

The spacer, of 90% tantalum-10% tungsten, is designed for 150-g loads in all directions with an appropriate safety factor (see Appendix C, Part 1). Tantalum has previously been used for this part but the alloy is considerably stronger. It also appears to be free of long-term high-temperature effects which could cause failure.

The diode is designed so that all the alumina parts are under compression at all times. Shear and tension do not occur. The sizing is consistent with the strength characteristics of the alumina. Alumina is always brazed to niobium so that the thermal expansion characteristics of the two components are well matched. The previously mentioned high-temperature vanadium braze is also consistently utilized. Considerable experience already exists in the use of this braze.

e. Diode Replacement

The diode is replaceable since there is no contact between the heat source and the emitter backup piece. The diode is threaded and screws into a retaining plate that serves to transfer heat from the collector to the backup piece and then to the heat rejection fins. There is a chance that the threads will "weld" over a long term, but this should be slowed by the dissimilar metals used at the joint. The threaded part of the diode is niobium, and the part it screws into is copper backed up by inconel. This assembly is indicated on Figure C4, which also shows temperature distribution on the diode.

f. Manufacturing Ease

Diode construction materials are basically tantalum and niobium,

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Figure 24. Flat Plate Diode Concept No. 3.

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both of which are compatible with present-day manufacturing techniques. Alumina electrical insulation can be readily obtained in the shapes necessary for this design. A simplified assembly drawing of the diode is shown in Figure 46.

g. Development

One development problem in this design concerns the insulation between the collector, emitter lead and the backup plate. All of these parts are brazed using vanadium so that good heat transfer characteristics are obtained between the collector and the collector backup plate. It is probable that the alumina will crack, even though it is brazed to niobium, in these large-diameter regions. Since this portion of the diode needs no mechanical strength and does not serve as a seal, cracking will not be a problem provided the cracks occur parallel to the heat flow. Cutting thin slots in the alumina in this part of the diode is one possible solution so that the cracking will occur, if it does at all, in the desirable direction. Thus, diode performance would remain unaffected.

h. Series Operation

Six diodes are connected in series. No allowance has been made for degradation in performance in going from single diode operation to series operation.

Flat plate diodes have been operated in the volume ignition mode in series and no measurable change in output power has been found.*

2. Cesium Pressure Control

Cesium pressure in the diodes is controlled by maintaining the cesium reservoir temperature. Each diode has a separate reservoir. This arrangement eliminates electrical insulation in contact with cesium at the reservoir, facilitates diode replacement, and enables the use of precharged diodes. All of these would be problems with a common reservoir.

The reservoir tubulation is constructed of niobium.

*Measurements taken on SNAP-13 - Martin Nuclear Laboratories, 9/18/62.

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Figure 46. Diode Exploded View.

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Each reservoir is coated with alumina for electrical insulation purposes. They are contained in a common niobium heat block for thermal control, as shown in Figure 45. The niobium is heated by a small (1-3 watts) electric heater to maintain the temperature and the temperature is measured by a thermistor. A separate control (not considered in this design, but located with the dc-dc converter) uses generator-produced power to maintain the block temperature as indicated by the thermistor.

The lower end of the generator is designed to operate cooler than the desired cesium reservoir temperature. By brazing a copper fin structure inside the lower generator dome, the cesium reservoir block is surrounded by a "cool" environment. The block is then heated as necessary to maintain design temperature. Heat requirements are minimized by thermally insulating the reservoir block from the fin structure.

The thermal insulation used in the reservoir area must be a type that outgasses quickly and easily with no contaminants. Thermal shields may be used in this area. They are not included in this design because of problems in accurately calculating heat flow. The design presently calls for Owens Corning Fiber Glass AA and it is expected to work. Tests must be performed to verify the design.

3. Fuel Block

The fuel block is composed of approximately a one-to-one ratio of fuel to graphite. The graphite is necessary for heat conduction purposes. Internal block temperatures are prohibitively high without it. Graphite was used rather than some other high-temperature material because it has the best heat conducting capability per unit weight of the materials that could be used.

Each fuel pellet is surrounded by 10 mils of rhodium for ease of handling in the hot cell. It is doubtful that a 10-mil layer can be remote welded to form a sealed can and it may be necessary to use a thicker layer in the weld region. The fuel material, either cerium metal, carbide or sulphide, will ignite spontaneously, hence the use of rhodium to clad each capsule once it is formed considerably reduces the handling risk.

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The graphite is presegmented so that the fuel block will fall apart, enabling the fuel to burn up during re-entry from orbit. If the graphite remained intact around the fuel, it would act as an ablative coating and might slow or prevent re-entry burnup. The thermal characteristics of the fuel block are not changed by the segmentation provided it is done parallel to heat flux lines.

The clad fuel pellets and the segmented graphite are clad with rhodium, an oxidation-resistant metal. The clad will serve as the containment for the fuel in case of a low-altitude (less than 100,000 to 150,000 ft) abort during launch. It will also prevent exposure of the fuel in the event of some other accident that punctures the generator case.

Rhodium has a high vapor pressure¹⁹ and is relatively soft and weak at the fuel block operating temperatures. It is clad with the tantalum alloy 90% tantalum-8% tungsten-2% hafnium. This is one of the stronger high-temperature alloys available. The alloy oxidizes in air at high temperature and cannot be used for containment. It is intended to provide a strong block that, properly protected, will withstand generator impact on granite. The generator case would break if subjected to this type of terminal velocity impact, and the exposed tantalum alloy would be slowly oxidized. However, it would have protected the block during impact, and would not be necessary afterward.

The outside clad also has six sets of fins on the bottom. These mesh with the emitter backup plate fins on the diode to provide the necessary heat transfer.

All welds on the block and fuel capsules are to be made in a helium atmosphere. Thus, all gaps between the various materials are filled with helium. The temperature drops across these interfaces are negligible.

The process of sealing the fuel in three separate containments, the rhodium capsules, the outer rhodium can and the tantalum

19. Dushman, "Scientific Foundations of Vacuum Techniques," John Wiley (1949).

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alloy can, enables the production of a fuel block which should be free of contamination from the fuel.

Examination of the thermal expansion characteristics of the materials of the fuel block materials will show them to be incompatible. However, the graphite portion will be sectioned to improve burnup capability and the expansion of the fuel capsules will not be restricted by the fuel block. The greater expansion of the outer rhodium over the graphite can be compensated for by the use of self-adjusting graphite shims which will continually contact the rhodium can. The Ta-8W-2Hf container can be made large enough to compensate for the higher expansion rate of rhodium, so a fit will be achieved at the operating temperature. Close fits are not required because the helium fill gas prevents high temperature drops.

No compatibility data exist for rhodium in contact with the cerium fuel forms. Compatibility barriers could be included if necessary. Graphite should be compatible with rhodium from the gross reaction standpoint at the operating temperature, although there is some solution of carbon in rhodium at high temperatures.²⁰

Several techniques were considered to support the fuel block. The one chosen causes minimum heat leakage. It is illustrated in Figure 47. The cylindrical thermal shields are supported externally by L-shaped cylindrical support structures at the top and bottom. A short space between each shield is filled with a thin (1 mil) layer of alumina. The block rests inside the shields. The outside thermal shield is clamped by the top and bottom edges and holds the block by compressing through the alumina.

An alumina layer is attached to one side of each shield, and then sandwiched as shown in Figure 47. This provides a thermal contact resistance between the tantalum and alumina layers. The heat leakage will be small. A layer will be formed by flame spraying the Al_2O_3 on a flat piece of tantalum and grinding to the required thickness. The layer

20. Hansen, M., "Constitution of Binary Alloys," McGraw Hill (1958).

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Figure 47. Thermal Shield Detail.

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will be slotted approximately twice per centimeter so that it doesn't peel when the thermal shield is rolled up to form a concentric shape. The alumina will be cured after the shields are formed into a concentric shape.

Spacing between shields, at positions other than the corners, is maintained by dimpling the shields.

4. Heat Dump Mechanism

Approximately $3/4$ of the heat crossing the diodes is transferred by electrons. Since the diodes require 1700 watts, the electron cooling amounts to $1700 \times 3/4 \sim 1300$ watts. Under proper conditions of increased current flow and higher emitter temperature, this value could be increased to a maximum of 1700 watts.

The excess heat at the beginning of life is about 7500 watts. Therefore the excess heat cannot be controlled by the electron cooling method of power flattening.

A careful study of the rejection of heat at the beginning of life leads to a thermal shutter concept, the same solution as used on previous isotope-heated generators.

As shown in Figure 45 the heat is dumped through six ports in the thermal shields. The outside set of shields is rotated to provide the control. At a full open position, all of the heat can be dumped with the generator open circuited. The fuel block will remain cooler than the normal operating temperature. At the full closed position the heat flow is retarded. The generator is designed so that the "full closed" position is past the physically closed position so as to reduce heat leakage.

The movable thermal shields are connected at the top to several short rods that extend through slots in the fuel block upper support member. These rods bend at right angles and connect to the bottom of the shutter drive shaft assembly.

The drive shaft is a hollow thin wall tube designed to crush if the generator impacts on the end. The shaft turns in graphite bearings located at each end. It is turned by an actuator-driven circular control

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plate. Upon impact, the plate would be driven into the hollow space by the thermal actuator reservoir. It would fit into the space allotted and would crush impact structure when it reached the end of the hole provided for it.

The thermal actuator is a NaK-driven SNAP-11 (Surveyor)²¹ type, the only difference being in the pivot attachment. Since an incompressible liquid is used, considerable force could be exerted by the piston-bellows-type actuator, if necessary.

The movement required is only 15 to 20° from full open to full closed. Thus, no linkage levers are necessary.

The motive force for the actuator is provided by the electrically heated actuator reservoir. The reservoir is filled with NaK which, when heated, expands to close the shutters. One to three watts of heat will be sufficient to completely close the shutters.

The shutter actuator is designed to close when heat is applied, constituting most probable fail-safe operation. If the heater were to burn out or electrical connection to the heater were lost, the fuel block temperature would drop because the shutters would move to the full open position. If they were to move to the full closed position, the rhodium in the fuel block would melt, although the tantalum alloy outside the block surface would remain intact. In a remote instance, if the block were exposed to air after overheating, the outside surface would be oxidized away, and, since the resolidified rhodium would probably be pitted, the fuel would be released.

The power to the thermal actuator reservoir will be provided by a controller which operates by sensing generator current. The voltage level is designed to be constant through the use of a voltage regulator. The output power is directly proportional to the current flow. If the current flow became too low, the electrical heat would be increased slightly at the reservoir, and the shutters closed slightly. This would increase the block temperature, hence the diode emitter temperature, and

21. SNAP-11 Project Surveyor, AEC Contract At (30-1) 2952.

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the generator power output would increase.

If a diode were lost by short circuit, the voltage from the generator would decrease, but the current would not. Thus the shutters would be unaffected. If a diode were lost by open circuit or a short were to occur in some portion of the system, no power would be available to heat the reservoir, and the shutters would open. Further careful study is necessary to assure fail-safe operation in the event of a gradual degradation in generator performance.

This method of control eliminates the problems associated with trying to control the block temperature in a more direct manner. It operates by controlling output power from the generator.

All parts of the system in contact with NaK are 316 stainless steel. This is compatible up to 1500° F, considerably above the temperatures considered for this application.

The thermal shields are constructed of tantalum since it has a low emissivity when polished, is relatively easy to fabricate and is compatible with the high-temperature operation of the layers near the fuel block.

5. Heat Rejection*

a. From the Fuel Block

Heat from the fuel block is rejected to a heavy tapered cylinder outside the movable thermal shields, through a brazed joint to the copper heat dump members and into the generator skin through another brazed connection. The skin radiates the heat to space.

The generator skin is composed of a heavy René 41 outer layer to provide strength, a thick copper middle layer to provide good radial heat transfer characteristics, and an inner thin inconel clad. The copper heat dump members are also clad with a thin inconel layer because of the high copper vapor pressure at these temperatures.

The technique of dumping heat along the entire surface of the

* Detailed analysis is found in Appendix C.

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block into the generator surface reduces temperature gradients in the block and the generator skin. With the amount of heat to be rejected, and the size of the fuel block, the heat cannot be dumped from one end unless block temperatures become higher at the maximum temperature point.

b. Heat Rejection from the Diodes

Heat from the diodes is rejected to the copper diode mounting plate and conducted to the copper radiator fin. The heat is rejected from both sides of the radiator fin to space. A polished cylindrical foil is placed between the inside of the radiator fin and the diode enclosure dome so that heat is not rejected to the cesium reservoir area.

The copper in these areas is cooler than in the heat dump areas, but a clad is still necessary where the copper is exposed to air to prevent oxidation. Nickel is suitable for use at this point.

The diode mounting plate is backed up by inconel to give structural strength. A complete thermal mapping of the generator is shown by Figure 48.

6. Crushable Structure and Orientation Fin

The impact conditions required by the generator cannot be met with large impact shells either around the fuel block or on the exterior of the generator without a large weight sacrifice. A crushable structure to reduce impact has been chosen as the best alternative. Rene 41 has been chosen as the crushable structure.

The crushable structure is shown in Figure 45 and in Figure 49. The structure shown in Figure 49 is formed of corrugations rather than honeycomb to reduce the weight. To work properly, the structure must crush and not buckle. If one component were to buckle, it is effectively removed from the structure as a support member. The continuous curvature of the corrugation resists buckling at a lower weight than does a flat plate in honeycomb structure.

The generator is designed to impact at terminal velocity only on one end. It is oriented by a drag fin attached to the lower end which is aerodynamically stable. This fin also reduces the impact velocity, considerably reducing the impact structure weight. The

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Figure 48. Beginning-of-Life Temperature Profile.

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Figure 49. Crushable Structure.

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radiator fin was necessary to cool the diode mounting plate, and was utilized to serve as the generator end of the drag fin as well. The rest of the drag fin is composed of a conically shaped section of the satellite skin.

The drag fin is made of aluminum alloy to reduce the weight as much as possible. The fin weight has been optimized with respect to the impact structure weight to achieve a minimum weight satellite package. The greater the fin size, the lower the impact velocity, and thus the lighter the impact protection structure. Thus a minimum weight results when total generator weight plus fin weight is plotted against fin diameter. Such a plot is shown in Figure 50. The derivation of this analysis is shown in Appendix A. The drag fin is considered as part of the satellite since it is needed to protect the satellite during launch and to support the generator from the launch vehicle. The radiator fin is considered part of the generator.

Although the crushable structure will absorb all the energy resulting from the impact, the fuel block will not remain intact unsupported. The highly conservative assumption was made that the internal structure of the fuel block would behave like a liquid under impact conditions, and the block support structure was designed accordingly. Since the available refractory metals are relatively weak and have high densities, the necessary core support was placed outside of the thermal shields. In an impact, the fuel block will deform and crush the shields. This relatively small movement will be stopped by the tapered René 41 cylinder outside the shields. No further movement of the block in the radial direction will occur.

The upper dome of the generator is designed to flatten under impact and form a "plate" under the impact cushion. This also absorbs a small amount of energy. When the dome flattens, the actuator reservoir is driven up into the well in the cushion, shearing off the actuator arm. The control plate fits into the well and serves as a piston on the crushable structure at the bottom of the well. The actuator is partially flattened and dents the impact cushion somewhat, but not seriously. The actuator support is driven past the cushion and causes no damage to the crushable

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Figure 50. Weight Optimization; 250-Watt Cerium Generator.

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structure. The entire cushion structure then compresses for half its length to absorb the energy of impact. The NaK reservoir will also crush during this phase of the impact.

The crushable structure is constructed of René 41. This material is one of the strongest materials available for "moderate" temperature usage.

Since any analysis of this type behavior is at best approximate, appropriate testing programs will be necessary. The analysis has been conservative; therefore, it is believed that a testing program will cause weight reductions rather than weight increases to make the impact successful.

The detailed investigation of the impact problem is presented in Appendixes A and D. The generator weight breakdown is also contained in Appendix A.

7. Electrical and Mechanical Connections to Satellite

Since the generator must be handled remotely, it is extremely important that the connections to the satellite be simple. This has been achieved through the use of plug-in type connectors and a modified Marmon clamp.

The electrical leads from the generator are contained in three tubes. One tube contains the main power lead, another two power leads for the reservoirs, and the third tube contains two leads for the thermistor on the cesium reservoir. The generator case serves as a common ground for the other main power lead, and for each of the reservoir heaters.

The leads terminate in electrical lead-throughs that are commercially available. These operate at temperatures much lower than any other portion of the generator, thereby avoiding a lead-through temperature problem. Male fittings on the other end of the lead-throughs complete the generator portion of the system.

The tubes are also used to support the generator since the copper radiator fin is relatively weak. The tubes pass through the diode support plate and terminate in a structural member that acts as

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the lower fuel block support and is tied into the skin of the lower end of the generator. A weld on the skin connects the upper and lower ends of the generator together after fueling. The structural member rests against the tapered René 41 cylinder, but is not attached to it.

The satellite should have three matching sockets to receive the electrical lead prongs, and a ring to match the ring on the generator. The connection between the generator and satellite is discussed further in Section IV C.

8. Outside Case

The generator case serves as a vacuum chamber for the diodes. It is constructed so that it will contain a vacuum of 10^{-6} mm Hg. It is possible to design test generators with flange connections between the diode enclosure dome and the case. To replace the diode enclosure dome on a fueled generator, separation would occur at the final case weld. This feature provides ease of repair or diode replacement.

The case is designed to withstand a one-atmosphere pressure differential with a suitable safety factor.

9. DC-DC Converter and Voltage Regulator

a. Converter Specifications

The dc-dc converter specifications for the system are:

Input: 4.14 volts dc, 68 amps*

Output: 28 volts dc ($\pm 1\%$), 250 watts

b. Converter Design

The specifications define an end-of-life converter efficiency of 89% minimum. Referring to Figure 37, Section III-I, at 4.14 volts input, 89% efficiency may be achieved in a converter of weight less than 10 pounds and 122-cubic-inch volume. Thus it is necessary to compute the transistor dissipation and rectification loss and choose a transformer design suitable to provide a conversion efficiency of 89%. The volume and weight of a theoretically packaged unit may then be ascertained. This work is described in Appendix F.

* This figure is inconsistent with the final generator design of 3.94 volts. Since this phase of the study proceeded concurrent with other efforts, these values were initially selected. The variance causes negligible change in the data presented.

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Three transistors are required for each side of the converter. Each transistor will be a selected Motorola MP-500 series unit. Operating frequency will be 500 cps. The total transistor losses, base drive losses, and rectification losses are 13.72 watts. Since the total losses cannot exceed 31 watts (for 89% efficiency), 17.28 watts can be lost in the transformer. The loss will be divided, one watt in the switching unit and 16.28 watts for the main unit. The transformer weight corresponding to this requirement is 4.5 pounds (see Figure 40, page 98).

c. Regulator Weight and Volume

The size and weight of the regulator will be primarily due to the heat sinks and output transistors. The maximum allowable transistor junction temperature is 150°C at a heat dissipation of 10 watts. The thermal resistance from the transistor junction to the case is approximately 3°C/watt , and the maximum allowable case temperature is 120°C . The sink has a thermal resistance of 3.5°C/watt . A mica insulator between the transistor and the heat sink will add 0.5°C/watt , so that the maximum ambient temperature in which the regulator will operate is 80°C (173°F).

Thermoelectric cooling is not useful in cooling the output regulating transistors since little gain is achieved without dropping the efficiency of the system.

The size of the regulator can be approximated by the heat sink size plus an additional 6 cubic inches for the remainder of the circuitry. The heat sinks are 1.5 inches by 1.3 inches by 4.8 inches each, or a volume of 9.3 cubic inches. Hence the total regulator volume would be approximately 25 cubic inches and would operate in an ambient temperature suitable for the converter. The weight of the regulator would be approximately 0.75 pound.

d. Converter Weight and Volume

The converter volume and weight are ascertained using three transistors on each side of the converter. Each transistor dissipates approximately 2.6 watts. Mounting the three units on a common heat sink yields a total dissipation of 7.8 watts. As before, the heat sink

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rise would be approximately 15° C, allowing an operating ambient of about 80° C maximum. The volume of the three transistors and associated heat sink would be 6.7 by 4.5 by 0.75, or 22.6 cubic inches. The total volume for both sinks would be approximately 50 cubic inches, and the total weight for this combination about two pounds. The transformer has been previously selected and is a 25-cubic-inch unit having a weight of about 4.5 pounds. Assuming a packaging density of 50%, a package volume of about 150 cubic inches and a weight of about 8.5 pounds would be obtained.

The combined volume and weight of the converter and regulator would be approximately 175-cubic-inch volume and 9.5 pounds. The volume can possibly be made smaller depending on ambient operating temperatures and packaging techniques.

C. GENERATOR HANDLING

1. Fueling

Fueling is accomplished by placing the fuel block in the upper section of the generator case. This generator and block are then placed into a generator fueling fixture. The fixture is partially evacuated to $1 \text{ by } 10^{-6}$ torr and the bottom section of the generator placed into closure position. Generator output is checked and the closure weld made on the generator case.

By evacuating the fueling fixture, a leak check can be made of the casing weld. Standard helium leak detection methods will be used by letting helium into the generator through the evacuation pinch-off tube.

The welding fixture and generator loading fixture are sophisticated mechanisms, containing motor-driven devices. All controls can be console-mounted outside the hot cell for operator convenience.

The fueled and checked generator may now be transferred to a shipping container. This container is also used in the installation procedure.

2. Diode Replacement

Diode replacement will require breaking the weld and the electrical lead to the thermal actuator. The lower end of the generator that

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contains the diodes can then be removed from the hot cell.

The operation must take place in an inert atmosphere. The procedure requires that the generator be held with the diode enclosure dome upright.

- a. Remove diode enclosure dome by breaking the braze at the diode mounting plate. The cesium reservoir fins are brazed to the dome and will come off also.
- b. Remove insulation around cesium reservoir block.
- c. Remove cesium reservoir block.
- d. Disconnect heater leads and remove heater.
- e. Squeeze reservoir bulbs together and remove bulb retaining plate.
- f. Remove support plate beneath bulb retainer plate.
- g. Remove cesium reservoir support tube.
- h. Disconnect electrical leads to diode that is to be removed.
- i. Unscrew diode and lift out.

The replacement is the inverse. Only one braze is necessary, that of the diode enclosure dome to the diode mounting plate. The electrical connections are envisioned as clamp-type connections.

The generator must be evacuated through the pinch-off tube (shown on support tube in the drawing) prior to operation after repair.

3. Transportation

The shipping cask is designed for 10 mr/hr at one meter. The cask surface temperature is about 300° F and it is therefore protected by a heavy wire mesh. This is shown in Figure 51. The head mount is provided to remove heat from the thermal actuator end of the generator and prevents overheating in these regions. The generator is held in the cask by the mounting ring. This connects to the ring on the generator that supports the generator on the satellite.

4. Launch Site Handling

The shipping cask also serves as the site handling cask. The wire screen is removed and the cask lifted off the pallet and positioned above the satellite by a crane.

A mobile personnel shield must be provided on top of the gantry to work on the generator. This is shown in Figure 52.

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Figure 51. Shipping Cask.

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Figure 52. Mobile Personnel Shield.

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The generator is installed by opening clamshell doors on the bottom of the shipping cask and lowering the generator from the cask using the cables provided as part of the cask. Independent cable support of the generator prevents cask weight from being transmitted to the satellite. The electrical connections are made automatically when the generator is lowered onto the satellite, since plug-in type connections are made in the feet of the three generator support tubes.

After setting the generator on top of the satellite, the shipping cask is swung away from the generator. A Marmon-type clamp is lowered over the generator and closed to clamp the generator to the satellite. Installation is then complete.

If the generator is to be removed from the satellite, the inverse procedure is used. The use of a shielded operator permits minor repairs to be made with the generator in place.

5. Launch and Orbit

If a mishap occurs, several explosive bolts holding the drag fin will be blown to separate it from the satellite, and one bolt holding the extension apparatus to the generator mount will be blown. This separates the generator from the satellite and the generator will impact as shown in Figure 44.

If orbit is achieved, only the bolts holding the drag cone will be blown. This will extend the generator from the rest of the satellite as shown in Figure 44. This arrangement reduces the dose rate to the satellite without using heavy shielding (2.4 inches of lead would be required), thermally isolates the generator (1500° F at some points) from the satellite, and serves to orient the satellite.

D. SAFETY CONSIDERATIONS

1. Basic Safety Philosophy

In establishing the safety philosophy for a radioisotope-powered generator, the mission requirements as well as the nature and quantity of the radioisotope fuel must be considered. Four fuels were originally studied for this application: curium 242, polonium 210, plutonium 238

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and cerium 144. The first three, being alpha emitters, are more appealing with respect to safety and handling. Cerium 144, however, was selected as the fuel for this generator because of its current availability. A mission application to MIDAS, launched from the Pacific Missile Range, was assumed.

The primary concern in establishing the safety philosophy of a system is the degree of containment of the radionuclide fuel and its radiations. The formulation of the philosophy was influenced by the following:

- a. Approximately 1.5×10^6 curies of Ce 144, a beta and gamma emitter, are required for a 250-watt generator system.
- b. The prescribed mission predicts that the generator can impact anywhere on the earth's surface from its polar orbit. The generator is directly oriented in its re-entry path by the drag fin.
- c. Land impact in an inhabited area cannot be tolerated because the dose rate at one meter from an unshielded 10^6 curie Ce-144 source is in the order of 5×10^4 r/hr.

Thus, the only adequate safety philosophy for this system is: absolute containment of the fuel in the biosphere, complete burnup and dispersion in the atmosphere above 100,000 feet, and permissible ocean release at depths exceeding 6000 feet.

The implications of using large quantities of Ce 144 for a space power application must be given careful consideration. Establishment of a safety philosophy and adherence to safety design criteria do not in themselves eliminate all risk. Use of the proposed system involves a "grey area" in which the structure may be exposed to limited aerodynamic heating effects during certain abort conditions. This could result in a partially burned-up system impacting with subsequent release of the fuel on land or in shallow water. Acceptance of this grey area is tolerable provided that the credible impact point is either over deep ocean or a nonpopulated land area. The exact boundaries of the grey area will be fully defined and evaluated as part of the final safety evaluation for this system.

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Impact of a fully contained system, even with no exposure to aerodynamic heating effects following abort, represents a hazardous situation if the impact point is over shallow water or inhabited land areas.

Any radiation exposure carries a finite probability of injury. Although it is desirable to prevent any radiation exposure whatsoever, such is not possible because of practical considerations. It is wise, therefore, to prescribe basic safety standards that are compatible with the job to be done.

2. Safety Design Criteria

The safety design criteria for this system are, to a great extent, dictated by the unusually large quantity of radioisotope fuel and the resulting magnitude of potential hazards. These criteria are formulated with respect to the various phases in the life of the generator system: specifically, prelaunch, launch, orbital and postorbital.

a. Prelaunch Criteria

The safety requirements during the prelaunch handling, transportation and checkout operations are as follows:

(1) Sufficient shielding shall be provided during transportation to comply with Interstate Commerce Commission regulations for shipment of radioactive materials. ICC regulations permit maximum dose rates of 200 mr/hr at the surface and 10 mr/hr at one meter from the isotope source.

(2) The fuel containment structure must be capable of dissipating sufficient heat to the shipping cask so that the melting point of the lowest temperature solid present will not be reached when stored in an environment with a maximum ambient temperature of 120° F.

(3) The shipping cask shall satisfy the requirements of 10 CFR 72.²²

(4) The shielding will be removed immediately prior to launch and all unprotected personnel excluded from the immediate area when the generator is unshielded.

22. Code of Federal Regulations, Title 10, Part 72.

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b. Launch and Early Ascent

An abort or other accident during this phase of operation could result in exposure of the generator system to severe structural and thermal stresses. If the containment structure satisfies the basic philosophy under these conditions, it will likely meet all safety criteria during the entire mission. The criteria for this phase of operation are as follows:

(1) Fuel containment shall remain intact if exposed to over-pressure and fire due to detonation of missile propellants.

(2) Fuel containment shall remain intact if exposed to corrosive action of missile propellants.

(3) The containment structures shall be designed to collectively withstand impact at terminal velocity upon a rigid medium. Such impact could result from an abort at altitudes where aerodynamic heating effects are insufficient for burnup.

(4) The containment structure shall resist hydrostatic pressure and corrosive action of seawater at depths up to 6000 feet for a period of time sufficient to allow decay of the contained activity to acceptable levels.

(5) Fuel containment shall remain intact when exposed to thermal conditions resulting from underground burial.

(6) Aerodynamic heating effects shall completely burn up and disperse the radiocerium fuel in the atmosphere at altitudes above 100,000 feet in the event of abort above that altitude.

This implies a "black-white" situation: no burnup below 100,000 feet, complete burnup above 100,000 feet. A grey area comprising certain abort conditions in which the structure experiences only partial burnup has not been allowed.

c. Orbital

The safety criteria do not apply during the successful orbital phase of the mission.

d. Postorbit

Since re-entry from orbit will be random and since complete

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burnup of the system is the only scheme compatible with the established safety philosophy, the safety design criterion for this phase of operation is that the entire system shall be completely consumed and dispersed, at altitudes above 100,000 feet, by aerodynamic heating effects upon re-entry from orbit.

3. Cerium-144 Fallout due to Burnup Early in Life

This analysis assumes an early orbital abort resulting in complete burnup and dispersion of the fuel above 100,000 feet. The calculations are therefore based upon burnup at the beginning of generator life, when the total activity is present. The consequences of a fuel release at any later time in life will, of course, be less severe because part or all of the activity will have decayed. MIDAS-type missions are launched in a 2000-nautical-mile circular polar orbit. A successful orbit will have a lifetime of well over 1000 years. In 1000 years, cerium 144 will have decayed below significant levels.

Maximum Activity Burden and Concentration in the Troposphere

The maximum activity burden and concentration in the troposphere resulting from an atmospheric release are of interest because this layer of the atmosphere is immediately adjacent to the earth's surface and therefore in contact with the general population. The time at which the maximum tropospheric burden occurs is calculated from Equation G8, Appendix G.

$$A_3(t) = B_1 \left[\exp \left(- (k_1 + \hat{\lambda}) t \right) \right] - B_2 \left[\exp \left(- (k_2 + \hat{\lambda}) t \right) \right] + B_3 \left[\exp \left(- (k_3 + \lambda) t \right) \right]$$

$A_3(t)$ is plotted as a function of time in Figure 53 and $t_{\max}$ is found to be 275 days. The maximum activity burden in the troposphere at this time is 5.25×10^3 curies.

The concentration of radioactivity in the troposphere is found by dividing the burden by the total volume. Recent studies of bomb fallout patterns showed that two thirds of the tropospheric burden lies between the 30° and 60° latitudes in the hemisphere where the material is released.²³

23. Eckert, Iblee, Irvine, "Prandtl Number, Thermal Conductivity and Viscosity of Air-Helium Mixtures," September 1960, NASA-IN-D-533.

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Figure 53. Cerium-144 Activity Residing in Troposphere.

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Figure 54. Cerium 144 Deposited on Earth's Surface.

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The volume of this region, for a height of 40,000 feet is $8.7 \times 10^{17} \text{ m}^3$. The maximum tropospheric concentration would thus be $6 \times 10^{-15} \mu\text{c/cm}^3$. Since the mpc* for Ce 144 in air is $3 \times 10^{-9} \mu\text{c/cm}^3$, the maximum concentration is about five orders of magnitude below the mpc.

Maximum Activity Burden and Concentration on the Earth's Surface

The time at which the maximum surface burden occurs is calculated from Equation G10:

$$A_4(t) = -D_1 \left[\exp \left(- (k_1 + \lambda) t \right) \right] + D_2 \left[\exp \left(- (k_2 + \lambda) t \right) \right] - D_3 \left[\exp \left(- (k_3 + \lambda) t \right) \right] + D_4 \left[\exp \left(- \lambda t \right) \right]$$

$A_4(t)$ is plotted as a function of time in Figure 54 and t_{max} is found to be 500 days. The maximum activity burden at this time is 4.2×10^4 curies. Figure 54 does not represent the true surface burden as the calculations do not account for washout of activity from the soil into streams, rivers and oceans. However, a conservative result may be computed by dividing maximum surface burden by surface area. Again, two thirds of the activity will lie in a 30° to 60° latitude band about one hemisphere. The surface area of a spherical segment is $2 \pi r h$, where r = sphere radius and h = segment height. For the earth, $r = 6.38 \times 10^6$ meters and h in the 30° to 60° segment is $6.38 \times 10^6 (\sin 60^\circ - \sin 30^\circ) = 2.33 \times 10^6$ meters. The surface is then 9.34×10^{13} square meters. This results in a maximum surface concentration of $4.5 \times 10^{-8} \mu\text{c/cm}^2$.

4. Causes of Aborted Missions

a. The Atlas-Agena Launch Vehicle

The booster-sustainer stage consists of two main booster engines and a sustainer engine which are fed from common propellant tankage. The propellants for this stage consist of a mixture of liquid oxygen (177,000 pounds) and RP-1 (83,000 pounds). From launch, the engines boost the vehicle to an altitude of about 250,000 feet and a velocity of about 10,000 feet per second. At this point, the outboard booster engines and skirt separate from the vehicle, and the single remaining sustainer engine continues to provide thrust until the propellants

* Maximum permissible concentration.

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are expended. At this point (altitude ~860,000 feet, velocity ~18,500 feet per second), the vernier rockets apply flight attitude correction which terminates after approximately 10 seconds of operation. After this alignment, the injection stage separates from the remainder of the booster-sustainer vehicle.

The achievement of the desired flight profile requires that the injection stage coast for about five minutes before it starts up almost at orbital altitude. From this point, it provides thrust for about 100 seconds before it injects itself and the payload into a 2000-nautical-mile circular orbit. The final stage propellants are inhibited red fuming nitric acid (4770 pounds) and unsymmetrical dimethylhydrazine (1870 pounds). These propellants are hypergolic, i.e., they ignite spontaneously when mixed.

The final stage is joined to the basement booster by an adapter section and is divided into forward, mid-body and aft sections. The forward section bears the structural loads and houses the payload and propellant tanks. The separation point between the stages is located at the lower load ring of the mid-body, where separation is accomplished by explosive bolts.

Each stage is equipped with a missile safety subsystem which provides a means of determining location, behavior and projected missile impact point to the range safety officer in addition to means of terminating powered flight and destroying the missile. The safety subsystem hardware consists of a transponder and command receivers associated with shutdown and destruct circuitry. Vehicle destruct is achieved with explosive charges placed to destroy the propellant tanks, thus terminating the rocket thrust.

b. Definition of Aborted Missions

The aborted missions described herein are typical of those that could occur with the Atlas-Agena vehicle. A comprehensive probability study of Atlas-Agena impacts and aborts has been performed for the NASA Ranger Program.²⁴ A similar study would be anticipated for the mission

²⁴. Kopecek, J. T. and Moller, J. K., "Range Safety Analysis," SSTG-TR-61-148, March 1961

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under consideration as part of the generator development safety program.

Aborted missions are of four types: launch failures, ascent failures, final stage failures, premature orbital decay and re-entry of the satellite.

Launch Failures - Launch failures are those which occur on or directly above the launch pad and cover a time span of several minutes prior to lift-off to approximately 15 seconds after the vehicle is airborne. The vehicle will be at an altitude of about 1000 feet 15 seconds after launch, and its velocity vector is vertical throughout this period.

A propellant tank failure may result from overpressurization or spontaneous structural failure. The mixture of liquid oxygen and RP-1 fuel can be ignited by sparks or hot engine components. The LOX will vaporize rapidly and some of the RP-1 will soak into the launch pad or drain into the flame bucket on the pad. Any resulting fire will be gravity fed until the collapse of the missile structure allows it to reach the unexpended fuel in the tanks. Combustion of the second stage is quite probable, but subsequent to rather than simultaneous with the first-stage combustion.

A propulsion failure can occur throughout the entire thrusting period. Failures during the launch period can be attributed to restricted fuel flow pump failure, incomplete combustion of propellants, or other malfunctions of the booster engines. Such a failure will cause the vehicle or its remnants to impact on or near the launch pad. Very low-altitude fallback failures will cause the vehicle structure to be crushed on the launch pad, releasing the propellants and resulting in a major conflagration. Airborne ignition of propellants is less serious. Due to poor mixing, diffusion of propellants and selective separation of missile components and propellants by drag, destruct charges and gravity forces, a midair fire yields less energy than fallback.

Guidance failures during the launch sequence are unlikely because the vehicle is in a vertical climb during this period. A destruct capability is incorporated in the boosters to enable the range safety officer to destroy the vehicle if its performance is significantly different from

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the desired vertical trajectory and inflight correction is impossible. Debris from vehicle destruct will be scattered over an area within the range safety impact zone.

Ascent Failures - Ascent failures are those that can occur during booster-sustainer stage operation from 1000-foot altitude up to, but not including, final stage ignition. Ascent failures to be considered are those which can occur at critical points on the ascent trajectory. Throughout the ascent phase, range safety destruct capability will be present in case of significant deviations from the prescribed trajectory.

Pitch-over is the point in the ascent trajectory at which the vehicle departs from the vertical climb to begin its downrange travel and acceleration to orbital speed. If the pitch program is not initiated or if a propulsion failure occurs at that point, the missile or its debris will subsequently impact essentially at the launch site.

Maximum dynamic pressure occurs approximately one minute after launch. At this point, maximum aerodynamic loads are imposed on the missile. After a failure, the main body of the vehicle would coast to slightly higher altitude and then impact approximately two miles downrange, still within the range safety impact zone.

The booster engines of the vehicle, attached outboard of the sustainer, deliver thrust for about 140 seconds. At that time they are separated and tumble away from the vehicle. This occurs at an altitude of approximately 250,000 feet and a downrange distance of 50 miles. A complete propulsion failure at this time would cause the vehicle to coast to an altitude of about 585,000 feet. If complete burnup were not effected at this altitude, the system would impact about 625 miles downrange.

The sustainer engine will terminate thrusting about 285 seconds after lift-off. At this time, the spent booster, injection stage and payload will be at an altitude of 860,000 feet. A failure at the time of sustainer engine burnout would cause the vehicle to coast to an apogee of approximately 1,500,000 feet. If complete burnup did not occur at this altitude, the remains of the system would impact about 2000 miles downrange.

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Final Stage Failures - Failures during final stage operation can be caused by malfunctions in propulsion, propellant feed or guidance systems. At the point of ignition, the probability of a vehicle malfunction is relatively high since a complicated sequence of events must take place. After steady-state engine operation has been achieved, the probability of malfunction is considerably reduced. Final stage failures comprise most of the grey area as discussed in a previous section.

5. Consequences of Aborted Missions

An abort during the launch or preorbital phase of the mission which does not cause complete burnup of the generator system would probably result in one of the following situations:

a. The generator might impact and penetrate the earth's surface to a maximum depth of approximately eight feet. In this condition, the intense radiations would be at least partially shielded by the surrounding earth medium. Although the impact will not breach the fuel containment, partial meltdown might occur. This will be investigated further when the final system configuration is fixed.

Impact on land is probable only in the immediate vicinity of the launch site. Recovery of the system would represent a complex operation but could be accomplished without personnel overexposure if adequate plans and special retrieval equipment were available.

b. The generator might impact on a hard surface. This condition, too, is probable only in the immediate vicinity of the launch site. The fuel containment structure will not be rendered ineffective either by impact or subsequent fire, thus precluding widespread contamination of the environs.

c. The system might impact in shallow offshore water. The mechanical forces imposed on the containment structure would be less severe than in the case of land impact. Contact between cold water and the hot fuel capsules could result in severe thermal shock. Further investigation is necessary to determine the magnitude of this problem. Recovery operations would be aided by the shielding effect of the water. The ocean on the

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launch azimuth is about 70 feet deep one mile from the shoreline. At four miles out, the water is 250 feet deep; the bottom is relatively smooth and sandy. Recovery of the generator from shallow water (up to 500-foot depth) will be effected if possible, as its presence represents a potential hazard. Recovery of aborted vehicles impacting in shallow waters is presently carried out in depths up to a few hundred feet.

d. Impact in deep downrange water is the most likely fate of the generator following an abort which does not result in burnup of the system. Deep-water impacts can theoretically occur at depths up to 36,000 feet. The generator would come to rest on the ocean bottom and there would be no attempt at recovery. The fuel containment will resist hydrostatic pressure forces and corrosive action of the sea at depths up to 6000 feet (2680 psi) for sufficient time to reduce the activity to an acceptable level. Even if all of the cerium 144 were released at depths below 2000 feet, no appreciable hazard would exist. Vertical diffusion below the thermocline layer of the ocean (2000-foot depth) is nil and it would take hundreds of years for water from that depth to reach the surface. Water from depths greater than 6000 feet probably never reaches the upper, or mixed, layer of the ocean. Furthermore, horizontal dispersion is rapid and activity concentrations decrease exponentially with distance from the source.

The radiocerium could enter the biological cycle through ingestion by marine organisms. Fish tend to concentrate cerium in their bodies to an equilibrium concentration 8000 times greater than ambient.²⁵ Although commercial fishing does not extend below 6000 feet, the radiocerium could conceivably be escalated to this depth by means of marine food chains.

6. Consequences of a Total Activity Release to the Ground

No accident could be more severe than one which results in total release of the radiocerium fuel on or near the ground. The fuel form to be chosen is likely to undergo spontaneous oxidation on contact with air. The credibility of such an accident cannot be established in this

25. "Radioactive Waste Disposal Into Atlantic and Gulf Coast Waters," National Academy of Sciences, National Research Council, Publication No. 655, 1959.

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feasibility study. However, the basic safety philosophy of this system design is to prevent the occurrence of such an event. An analysis was performed to estimate the order-of-magnitude consequences of a hypothetical release. The analysis is predicated on the following valid but highly conservative assumptions:

- a. The release occurs in the immediate vicinity of the launch pad.
- b. The total quantity of radiocerium fuel (1.55×10^6 curies) is instantaneously released as a cloud.
- c. The horizontal axis of the cloud does not rise, but remains at a height of 10 meters from the ground.
- d. Meteorological parameters at the Pacific Missile Range approximate average conditions.²⁶

Sutton's equation²⁷ for an instantaneous source is given as:

$$\chi = \frac{2Q}{\pi \left(\frac{3}{2}\right) (c^3) (d^3) \left(\frac{2-n}{2}\right)} \exp \left[-\left(\frac{x^2}{(c^2)} + \frac{y^2}{(d^{2-n})} + \frac{h^2}{(d^{2-n})} \right) \right]$$

where: χ = radioactive cloud concentration at ground level and vertical center line of cloud, $\mu\text{c/cc}$

Q = source strength = 1.55×10^6 curies

c = diffusion coefficient = 0.4 meters

d = downwind distance from point of release, meters

n = nondimensional stability parameter = 0.25

x = downwind distance from cloud center = 0

y = crosswind distance from cloud center = 0

h = height of plume = 10 meters

The values chosen for c and n are assumed average values since these data are not available for conditions at the PMR; x and y = 0 because concentrations at ground level, 10 meters below the geometric center of the cloud, are desired.

26. Newcombe, C. L., "Evaluation of Radiation Hazards Associated with Operation of Nuclear Powered Space Units at Pacific Missile Range," U.S.N.R.D.L. TR-545, February 1962.

27. "Meteorology and Atomic Energy," U.S. Department of Commerce, Weather Bureau, July 1955.

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The cloud concentrations at various downwind distances from the release are presented in the following table:

Radio Cloud Concentrations as a Function of
Distance from Source

<u>Distance from Release, Meters</u>	<u>$\left(\mu\text{c}/\text{cm}^3 \right)$</u>
50	1.5×10^2
100	4.0×10^1
200	7.5×10^0
500	5.2×10^{-1}
1,000	1.2×10^{-1}
5,000	1.7×10^{-3}
10,000	2.7×10^{-4}
50,000	4.0×10^{-6}
100,000	6.5×10^{-7}
500,000	4.0×10^{-9}
1,000,000	1.5×10^{-9}
5,000,000	2.3×10^{-11}

The calculations show that the center line cloud concentrations would be above the mpc ($3 \times 10^{-9} \mu\text{c}/\text{cc}$) for a distance of approximately 300 miles from the source. The cloud concentrations at locations other than the center line would, of course, be considerably lower.

The absolute values of radioactive cloud concentrations are not significant in a study of this nature. The magnitude of the concentrations do, however, show that a ground release would be intolerable at the Pacific Missile Range launch site.

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V. USE OF OTHER FUELS IN THE
CERIUM-144 GENERATOR DESIGN

A. INTRODUCTION

A short study was performed to illustrate the use of the fuels Pu 238, Po 210 and Cm 242 in the Ce-144 design. It was specified that the entire diode portion and the generator diameter would remain unchanged. Changes were allowed in the crushable structure, generator length, thermal control and fuel block. The analytical background for this work is given in Appendix E. No analysis was done in regard to the impact structure.

The use of these alpha-emitting fuels in the Ce-144 generator presents a misleading picture, since the generator is poorly suited for the application. The generator is designed to burn up upon re-entry from orbit, a requirement inconsistent with large quantities of long-lived alpha-emitting fuels. The weight and efficiency are considerably poorer than would be expected from a generator specifically designed to utilize a specified fuel.

The conceptual generators studied in this section are not operational in the sense that they provide fuel burnup during re-entry. An arrangement that might meet these criteria is shown in Figure 55. No careful attempt was made in this study to design the fuel block to withstand impact. However, the generator case illustrated could be designed to remain intact. Electrical leads passing through the generator case would comprise the primary problem.

The alpha-emitting fuels were considered under the assumption that significant helium gas pressure would be released from the capsule.

B. PLUTONIUM 238

The Pu-238-fueled generator has a computed efficiency of 8.6%, a design life of 1 to 5 years, and weighs 111.5 pounds. A weight summary is presented in Table 8.

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Figure 55. Plutonium Generator.

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~~CONFIDENTIAL~~TABLE 8WEIGHT SUMMARY

250-Watt(e) Plutonium Generator

<u>Item</u>	<u>Weight, Pounds</u>
Fuel	14.5
Fuel capsules	16.0
Fuel block	4.0
Fuel block cladding	3.0
Diode hot side radiator	4.0
Thermal shields	4.0
Diode mounting and radiator	14.0
Cesium reservoir and miscellaneous items	1.5
Diode assemblies	17.0
Insulation	1.0
Outer shell	14.0
Crushable structure	16.0
Miscellaneous electrical and mechanical items	<u>2.5</u>
Total	111.5

Note that the fuel clad weight is 16 pounds, and the fuel block another 7 pounds. These capsules are small enough that they might impact intact with no slowing down or orientation necessary.

The thermal actuator and control has been eliminated since the heat production rate of the fuel is relatively constant. The only other changes were a reduction in impact structure (which could probably be completely eliminated by careful design with the smaller fuel capsules), a shortening of the fuel block, and a shortening of the generator.

The thermal efficiency could be increased by making the fuel block diameter and height equal. This would decrease the surface area per unit volume and consequently the heat losses. Such a change would be consistent with the diode design, but the diodes would have to be moved to fit on the fuel block.

C. CURIUM 242 and POLONIUM 210

The use of Cm 242 and Po 210 in the Ce-144 generator is treated by considering only Cm 242 since the two fuels are quite similar. The

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resulting design could be used with either fuel.

Curium 242 leads to a generator that is 10.2% efficient at the end of life with a design life of six months. The generator's design weight is 88 pounds. A weight summary is given in Table 9.

TABLE 9
WEIGHT SUMMARY

<u>Item</u>	<u>Weight, Pounds</u>
Fuel plus matrix	1.0
Fuel capsule	5.0
Fuel block	3.0
Fuel block cladding	2.0
Diode hot side radiator	4.7
Thermal shields	2.5
Thermal shutter	1.5
Diode mounting and radiator fin	14.0
Cesium reservoir and miscellaneous items	1.5
Thermal actuator and linkage	1.8
Diode assemblies	17.0
Heat dump plate and shell cladding	13.0
Insulation	1.0
Outer shell	10.0
Crushable structure	7.0
Miscellaneous electrical and mechanical items	<u>3.0</u>
Total	88.0

A number of changes from the Pu-238 concept are necessary. A heat dump is required, but with the small fuel block height, there is insufficient area on the side of the block to reject the heat. The actuator would therefore be used to open ports in the top of the thermal shields. The heat would be rejected to a heat sink plate and then into the generator skin. The crushable structure would probably be unnecessary. There is no question regarding the ability to impact the Cm-242 fuel capsules since they would be extremely small, and relatively large quantities of clad material could be used to provide high strength, provided the theoretical amount of helium produced does not have to be contained.

D. SAFETY WITH ALPHA-EMITTING FUELS

1. Safety Philosophy

Complete burnup and dispersion upon re-entry from orbit was the course prescribed for the cerium-fueled system. However, the assumed safety

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philosophy adopted for generators containing large quantities of alpha-emitting fuels is that of absolute containment at all times under all conditions, or, in other words, intact re-entry.

Intact postorbital re-entry and earth impact are accomplished by using ablative or heat-absorbing materials to combat aerodynamic heating or high-strength, high-temperature containment materials to withstand impact. The advantages of intact re-entry over high-altitude burnup are as follows:

a. The release of large quantities of radioactivity to the environment represents a finite hazard to the world's inhabitants. Numerous studies have been conducted to determine the phenomena governing environmental dispersion, decay and fallout of radioactive particulate matter. Although the basic physical principles are understood, experimental data are, at the present time, inconclusive. There is undoubtedly a limit to the quantity of activity which man can release to the biosphere before the danger or saturation point is reached. It is therefore judicious to minimize the release of activity to the environment.

b. Intact re-entry does not involve the grey area which is present in a system designed for re-entry burnup. The grey area comprises certain abort conditions in which the structure experiences only partial burnup preceding impact.

c. Intact re-entry is the only scheme which assures control and accountability of the isotope at all times in the biosphere.

The above discussion is not intended to negate the choice of re-entry burnup for the design of the cerium-fueled generator. While intact re-entry is advantageous for alpha-emitting fuels, it is not suitable for large quantities of beta and gamma emitters unless controlled re-entry at the predetermined point on the earth's surface can be effected. The reliability of current control systems is insufficient to meet the established safety requirements.

2. Safety Design Criteria

The basic safety design criteria established for the cerium generator are applicable to the alternate fuels, with one major exception.

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The generator structure, in this case, must be covered with an ablative or heat-absorbing material and be capable of surviving the most stringent aerodynamic heating regime which it might encounter during re-entry into the earth's atmosphere. The structure must also survive subsequent earth impact at terminal velocity. An additional consideration necessitated by the use of alpha-emitting fuels involves the phenomenon of gas generation. Studies are presently being conducted to determine whether significant helium gas pressures are produced as a result of alpha decay. The criterion adopted for this generator is that all gas generated, directly or indirectly, by radioactive decay shall be leaked from the capsule if large quantities of gas are generated.

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VI. DEVELOPMENT AND TESTING

This design has been generated on the basis that development would be kept to a minimum. However, considerable work is still necessary to assure proper functioning of the design.

A. RELIABILITY

1. Introduction

Reliability is becoming more important in the isotope generator field. Therefore, a program is described in this section to investigate reliability in a practical manner.

2. Program Description

The reliability efforts during the initial development phase of this generator system should be based on the "best estimate" of reliability. As the work progresses, improvement will be directed toward providing 50% confidence and 90% reliability.

When a specific mission has been determined and firm reliability requirements established for that mission, a reliability demonstration program can be proposed. The demonstration program should consider all development tests.

3. Method of Investigation

The existent test data should be reviewed to establish the characteristics of each device that must be improved and to indicate the best course for improvement. Reliability characteristics such as life, failure rate, parameter degradation and design safety margins should be included.

Failure during testing must be analyzed to determine causes and to indicate the proper redesign. Test data analysis can also provide information for other design decision, to evaluate parameter distribution, and to estimate reliability. The recommended techniques include:

- a. Analysis of Variance - Factorial Analysis and Latin Square techniques.
- b. Estimation of mean and standard deviation.
- c. Confidence interval estimation of Mean-Time-To-Failure and Mean-Time-Between-Failures.

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Estimation of parametric values requires that some assumptions be made. The following assumptions appear reasonable unless the data prove them invalid:

- a. Wearout characteristics are normally distributed.
- b. Random failures occur at a constant rate after an initial period of high failure rate.
- c. The initial "high-failure" period is 50 hours.
- d. The tested items are indicative of final produced items if the design is unchanged.
- e. Parameter values are normally distributed.

4. Reliability Formulation

One of the objectives of reliability studies is the definition of system reliability requirements which are realistic and that, when considered in combination with all other pertinent design factors, optimize the balance between reliability and total cost. Where similar programs are being carried on in different areas, it is necessary that control information facilities be established to avoid needless duplication of testing.

Prior to manufacturing test apparatus, it is necessary that specifications and standards be established for use in manufacturing and inspection.

When design changes or changes in requirements are dictated, the change should take into consideration the effect on the reliability of the system. The same design considerations given to the basic design to produce a reliable system should be applied to the change.

5. Quality Assurance Provisions

The reliability program should include provisions for review and evaluation of significant designs before they are finalized. Test and failure data should be used for corrective action as early as possible in the design phase.

A planned and scheduled test program should be conducted during design and development phases to estimate reliability achieved and to provide for feedback of data to be used as a basis for making reliability

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improvements. All items having a significant bearing on the inherent reliability should be tested as early as practicable in the development program. This will tentatively establish that the item is suitable for the system application.

Manufacturing processes should be controlled to assure that variations which occur do not excessively degrade the design reliability. The program should include investigation and analysis of failures during production.

B. TESTING

1. Introduction

The objective of the test program is to provide detailed information about generator subsystems, generator assemblies, and the thermionic system as a whole. Reliability test information will be obtained for the subsystems, rather than for the complete thermionic system. A reliability evaluation of the complete system would require large quantities of time and money and is not considered feasible.

A successful reliability test for each subsystem requires that seven of each final subsystem design be life tested without failure. Seven of each should be considered a required minimum to provide approximately a 50% confidence level at 90% reliability.

2. Development Program

Completion of a successful development program requires parametric testing of subassemblies as discussed in the following subsections.

a. Diode Assembly

Cesium Seal

The cesium seal configuration should be tested to determine its sealing and cesium-corrosion-resistance capabilities for a period of 10,000 hours. Previous testing of cesium seals of similar design and materials have been completed for a period of 1000 hours at higher than the design temperature of 600 to 800° K. These tests have shown that the materials of construction are compatible at design temperatures and that cesium corrosion was negligible. However, further testing is

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required to prove the seal integrity for 10,000 hours.

The seal assemblies should be tested by weighing each seal, helium leak testing, and then backfilling with cesium. The seal assembly should be subjected to this cesium atmosphere at 600 to 800° K for 10,000 hours and then reweighed to determine weight loss and leak tested to prove integrity.

Diode Spacer

The diode ring spacers should be evaluated to determine creep-resistant qualities and structural strength over the expected temperature range. The emitter and emitter backup plate are supported by the spacer and, during testing, this mass should be simulated by a mock-up of similar materials.

Diode Characteristics

A variable-spacing flat plate device utilizing iridium as the emitter should be used to determine the optimum spacing. Preliminary work has been started in this area but significant results have not yet been obtained.

After determining the optimum spacing, a flat plate diode should be constructed and tested to determine E-I characteristics. The isotopic fuel source can be simulated during the test by an electrical heater. Improvements in design are to be consecutively incorporated in succeeding diodes.

Cesium temperature should be monitored during the diode tests to determine the optimum temperature required for maximum power densities and efficiencies. Required accuracy of cesium temperature must also be determined during these tests.

Alumina Insulator

The production of an electrically insulating but thermally conducting alumina insulator between the collector and spacer ring necessitates development. However, since this is not a vacuum-tight seal the problems should not be great. By employing niobium next to the ceramic to reduce stresses and by slotting the ceramic radially so that it will break across rather than parallel to the interface, a

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thermally conducting path would be provided. The feasibility of accomplishing this must be proven. Once this is shown to be feasible, the reliability will be determined by diode module tests.

Emitter Lead Compatibility

Techniques must be developed for electron beam welding the tantalum-10 tungsten spacer ring to the niobium which is adjacent to the alumina insulator. Although no problem is anticipated, it must still be proven by hardware development tests.

Diode Module

A diode module consists of a flat plate diode and spacer, cesium seal and cesium reservoir. After proving out the various components of the module, it is necessary to assemble the module for testing to determine its thermionic and thermal characteristics.

Test data must be obtained for 10,000 hours or until such time that the modules exhibit a constant failure rate to fulfill the reliability requirements. Operating conditions during testing will have been previously determined from module component tests.

The final diode module configuration must undergo dynamic testing to determine its shock and vibration capabilities. A mock-up of the diode support structure can be used for these tests. After successful completion of dynamic testing at design conditions, the diode module should be tested to destruction.

During the dynamic tests, the diode must be operating at design conditions. The isotopic fuel can be simulated by electrical heaters.

Series Connection Test

Successful operation of series-connected diode modules depends upon the similarity of certain critical parameters. Some of these parameters are the cesium and emitter temperature and the voltage across each diode. A test program should be undertaken to determine the degree of similarity required and the action necessary to minimize conditions causing dissimilarity when six diodes are connected in series.

b. Thermal Shutter

Thermal Mock-Up

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A thermal mock-up of the fuel block and thermal shutter should be tested to determine the system heat dissipation capabilities. The fuel block and fuel may be simulated by means of similar materials and electrical heaters. However, the thermal shutters must be identical to the flight article.

Control System

The thermal shutter control system is dependent on the output current from the thermionic converter. A current higher than design indicates that the fuel block is exceeding design temperature. As a result, power to the heater in the control system is reduced causing a decrease in the NaK temperature. Thermal contraction of the NaK causes the shutter to open, thus dissipating excess heat.

A test program should be instigated to determine the accuracy and structural integrity of the control system. A mock-up of the system may be tested to determine the capabilities of NaK containment under all the thermal and environmental conditions.

Power requirements of the heater should be determined along with the best method of heater control. A proportional-type control may be more desirable than on-off control. Heater integrity must be evaluated for this application. Continuous cycling of the heater may result in early failure and thus failure of the complete system.

In all cases, exact conditions must be simulated for the design lifetime or until a constant failure rate is obtained.

c. Cesium Control System

Cesium reservoir temperature control is dependent upon a resistance heater and a thermistor. The relatively low temperature of the reservoir allows use of conventional thermistors. This will control heater operation by either on-off switching or continuous control.

The cesium reservoir control system should be tested to determine the power requirements of the heater and the accuracy and response time of control. Use of an on-off or continuous-type control must also be determined.

Structural integrity of the system must be evaluated for all

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environments while the system is operating at design conditions.

d. Fuel Block

Structural Support

The fuel block is supported by means of a ring channel and thermal shields. This type of support has not been used previously and must be evaluated. A mock-up of the fuel block and support mechanism should be tested to evaluate its characteristics during shock and vibration design conditions.

The application of alumina to the thermal shields requires development. A number of methods are possible (we have previously discussed only the first method):

(1) Flame spraying followed by grinding to the desired thickness and vapor deposition. Difficulties might be encountered in flame spraying as the tantalum foil must have its surface roughened to produce mechanical adhesion. This roughness might be more than the desired thickness.

(2) Application of aluminum to tantalum followed by anodization of the aluminum.

(3) Electrophoretic deposition of alumina followed by sintering. The best technique must be determined and the process developed.

Materials of Construction

Graphite clad with rhodium and tantalum alloy will be used to contain the fuel capsules. Graphite outgassing at high temperatures may cause pressure buildup in the fuel block. A small development program should be undertaken to determine the best methods for prevention of graphite outgassing.

The compatibility of rhodium with the cerium fuel forms has not been determined. Experiments at a temperature above the highest anticipated operating temperature should be run for extended periods to determine compatibility. Although the phase diagrams indicate no problem between graphite and rhodium, compatibility studies between these materials should also be run for an extended period.

Rhodium is a relatively brittle material and a process for shaping it must be developed. Since rhodium is not normally used in such

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applications, a technique for welding should be developed.

Some consideration should be given to welding the tantalum alloy block case with this large a diameter. Problems may also occur with the rhodium liner when the outside case is welded. This must be investigated.

Since the block outside case is composed of a new alloy containing a relatively volatile constituent, hafnium, further work will be necessary to determine the compatibility of this material with a high-vacuum environment.

3. Generator Testing

a. Electrically Heated Models

Parametric Testing

Prototype generator models should be tested to determine the operating parameters of the conversion system. Data points should be obtained so that an E-I plot can be determined. From these data, necessary design changes can be determined and incorporated into succeeding generators.

Dynamic Tests

After completion of parametric testing, the prototype generators should undergo dynamic tests. With the isotopic fuel simulated by electrical heaters, the generator should be subjected to the design shock and vibration loads. During this test, the generator must be operating normally at design conditions.

Environmental Tests

The prototype generators must be capable of operating at design conditions in various environments. Therefore, an electrically heated generator should be tested to determine its operating characteristics in various environments. These environments can be specified after mission definition.

After completing the dynamic and environmental tests, the generator should be checked to determine if any operating parameters have changed.

b. Acceptance Tests

Fueled Generators

The final flight article must be tested in accordance with acceptance specifications. A complete system with the exception of the isotopic

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The dc-dc converter is designed using present state-of-the-art devices and techniques. Further work in the following areas could improve the size and efficiency:

- (1) The utilization of circuit techniques to reduce the switching losses of the transistor switches.
- (2) Mathematical analysis to choose the optimum number of transistors for a given efficiency, size and weight.
- (3) An analysis of the parameter changes with temperature and the design of suitable compensating devices.
- (4) Hybrid switching techniques to lower the present semiconductor losses.
- (5) Optimizing transformer efficiency versus weight.

Of the above, Items 2, 3 and 5 could be a study program with little or no experimental data required. Items 1 and 4 are considerably beyond present state-of-the-art techniques and would require experimental as well as theoretical work.

5. Handling Procedures

a. Fuel Capsules

Capsule Handling

Hard gamma radiation emitted by the proposed fuel (Ce 144) necessitates remote handling procedures. To acquaint hot cell facility personnel with the required handling methods, several trial runs demonstrating fuel encapsulation will be accomplished using dummy fuel capsules and fuel.

Demonstration runs will also be required for fueling and defueling the generator remotely. As before, dummy fuel blocks will be used.

b. Fueled Generators

Closure and Check-Out

Final closure and system check-out will require remote handling methods. Therefore, a demonstration device will be used to show system closure and check capabilities. Electrical heaters will be used to simulate the isotopic fuel.

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6. Fuel Form

It has not been possible to recommend a fuel form that meets all of the criteria. A program is necessary so that an intelligent decision can be made between cerium metal, the carbide or the sulphide.

7. Safety Tests

Analytical techniques are used in establishing safety design criteria and specifications on the basis of poorly defined theory. Thus, it is necessary to prove the validity of the analytical results by testing. These tests utilize a series of test specimens to investigate the safety and integrity of the system when subjected to the most stringent framework of conditions in terms of mechanical, thermal and chemical forces.

A comprehensive safety test program is of paramount importance in the design of this system because of the magnitude of the potential hazards associated with the required fuel quantity. Since the nuclear safety of the entire system is fundamentally determined by the degree of containment of the radionuclide fuel, particular emphasis must be placed on the fuel containment structures. Thus, the program should be designed to evaluate the performance of the generator structure under simulated conditions of terminal velocity impact and the thermal and pressure environment of a missile abort.

a. Terminal Velocity Impact Test

The objective of this test is to determine the structural integrity of the fuel containment. The generator would experience maximum forces if aborted from the launch vehicle prior to orbital injection and then impacted at terminal velocity upon a rigid material such as granite.

Full-scale simulated generators and fuel capsules at operating temperature should be impacted on granite at velocities equal to and exceeding the terminal velocity of the operating system. The specific test parameters should include impact pressures as a function of time, density of compressed material, velocity of the specimen and flow patterns in the specimen.

Test sample mass and dimensions should be measured before and after impact. Impact velocity may be measured by means of high-speed

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photography. Following impact, the specimens should be inspected visually and radiographically to determine whether fuel containment has been breached.

b. Thermal Environment Test

The system would experience maximum thermal effects if subjected to a missile fire on the launch pad. The thermal environment test should be designed to subject specimens simulating complete generators, fuel blocks and fuel capsules to an environment equivalent to that of a burning missile. The specific purposes of the test are to determine the heat fluxes generated by a burning missile and the effect upon the thermal integrity of the fuel containment structures.

c. Plasma Jet Tests

The basic design philosophy for this system requires complete burnup during orbital re-entry at altitudes above 100,000 feet. Although plasma jet tests do not duplicate all re-entry heating conditions, the high stagnation heating rates attainable provide absolute assurance that the system will be consumed under given conditions; they will predict the relative properties of the various materials tested.

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VII. CONCLUSIONS AND RECOMMENDATIONS

An accurate analysis of the system and its potential has been made. It is concluded that the Ce-144 generator system is feasible, and can be developed in approximately three years. The Ce-144 fuel would cause a significant problem, and very careful consideration of its containment is necessary.

Two 250-watt generator subsystems were considered in the design study to provide reliability by redundancy and decreased fuel handling requirements for a 500-watt(e) system. A single 250-watt subsystem also provides flexibility in meeting a 250-watt(e) requirement.

The weight for a 250-watt generator subsystem, satellite mounted, with an operational life of one year is:

Generator	143 lb
Converter	9.5 lb
Drag Fin	<u>37 lb*</u>
Total	≈ 190 lb

A consideration that could save weight and simplify the generator impact problem involves the entire satellite package. If the terminal velocity of the satellite with the generator attached can be lessened, considerable weight could be saved. It would be required in this situation that the satellite not break up in an abort. This situation cannot be considered, however, until the entire system is more firmly defined.

The use of Pu 238 in this generator design is attractive, but not recommended. A design specifically adapted to Pu-238 fuel would be more efficient.

The availability of Pu 238 should be carefully considered. A priority assignment in this area could result in quantities of fuel that would become available at approximately the same time as the generators. This system is quite attractive, and generators in the weight range 90 to 120 pounds per 250-watt system could result. Mechanical heat dump techniques would not be required.

* Double usage as generator launch vehicle support structure and satellite skin.

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The use of Cm 242 or Po 210 for this application requires too much fuel in comparison to the availability.

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APPENDIX A - GENERATOR STRUCTURAL ANALYSIS

OUTLINE

I. General Criteria

1. Description of Generator
2. Loading Considered
3. Impact Load Criteria
 - a. General Considerations
 - b. Energy Balance Method
 - (1) Selection of U values (unit strain)
for cushion elements
 - (2) Strain energy values and physical
properties of generator materials

II. Analysis

1. Generator Weights
2. Stress Analysis, Steady-State Loading
3. Impact Analysis of Fuel Containment Structure
 - a. Loading and Critical Components
 - (1) Dynamic Pressure (g)
 - (2) Inertia Load (P)
 - b. Expression for Maximum Stress
 - c. Stress and Margin of Safety Calculation
4. Preliminary Design of Impact Cushion
5. Sizing of Drag Cone for Optimum Design
 - a. Strain Energy and Terminal Velocity
 - b. Calculations for Available Strain Energy
 - c. Size Drag Cone

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I. GENERAL CRITERIA

1. Description of Generator

The generator consists of a rectangular cylinder ending in a hemispherical dome provided with a drag cone and a heat sink cone

The interior houses the fuel cell, its equipment and an impact cushion which protects the fuel cell

The assembly is all welded or brazed. The materials of construction are:

Cylinder - René 41

Heat radiator - copper

Drag cone - titanium alloy (later changed to aluminum)

The drag cone is reinforced by a Marmon-type ring flange.

2. Loading Considered

In this analysis two loadings shall be considered:

a. Steady state - one atmosphere external pressure

b. Impact - maximum kinetic energy developed by the generator

when considered as a free-falling projectile.

3. Impact Load Criteria

a. General Considerations

Because present literature and/or empirical equations are only available for impact effects where the condition of the projectile is unimportant (such as piercing a concrete wall with a high-velocity shell), it will not be possible to present a classical solution for the impacting of a thermionic generator over all types of impact surfaces. Also, since the behavior of metals under semi- or plastic

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conditions has not been finally established, use is made of approximate solutions to evaluate the metal's capacity to absorb energy. The most important aspect in the present problem is to protect the fuel cell from disintegrating after impact. For the above reasons, the steps followed in the analysis are at best approximate and usually predicated on certain assumptions.

The physical properties of the impacting bodies, such as hardness, toughness, elastic properties, density and bulk modulus, interact to cause deformation, shortening, spreading or rupturing in both colliding bodies. The final condition of these bodies (especially the projectile) is the main concern of this study. Only by providing areas of large strain absorption is it possible to protect the projectile (thermionic generator) from disintegrating. In general, the analysis was made practical by:

- (1) Reducing the terminal velocity through the addition of drag surfaces.
- (2) Providing aerodynamic stability to assure a collision at one definite point.
- (3) Using high-strength materials with large final deformation at given operating temperatures.
- (4) Proportioning the cushion elements to secure a uniform (instead of local) deformation.

b. Description of Energy Balance

An energy balance method was used for evaluating the effects of impact where the energy input, viz., the kinetic energy developed by the falling generator mass, was applied to the generator inertia cushion and balanced by the developed strain energy of the deformed cushion.

A general expression is developed as follows:

$$K.E. = UV \quad \text{Eq. (A1)}$$

where K.E. = kinetic energy at impact (in.-lb)

U = unit strain energy spent in
deforming cushion (in.-lb/in.³)

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V = volume of cushion (in.³)

now

$$K.E. = 1/2 [m_o + m_1] v^2 \times 12 \quad \text{Eq. (A2)}$$

where

m_o = mass of fuel cell (slugs)

m_1 = mass of fuel cell cushion (slugs)

v = impact velocity (ft/sec)

and

$$U = 1/3 \frac{e}{100} [F_{TY} + 2F_{TU}] \quad (\text{Ref. 28})$$

Where

e = percent elongation (%)

F_{TY} = material yield strength (psi)

F_{TU} = material ultimate strength (psi)

now let $K_2 = \frac{F_{TY}}{F_{TU}}$ and $K_1 = 2 + K_2$

thus

$$U = \frac{e}{300} F_{TU} K_1 \quad \text{Eq. (A3)}$$

substituting Equations A2 and A3 into A1

$$6 [m_o + m_1] v^2 = \frac{e}{300} F_{TU} K_1 V$$

rearranging

$$m_1 = \frac{e}{1800} \frac{K_1 V}{v^2} - m_o \quad \text{Eq. (A4)}$$

where

$$m_1 = \frac{\text{cushion weight}}{\text{accel. of gravity}} = \frac{W_1}{g} = \frac{W_1}{32.2}$$

$$m_o = \text{weight of fuel cell} = \frac{W_o}{32.2}$$

thus Equation A4 in terms of W_1 and W_o becomes

$$W_1 = \frac{0.0179 e K_1 V}{v^2} - W_o$$

28. Merriman, M., "Mechanics of Materials" 11th edition, 1916. P 306.

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(1) Criteria for selection of strain energy (U) values for cushion elements.

The true value of U depends on

- (a) Stress distribution over cushion.
- (b) Buckling characteristics of its components.
- (c) Material properties at operating temperature.
- (d) The type of protection required for the fuel cell in case it impacts other than normal to the impact surface.

(2) Strain energy (U) values and physical properties of generator materials.

The materials used in the construction of the thermionic generator and their available unit strain energy with other physical properties are shown in Table A1.

II. ANALYSIS

1. Generator Weights

The generator is broken down into two sections for the purpose of weight calculations.

Section 1 - Drag fin and impact cushion.

Section 2 - All other components.

Section 2 weights are further defined as the generator "fixed-weight" and are listed in Table A2.

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TABLE A1
STRAIN ENERGY AND PHYSICAL PROPERTIES
OF GENERATOR COMPONENT MATERIALS

1	Material	Titanium	René 41 R	Ta-8W-2 Hf	Rene 41.2
2	Designation	6 Al-4V	Ref. 32	Fig. D3	Ref. 32
3	Operating °F	800	1500	2800	1000
4	F_{tu} , psi	82000	126000	25000	203000
5	F_{ty} , psi	72000	118000	22000	147000
6	e, % elongation	10	14	63	14
7	E, psi (Young's modulus)	11.7 (10) ⁶	24 (10) ⁶	24.2 (10) ⁶	27.2 (10) ⁶
8	u, lb/in. ³ (density)	.163	.30	.71	.30
9	$K_2 = (5)/(4)$	.878	.937	.880	.724
10	e/300	.0333	.0467	.210	.0467
11	$2 + K_2 = 2 + (9)$	2.878	2.937	2.880	2.724
12	$F_{tu} (11) = (4) \times (11)$	236000	370060	72000	553000
13	$U \text{ in.-lb/in.}^3 = (12) \times (10)$	7860	17204	15120	25825
	Reference	ANC-5 Mar. 1954	Ref. 32	-	Ref. 32

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2. Stress Analysis, Steady-State Loading

Applicable generator components are evaluated for an external pressure loading of 1 atmosphere. A sketch of these generator components showing overall dimensions is as follows:

- A - Cylinder
- B - Semisphere
- C - Short Cylinder
- D - Upper Dome
- E - Clamp
- F - Flat Bulkhead

The analysis of components is as follows:

Cylinder (Part A)

Design pressure = 14.7 psi (external)

Material - inconel SB-168 as rolled (Ref. 29)

Design temperature = 800° F

$F_{TU} = 85,000$ psi ; $E = 26.7(10)^6$ psi

$F_{TY} = 20,000$ psi ; % elongation = 47%

Allowable collapsing pressure, P_c , (Ref. 30)

$$P_c = \frac{t_c}{R} \left[\frac{F_{TY}}{1 + 4 \frac{F_{TY}}{E} \left(\frac{R}{t}\right)^2} \right]$$

29. Technical Bulletin, T-T September 1959, INCO Alloy Products, 67 Wall Street, New York 5, N. Y.

30. Roark, "Formulas for Stress and Strain," 3rd Edition, P258.

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Assuming t_c = shell thickness = 0.072 in.

R = shell avg radius = 4.875 in.

P_c = 20.04 psi

$$\text{Margin of Safety} = \text{M.S.} = \frac{P_c}{P_{\text{actual}}} - 1 = 0.35$$

Semisphere (Part B)

Material elastic constants: $E = 22.695(10)^6$ psi

$\nu = 0.29$

Allowable collapsing pressure, P_c , (Ref. 30, page 306)

$$P_c = \frac{2Et^2}{R^2 \sqrt{3(1-\nu^2)}} \quad \text{where } t = 0.062 \text{ in.}$$

$$R = 4.88 \text{ in.}$$

P_c = 4420 psi, M.S. large

Short Cylinder (Part C)

Material properties and expression for critical pressure
same as for Cylinder (Part A)

$t = 0.064$ in., $R = 3.65$ in.

P_c = 32.6 psi

$$\text{M.S.} = \frac{32.6}{14.7} - 1 = 1.22$$

Upper Dome (Part D)

thickness = $t = 0.64$ in.

By inspection, the upper dome is satisfactory.

Flat Bulkhead (Part F)

Material - Copper (soft)

Properties @ 800° F

$F_{TU} = 4700$ psi (Ref. 31)

$F_{TY} = 15000$ psi (Ref. 31)

31. Marks, L. S., "Mark's Handbook," 5th Edition, 1951, P598.

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TABLE A2
WEIGHT SUMMARY, FIXED WEIGHTS

<u>Item</u>	<u>Description</u>	<u>Weight</u>
1	Fuel	19.5 lb
2	Fuel Cladding	2.2
3	Fuel Block	8.0
4	Fuel Block Cladding	3.9
	a. Rhodium	
	b. Tantalum 10W	
5	Diode Radiator Plate	4.7
6	Thermal Shields	
	a. Fixed	3.0
	b. Movable	2.0
7	Diode Mounting and Radiator Fin	14.0
8	Cesium Reservoir and Miscellaneous Items	1.5
9	Thermal Actuator and Linkage	1.7
10	Diode Assembly	17.0
11	Heat Dump Radiator Members and Cladding	9.5
12	Insulation	1.0
13	Outer shell	18.5
14	Miscellaneous Electrical and Mechanical Hardware	<u>3.0</u>
	Total	109.5 lb

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$$\text{Density} = 529 \text{ lb/ft}^3 = U = .306 \text{ lb/in.}^3$$

$$E = 16(10)^6 \text{ psi}$$

(one-inch-wide strip)

$$w = 14.7 \text{ psi}$$

$$P = \frac{14.7 \times .785 D^2}{\pi D} = 26.8 \text{ lb}$$

$$R = 18.1 + 26.8 = 45 \text{ lb}$$

$$\text{Shear } M_{\max} = 35.9 \times 1.23 =$$

$$44 \text{ in.-lb/in.}$$

$$t_r = \sqrt{\frac{6M}{\sigma}} = \sqrt{\frac{.0176}{\sigma}} = .133 \text{ in.}$$

$$t \sim .156 \text{ (min)}$$

3. Impact Analysis of Fuel Containment Structure

The fuel containment structure shall be analyzed to show adequacy for an impact load based on its own mass and an assumed terminal velocity of 210.9 ft/sec.

The general arrangement of the containment structure is shown below.

- A - Fuel Cell
- B - Containment Cover
- C - Containment Cylinder
- D - Containment Bottom Plate
- E - Cushion Tapered Cylinder

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a. Loading and Critical Components

It is assumed that the primary structural members, cylinders C and E, will reach the total applied loading and that this loading shall include the following:

Dynamic pressure load (g) - due to the impacting mass of parts A and B

Inertia load (P) - due to the impacting mass of part C

(1) Dynamic pressure g

$$g = \rho v^2$$

where

$$\rho = \text{mass density} = \frac{m}{V} = \frac{wt}{G \cdot V}$$

$$G = 32.2 \text{ ft/sec}^2$$

$$wt = \text{wt of A} + \text{wt of B} = 38.3 + 3.71 = 42.01 \text{ lb}$$

$$V = \text{volume of cell} = 0.158 \text{ ft}^3$$

thus

$$\rho = 8.23 \text{ slugs/ft}^3$$

$$v = \text{assumed impact velocity} = 210.9 \text{ ft/sec.}$$

thus

$$g = 2542 \text{ psi}$$

It is assumed that g acts as a uniformly distributed pressure as follows:

$$g(y) = \frac{2542}{6.5} y = 391.1 y$$

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(2) Inertia load P

$$K.E. = \text{developed kinetic energy of part C} = \frac{1}{2} M_c v^2$$

where

$$M_c = \text{mass of c} = \frac{\text{wt. of c}}{32.2} = \frac{13.48}{32.2} = 0.419 \text{ slugs}$$

thus

$$K.E. = 9340 \text{ ft-lb}$$

assume that

$$K.E. = K P \delta$$

or

$$P = \frac{K.E.}{K \delta}$$

where

δ = deflection of cushion pad under fuel cell, assumed
as 1/2 of total depth

$$\delta = 2 \text{ in.} = 0.167 \text{ ft}$$

K = amount of energy to be absorbed by the containment
structure

$$K = 0.75$$

thus

$$P = 74570 \text{ lb}$$

an equivalent inertia load factor is found by

$$\frac{P}{\text{wt. of c}} = 5532 \text{ g's}$$

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It is assumed that P acts as a uniformly increasing load as follows:

thus

$$P(y) = \frac{7.4570}{6.5} y = 11472 y$$

- b. Develop Expression for Maximum Stress in Cylinders C and E
As a percentage of total stress determine relative stress in cylinders C and E.

Consider cylinders C and E to act as a composite structure.

R = avg radius

$$R_C = 3.65 \text{ in.}$$

$$R_E = 3.775 \text{ in.}$$

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Considering a segment of the cylinder the principal stresses are shown as follows:

where

σ_H = circumferential stress due to dynamic pressure g

σ_C = compressive stress due to inertia load P

For a composite wall the radial displacements of both cylinders are equal and are given by

$$\text{radial displacement} = E_c = \frac{R_c}{E_{Tc}} (\sigma_{Hc} + \nu \sigma_{Cc}) \quad \text{Eq. (A5)}$$

$$E_E = \frac{R_E}{E_{TE}} (\sigma_{HE} + \nu \sigma_{HE}) \quad \text{Eq. (A6)}$$

$$\text{where } E_c = E_E \quad \text{Eq. (A7)}$$

and E_T = Tangent modulus of elasticity

Consider cylinder C (alloy Ta - 8W - 2 Hf @2800° F)

$$\sigma_{Hc} = \frac{g(y) R_c}{t_c} = 29.2 g(y) \quad \text{for } t_c = 0.125 \text{ in.}$$

$$\sigma_{Cc} = \frac{0.4 P(y)}{A_c} = 0.136 P(y) \quad \text{for } A_c = 2.94 \text{ in.}$$

$$\text{and since } \frac{P(y)}{g(y)} = \frac{74570}{2542} = 29.34 \quad (\text{Ref. Paragraphs 3a-1 and 2})$$

$$\sigma_{Cc} \text{ (in terms of } g(y)) = 1.16 g(y)$$

$$\text{Let } \bar{\sigma}_c = (\sigma_{Hc} + \nu \sigma_{Cc}) \text{ where } \nu = \text{poissons ratio}$$

$$\nu = 0.29$$

$$\bar{\sigma}_c = 30.36 g(y)$$

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$$E_{T_c} = \frac{F_{Tu}}{2U} \quad \text{where} \quad \begin{array}{l} F_{Tu} = \text{Wt. tensile str.} = 25,000 \text{ psi} \\ U = 15,120 \text{ in.-lb/in.}^3 \text{ (Ref. Table A1)} \end{array}$$

thus

$$E_{T_c} = 20,607 \text{ psi}$$

Consider cylinder E (material René 41 @ 1500° F)

$$\sigma_{H_E} = \frac{g(y) R_E}{t_E} = 17.92 g(y) \quad \text{for } t_E = 0.125 \text{ in.}$$

$$\sigma_{C_E} = \frac{0.6P(y)}{A_E} = 0.119 P(y) \quad \text{for } A_E = 5.04 \text{ in.}$$

$$\text{and since } \frac{P(y)}{g(y)} = 29.34$$

$$\sigma_{C_E} = 3.49 g(y)$$

$$\text{let } \bar{\sigma}_E = (\sigma_{H_E} + v \sigma_{C_E})$$

where $v = 0.3$

$$\text{thus } \bar{\sigma}_E = 19.52 g(y)$$

$$E_{T_E} = \frac{F_{Tu}}{2U}$$

where $F_{Tu} = 126,000 \text{ psi}$

$$U = 17,204 \text{ in.-lb/in.}^3$$

(Ref. Table A1)

thus

$$E_{T_E} = 432,575 \text{ psi}$$

Now from Equations A5, A6 and A7

$$\bar{\sigma}_C = \frac{R_E}{R_C} \frac{E_{T_c}}{E_{T_E}} \bar{\sigma}_E = 0.0494 \bar{\sigma}_E$$

$$\text{and since } \bar{\sigma}_E = 19.52 g(y)$$

$$\bar{\sigma}_C = 0.964 g(y)$$

and since the total stress is

$$\bar{\sigma}_C + \bar{\sigma}_E = 30.36 g(y) + 19.52 g(y) = 49.88 g(y)$$

$$\bar{\sigma}_C = 0.964 g(y)$$

$$\bar{\sigma}_E = 48.92 g(y)$$

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thus

$$\bar{\sigma}_C = 2\% \text{ of total}$$

$$\bar{\sigma}_E = 98\% \text{ of total}$$

Considering an element of shell the maximum shear stress, σ_p , as a function of the principal stresses, σ_H and σ_C , is given by

$$\sigma_p = 1/2 (\sigma_H + \sigma_C) 2 \sin \theta \cos \theta$$

where

$$\theta = \tan^{-1} \frac{\sigma_C}{\sigma_H}$$

c. Stress Calculations

Due to the variable cross section of cylinder E, the value of stress will vary along its length; thus, stress levels at several points along the length shall be calculated.

Geometry of cylinder E

where

0, 1, 2, 3 and 4 indicate levels

①, ②, ③ and ④ indicate sections

D_o = inside diameter

y level	Section	t thickness (inch)	A area (inch ²)	V volume (inch ³)
0	①	.072	1.712	4.819
1	②	.1503	3.612	8.270
2	③	.2285	5.548	11.756
3	④	.3072	7.535	7.912
4		.35	8.632	

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TABLE A3

TABULAR COMPUTATION FOR MAXIMUM SHEAR STRESS (σ_p)
AND PRINCIPAL STRESSES (σ_H AND σ_C) IN CYLINDERS C AND E

	SECTION		1	2	3	4
(1)	y	in.	1.83	3.66	5.5	6.5
(2)	t_c	in.	.125	.125	.125	.125
(3)	πD_c	in.	23.562	23.562	23.562	23.562
(4)	$A_c = (3) \times (2)$	in. ²	2.94	2.94	2.94	2.94
(5)	$t_E = 0.043(1) \times 0.72$	in.	.1503	.2285	.3072	.350
(6)	$D_E = 7.5 + (5)$	in.	7.6503	7.7285	7.8072	7.850
(7)	$A_E = 3.14(6) \times (5)$	in. ²	3.612	5.548	7.535	8.632
(8)	$g = 391.1(1)$	psi	715.7	1431.4	2151.1	2542.2
(9)	$\sigma_{H_c} = 29.2(8)$	psi	20898	41797	62812	74232
(10)	$3.775(8)$	-	2702	5404	8120	9597
(11)	$\sigma_{H_E} = (10)/(5)$	psi	17980	23650	26432	27420
(12)	$\sigma_{H_{tot}} = (9)+(11)$	psi	38878	65447	89244	101652
(13)	$\sigma_{H_c} \text{ (actual)} = 0.02(12)$	psi	776	1309	1785	2033
(14)	$\sigma_{H_E} \text{ (actual)} = 0.98(12)$	psi	38102	64138	87459	99619

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TABLE A3 (Cont'd)

(15)	$P_c = 4590(1)$	lb	8400	16800	25245	29835
(16)	$\sigma_{C_c} = (15)/(4)$	psi	2860	5715	8590	10148
(17)	$P_E = 6885(1)$	lb	12600	25200	37870	44755
(18)	$\sigma_{C_E} = (17)/(7)$	psi	3488	4542	5026	5185
(19)	$\tan \theta_c = (16)/(13)$	-	3.69	4.37	4.82	5.0
(20)	θ_c	deg	$74^\circ 50'$	$77^\circ 7'$	$78^\circ 18'$	$78^\circ 42'$
(21)	$2 \sin \theta_c \cos \theta_c$		.505	.435	.397	.384
(22)	$\tan \theta_E$		.0916	.0709	.0526	.0521
(23)	θ_E	deg	$5^\circ 14'$	$4^\circ 3'$	$3^\circ 1'$	$2^\circ 59'$
(24)	$2 \sin \theta_E \cos \theta_E$		.182	.141	.105	.104
(25)	$\sigma_{P_c} = 1/2 [(13)+(16)] \times (21)$	psi	918	1528	2060	2339
(26)	$\sigma_{P_E} = 1/2 [(14)+(18)] \times (24)$	psi	3785	4842	4855	5450

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The calculations for maximum shear stress in cylinders C and E shall be presented in tabular form and the general procedure used is outlined as follows:

- (1) Calculate total circumferential stress felt by both cylinders ($\sigma_{H_C} + \sigma_{H_E}$) due to dynamic pressure, g.
- (2) Calculate circumferential stress in each cylinder assuming:
 - cylinder C feels 2% of total
 - cylinder E feels 98% of total
- (3) Calculate axial compressive stress, σ_C , in each cylinder due to inertia load P, assuming:
 - cylinder C feels 40% of total P
 - cylinder E feels 60% of total P
- (4) Calculate maximum combined shear stress in each cylinder by

$$\sigma_p = 1/2 (\sigma_H + \sigma_C) 2 \sin \theta \cos \theta$$

For cylinder E average section values of geometry shall be used and are given as a function of elevation (y) as follows:

$$t_E(y) = \text{avg thickness} = 0.043 y + 0.072$$

$$(\pi D)_E(y) = \text{avg circumference} = 24.6 + 0.0559 y$$

$$A_E(y) = \text{avg area} = 1.77 + 1.064y + 0.0024 y^2$$

The inside diameters are taken as

$$D_E = 7.5 \text{ in.}$$

$$D_C = 7.3 \text{ in.}$$

Check margins of safety (M.S.)

For cylinder C

$$F_{TY} = 20,000 \text{ psi}$$

$$F_S = \text{allowable shear stress} = .61 F_{TY} = 13420 \text{ psi}$$

in shear (line 25, Table A3)

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$$M.S. = \frac{13420}{2339} - 1 = 4.74$$

in compression (line 16, Table A3)

$$M.S. = \frac{20000}{10148} - 1 = 0.97$$

For cylinder E

$$F_{TY} = 117,180 \text{ psi}$$

$$F_S = 71,500 \text{ psi}$$

in shear (line 26, Table A3)

not critical

in tension (line 14, Table A3)

$$M.S. = \frac{117,180}{99619} - 1 = 0.175$$

4. Preliminary Design of Impact Cushion

The components of the impact cushion shall be sized using the inertia load, developed in Paragraph 3a-1, as a basis. All cushion component weights shall also be calculated.

The weights needing computation besides the Containment Cylinder are:

1. Cushion Cylinder (upper)
2. Cushion Cylinder Corrugations
3. Fuel Cell - bottom plate
- 3A. Cushion = top plate
4. Cushion - top plate tunnel
5. Cushion - inner cylinder
6. Cushion - impact plate
7. Cushion - continuation of (1) = cylinder - lower
8. Containment cylinder - upper
9. Cushion - outer cylinder
10. Corrugations (main cushions)
11. Cushion - tunnel web plates

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~~CONFIDENTIAL~~Cushion Cylinder

9.83 lb

Cushion Cylinder Corrugations

$$\pi D = 23.6 \text{ in.}$$

Corrugation

$$p = .359 D$$

P = corrugation pitch, inches

D = corrugation depth

We = equivalent flat sheet = 1.228 W

W = true length of sheet

Ac = area = 1.228 W t

t = corrugation thickness

$$P = 1.47 \frac{P}{D} = 2.0 \therefore D = \frac{1.47}{2.0} = .735 \text{ in. } t = .032$$

$$A_c = 1.228 \times P \times t = 1.81 t = .058 \text{ in.}^2$$

$$p = .262 \quad L = 10.75 \quad \frac{L}{p} = 41.0$$

$$\frac{r}{P} = .282 \quad r = .415 \quad \text{Total } A_c = 16 \times .058 = .928 \text{ in.}^2$$

$$F_c (\text{allowable}) \sim 113000 - 11.15 \left(\frac{L}{p} \right)^2 = 94260 \text{ psi}$$

Use 90,000 psi

$$P_c (\text{allowable}) = 90,000 \times 1.81 \times .032 = 5213 \text{ lb}$$

$$\text{Corrugation weight} = \text{area} \times 1 \times .3$$

$$= .928 \times 10.75 \times .3 = 3.0 \text{ lb}$$

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Fuel cell - bottom plate

Bottom plate - $u = .71 \text{ lb/in.}^3$ $t = .090$

Surface = $.785 (7.5)^2 = 44.16 \text{ in.}^2$

$V = 44.16 \times .090 = 3.97 \text{ in.}^3$

$W = 3.97 \times .71 = 2.82 \text{ lb}$

Cushion - top plate

$t = .125$ $u = .30$

$V = 44.16 \text{ in.}^2 \times .125 = 5.52 \text{ in.}^3$

$W = 5.52 \times .3 = 1.66 \text{ lb}$

Cushion - top plate tunnel

$D = 2.5''$ $t = .064$

$V = 4.9 \times .064 = .314 \text{ in.}^3$

$W = .314 \times .3 = .94 \text{ lb}$

Cushion - inner cylinder

$\frac{r}{P} = .282$ $p = .48$ $r = .282 \times .48 = .135 \text{ in.}$

$t = .032$ $\frac{r}{t} = \frac{.135}{.032} = 4.22$ tube 5 must have

the same $\frac{r}{t}$ $R_5 = 1.25$

$\therefore t = \frac{1.25}{4.2} = .30$

$\therefore \text{Area} = \pi \times 2.5 \times .30 = 2.356 \text{ in.}^2$

$W = 2.356 \times 4.0 \times .3 = 2.83 \text{ lb}$

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Carries .4 of $\bar{P} = 29830 +$ the inertia load of member $\sim$
 5532 x its own weight.

Approximate weight: $D = 7.5 \text{ in.}$ $t \sim .125$

$$\text{Area} = \pi D t = 2.94 \text{ in.}^2$$

$$L = 4.25 \text{ in.}$$

$$\text{Vol.} = 2.94 \times 4.25 = 12.5 \text{ in.}^3$$

$$\text{Wt.} = 12.5 \times .3 = 3.75 \text{ lb}$$

$$\therefore \text{Additional load} = 3.75 \times 5532 = 20,745 \text{ lb}$$

$$\text{Total load} = 20,745 + 29,830 = 50,575 \text{ lb}$$

$$\text{Allowable stress} = 117,180 \text{ psi}$$

$$\sigma_c = \frac{50,575}{2.94} = 17,202 < 117,180$$

Containment cylinder-upper

$$\text{Area} = 2.94 \text{ in.}^2 \quad t = .125 \quad u = .71 \text{ lb/in.}^3$$

$$\text{Vol.} = 2.94 \times 6.5 = 19.11 \text{ in.}^3 \quad l = 6.5$$

$$\text{Weight} = 19.11 \times .71 = 13.57 \text{ lb}$$

Cushion - outer cylinder

This cylinder must have the same $\frac{r}{t}$ as the corrugations inside of cushion @ $D = 7.5 \text{ in}$ in order to buckle at the same stress.

$$\frac{r}{P} = \frac{\text{corr. rod}}{\text{pitch}} = .282 \quad P = 1.47$$

$$t = .020''$$

$$\therefore r = .282 \times 1.47 = .415''$$

$$\therefore \frac{r}{t} = \frac{.415}{.020} = 20.75$$

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$$R = 3.75 \quad \therefore \frac{3.75}{t} = 20.7 \quad t = .181$$

$$\therefore A = 23.5 \times .181 = 4.25 \text{ in.}^2$$

$$V = 4.25 \times 4.25 = 18.0625 \text{ in.}^3$$

$$\text{Weight} = 18.0625 \times .3 = 5.4 \text{ lb}$$

Corrugations - main cushion

1. Diameter	2.5	3.33	4.17	5.0	5.83	6.67	7.5
2. Corrugation Pitch	.491	.654	.819	.982	1.145	1.310	1.473
$= P = \frac{\pi D}{16}$							
3. Depth = D			.416				
4. P/D	1.180	1.572	1.969	2.361	2.752	3.149	3.541
5. K_W (Ref. 32)	2.8	1.60	1.51	1.50	1.35	1.25	1.20
6. Length of Corrugation	7.85	10.46	13.10	15.71	18.32	20.95	23.56
7. True Length	21.99	16.74	19.78	23.56	24.73	26.19	28.27
8. Area-Corrugation	.704	.536	.633	.754	.791	.838	.905

$$\Sigma \text{Corrugation Area} = 5.16 \text{ in.}^2 \quad L = 4" \quad = .3$$

$$\text{Weight (cushion)} = 6.19 \text{ lb}$$

$$\text{Tunnel Web Plates} \quad L = 2 \text{ in.} \quad \frac{R}{t} = 4.22$$

$$1.25 R$$

to have plates buckle
at same time

$$\frac{KL}{r} \text{ of plate} = \frac{K}{r} \text{ of cylinder}$$

$$\frac{L}{b} = \frac{2}{1.25} = 1.6$$

$$\therefore \frac{KL}{r} (\text{plate}) = 1.63 \times \frac{b}{t} = 9.5$$

$$t = \frac{1.63 \times 1.25}{9.5} = .214"$$

$$\text{Area} = 2 \times 2.25 \times 2.14 = .963 \text{ in.}^2 \quad \mu = .3$$

$$32. K_W = \frac{\text{Developed Width of Corrugated Sheet}}{\text{Actual Width of Corrugated Sheet}}$$

Bruhn, E. F., Analysis and Design of Airplane Structures, Tri State Offset Company, Cincinnati, Ohio, 1952.

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$$\text{Vol.} = .963 \times 2.0 = 1.93 \text{ in.}^3$$

$$\text{Weight} = 1.93 \times .3 = .58 \text{ lb}$$

Weight Summary - Cushion + Fuel Cell

<u>Item</u>	<u>Description</u>	<u>Weight</u>
1	Cushion cylinder (upper)	9.83 lb
2	Cushion-cylinder corrugations	3.0
3	Fuel cell-bottom plate	2.82
3A	Cushion-top plate	1.66
4	Cushion-top plate tunnel	.094
5	Cushion-inner cylinder	2.83
6	Cushion-impact plate	3.72
7	Cushion-cylinder (lower)	3.75
8	Containment cylinder (upper)	13.57
9	Cushion-outer cylinder	5.40
10	Corrugations (main cushions)	6.19
11	Cushions-tunnel web plates	.58
12	Fuel cell-top disk	<u>2.82</u>
		56.264 lb
	Fuel cell	<u>38.30</u>
	Total Weight (cushion + fuel cell)	<u>94.564 lb</u>

5. Sizing of Drag Cone for Optimum Design

a. Strain Energy and Terminal Velocity

For the strain energy in the elastic range use the strain energy stored in a bar $U = \frac{\bar{\sigma}^2}{2E} \text{ in. lb/in.}^3$. During the plastic

range the stored energy equals the area under the stress strain curve given by:

$$U = \frac{1}{3} e \left[F_{ty} + 2 F_{tu} \right] \text{ in. lb/in.}^3 \text{ (see sketch)}$$

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For the Elastic Range

For the Plastic Range:

$$KE = \frac{1}{2} \bar{P} \delta$$

$$KE = \bar{x} \bar{P} \delta$$

where $\bar{x} = <1.0> \frac{1}{2}$. For this study $\bar{x}$ used is $\frac{3}{4}$

where $\bar{P}$ is a constant load acting through deflection δ

where δ is the first deformation in inches.

Velocity at impact:

$$v_t = \sqrt{\frac{2w}{p C_D S}} \quad \begin{array}{l} - p = \text{mass density of air.} \\ w = \text{weight of body, lb} \end{array} \quad \begin{array}{l} \text{SLUGS} \\ \text{ft}^3 \end{array}$$

C_D = drag coefficient

S = area, square feet

Energy Losses

The kinetic energy to be absorbed at impact is affected by:

- (1) Coefficient of restitution depending on the physical characteristics of the "target" and "projectile."
 - (2) The inertia of the colliding bodies and
 - (3) That part spent in changing the bodies' temperature.
- For this report, the coefficient of restitution (generator

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impacting on granite) $\sim \frac{E_g}{E_g + E_s} = \epsilon$ where:

$$E_g \text{ (granite)} = 5.0(10)^6 \quad E_s \text{ (steel)} = 31(10)^6$$

$$\therefore \epsilon = \frac{5.0}{5.0 + 31.0} = .139$$

Thus the energy to be absorbed by shell =

$$1 - .139 = .861$$

For an axial impact:

$$K = \frac{1 + \frac{1}{3} \frac{W_1}{W_o}}{(1 + \frac{1}{2} \frac{W_1}{W_o})^2} \quad \text{where } W_o = \text{weight of moving body}$$

$$W_1 = \text{weight of target}$$

If $W_o = 183.35 \text{ lb}$ (fixed weight plus cushion plus fin)

$$W_1 = 10 \text{ lb} \quad W = 1833.5 \text{ lb} \quad \frac{W_1}{W} = 10$$

$$K = \frac{1 + \frac{10}{3}}{(1 + 5)^2} = .037 \text{ (target)}$$

$$\therefore 1 - .037 = .963 \text{ (generator)}$$

Heat Losses are Neglected

Based on the above, the energy input $KE = \frac{1}{2} M_o v_t^2$,
 where $M_o = \frac{W_o}{32.2}$ and $v_t = 220 \sqrt{\frac{W_1}{W_o}}$, is multiplied by a factor =

$.861 \times .963 = .83$, to arrive at the actual energy to be converted into strain energy.

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For first cycle calculations the following weight breakdown for the weight of moving body, W_o , is used:

Component	Weight (lb)	% W_o
Fixed Weight*	111.92	61.16
Fin	14.82	8.10
Cushion	56.264	30.74
	$W_o = \Sigma W = 183.004$	$\Sigma = 100\%$

b. Calculations for Available Strain Energy

The available strain energy of the generator components, based on geometry and material physical properties, shall be calculated. Also, using an assumed terminal velocity of 220 ft/sec the component design, as previously given, shall be re-evaluated.

The elements which can absorb strain energy are:

- (1) The outer shell up to the impact plate
- (2) Fuel cell container
- (3) Cushion cylinder adjacent to containment, above containment bottom plate.
- (4) Bottom of cushion cylinder (between impact plate and bottom of containment).
- (5) Cushion under fuel cell containment

Shell

It is assumed that this shell collapses after impact. Material is changed from inconel SB-168 as rolled to René 41 with the following properties:

Operating temperature = 1000° F

$F_{tu} = 203,000$ psi

$F_{ty} = 147,000$ psi

*Includes a slightly heavier shell than previously considered.

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$$e = 14 \%$$

(Ref. 33) Operating temperature =
1500° F

$$E = 27.2 (10)^6$$

U = strain energy - maximum

$$= \frac{1}{3} \times \frac{14}{100} \left[147,000 + 406,000 \right] = .0467 (553,000) =$$

$$25,825 \text{ in.-lb/in.}$$

Present volume = 9.256 with $t = .062$. Wt. = 2.76 lb

Available energy = 9.256 x 25,825 = 239,050 in.-lb.

Since it is desired to collapse this dome the full U is used.

In order to obtain benefit from the crushed dome its thickness is changed from .062 in. to .072 with a total weight =

$$2.76 \frac{.072}{.062} = 3.20 \text{ lb}$$

The available U = 239050 x 1.16 = 277600 in.-lb.

$$\text{new area} = \pi \times 9.75 \times .072 = 2.21 \text{ in.}^2$$

(The dome deflection will be discussed below)

Edge Fixed But Not Held

Lower Dome

(Ref. 30, Page 273)

$$y_{\text{max}} = A \frac{PR_2}{ET^2}$$

$$\text{Max stress @ Pole} = B \frac{P}{t^2} = \text{membrane stress}$$

$$\text{Max } \sigma_b \text{ @ Pole} = C \frac{P}{t^2} = \text{bending stress}$$

As a function of

$$\mu = 4 \sqrt{12(1-\nu^2)} \left(\frac{R_o}{\sqrt{R_2 t}} \right) \quad R_o = .423''$$

33. Materials in Design Engineering, Mid-October 1961.

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$$\mu = 4 \sqrt{12 (1 - .29^2)} \left(\frac{.85}{\sqrt{4.875 \times .062}} \right) = 4 \sqrt{10.9908} \left(\frac{.423}{\sqrt{.30225}} \right)$$

$$\mu = 1.4$$

$$A = 0.280$$

$$B = 0.140$$

$$C = 0.263$$

From table from
Ref. 30

$$y_{\max} = A \frac{PR_2}{ET^2}$$

$$y_{\max} = .280 \frac{170 \times 4.875}{28.7 (10)^6 \times .062^2}$$

$$= .002103 \text{ in.}$$

$$t = .062$$

$$E = 28.7(10)^6$$

$$P = 170 \text{ lb}$$

$$\text{Max stress @ pole} = B \frac{P}{t^2} = .140 \frac{170}{.062^2} = 6190 \text{ psi}$$

$$\text{Max } \sigma_b \text{ @ pole} = C \frac{P}{t^2} = .263 \frac{170}{.062^2} = 11630 \text{ psi}$$

Dome Deflection under Impact*

$$1/2 Q \underline{q} = P (\eta h + \underline{q})$$

$$\underline{q} = y + [y^2 + 2 \eta h y]^2$$

where: Q = max load at impact lb

P = static load = 170 lb

y = .0021 inches ($t = .062$)

In order to get y for .072

$$y = .0021 \frac{(6.2)^2}{(7.2)^2} = .0016 \text{ in.}$$

h = height of drop in inches

$$\text{From KE} = \frac{1}{2} M v^2 \text{ where } M = \frac{170}{32.2} = 5.28 \text{ slugs}$$

$$v^2 = 220^2 = 48400 \text{ ft}^2/\text{sec}^2$$

* Reference 28 on page A-3.

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$$KE = 127,800 \text{ ft-lb}$$

$$\eta = .83$$

$$\therefore \eta KE = 106,100 \text{ ft-lb}$$

$$\text{and } \eta KE = \bar{P}n \text{ or } h - \frac{106100}{170} = 624 \text{ ft} = 7488 \text{ in.}$$

$$\therefore \underline{q} = .0016 + \left[.0016^2 + 2 \times 7500 \times .0016 \right]^{1/2}$$

$$\underline{q} = 4.9 \text{ in.}$$

$$1/2 Q = \frac{P(7500 + 4.9)}{4.9} = 260,375 \text{ lb}$$

Since 1/2 is changed to 3/4

$$3/4 Q = 1.5 \times 260,375 = 390,600 \text{ lb}$$

$$\text{and } U = 390,600 \times 4.9 = 1,913,940 \text{ in-lb}$$

Since the total energy of the shell dome = 277,600 in-lb it means that the shell will not deflect 4.9 inches before crushing but

$$= \frac{277,600}{390,600} = .71''.$$

$\therefore$ The total available U for shell dome = 277,600 in-lb

Available Strain Energy Fuel Cell Containment

$$U = 15120 \text{ in-lb/in.}^3$$

$$\text{Actual area} = 2.94 \text{ in.}^2 \quad t = .125$$

$$\text{Max } \sigma_p = 6705 \text{ psi}$$

$$\text{Since } \sigma_p (\text{allowable}) = 13,420 \text{ psi}$$

$$t_\eta = \text{new thickness} = .125 \frac{6705}{13,420} = .0625 \text{ in.}$$

$$\text{new area} = 1.47 \text{ in.}^2$$

$$\text{new volume} = 9.56 \text{ in.}^3$$

Because of triangular stress distribution

$$V_{\text{actual}} = 4.778 \text{ in.}^3 \text{ and available strain energy} =$$

$$4.778 \times 15,120 = 72,250 \text{ in-lb.}$$

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New weight of containment:

$$13.57 \times .50 = 6.79 \text{ lb}$$

$$\text{Saving} = 6.78 \text{ lb}$$

Available energy in cushion (above)

Containment Bottom Plate

$$U_c = 17204 \text{ in-lb/in.}^3$$

$$\text{Weight} = 32.76 \times .3 + (3.0 \times \frac{6.5}{10.75}) = 11.642 \text{ lb}$$

$$\text{Volume} = \frac{11.642}{.3} = 38.8 \text{ in.}^3$$

$$\text{Max stress} = 96,264 \text{ psi}$$

Since allowable = 117,180 psi, the volume can be reduced to

$$38.8 \frac{96,264}{117,180} = 31.9 \text{ in.}^3$$

$$\therefore \text{New weight} = 11.642 \frac{31.9}{38.8} = 9.57 \text{ lb}$$

$$\text{Saving} = 2.07 \text{ lb}$$

$$\text{New volume} = 31.9 \text{ in.}^3$$

Since stress distribution is triangular available

$$\text{strain energy} = \frac{32}{2} \times 17,204 = 275,270 \text{ in-lb.}$$

Available Energy Bottom of Cushion Cylinder

(Between impact plate and bottom of containment)

$$U_D = 17,204 \text{ in-lb/in.}^3$$

$$\text{Weight} = 3.75 + \left[3.2 \frac{4.25}{10.75} \right] = 5.01 \text{ lb}$$

$$\text{Vol} = \frac{5.01}{.3} = 16.7 \text{ in.}^3$$

Since this element is loaded by (1) friction between containment and cylinder and (2) its own inertia, it is assumed 65% efficient to store strain energy.

$$\therefore \text{Available energy} = .65 \times 16.7 \times 17,204 = 186,750 \text{ in-lb}$$

Cushion Under Fuel Cell - Available Strain Energy

$$U_E = 25825 \text{ in-lb/in.}^3$$

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Weight

<u>Description</u>	<u>Weight (Pounds)</u>
Cushion-cylinder corrugations (lower only)	1.19
Cushion-inner cylinder	2.83
Cushion-lower cylinder	3.75
Cushion-outer cylinder	5.40
Corrugations (main cushions)	6.19
Cushions-tunnel web plates	<u>.58</u>
	19.94-1.19 =
	18.75

$$\therefore \text{Vol} = \frac{18.75}{.3} = 62.4 \text{ in.}^3$$

$$\text{Available energy} = 25,825 \times 62.4 \times \frac{147,000}{203,000} = 1,170,000 \text{ in.-lb}$$

Diagram and Weight of Fuel Cell and Cushion

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<u>Item</u>	<u>Description</u>	<u>Weight</u>
1	Cushion-cylinder (upper)	7.76 lb
2	Cushion-cylinder corrugations	3.00
3	Fuel cell-bottom plate	2.82
3A	Cushion-top plate	1.66
4	Cushion-top plate tunnel	.094
5	Cushion-inner cylinder	2.83
6	Cushion-impact plate	3.72
7	Cushion-cylinder (lower)	3.75
8	Containment cylinder (upper)	6.79
9	Cushion-outer cylinder	5.40
10	Corrugations (main cushions)	6.19
11	Cushions-tunnel web plates	.58

* $\Sigma 44.59$ lb

* Actual value of cushion weight

= 0.28 lb

Summary - Available Strain Energy

<u>Item</u>	<u>Description</u>	<u>ΔU</u>	<u>%</u>
A	Shell dome	277,600	14.01
B	Fuel containment	72,250	3.65
C	Cushion above fuel cell bottom plate	275,270	13.89
D	Bottom of cushion cylinder	186,750	9.42
E	Cushion under fuel cell	<u>1,170,000</u>	<u>59.04</u>

$\Sigma 1,981,870$ lb 100

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$$\text{Original } W_o = 183.004 \text{ lb}$$

Summary of Weight Savings:

- (1) Drag fin made from titanium =

$$W = (9.14 + 5.68) \frac{163}{.298} = 8.11 \text{ lb}$$

$$\text{Saving} = - 6.71 \text{ lb}$$

- (2) Increase - shell dome = +.44 lb

- (3) Containment = - 6.78

- (4) Upper cushion = - 2.07

$$\therefore W_o \text{ (second cycle)} = 183.004 - 15.12 = 167.88 \text{ lb} \sim 168 \text{ lb}$$

Impact Velocity

$$v_t = 220 \text{ ft/second (assumed)}$$

$$\text{based on } W_o = 100 \text{ lb}$$

$$\text{new } v_t = 220 \sqrt{\frac{1.68}{1.00}} = 220 \times 1.3 = 286 \text{ ft/sec}$$

$$\begin{aligned} \text{Gross energy input} &= 1/2 m v^2 = \frac{168}{64.4} (82,944) = 216400 \text{ ft-lb} \\ &= 2,596,800 \text{ in.-lb} \end{aligned}$$

$$\begin{aligned} \eta \text{ (reduction .83)} \therefore \text{net input} &= .83 \times 2,596,800 = \\ &2,155,350 \text{ in.-lb} \end{aligned}$$

$$\text{The available } U = 1,981,870 \text{ in.-lb} < 2,155,350 \text{ in.-lb}$$

This can be balanced by additional drag area with a negligible additional weight.

It is concluded that the energy balance will be satisfactory as noted.

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c. Size Drag Cone

The drag cone shall be sized to yield an impact energy which is less than the available energy as developed in Paragraph 5b (i.e., $U = 1,981,870 \text{ in.-lb}$).

The analysis is carried out using the following computations:

(1) Drag cone weight vs parameter $\frac{D_2}{D_1}$

(2) Drag coefficients vs $\frac{D_2}{D_1}$

(3) Size of cone for thermionic generator terminal velocity for a given available strain energy in the body.

Drag Cone Weight vs Parameter $\frac{D_2}{D_1}$

D_o = Generator Diameter

Data:

$$D_o = 9.75 \text{ in}$$

$$D_1 = 13.1 \text{ in}$$

$$D_2 = K_1 D_1 \text{ where } K_1 = \frac{D_2}{D_1} \text{ ratio}$$

$$\theta = 25^\circ$$

$$\sin \theta = .42262$$

$$\cos \theta = .90631$$

$$\tan^{-1} \theta = .46631$$

Equations:

$$D_2 = K_1 D_1$$

$$h = \frac{D_2 - D_1}{2 \tan \theta} = 1.0722 \left[D_2 - D_1 \right]$$

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$$L = \frac{h}{\cos \theta} = 1.183 (D_2 - D_1)$$

$$S_c = \text{cone surface in.}^2 = 1.86 \left[D_2^2 - D_1^2 \right]$$

$$W_c = \text{cone weight} = S_c \times t_c \times \mu_c \text{ where:}$$

$$\mu_c = .163 \text{ lb/in.}^3 \text{ titanium}$$

$$\mu_c = .102 \text{ lb/in.}^3 \text{ aluminum alloy}$$

$$W_{cr} = \text{weight of stiffening rings}$$

$$\text{If } W_{R_1} = \text{weight of ring 1} = \pi D_1 \times .27 \times \mu$$

$$= 3.1416 \times 13.1 \times .27 \times .163$$

$$= 1.811 \text{ lb}$$

$$\text{If } W_{R_4} = \text{weight of ring (4)} = \pi K_1 D_1 \times .27 \times \mu$$

$$= 1.811 K_1$$

$$\text{Then } W_{R_2} = \text{weight of ring(2)} = W_{R_1} + \frac{W_{R_4} - W_{R_1}}{3}$$

$$\text{Then } W_{R_3} = W_{R_1} + 2/3 (W_{R_4} - W_{R_1})$$

Weight Fin vs D_2/D_1 , Aluminum

1	$K_1 = D_2/D_1$	2.4	3.0	3.5	4.0	5.0
2	D_2 in.	31.44	39.30	45.85	52.40	65.50
3	$D_2 - D_1 = (2) - 13.1$ in.	18.34	26.20	32.75	39.30	52.40
4	$L = 1.183(3)$	21.70	30.99	38.74	46.49	61.99
5	$(2)^2$	988.47	1544.49	2102.22	2745.76	4290.25
6	$(5) - D_1^2 = (5) - 171.61$	816.86	1372.88	1930.61	2574.15	4118.64

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7	$S_c = 1.86(6)$	1520	2553	3590	4787	7660
8	$W_c = (7) \times .064 \times .102$	9.94	16.67	24.45	31.15	50.05
9	W_{R_1}	-----1.811 lb -----				
10	$W_{R_4} = 1.811 K_1$	4.35	5.43	6.34	7.24	9.06
11	$\frac{(10)-(9)}{3}$	.8463	1.206	1.510	1.810	2.416
12	$W_{r_2} = (9)+(11)$	2.657	3.017	3.321	3.621	4.227 lb
13	$.667 (10)-(9)$	1.693	2.413	3.019	3.620	4.833
14	$W_{R_3} = (9)+(13)$	3.504	4.224	4.830	5.431	6.644 lb
15	$\Sigma W_c + W_{R_1} + W_{R_2} + W_{R_3} + W_{R_4}$	22.26	32.25	40.73	49.25	71.79

Determination of Drag Coefficient vs $\frac{D_2}{D_1}$

$$C_D = .5 + .28 \frac{S_b}{S_r} \quad (\text{See Appendix D})$$

where C_D = drag coefficient

S_b = projected area $\square'$ corresponding to D_2

S_r = projected area $\square'$ basic cylinder

$$S_b = \frac{\pi D_2^2}{4 \times 144}$$

$$S_r = \frac{\pi \times 9.75^2}{4 \times 144} = .5185 \square'$$

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1	$D_2/D_1 = K_1$	2.4	3.0	3.5	4.0	5.0
2	D_2	31.44	39.30	45.85	52.40	65.50
3	$S_b = \pi(2)^2/576$	5.391	8.424	11.466	14.976	23.400
4	S_r	_____ .5185 _____				
5	S_b/S_r	10.397	16.247	22.114	28.883	45.130
6	$.28 S_b/S_r = .28(5)$	2.911	4.549	6.192	8.087	12.636
7	$C_D = .5 + (6)$	3.411	5.049	6.692	8.587	13.136
8	$C_D \cdot S_r = (7) \times (4)$	1.769	2.618	3.470	4.452	6.811
9	$1/2 \rho C_D S_r = \text{sea}$					

level =

 K_2

$$= .00117 C_D S_r \quad .00207 \quad .00306 \quad .00405 \quad .00520 \quad .00796$$

The terminal velocity of a falling body in the atmosphere v_t
is computed from the basic equation:

$$W_o = 1/2 \rho C_D S_r v^2 \quad \text{Eq. (A7)}$$

where W_o = total weight lb

v_t = terminal velocity ft/sec

$$\text{If } 1/2 \rho C_D S_r = K_2$$

$$\text{then } W_o = K_2 v_t^2 \quad \text{or} \quad v^2 = \frac{W_o}{K_2}$$

$$\text{and } v = \sqrt{\frac{W_o}{K_2}}$$

where $\rho = .002337$ slugs/cubic foot

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Terminal Velocity for a Body Consisting Only
of Tail Weights vs D2/D1, Titanium Construct

1	$K_1 = D_2/D_1$	2.40	3.0	3.5	4.0	5.0
2	K_2	.00207	.00306	.00405	.00520	.00796
3	$W_T = \text{tail weight}$	28.18	41.11	53.75	68.04	101.65
4	$W_c / K_2 = (3)/(2)$	13614	13435	13272	13085	12770
5	$v_c = \sqrt{(4)} \text{ ft/sec}$	116.68	115.91	115.20	114.39	113.00

Terminal Velocity if $W_g = \text{fixed weight of generator} = 121.4 \text{ lb}$

6	$W_g/W_t = 121.4/(3)$	4.308	2.954	2.259	1.784	1.194
7	$\sqrt{(6)}$	2.076	1.719	1.503	1.336	1.093
8	$v_g = (5) \times (7) \text{ ft/sec}$	242.23	199.25	173.15	152.83	123.51

Terminal Velocity for Body with $W_o = W_t + W_g$

9	$v_o = (5) + (8) \text{ ft/sec}$	358.91	315.16	288.35	267.22	236.51
10	$\Sigma W = 121.4 + (3)$	149.58	162.51	175.15	189.44	223.05

Terminal Velocity for Entire Body Weight

$$W_o = W_T + W_g + W_c \quad \text{Eq. (A8)}$$

where $W_c = \text{weight of energy absorber cushion}$

From preliminary estimates W_c is a function of v_t^2 .

$$W_c = 40.28 \text{ lb}$$

$$\therefore W_c = K_o v_t^2 = K_o (63,617)$$

$$K_o = \frac{40.28}{63,617} = .000633$$

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$$\therefore W_c = .000633 v^2 \quad \text{Eq. (A9)}$$

$$v_g = v_c \sqrt{\frac{W_g}{W_c}} \quad \text{ft/sec}$$

$$\text{Since } W_o = 1/2 \rho C_D S_r v^2 \text{ and } 1/2 \rho C_D S_r = K_2$$

$$\text{but } W_o = W_T + W_g = v_t^2 (K_2 - .000633) \therefore v_t^2 = \frac{W_T + W_g}{K_3}$$

11	K_1	2.4	3.0	3.5	4.0	5.0
12	K_2	.00207	.00306	.00405	.00520	.00796
13	$K_2 - .000633 = K_3$	.00144	.00243	.00342	.00457	.00733
14	$W_c + W_g$	149.58	162.51	175.15	189.44	223.05
15	$(14)/K_3 = (14)/(13) = v_t^2$	103875	66875	51215	41450	30430
16	$\sqrt{(15)} \text{ ft/sec}$	322.30	258.60	226.31	203.59	174.44
17	$W_c = .000633(15)$	65.753	42.332	32.419	26.238	19.262
18	$W_o = (14) + (17)$	215.33	204.84	207.57	215.68	242.31
19	$v_t^2 = W_o / (12)$	104024	66940	51252	41477	30441
20	$\frac{W_o}{64.4} = M/2 = \text{slugs}$	3.344	3.181	3.223	3.349	3.763
20A	$\sqrt{(19)} = v_t \text{ ft/sec}$	322.53	258.73	226.39	203.66	174.47
21	$KE = 1/2 m v^2 = (19) (20)^1$ lb	347856	212936	165185	138906	114550
22	$KE = \text{in} \cdot \text{lb} (10)^{-6}$	4.1743	2.5552	1.9822	1.6669	1.3746
23	$KE (\text{net}) = (22) \times .83$ $(10)^{-6}$	3.4646 in. lb	2.1208 in. lb	1.6452 in. lb	1.3835 in. lb	1.1409 in. lb

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Conclusions.

Since it is shown that the impact energy for a $\frac{D_2}{D_1}$ of 3.0 is 2,120,800 in.-lb and for a $\frac{D_2}{D_1}$ of 3.5 is 1,645,000 in.-lb and that the available strain energy of the generator is 1,981,870 in.-lb a tail cone with $\frac{D_2}{D_1}$ of between 3.0 and 3.5 is selected.

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APPENDIX B

DC-DC CONVERTER DATA

1. Comparison of Diode Rectifiers and Transistor Circuit Rectifiers

Consider a system of 28-volt output and 10-ampere average current utilizing circuitry of Figures B1 or B2 below:

Figure B1

Figure B2

For the system of Figure B1 rectifier losses are equal to the voltage drop (average) times the average current for each diode.

$$P = 1.0 \times 5 = 5 \text{ watts power loss}$$

or a total of 10 watts for the rectifying system. Considering the circuit of Figure B2, Q1 and Q2 are low loss units since they are extremely low voltage drop germanium units. Q3 and Q4 are required to drive Q1 and Q2 and provide isolation of the load during nonconduction periods. E1 and E2 are in the order of one volt. The collector-emitter drop of Q3 and Q4 is approximately 0.15 volt.

This yields the following power loss per transistor.

$$\text{Saturation loss} = 0.1 \times 5 = 0.5 \text{ watt}$$

$$\text{Base losses} = 1 \times 0.2 = 0.2 \text{ watt}$$

This is a total loss of 1.4 watts (neglecting the small additional copper loss of the transformer).

2. Converter Parametric Study

This appendix covers those calculations pertinent to the design of

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converters operating at 1-, 2-, 3- and 5-volt inputs. In addition, the comparison between the Royer conventional converter and the self-rectifying converter is given.

- a. Converter Design for 1-Volt Input at 333.3 Amps.

Transistor Loss

Assume 7 transistors in parallel on each side of converter switching a current of 47.5 amps each.

$$\text{Base drive} = \frac{47.5}{25} = 1.9 \text{ amps}$$

Base drive loss per transistor

$$P_{BE} = \frac{1.90}{2} \times 1 = 0.95 \text{ watts}$$

Total base drive power

$$P_{BE} (\text{Total}) = 0.95 \times 14 = 13.3 \text{ watts}$$

Switching and Saturation Losses

Operating frequency 500 cps

Transistor rise time $t_R = 30$ microseconds

Transistor fall time $t_F = 40$ microseconds

$$\begin{aligned} P_S &= \frac{1}{6} \left[2 V_S I_C f (t_R + t_F) \right] \\ &= \frac{1}{6} \left[(2)(1)(47.5)(500)(70 \times 10^{-6}) \right] \\ &= 0.555 \text{ watt} \end{aligned}$$

$$P_S \text{ Total} = 0.55 \times 14 = 7.78 \text{ watts}$$

$$\begin{aligned} P_C (\text{per unit}) &= R_S I_C^2 \left[\frac{1}{2} - f (t_R + t_F) \right] \\ &= (0.002) (47.5)^2 \left[0.5 - 500 (70 \times 10^{-6}) \right] \\ &= 2.26 \text{ watts} \end{aligned}$$

$$P_C (\text{Total}) = 14 \times 2.26 = 31.6 \text{ watts}$$

$$\begin{aligned} P_B &= 2 V_S I_{CO} \left[\frac{1}{2} - f (t_R + t_F) \right] \\ &(\text{per unit}) \end{aligned}$$

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$$= (2) (1) (5 \times 10^{-3}) [0.5 - 500 (70 \times 10^{-6})]$$

$$= 0.005 \text{ watt}$$

$$P_B (\text{Total}) = 14 \times .005 = 0.07 \text{ watt}$$

Total Transistor Dissipation and Base Drive Losses =

$$7.78 + 31.6 + 0.07 + 13.3 = 52.75 \text{ watts}$$

Rectifier Losses - Assuming 250-watt 28-volt output

$$P_T = 0.1 \times \frac{9.8}{2} \times 2 = 0.98 \text{ watt}$$

Assuming a gain of 30

$$P_{BE} = 0.326 \times 1 = 0.326 \text{ watt}$$

$$\text{Total Rectification Losses} = 1.31 \text{ watts}$$

The self-rectifying circuit cannot be efficiently used since insufficient load current is available for base drive current.

Transformer Losses (Main Transformer)

Transformer designs of three efficiencies are given beginning on page B-9. The losses for these units are given on page B-5.

$$\text{Loss of transformer design No. 1} = 10.38 \text{ watts}$$

$$\text{Loss of transformer design No. 2} = 13.98 \text{ watts}$$

$$\text{Loss of transformer design No. 3} = 5.64 \text{ watts}$$

Transformer Losses (Switching Transformer)

The switching transformer is assumed to be the same for each unit and will have a loss constant at 1 watt.

The total losses of the converter for 1-volt input may now be summed up as follows for each design.

Using transformer design No. 1

$$\text{Total transistor losses} = 52.75 \text{ watts}$$

(Including base drive)

$$\text{Transformer losses} = 11.38 \text{ watts}$$

$$\text{Rectification losses} = \underline{1.31} \text{ watts}$$

$$\text{Total converter Losses} = 65.44 \text{ watts}$$

Using transformer design No. 2

$$\text{Total converter Losses} = 68.94 \text{ watts}$$

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Using transformer design No. 3

Total converter losses = 60.70 watts

Converter Efficiency

Transformer design No. 1

$$\text{Eff} = \frac{333 - 65.44 \times 100}{333} = \frac{267.56 \times 100}{333} = 80.2\%$$

Transformer design No. 2

$$\text{Eff} = \frac{333 - 68.94 \times 100}{333} = \frac{264.39 \times 100}{333.33} = 79.5\%$$

Transformer design No. 3

$$\text{Eff} = \frac{333.33 - 60.7 \times 100}{333.33} = \frac{272.63 \times 100}{333.33} = 81.9\%$$

Volume and Weight

The converter volume and weight of each design is estimated below:

Transformer design No. 1 - 132 cu in. volume 13 lb weight

Transformer design No. 2 - 122 cu in. volume 10 lb weight

Transformer design No. 3 - 200 cu in. volume 23 lb weight

b. Converter Design for 2-Volt Input at 161.5 Amps.

Conventional Royer Design

Transistor Loss

Assume 4 transistors in parallel on each side of converter switching a current of 40.4 amps each.

$$\text{Base drive} = \frac{40.4}{25} = 1.62 \text{ amps}$$

Base drive loss per transistor

$$P_{BE} = \frac{1.62}{2} \times 1 = 0.81 \text{ watts}$$

$$P_{BE} \text{ (Total)} = 0.81 \times 8 = 6.48 \text{ watts}$$

Switching and Saturation Losses

$$P_S = \frac{1}{6} \left[(2) (2) (40.4) (500) (7 \times 10^{-5}) \right] = 0.94 \text{ watt per unit}$$

$$P_S \text{ (Total)} = 8 \times 0.94 = 7.5 \text{ watts}$$

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$$P_C \text{ (per unit)} = (0.002)(40.4)^2 \left[\frac{0.5 - 500}{70 \times 10^{-6}} \right] = 1.625 \text{ watts}$$

$$P_C \text{ (Total)} = 8 \times 1.625 = 13 \text{ watts}$$

$$P_B \text{ (per unit)} = (2)(2)(5 \times 10^{-3}) \left[\frac{0.5 - 500}{70 \times 10^{-6}} \right] = 0.01 \text{ watt}$$

$$P_B \text{ (Total)} = 0.08 \text{ watt}$$

Total transistor dissipation and base drive losses =

$$6.48 + 7.5 + 13 + 0.08 = 27.06 \text{ watts}$$

Rectifier Losses = 1.31 watts

(Same as 1-volt input)

Transformer Losses (Main Unit)

(Same as 1-volt input)

$$\text{Design No. 1} = 10.38 \text{ watts}$$

$$\text{Design No. 2} = 13.98 \text{ watts}$$

$$\text{Design No. 3} = 5.64 \text{ watts}$$

Transformer Loss (Switching Unit)

(Same as 1-volt input)

$$\text{loss} = 1 \text{ watt}$$

Total Losses

$$\text{Design No. 1} = 39.75 \text{ watts}$$

$$\text{Design No. 2} = 42.35 \text{ watts}$$

$$\text{Design No. 3} = 35.01 \text{ watts}$$

Converter Efficiency

Design No. 1 Efficiency =

$$\frac{323 - 39.75 \times 100}{323} = \frac{283.75 \times 100}{323} = 87.6\%$$

Design No. 2 Efficiency =

$$\frac{323 - 42.35 \times 100}{323} = \frac{280.95 \times 100}{323} = 86.9\%$$

Design No. 3 Efficiency =

$$\frac{323 - 35.01 \times 100}{323} = \frac{287.99 \times 100}{323} = 89.1\%$$

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c. Converter Design for 2-Volt Input, Self-Rectifying Circuit

All losses are the same as for the Royer circuit except rectification and base drive losses. These are as follows:

Rectification loss = 0

Base drive current = 9.8 amps total

Base drive loss per unit = $\frac{9.8}{4} \times \frac{1}{2} \times 1 = 1.24$ watts

P_{BE} (Total) = (1.24) (8) = 9.8 watts

This is an increase of 3.32 watts over the Royer circuit, or an overall converter loss of about 1.6 watts more for the self-rectifying circuit over the Royer circuit.

It is apparent that the crossover point exists between 1.41 volts and 2 volts where the Royer circuit and self-rectifying circuit have equal losses. This point is found as follows:

The rectifier loss at 28-volt output and 9.8 amps is 1.31 watts.

For a transistor current gain of 25

The optimum transformation ratio for the self-rectifying circuit occurs when switching 245 amps since this requires 9.8 amps base current. With 330 watts input power, this occurs at 1.35 volts. The equal loss point occurs where the additional load current increases the base drive losses by 1.31 watts. At 1-volt emitter base drop, this point is at a drive current 1.31 amps higher than that required. For a current gain of 25, a base current of 8.49 amps will switch 212 amps which at 330-watt input represents a voltage level of 1.56 volts. This level is a crossover point above which the self-rectifying circuit will have higher losses than the Royer type using transistor circuit rectification. The gain in efficiency at best in the self-rectifying circuit (at 1.35-volt input) is about 0.4% falling linearly to no improvement at 1.56-volt input. For the above reasons the self-rectifying circuit is no general improvement over the conventional-type circuit using transistor circuit rectification.

d. Design for 3-Volt Input at 104.11 Amps

Transistor Loss

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Assume 4 transistors in parallel on each side of converter switching a current of 26 amps each.

$$\text{Base drive} = \frac{26}{25} = 1.04 \text{ amps}$$

$$P_{BE} \text{ (per unit)} = \frac{1.04}{2} \times 1 = 0.52 \text{ watt}$$

$$P_{BE} \text{ (Total)} = 0.52 \times 8 = 4.16 \text{ watts}$$

Switching and Saturation Losses

$$P_S \text{ (per unit)} = \frac{1}{6} \left[(2)(3)(26)(500)(70 \times 10^{-6}) \right] = 0.91 \text{ watt}$$

$$P_S \text{ (Total)} = 0.91 \times 8 = 7.25 \text{ watts}$$

$$P_C \text{ (per unit)} = (0.002) (26)^2 \left[0.5 - 500 (70 \times 10^{-6}) \right] = 0.675 \text{ watt}$$

$$P_C \text{ (Total)} = 0.675 \times 8 = 5.4 \text{ watts}$$

$$P_B \text{ (per unit)} = (2)(3)(5 \times 10^{-3}) \left[0.5 - 500 (70 \times 10^{-6}) \right] = 0.015 \text{ watt}$$

$$P_B \text{ (Total)} = 8 \times 0.015 = 0.12 \text{ watt}$$

Total transistor dissipation and base drive losses =

$$4.16 + 7.25 + 5.4 + 0.12 = 16.93 \text{ watts}$$

Rectifier Losses = 1.31 watts

(Same as 1-volt input)

Transformer Losses (Main Unit)

(Same as 1-volt input)

Design No. 1 = 10.38 watts

Design No. 2 = 13.98 watts

Design No. 3 = 5.64 watts

Transformer Loss (Switching Unit)

(Same as 1-volt input)

loss = 1 watt

Total Losses

Design No. 1 = 29.62 watts

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Design No. 2 = 33.22 watts

Design No. 3 = 24.88 watts

Converter Efficiency

$$\text{Design No. 1} = \frac{312.3 - 29.62}{312.3} \times 100 = \frac{282.68}{312.3} \times 100 = 90.6\%$$

$$\text{Design No. 2} = \frac{312.3 - 33.22}{312.3} \times 100 = \frac{279.08}{312.3} \times 100 = 89.5\%$$

$$\text{Design No. 3} = \frac{312.3 - 24.88}{312.3} \times 100 = \frac{287.42}{312.3} \times 100 = 92.0\%$$

e. Converter Design for 5-Volt Input at 58.82 Amps

Transistor Loss

Assume 2 transistors in parallel on each side of converter switching a current of 24.41 amps each.

$$\text{Base drive} = \frac{24.41}{25} = 0.975$$

$$P_{BE} \text{ (per unit)} = \frac{0.975}{2} \times 1 = 0.487 \text{ watt}$$

$$P_{BE} \text{ (Total)} = 0.487 \times 4 = 1.95 \text{ watts}$$

Switching and Saturation Losses

$$P_S \text{ (per unit)} = \frac{1}{6} [(2)(5)(24.4)(500)(70 \times 10^{-6})] = 0.855 \text{ watt}$$

$$P_S \text{ (Total)} = 0.885 \times 4 = 3.42 \text{ watts}$$

$$P_C \text{ (per unit)} = (0.002)(24.4)^2 [0.5 - 500 (70 \times 10^{-6})] = 0.59 \text{ watt}$$

$$P_C \text{ (Total)} = 0.59 \times 4 = 2.36 \text{ watts}$$

$$P_B \text{ (per unit)} = (2)(5)(5 \times 10^{-3}) [0.5 - 500 (70 \times 10^{-6})] = 0.0192 \text{ watt}$$

$$P_B \text{ (Total)} = 0.0192 \times 4 = 0.0768 \text{ watts}$$

Total transistor dissipation and base drive losses =

$$1.95 + 3.42 + 2.36 + 0.077 = 7.71 \text{ watts}$$

Rectifier Losses

(Same as 1-volt input) = 1.31 watts

Transformer Losses (Main Unit)

(Same as 1-volt input)

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Design No. 1 = 10.38 watts

Design No. 2 = 13.98 watts

Design No. 3 = 5.64 watts

Transformer Loss (Switching Unit)

(Same as 1-volt input)

loss = 1 watt

Total Losses

Design No. 1 = 20.40 watts

Design No. 2 = 24.0 watts

Design No. 3 = 15.66 watts

Converter Efficiency

$$\text{Design No. 1} = \frac{294.1 - 20.4}{294.1} \times 100 = \frac{273.7}{294.1} \times 100 = 92.8\%$$

$$\text{Design No. 2} = \frac{294.1 - 24.0}{294.1} \times 100 = \frac{270.1}{294.1} \times 100 = 91.8\%$$

$$\text{Design No. 3} = \frac{294.1 - 15.66}{294.1} \times 100 = \frac{278.44}{294.1} \times 100 = 94.6\%$$

3. Transformer Design

a. Transformer Design No. 1 - 1-Volt Input

Input voltage 0.9

Frequency 500 cps

Primary current 333 amps

Load current 9.6 amp

Secondary voltage 29

Core: square stack E_1 14 interleaved 1 x 1 0.006 Mumetal

$$\text{AC: } 1.25 \times 1.25 \times 0.92 = 1.44 \text{ in.}^2 = 9.3 \text{ cm}^2$$

Coil form: 1-5/16 x 1-9/32 x 0.060 x 2-1/16

Using 1 turn primary

$$B_M = \frac{0.9 \times 10^8}{4 \times 1 \times 500 \times 9.3} = 4850 \text{ gauss}$$

Core weight = 3.9 lb

Core loss = 0.35 watt /lb

Core loss = 0.35 x 3.9 = 1.36 watts

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$\frac{11}{16}$	$\frac{26}{32}$
$\frac{4}{16}$	$\frac{8}{32}$
$1\frac{7}{16}$	$1\frac{14}{32}$
$\frac{4}{16}$	$\frac{8}{32}$
$1\frac{13}{32}$	$1\frac{13}{32}$
$\frac{4}{16}$	$\frac{8}{32}$
$1\frac{7}{16}$	$1\frac{14}{32}$
$\frac{4}{16}$	$\frac{8}{32}$
$\frac{11}{16}$	$\frac{22}{32}$

$1/4''$ = turning length of copper around a corner.

$\frac{217}{32}$ total copper length

$$\text{Copper cross section} = \frac{1}{4} \times \frac{7}{8} = 0.218 \text{ in.}^2$$

$$\text{DCR/in.} = \frac{0.00816}{0.218} \times 0.0848 \times 10^{-3} = 3.17 \times 10^{-6}$$

$$\text{Primary DCR} = 2 \times 6.55 \times 3.17 \times 10^{-6} = 4.15 \times 10^{-5}$$

$$\text{Primary copper loss} = 4.15 \times 10^{-5} \times \frac{(333)^2}{2} = 2.3 \text{ watts}$$

$$N_S = \frac{29}{0.9} \times 1 = 32 \text{ turns each side of center tap using 3 layers No. 15}$$

22 turns/layer

$$\begin{aligned} \text{MT} &= 2 \left(1\frac{15}{16}\right) + 2 \left(1\frac{29}{32}\right) + (0.234) \\ &= 3.88 + 3.81 + 0.735 \\ &= 8.43'' \end{aligned}$$

$$\text{DCR} = 8.43 \times 64 \times 0.271 \times 10^{-3} = 0.146$$

$$\text{Secondary copper loss} = \frac{(9.6)^2}{2} \times 0.146 = 6.72 \text{ watts}$$

$$\text{Total transformer loss} = 10.38 \text{ watts}$$

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Transformer weight approximately 8 lb

Transformer volume approximately = 32 cu in.

b. Transformer Design No. 2 - 1-Volt Input

Input voltage 0.9

Frequency 500 cps

Primary current 333 amps

Load current 9.6 amps

Secondary voltage 29 volts

Core: square stack E_I 112 interleaved 1 x 1 0.006 Mumetal

AC: $1.125 \times 1.125 \times 0.92 = 1.17 \text{ in.}^2 = 7.55 \text{ cm}^2$

Coil form: $1\frac{5}{32} \times 1\frac{3}{16} \times 0.060 \times 1\frac{5}{8}$ Lg.

Using 1 turn primary

$$B_M = \frac{0.9 \times 10^8}{4 \times 1 \times 500 \times 7.55} = 5950$$

Core weight = 2.58 lb

Core loss = 0.45 watt /lb

Core loss = $2.58 \times 0.45 = 1.16$ watts

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~~CONFIDENTIAL~~Primary Turn ConfigurationCopper Turn Developed Length

$\frac{9}{16}$	$\frac{18}{32}$
$\frac{1}{4}$	$\frac{8}{32}$
$\frac{5}{16}$	$1 \frac{10}{32}$
$\frac{1}{4}$	$\frac{8}{32}$
$1 \frac{9}{32}$	$1 \frac{9}{32}$
$\frac{1}{4}$	$\frac{8}{32}$
$1 \frac{5}{16}$	$10 \frac{10}{32}$
$\frac{1}{4}$	$\frac{8}{32}$
$\frac{9}{16}$	$\frac{18}{32}$
<hr/>	
$3 \frac{97}{32}$	total length of copper

$1/4''$ = turning length of
copper around corner.

$$\text{Copper cross section} = 1/4 \times 5/8 = 0.156 \text{ in.}^2$$

$$\text{DCR/in.} = \frac{0.00816}{0.156} \times 0.0848 \times 10^{-3} = 4.45 \times 10^{-6}$$

$$\text{Primary DCR} = 2 \times 4.45 \times 10^{-6} \times 6.03 = 5.36 \times 10^{-5}$$

$$\text{Primary copper loss} = 5.36 \times 10^{-5} \times (3.33 \times 10^2)^2 = 2.97 \text{ watts}$$

$$N_S = \frac{29}{0.9} \times 1 = 32 \text{ turns each side of center tap}$$

Using 3 layers No. 17

22 turns/layer

$$\begin{aligned} \text{MT} &= 2 \left(1 \frac{13}{16}\right) + 2 \left(1 \frac{25}{32}\right) + (0.193) \\ &= 3.630 + 3.56 + 0.605 \\ &= 7.8'' \end{aligned}$$

$$\text{DCR} = 7.8 \times 0.430 \times 10^{-3} \times 64 = 0.214$$

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$$\text{Secondary copper loss} = \frac{I^2}{2} R = \frac{(9.6)^2}{2} = 0.214 = 9.85 \text{ watts}$$

$$\text{Total transformer loss} = 9.85 + 2.97 + 1.16 = 13.98 \text{ watts}$$

Transformer weight approximately 5 lb

$$\text{Volume of transformer} = 2.81 \times 2.25 \times 3.375 = 22 \text{ cu in.}$$

c. Transformer Design No. 3 - 1-Volt Input

Input voltage = 0.9

Frequency = 500 cps

Primary current = 333 amps

Load current = 9.6 amps

Secondary voltage 29

Core: square stack of E_I36 interleaved 1 x 1 0.006 Mumetal

$$\text{AC: } 1.625 \times 1.625 \times 0.92 = 2.45 \text{ in.}^2 = 15.8 \text{ cm}^2$$

$$\text{Coil form} = 1-21/32 \times 1-11/16 \times 0.060 \times 2-1/2$$

Using 1 turn primary

$$B = \frac{0.9 \times 10^8}{4 \times 1 \times 500 \times 15.8} = 2850$$

Core weight = 8.95 lb

Core loss/lb = 0.13 watt /lb

$$\text{Core loss} = 0.13 \times 8.95 = 1.16 \text{ watts}$$

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~~CONFIDENTIAL~~Primary Turn ConfigurationCopper Turn Developed Length

	$\frac{3}{4}$	$\frac{24}{32}$
	$\frac{1}{2}$	$\frac{16}{32}$
1	$\frac{13}{16}$	1 $\frac{26}{32}$
	$\frac{1}{2}$	$\frac{16}{32}$
1	$\frac{25}{32}$	1 $\frac{25}{32}$
	$\frac{1}{2}$	$\frac{16}{32}$
1	$\frac{13}{16}$	1 $\frac{26}{32}$
	$\frac{1}{2}$	$\frac{16}{32}$
	$\frac{3}{4}$	$\frac{24}{32}$

3 $\frac{189}{32}$ total length
of copper

$1/2''$ = turning length of copper
around corner.

$$\text{Copper cross section} = \frac{1}{2} \times 1\frac{3}{32} = 0.58 \text{ in.}^2$$

$$\text{DCR/in.} = \frac{0.00816}{0.548} \times 0.0848 \times 10^{-3} = 1.26 \times 10^{-6}$$

$$\text{Primary DCR} = 2 \times 8.91 \times 1.26 \times 10^{-6}$$

$$\text{Primary copper loss} = 2.24 \times 10^{-5} \times \left(\frac{333}{2}\right)^2 = 1.24 \text{ watts}$$

$$N_S = \frac{29}{0.9} \times 1 = 32 \text{ turns each side of center tap}$$

No. 10 wire 4 layers 16 turns/layer

$$\begin{aligned} \text{MT} &= 2 \left(2\frac{13}{16}\right) + 2 \left(2\frac{25}{32}\right) + (0.510) \\ &= 5.81 + 5.55 + 1.6 \\ &= 12.96'' \end{aligned}$$

$$\text{Secondary DCR} = 12.96 \times 64 \times 0.0848 \times 10^{-3} = 0.0705$$

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Secondary copper loss = $0.0705 \times \frac{(9.6)^2}{2} = 3.24$ watts

Total transformer loss = $1.16 + 1.24 + 3.24 = 5.64$ watts

Transformer weight approximately 18 lb

Transformer volume approximately = 100 cu in.

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APPENDIX C

GENERATOR ANALYSIS

1. Emitter Spacer Strength

a. Introduction

The design chosen for the system utilizes the emitter spacer as a support for the emitter and emitter backup piece. It is therefore necessary to investigate the behavior of the lead to see if the required spacing will be maintained between the emitter and collector, and to see if the structural characteristics are sufficient under launch vibration conditions.

A launch load of 150 g's will be assumed and the emitter lead analyzed in the vertical and horizontal planes.

The following three materials will be considered:

- (1) Tantalum
- (2) Tantalum-10% tungsten
- (3) Tantalum-8% tungsten-2% hafnium

The critical stress will be compared to the allowable stresses and corresponding margins of safety will be shown. When the thermally optimized design shows a negative margin, a resizing of the spacer will be made based on allowable stress values.

The allowable stress values used in this analysis are based on limited data and are intended for preliminary comparison purposes. For the final design analysis a re-evaluation of the spacer should be made using better allowable stress data.

b. Spacer Geometry

The design analyzed is shown in the following sketch:

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In the structural model, plates (1) and (2) will be much thicker than the spacer and will operate at a lower temperature. It is assumed that plates (1) and (2) are infinitely more rigid than the spacer, and thus the spacer may be considered as a cantilever being fixed at plate (1) and supporting the emitter at its free end. The structural model is therefore:

The spacer geometry is approximately $t=0.004$ inch and $\ell=11/16$ inch based on an optimization between heat and electrical losses.

c. Loading

To find the loading on the spacer it is necessary to calculate the weight and center of gravity location of the emitter backup piece.

Weight Calculation

Assume Tantalum
 $p = 0.6 \text{ lb/in.}^3$

Volume of Emitter

$$V_1 = .785 (1.02)^2 (.5) = .408 \text{ in.}^3$$

$$V_2 = .785 [(1.438)^2 - (1.02)^2](.0625) = .0515 \text{ in.}^3$$

$$V_3 = .785 [(2)^2 - (1.02)^2](.125) = .2905 \text{ in.}^3$$

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$$V_4 = .785 (.125)^2 (.438) = .0054 \text{ in.}^3$$

$$V_5 = .785 [(1.125)^2 - (1.75)^2] (.438) = .172 \text{ in.}^3$$

$$V_6 = .785 [(2)^2 - (1.75)^2] (.438) = .323 \text{ in.}^3$$

$$V_{TOT} = \Sigma V = 1.2504 \text{ in.}^3$$

$$\text{Emitter Wt.} = \Sigma V \rho = 1.2504 (.6) = 0.75 \text{ lb}$$

Therefore, the design load, P, is:

$$P = .75 (150)$$

$$P = 112.5 \text{ lb}$$

Center of Gravity Calculation

Unit Volume (V_n)	Unit C.G. Location ($\bar{y}_n$)	$V_n \bar{y}_n$
$V_1 = .408$	$y_1 = .25$	.102
$V_2 = .0515$	$y_2 = .34375$	.0177
$V_3 = .2905$	$y_3 = .4375$	.1271
$V_4 = .0054$	$y_4 = .71875$	.0039
$V_5 = .172$	$y_5 = .71875$	.1236
$V_6 = .323$	$y_6 = .71875$	.2322
$\Sigma V = 1.2504$		$\Sigma V \cdot y = .6065$

$$\bar{y} = \frac{\Sigma V \cdot y}{\Sigma V} = \frac{.6065}{1.2504}$$

$$\bar{y} = 0.485 \text{ in.}$$

d. Stress Analysis

Vertical Load

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$$\text{Uniform Tensile Stress} = S_t = \frac{P}{A}$$

$$\text{where } A \approx \pi Dt$$

$$\text{thus } S_t = \frac{P}{\pi Dt}$$

Eq. (C1)

Side Load

$$\text{Bending Stress} = S_b = \frac{MC}{I}$$

where $M = PX = \text{Bending Moment}$

$$C = R$$

$$I \approx \pi R^3 t = \text{Moment of Inertia}$$

thus

$$S_b = \frac{P X R}{\pi R^3 t} = \frac{P X}{\pi R^2 t}$$

Eq. (C2)

e. Stress Calculations

Vertical Load

$$S_t = \frac{P}{\pi Dt}$$

where for thermally optimized design

$$P = 112.5 \text{ lb}$$

$$D \approx 1 \frac{1}{8} \text{ inch}$$

$$t = 0.004 \text{ inch}$$

thus

$$S_t = \frac{112.5}{3.14 (1.125) (.004)} = 7960 \text{ psi}$$

The maximum bending stress will occur at the fixed base. However, this is not necessarily the point of critical stress. The spacer upper end is at a considerably higher temperature than the fixed end and thus has a lower allowable stress. Bending stress will be calculated at

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several points along the spacer length and compared to the allowable stresses at these points.

The upper end temperature will be assumed at 2650° F, and at the fixed end, 1340° F. A linear temperature distribution is assumed between both ends.

$$S_b = \frac{Px}{\pi R^2 t}$$

where $P = 112.5 \text{ lb}$
 $R = .5625$
 $t = .004 \text{ in.}$

thus
$$S_b = \frac{112.5}{3.14 (.5625)^2 (.004)} X = 28.25(10)^3 X$$

Point	X (in.)	S_b (psi)	Temp (°F)
1	.11	3110	2650
2	.2245	6340	2432
3	.339	9580	2214
4	.4535	12800	1996
5	.568	16100	1778
6	.6825	19300	1560
7	.797	22550	1340

$$T_x = M(X-.11) + T_1$$

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$$\text{where } M = \frac{T_2 - T_1}{\ell} = \frac{1340 - 2650}{.6875} = -1905$$

$$\text{thus } T_x = -1905 (x - .11) + 2650$$

ALLOWABLE STRESS VALUES

The allowable stress, S_a , is taken as 0.2% yield or 2/3 of the ultimate tensile strength, whichever is less.

Allowable stress values for the three materials being considered are as follows:

Point	Temp (°F)	Sa		
		Ta ⁽¹⁾ (psi)	Ta-10W ⁽²⁾ (psi)	Ta-8W-2H ⁽³⁾ (psi)
1	2650	4700	11200	21300
2	2432	5900	16680	35300
3	2214	7000	28000	53600
4	1996	8000	39000	59750
5	1778	9250	51700	63300
6	1560	11100	61700	66700
7	1340	15500	69400	69500

(1) -0.2% yield, see Figure C1

(2) -2/3 of ultimate, see Figure C2

(3) -2/3 of ultimate, see Figure C3

f. Resizing of Tantalum Spacer

Tantalum shows a negative margin to exist for the thermally optimized design (i.e., $t=0.004$ in. and $\ell=11/16$ in.) The maximum negative margin is -0.425 and is due to the horizontal inertia load.

The following calculation will show the required wall thickness based on the allowable stress at point 5 (i.e., $x=0.568$ in.) where the temperature is 1778° F.

$$S_b = \frac{Px}{\pi R^2 t}$$

or

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Figure C1. 0.2% Yield Strength vs Temperature for Tantalum Sheet.

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Source: Unpublished Data Generated by National Research Corp. via
DMIC Report 133, July 25, 1960. "Tantalum & Tantalum Alloys,"
Page 276, Table 81

Test Conditions - As Rolled 0.060 Inch Sheet Tested in Argon at an
Approximate Strain Rate of 0.01 In/In/Min

Note: For 100% Recrystallization Hold for One Hour at 2550° F

Legend:

- 0.2% Yield Strength
- Ultimate Strength
- △ % Elongation

Figure C2. Effect of Temperature on Tensile Properties of the Alloy Ta-10W.

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Figure C3. Effect of Temperature on Tensile Properties of the Alloy Ta - 8W - 2Hf.

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CALCULATION OF SAFETY MARGIN

Margins of Safety, M.S., are calculated as follows:

$$M.S. = \frac{\text{Allowable Stress} - \text{Actual Stress}}{\text{Actual Stress}}$$

Material	SIDE LOAD											
	Vertical Load			Point 1			Point 2			Point 3		
	Sb	Sa	M.S.	Sb	Sa	M.S.	Sb	* Sa	M.S.	Sb	Sa	M.S.
Ta	7960	4700	-.41 ▽	3110	4700	.51	6340	5900	-.068 ▽	9580	7000	-.27 ▽
Ta-10W	7960	11200	.41	3110	11200	2.6	6340	16680	1.63*	9580	28000	1.92
Ta-8W-2Hf	7960	21300	1.68	3110	21300	5.85	6340	35300	4.55	9580	55600	4.

SIDE LOAD (Cont)											
Point 4			Point 5			Point 6			Point 7		
Sb	Sa	M.S.	Sb	Sa	M.S.	Sb	Sa	M.S.	Sb	Sa	M.S.
12800	8000	-.375 ▽	16100	9250	-.425* ▽	19300	11100	-.425 ▽	22550	15300	-.32 ▽
12800	39000	2.05	16100	51700	2.21	19300	61700	2.2	22550	69400	2.08
12800	59750	3.67	16100	63300	2.94	19300	66700	2.46	22550	69500	2.08*

▽ Indicates negative margin of safety

* Indicates minimum margin of safety for side inertia load

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$$T_{\min} = \frac{Px}{\pi R^2 S_a}$$

where P = 112.5 lb
 X = 0.568 in.
 R = 0.5625 in.
 S_a = 9250 psi

$$\text{thus } t_{\min} = \frac{112.5 (.568)}{3.14 (.5625)^2 (9250)} \cong 7 (10)^{-3} \text{ in.}$$

g. Conclusions

Tantalum

For the thermally optimized geometry (i.e., t=0.004 inch and $\ell = 11/16$ inch), an overstressed condition was shown to exist for both side and vertical inertia loading. For the vertical load a negative margin of 0.41 was shown at the emitter end, and for the side load a negative margin of 0.425 was shown.

If tantalum is to be used as the spacer material a minimum wall thickness of approximately seven (7) mils is required to sustain the assumed 150-g inertia loading without exceeding the minimum allowable stress.

Alloy Ta - 10W

No overstress was found for side or vertical inertia loading for the thermally optimized geometry. The minimum margins of safety for both loads are: side load 1.63; vertical load 0.41.

Alloy Ta - 8W - 2Hf

This alloy has better high-temperature strength properties than either tantalum or alloy Ta-10W. No overstress was found for side or vertical loading for the thermally optimized geometry. The minimum margins of safety for both loads are: side load 2.08; vertical load 1.68.

h. Recommendations

The alloy Ta - 8W - 2Hf is relatively new. Only preliminary data on structural properties are available. There is a possibility that the

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hafnium content could cause contamination problems by virtue of "outgassing" due to its relatively low vapor pressure, whereas the alloy Ta-10W presents no such "outgassing" problem and is commercially available.

The alloy Ta - 10W will be used for the spacer material.

i. Analysis Limitations

The structural properties used in this analysis are based on limited test data, and the inertia load factor was assumed. For final analysis of the spacer a re-evaluation of the structural property data must be performed, and an inertia load factor based on actual vehicle vibration characteristics used.

2. Diode Thermal Analysis

a. Introduction

The diode thermal analysis is based on an emitter temperature of 1738° K and a collector temperature of 1000° K. From the emitter surface, increases in temperature occur through the tantalum backing plate and across the gap to the fuel block. From the collector surface, decreases in temperature occur through the niobium collector, the two alumina insulators, and the base plate on which the six diodes are attached by a threaded joint. At the external surface of the generator, a truncated conical surface serves the dual purpose of a radiation cooling fin for the collector and an aerodynamic skirt for the generator. The thermal analysis of each of the diode components is presented in the following subsections. A schematic drawing of the diode with the temperatures is shown in Figure C4.

b. Emitter Backing Plate

For analysis, the emitter backing plate was divided into two regions as depicted in the sketch below.

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Figure C4. Diode Assembly.

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In region I, the analytical model is "radial flow of heat with constant heat generation" for which:

$$\Delta T = \frac{S(r_2^2 - r_1^2)}{4K} = 30^\circ \text{ C radial} \quad \text{Eq. (C3)}$$

S = volumetric heat production rate = 20 w/cc
(this is obtained by considering the heat flux into region I and dividing I and dividing by its volume)

r_2 = outer radius = 2.54 cm

r_1 = inner radius = 1.27 cm

K = thermal conductivity of tantalum =

$$0.78 \frac{\text{watts}}{\text{cm}^\circ \text{ K}}$$

ΔT = radial temperature difference in region I

In each diode, 89% of the heat is transported across region II, the remainder being conducted through the spacer. For slab heat flow in one dimension:

$$\Delta T = \frac{ql}{KA} = 77^\circ \text{ C} \quad \text{Eq. (C4)}$$

q = axial heat rate = 252 watts

K = thermal conductivity of tantalum =

$$.78 \text{ watts/cm}^\circ \text{ K}$$

A = cross sectional area of plate = 4.8 cm²

ΔT = axial temperature difference in region II

l = length of backing plate = 1.15 cm

c. Backing Plate Fuel Block Region

Across these two boundaries, heat is transferred by radiation only. Consequently, both surfaces have been finned and grooved to improve the transfer area and view factors respectively. The average cold sink temperature at the top of the backing plate was taken as:

$$T_{\text{emitter}} + \Delta T_{\text{axial}} + \frac{\Delta T_{\text{radial}}}{2} = 1830^\circ \text{ K}$$

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The average temperature on the fuel block opposite a diode is given by:

$$T_B = \left[\frac{q}{\sigma F A} + T_{c.s.}^4 \right]^{1/4} = 1860^\circ \text{ K} \quad \text{Eq. (C5)}$$

q = heat rate/diode = 283 watts

σ = Stefan-Boltzmann constant

= 5.67×10^{-12} watts/cm²(°K)⁴

F = view factor $\frac{1}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}$

ϵ_1 = tantalum emissivity, grooved = 0.9

ϵ_2 = tantalum alloy block clad material, grooved = 0.9

A = finned area = 93.7 cm²

$T_{c.s.}$ = cold sink temperature = 1830° K

Some doubt exists on the attainability of a 0.9 emissivity due to difficulty in machining V-shaped grooves into already finned surfaces. For an emissivity of only 0.4, the average block temperature would be 1890° K, an increase of 30° K in the gap between the fins.

The temperature drop along the fins was neglected since they are relatively short. This assumption will be compensated for by the radial temperature distribution in the fuel block on the bottom surface, which was neglected in computing heat transfer to the diodes.

d. Collector

Through the niobium collector, heat flow is predominantly one-dimensional, for which

$$\Delta T = \frac{ql}{KA} = 81.5^\circ \text{ C} \quad \text{Eq. (C6)}$$

where q = heat rate = 203* watts

l = collector length = 1.11 cm

K = thermal conductivity of niobium .57 watt /cm-°K

A = cross section area of collector = 4.8 cm²

* Of the total 283 watts to the diode, 49 are used to produce the electrical power, and 31 are lead losses.

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e. Ceramic Insulators

Two alumina discs prevent shorting between the emitter lead and the collector. Heat flow is again one-dimensional. For each disc:

$$\Delta T = \frac{ql}{KA} = 23^\circ \text{ C} \quad \text{Eq. (C7)}$$

q = heat rate = 234 watts

l = insulator thickness = 0.076 cm (30 mils)

K = thermal conductivity of alumina = 0.087 watts/cm-°K

A = cross sectional area of insulators = 8.5 cm²

f. Collector Backup Plate

Heat flow from the base of a collector to the external fin is complex. Not only is heat transferred in three dimensions, but geometries are not analytically describable in simple terms. In addition, the diodes are screwed to the base plate resulting in poorly predictable heat transfer contact resistances. For order-of-magnitude calculations, however, this section of the diode was analyzed as follows:

Portion of Diode Contacting Alumina

In the niobium section directly against the collector, heat was assumed to be uniformly generated with radial flow.

$$\Delta T = \frac{S(r_2^2 - r_1^2)}{4K} = 15.6^\circ \text{ C} \quad \text{Eq. (C8)}$$

S = volumetric heat production rate = 6.65 watts/cc

r_1 = outer radius = 2.38 cm

r_2 = inner radius = 0.56 cm

K = thermal conductivity of niobium = .57 watts/cm-°K

An additional drop will occur due to axial heat flow in the portion of the diode that is threaded. Since this is a high radius portion, the drop will be small, and the 15.6° C will be used as 25° C to account for this.

Temperature Drop Across Threads

To allow for removable modules, each diode is screwed into the

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copper slab. Due to this solid-solid interface, a temperature difference exists. At the contact, the bearing pressure is

$$S_b = \frac{4PF}{\pi h(d^2 - d_r^2)} = 0.017 \times 10^9 \text{ dynes/cm}^2 \text{ (250 psi)} \quad \text{Eq. (C9)}$$

$$F = \frac{2T}{d_m} \left(\frac{\pi d_m - f p}{p + \pi f d_m} \right) = 0.736 \times 10^9 \text{ dynes (1660 lb)} \quad \text{Eq. (C10)}$$

P = thread pitch = 0.16 cm

h = thread engagement length = 2.7 cm

d = outside thread diameter = 5.7 cm

d_r = root diameter = 5.5 cm

f = coefficient of friction = 0.3

d_m = mean diameter = 5.62 cm

T = applied torque = 50 lb-ft = 6.78 x 10⁹ dyne-cm

With the bearing pressure calculated, empirical data of contact coefficient versus pressure were used for copper surfaces in a vacuum.³⁴

The coefficient was found to be 0.155 $\frac{\text{watts}}{\text{cm}^2}$ (273 $\frac{\text{Btu}}{\text{hr-ft}^2-\text{°F}}$).

The thermal contact area was found by considering each thread to have a contact area given by

$$\text{Area/thread} = \frac{\pi}{4} (d^2 - d_r^2) \quad \text{Eq. (C11)}$$

with a fine thread, there are 6.3 threads/cm. The total engagement is 2.7 cm. Finally, from the geometry of the system, it was assumed that 3/4 of the actual contact area would serve to transport the heat to the external fin. With these values the contact area was found to be 20 cm².

34. Graff, W. J., "Thermal Conductance Across Metal Joints," Machine Design, September 15, 1960.

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The temperature drop across the threaded joint is

$$\Delta T = \frac{q}{hA} = 75.5^\circ \text{C} \quad \text{Eq. (C12)}$$

$$q = \text{heat rate} = 234 \text{ watts}$$

$$h = \text{contact coefficient} = 0.155 \frac{\text{watts}}{\text{cm}^2 \cdot ^\circ \text{K}}$$

$$A = \text{contact area} = 20 \text{ cm}^2$$

g. External Diode Fin

This angled copper fin must dump 1406* watts at a temperature such that the collector operates at a maximum of 1000° K. A 10.2-cm fin will accomplish this with a root temperature of 772° K.

Figure C5. Fin Cross Sectional Area.

* Some of the heat from the diode was radiated and not conducted through the threads. However, all of it is assumed to be rejected by the diode fins.

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The conical portion of the fin will dump heat from both surfaces. Consequently the fin was divided into two regions, and an effective area computed for each. (Note from the sketch the position of the assumed fin root. The conical length is 10.2 cm and the total fin length is 13.0 cm.)

For the outermost surface an analytical model of two infinite planes (the fin and the generator surface) at an angle of 155° was considered resulting in a view factor⁽³⁵⁾ from the fin to space of 0.95. The outermost radiator area for the conical portion of the fin is consequently:

$$A_1 = 0.95 \times \pi(r_1 + r_2) \sqrt{h^2 + (r_2 - r_1)^2} = 862 \text{ cm}^2 \quad \text{Eq. (C13)}$$

where h, r₂ and r₁ are indicated on the sketch.

For a radiation fin,

$$q = \sigma \epsilon A \eta T_{\text{root}}^4$$

$$T_{\text{root}} = 772^\circ \text{ K}$$

$$\eta = \frac{\tanh N}{N} = .82 \text{ rectangular fin} \quad \text{Eq. (C14)}$$

$$N = L \sqrt{\frac{h}{k y_o}} = .856$$

$$h = E \sigma T_{\text{root}}^3 = .00235 \frac{\text{watts}}{\text{cm}^2 \cdot ^\circ \text{K}}$$

q = heat rate to be dumped = 1406 watts

ε = fin emissivity = 0.9 (attainable with v-shaped grooved surface)

$$\sigma = \text{Stefan-Boltzmann constant} = 5.67 \times 10^{-12} \frac{\text{watts}}{\text{cm}^2 \cdot (^\circ \text{K})^4}$$

$$K = \text{thermal conductivity of copper} = 3.55 \frac{\text{watts}}{\text{cm} \cdot ^\circ \text{K}}$$

$$\eta = \text{fin efficiency} = .82$$

35. Hamilton, D. C., and Morgan, W. R., "Radiant Interchange Configuration Factor," NASA TN-2836, December 1952.

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L = fin length = 13.0 cm
 h = radiation heat transfer coefficient
 y_o = semi fin root thickness = 0.16 cm

From the underneath portion of the fin, the radiation area was taken as the projected area:

$$A_2 = \pi (r_2^2 - r_o^2) = 610 \text{ cm}^2$$

$$A = A_1 + A_2 = 1472 \text{ cm}^2$$

Eq. (C15)

The fin efficiency was initially assumed since the calculation is iterative. (After determining the fin root temperature, one must verify the assumed value of efficiency.) Since the formula given applies to a rectangular fin, it was corrected according to Jakob and Hawkins³⁶ for a circular fin. The correction was -0.01.

The rejected heat is:

$$q = \epsilon \sigma A \eta T_{\text{root}}^4 = 2190 \text{ watts}$$

Eq. (C16)

Thus the fin is completely adequate to reject 1406 watts with an adequate safety factor to allow for heat leakage into the fin from other portions of the generator.

h. Diode Analysis Conclusions

The heat balances performed on the diode apply at any time during the operational life of the generator. In particular, the collector surface will operate at less than:

$$T_{\text{fin root}} + \Delta T_{\text{threaded contact}} + \Delta T_{\text{copper slab}} + \Delta T_{\text{insulators}} + \Delta T_{\text{collector}} = 1000^\circ \text{ K}$$

Eq. (C17)

At this value back emission from the collector to the emitter will be negligible.

3. Cesium Reservoir Analysis

The cesium reservoir is located and thermally shielded so that its

36. Jakob, H., and Hawkins, G. A., "Elements of Heat Transfer," 3rd Edition, Wiley.

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surrounding temperature is less than the optimum operation point. A small electric heater is then utilized to increase the temperature of the reservoir to the optimum point.

The following numerical technique may be applied to the spherical shell to obtain the temperature profile:

- Segment the spherical shell into 10-15 regions.
- Assume initial temperature (fin root temperature = 772° K).
- Apply the following equations to each region:

$$\sigma A_S \epsilon T_\eta^4 = \frac{2kA_c}{l} (T_{\eta-1/2} - T_{\eta+1/2}) \quad \text{Eq. (C18)}$$

σ = Stefan-Boltzmann constant

ϵ = emissivity of surface = .9

A_S = surface area per region

T_η = temperature at midpoint of η^{th} segment

k = thermal conductivity of shell = 0.19 watts/cm°C (inconel)

A_c = cross section area perpendicular to flow (cm²)

l = length of η^{th} segment

The temperature profile of the skin is obtained by a trial-and-error solution. The cesium reservoir surrounding temperature is found to be at about 530° K. The immediate area around the cesium reservoir block is surrounded by 0.32 cm of insulation. By this means, a very small heater (2-3 watts) is sufficient to produce a temperature increase of 100° K above its surroundings, assuring close reservoir control.

4. Overall Generator Efficiency

The end-of-life (design point) overall generator efficiency is a function of the thermionic efficiency and the system thermal losses. It is defined by:

$$\eta_{\text{overall}} = \frac{\text{electrical power developed}}{\text{summation of all heat inputs}} \quad \text{Eq. (C19)}$$

The heat inputs are of two types:

- (1) Thermal load to diodes

$$Q_{\text{diode}} = \frac{\text{electrical power developed}}{\text{thermionic efficiency}} = \frac{294}{17.29} = 1700 \text{ watts} \quad \text{Eq. (C20)}$$

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(2) Thermal shield losses

- a. Shield losses = 2 watts/cm²
 - b. Dimensions of fuel block = 17.8 cm dia x 18.4 cm lg
 - c. Total shield area = 1494 cm² (allows for diodes)
- $$Q_{\text{shield}} = (2) (1494) = 2988 \text{ watts}$$

The total heat input at the end of life is the sum of these losses:

$$Q_{\text{end}} = 1700 + 2988 = 4688 \text{ watts}$$

the overall generator efficiency is then:

$$\eta_{\text{overall}} = \frac{281}{4688} = .0600 \quad \text{Eq. (C21)}$$

where 281 is used instead of 294 to take into account the losses in the electrical connections and controls.

5. Beginning of Life Thermal Loading

Due to the short half-life of Ce 144 (285 days)* and the long operation time (390 days), a large initial excess of fuel is necessary. The fuel inventory at beginning of life is found by the relation

$$Q_{\text{begin}} = Q_{\text{end}} \exp \left[\frac{.693 t}{T_{1/2}} \right] = 2.6 Q_{\text{end}} = 12,200 \text{ watts} \quad \text{Eq. (C22)}$$

t = operation time = 390 days (1-year mission plus
25 days for fueling, testing, etc.)

$t_{1/2}$ = half-life of fuel = 285 days

6. Fuel Capsule Sizing

The fuel element length is assumed to be 16.5 cm to fit within a graphite block of length 18.4 cm. Fuel inventory volume is:

$$V = \frac{\text{fuel inventory}}{\text{power density}} = \frac{12,200}{6} = 2030 \text{ cc} \quad \text{Eq. (C23)}$$

A symmetrical arrangement of 22 fuel elements produces a diameter of 2.67 cm of bare fuel. The capsules are additionally clad with 10 mils of rhodium.

* Reference 22 on page 136.

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7. Fuel Block Analysis

The thermal analysis of the fuel block consists of obtaining the temperature gradients through the bare fuel, temperature drops at all interfaces, and the axial and radial drops through the graphite block.

a. Radial Fuel Gradient

The radial temperature drop through the cerium fuel is found from the heat conduction equation with uniform heat generation.*

$$\Delta T = \frac{Sr^2}{4k} = 76.7^\circ \text{ K} \quad \text{Eq. (C24)}$$

Where: r = fuel capsule radius = 1.33 cm

S = volumetric heat production rate = 6 watts/cc

k = thermal conductivity of fuel⁽³⁷⁾ =
.0346 watts/cm °K (estimated)

b. Interface Drops in Fuel Block

Helium fills all gaps in the fuel block and the temperature drops at the interfaces are negligible. For example, the temperature drop across an interface (excluding the radiation contribution) for a fuel capsule is:

$$\Delta T = \frac{ql}{kA} = 6.3^\circ \text{ K} \quad \text{Eq. (C25)}$$

q = heat load per capsule = 554 watts

l = maximum gap thickness = 3 mils = .0076 cm

k = gas thermal conductivity = 0.00485 watts/cm °K**

A = conduction area = 138 cm²

c. Axial and Radial Temperature Gradients in Fuel Block

An accurate analysis of fuel block temperature gradients is difficult because of the complexity. An analytical two-dimensional analysis is poor because the block is not homogeneous, but is composed

37. Vasilos, T., and Kingery, W. D., "Conductivity of Some Refractory Carbides and Nitrides," J. Am. Ceram Soc. Vol. 37. PP 409-414.

* Reference 36 on page C-20.

** Reference 23 on page 138.

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of graphite containing 22 holes which are filled with loose-fitting fuel capsules.

A one-dimensional approximation is possible if one notes that most of the radial and axial conduction occurs through the graphite portion of the fuel block. The one-dimensional axial temperature gradient is found by the relation for uniform heat generation.

$$\Delta T = \frac{ql}{2kA} = 302^\circ \text{C} \quad \text{Eq. (C26)}$$

l = fuel block length = 18.4 cm

q = heat flow to diodes = 2134 watts

(includes heat leakage through end thermal shield)

k = thermal conductivity of graphite = 0.52 watt /cm°C

A = cross-sectional area of graphite = 125 cm²

A one-dimensional radial temperature gradient is found by a similar technique. The equation for uniform heat production in a solid cylinder is given by

$$\Delta T = \frac{Sr^2}{4k} = 227^\circ \text{K} \quad \text{Eq. (C27)}$$

S = volumetric heat production = 6 watts/cc

r = radius of fuel block = 8.88 cm

k = thermal conductivity of graphite block = 0.52 watt /cm°C

Although the fuel block is not a solid cylinder of graphite, the relation holds to a good approximation since both the heat production rates and the effective value of thermal conductivity are reduced by the same amount.

According to the analysis technique, the axial temperature drop will remain the same during the generator life. However, in the actual case, the beginning-of-life axial gradient will be considerably less because of the heat dump ports along the fuel block sides. Any tendency for a nonuniform axial temperature will be compensated by the greatly increased heat rejection from the hotter portion of the block that "sees" through the heat dump ports. This occurs because heat rejection is by radiation only, and the heat rejection rate is proportional to the fourth

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power of the temperature. Therefore the axial gradient will be modified in Section 9 after the heat dump is analyzed.

The radial gradient will be a maximum at the beginning of life, and will be reduced as the heat dump ports are closed until, at the end of life, the small gradient will be due to heat leakage through the thermal shields.

In addition to the changes just discussed, one should consider the effect of multidimensional heat flow as compared to the single-dimensional flows considered. This will reduce the hottest point in the block to a point lower in temperature than actually calculated.

8. Heat Dump Analysis

a. Introduction

A heat dump mechanism is employed to dissipate the excess heat generated at the beginning of life. This is accomplished by using a rotating shutter to cover or uncover ports that allow the heat block to reject heat to the generator outer shell. Since 12,200 watts are available at the beginning of life, and the heat required for proper generator operation is 4688 watts, the difference, 7512 watts, must be dumped through the ports in the thermal shields.

b. Generator Surface Temperature

Opposite Heat Dump Ports

The generator surface through which the "dump heat" is rejected consists of copper 0.308 cm thick clad on both sides with inconel. Since the thermal conductivity of inconel is small in comparison to copper, heat flow in the inconel will be negligible.

Heat flow to the generator surface occurs at six points, one for each of the ports in the thermal shields. The heat is then distributed along the generator surface by conduction and rejected to space. Thus the surface will behave as a radiating fin, and the effect of the small temperature drop in the skin can be included by using an assumed fin efficiency of 0.9.

The surface area available for rejecting the 7512 watts is:

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$$A = (\pi) (\text{diameter}) (\text{length}) = (\pi) (24.5) (17.8) = 1369 \text{ cm}^2$$

Eq. (C28)

The surface temperature where the heat is rejected to the generator surface is therefore

$$T = \left(\frac{q}{\sigma \epsilon A \eta} \right)^{1/4} = 1046^\circ \text{ K}$$

Eq. (C29)

g = heat dump rate = 7512 watts

σ = Stefan-Boltzmann constant = $5.67 \times 10^{-12} \frac{\text{watts}}{\text{cm}^2 \cdot ^\circ \text{K}}$

ϵ = fin emissivity, coated or grooved = 0.9

A = radiation area = 1369 cm^2

η = fin efficiency = 0.9

c. Temperature Increase through Crushable Structure

The crushable structure is not capable of transmitting the heat from the ports to the generator skin. Six copper plates (clad with inconel) are provided to conduct the heat to the heat rejection surface. One plate is provided for each of the six ports. The plates are 0.635 cm thick, 2.54 cm in the radial direction and 15.9 cm in the axial direction.

The temperature drop is found by the relation

$$\Delta T = \frac{ql}{kA} = 97.2^\circ \text{ K}$$

Eq. (C30)

q = heat flow rate in each plate = 1252 watts

l = conduction length = 2.54 cm

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k = thermal conductivity of copper = 3.24 watts/cm°C

A = conducting area = 10.1 cm²

The inside temperature of the conductor is simply the root temperature of the fin plus the ΔT through the conductor.

$$T = 1143^{\circ} \text{ K}$$

d. Temperature Increase from Conduction Plates to Exposed Fuel Block

The excess heat is dissipated from the fuel block surface to the copper conducting plates within the crushable structure by radiation.

The temperature at the surface of the fuel block is:

$$T_S = \left[\frac{q}{\sigma AF} + T^4 \right]^{1/4} = 1750^{\circ} \text{ K} \quad \text{Eq. (C31)}$$

T = temperature of conductor = 1143° K

q = excess heat = 7512 watts

F = view factor = .82

A = total exposed area = 211 cm²

The exposed area is made up of six slots, 2.22 cm wide and 15.8 cm long.

9. Modification of Fuel Block Temperatures at Beginning of Life

The previously computed block temperatures can now be modified to more realistic numbers since data have been computed pertaining to the heat rejection surface characteristics. The radial temperature distribution in the block and in the fuel will remain about the same. However, the axial distribution will change significantly.

The heat will be dumped from the block with the ports fully open if the block surface is at 1750° K. If the block surface is effectively at some higher temperature, the ports will not be fully open at the beginning of life.

We have previously found that the average block temperature at the diode must be 1860° K to transmit the required heat for conversion to electricity. Since the diode centers are located on a radius of 5.72 cm as measured on the block, and the block is 8.88 cm in radius, the approximate temperatures along the bottom surface of the block will be (see Equation C27):

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<u>Position on Bottom Surface</u>	<u>Temperature, °K</u>
Center	1955
Diode	1860
Outside Edge	1728

where the temperature difference between the center and edge is, as calculated in Section 7b, 227° K. To provide a margin of safety, assume the surface temperature on the bottom edge is 1760° K so that the center of the block at the bottom becomes $1760 + 227 = 1987^{\circ}$ K. The thermal shields will always adjust to maintain the 1860° K value near the diodes since shield position is controlled by generator output, and hence diode temperature. Thus the 1760° K will be approximately the bottom outside edge fuel block temperature at beginning of life, and the shutter position will be such that this occurs.

Now consider the top of the block. The approximate axial temperature gradient calculation showed a gradient of 302° K (see Equation C26). This would indicate a top of block temperature of $1760 + 302 \approx 2060^{\circ}$ K at the outside edge. However, the heat rejection rate at this temperature would be $\left(\frac{2060}{1760}\right)^4 = 1.9$ times as great as at 1760° K. Thus we would be removing considerably more heat from the top end than will actually occur, showing the axial gradient calculation to be a poor approximation at the beginning of life.

To accurately compute the temperature at the top of the block is not feasible at this time because of the shortness of the study. However, utilizing the above considerations, an axial beginning-of-life gradient of 100° K appears reasonable. Thus, the top outer edge block temperature becomes $1760 + 100 \approx 1860^{\circ}$ K and the top center temperature becomes $1860 + 227 \approx 2090^{\circ}$ K. The maximum fuel center line temperature under these conditions would be $2090 + 97 \approx 2190^{\circ}$ K.

10. Rhodium Fuel Capsule Temperature in Air

Prior to loading the 22 rhodium fuel capsules into the graphite block, bare handling of the capsules will be necessary. The equilibrium

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temperature of each capsule was determined to be 1472° K. Heat is transferred by radiation and convection according to the relation

$$q = \epsilon \sigma A (T^4 - \theta^4) + hA (T - \theta) \quad \text{Eq. (C32)}$$

$$h = 9.13 \times 10^{-5} (T - \theta)^{1/4} \text{ watts/cm}^2 \text{ } ^\circ\text{C}$$

$$q = \text{heat load per capsule} = 554 \text{ watts}$$

$$\sigma = \text{Stefan-Boltzmann constant} = 5.67 \times 10^{-12} \text{ watts/cm}^2 \text{ } (^\circ\text{K})^4$$

$$A = \text{surface area of cylinder} = 148 \text{ cm}^2$$

$$\epsilon = \text{emissivity of oxidized rhodium} = .1$$

$$\theta = \text{ambient temperature} = 38^\circ \text{ C}$$

Solving by a trial-and-error procedure the temperature is 1472° K.

11. Beginning-of-Life Temperature with Shields Closed

At the end of life, the fuel block operates at approximately 1950° K average surface temperature. At this temperature, the heat loss through the thermal shields has been assumed to be 2 watts/cm². It is of interest to determine what happens if the thermal shields are accidentally closed at the beginning of life.

Since the heat is transmitted by radiation only, the heat loss will increase by the ratio $\left(\frac{T}{1950}\right)^4$ where T is the new block temperature. The heat load at end of life is 4688 watts, at beginning of life 12,200 watts. Thus, the block temperature if the ports are closed becomes:

$$\left(\frac{T}{1950}\right)^4 = \frac{12200}{4688} \quad \text{Eq. (C33)}$$

$$T = 2480^\circ \text{ K}$$

Since the rhodium inner container melts at 2240° K, it is absolutely necessary that the thermal shields not close at the beginning of life.

12. Fuel Block Temperature if Diodes Fail

If no electricity is used, the amount of heat that flows across the diodes is decreased by 71.6%. Thus, diode heat loss with no electricity flow = (1700) (.284) = 483 watts and the fuel block temperature (average) will increase from 1750° K to a temperature T defined by:

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$$\left(\frac{T}{1750}\right)^4 = \frac{12200}{12200 - (1700 - 483)} \quad \text{Eq. (C34)}$$

$$T = 1790^\circ \text{ K}$$

Hence no problem exists.

The value 1750° K was used in this calculation since this represents the fuel block surface temperature with the heat dump ports wide open, and complete loss of electrical output will cause the ports to open.

13. Adiabatic and Radiation Heating Analysis

The following equations were used for this analysis:

$$\text{Adiabatic: } Q_A/A = WC_P (T_{\max} - t_o) + Wh_f$$

$$\text{Radiation: } Q_R/A = \epsilon \sigma \Delta t T_{\max}^4$$

Where Q_A/A - total adiabatic heat

W - weight of material

C_P - specific heat of material

$T_{\max}$ - 5000° R or melting temperature of material

t_o - initial temperature of material

h_f - heat of fusion of material

A - surface area

Q_R/A - total radiation heat

ϵ - emissivity of material

σ - Stefan-Boltzmann's constant

Δt - approximate time at $T_{\max}$

For the materials tungsten and tantalum, a maximum temperature of 5000° R was assumed to be sufficient for destruction because of their high oxidation rates at high temperatures. The graphite segmented blocks were also raised to 5000° R before they were separated by dynamic pressure. This type of analysis is thought to be conservative.

The generator and fuel capsules are to be destroyed by aerodynamic heating and dynamic pressure during re-entry from orbit. A total heat

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TABLE C1

ADIABATIC AND RADIATION HEATING ANALYSIS OF 250-WATT GENERATOR

Material	Weight (lb)	Surface Area (ft ²)	C _P (Btu/ lb°R)	T _{max} (°R)	T _o (°R)	h _f (Btu/lb)	Q/A = C _P W (T _M -T _o)+Wh _f (Btu/ft ²)	ε	Δt (sec)	T _M ⁴ (°R) ⁴	Q _R /A=.483 x10 ⁻¹² εΔtT ⁴ (Btu/ft ²)	Q _T /A=Q _A /A + Q _R /A (Btu/ft ²)
Steel	12.9	8.96	.151	2960	1712	122	447	.8	20	71 x 10 ¹²	550	997
Tantalum	20.4	1.51	.044	5000	3600	---	832	.42	1	630 x 10 ¹²	128	960
Tungsten	12.3	1.54	.035	5000	3600	---	391	.35	2	630 x 10 ¹²	213	604
Rhodium	3.91	1.65	.06	4030	3600	---	83	.08	1	256 x 10 ¹²	9.9	92.9
Copper	22.6	3.17	.11	2441	1712	57	2982	.8	20	33 x 10 ¹²	255	3237
Graphite	5.37	1.15	.52	5000	3600	---	3399	.9	1	630 x 10 ¹²	274	3673
Totals							8134				1429.9	9563.9

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of approximately 9600 Btu/ft is required to destroy the generator and a fuel capsule. This quantity was calculated by an adiabatic and radiation analysis. The altitude, total heat available and velocity curves are presented in Figure C6 as a function of time from 400,000 feet, where the atmosphere is assumed to start. This figure shows that the fuel will be released to the atmosphere just below 200,000 feet.

14. Effect of Cesium Temperature on Diode Efficiency

The effect of variations in the cesium temperature on the diode is shown in Figure C7. This is used to determine how closely the cesium temperature must be controlled.

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Figure C6. Random Re-Entry of 250-Watt Generator.

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Figure C7. Thermionic Efficiency vs Cesium Temperature.

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APPENDIX D

AERODYNAMIC DRAG AND STATIC STABILITY STUDY

For the drag portion of this study it was necessary to obtain an expression to approximate the total drag on a blunt-nose cylindrical body with a flared skirt. The flared skirt was added to the generator to increase its drag and to provide aerodynamic stability during the terminal phase of the re-entry. The base drag of the flared skirt and forebody drag on the hemispherical nose are the larger contributors to total drag at low subsonic speeds and can be expressed as:

$$C_{D_T} = C_{D_N} + f C_{D_C} \frac{S_F}{S_C}$$

where C_{D_T} = Total drag coefficient at zero angle of attack and based on S_C

C_{D_N} = 0.5 - Drag coefficient of a hemispherical nose at zero angle of attack and based on S_C (Reference 38)

f = 2.8 - Factor (Reference 39)

C_{D_C} = 0.1 - Base drag coefficient at zero angle of attack and the reference area is its base area (Reference 40)

S_F = Base area of flared skirt

S_C = Cross-sectional area of the cylindrical body

38. Hoerner, S. F.: Fluid-Dynamic Drag. PP 3-17.

39. Knechtel, E. D., Wakefield, R. M., and Treon, S. L.: Transonic Static Aerodynamic Characteristics of a Low-Fineness-Ratio Body of Revolution Having a Blunt Ellipsoidal Nose and Flare Afterbodies of Various Angles and Base Areas. NASA TM X-113. January 1960. Confidential.

40. Knechtel, E. D., Wakefield, R. M., and Treon, S. L.: Effects of Spike-Mounted Flow Deflectors on the Transonic Aerodynamic Characteristics of a Blunt-Nose Body of Revolution Having a Cylindrical or Flared Afterbody. NASA TM X-574. October 1961. Confidential.

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The drag coefficient calculated by the foregoing method agrees favorably with experimental results for a flare angle of 10 degrees. The calculated coefficient is somewhat smaller than the experimental values for the same body at flare angles of 20 and 30 degrees,* but it is felt to give an adequate approximation for this study.

The criterion for static stability of any body is that the slope of the pitching moment coefficient, $C_{M_{c.g.}}$, about the center of gravity

versus angle of attack, α , must be negative.⁴¹ A comparison (Figure D1) was made with existing experimental data to see the effect of adding a flare and of increasing the base area ratio of a flared skirt. The base area ratio, B/S , is defined as the flared skirt base area to the cross-sectional area of the cylindrical body. From this figure it can be concluded:

- a. The addition of a flared skirt to a cylindrical body increases the static stability.
- b. At a constant flare angle, the static stability parameter is increased as the base area ration increases.

From this aerodynamic drag and static stability study, it can be surmised that the generator will be statically stable at zero angle of attack, a nose-first orientation, during re-entry and its impact velocity will be in the low subsonic range.

* Reference 39 on page D-1

41. Perkins, C. D., and Hage, R. E.: Airplane Performance Stability and Control. John Wiley and Sons, Inc.

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Figure D1. Static Stability Parameter vs Mach Number for a Blunt-Nosed Cylindrical Body with a Flared Skirt.

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APPENDIX E

THERMAL ANALYSIS FOR ALPHA-EMITTING FUELS

1. Introduction

Although at the beginning of the program such fuels as curium 242, polonium 210 and plutonium 238 were discarded from consideration due to availability, a cursory analysis for their adaptation to the present generator design is included. Only minor modifications have been made to the cerium generator design to include these fuels and consequently the generator is not optimum for use with alpha-emitting fuels.

2. Curium Generator

With this high power density material, the fuel may be arranged in the form of six capsules within a 17.78-cm-diameter cylindrical graphite block. The bare fuel diameter will be 3.81 cm. An energy balance between the heat production rate and the heat losses was made to determine the approximate fuel length:

$$q_{\text{lateral}} = (\pi DL) h = (111.6) L \text{ watts} \quad \text{Eq. (E1)}$$

D = diameter of graphite block = 17.78 cm

L = length of fuel block, cm

h = heat losses = 2 watts/cm²

q = heat flow rate, watts

$$q_{\text{diodes}} = \frac{\text{Power Developed}}{\eta_{\text{T/I}}} = \frac{294}{.1729} = 1700 \text{ watts} \quad \text{Eq. (E2)}$$

η = conversion efficiency, thermionic

$$q_{\text{ends}} = \left(\frac{\pi D^2}{2} - A \right) h = 930 \text{ watts} \quad \text{Eq. (E3)}$$

A = diode area $\approx 30 \text{ cm}^2$

The total heat load is the sum of these losses:

$$q_{\text{losses}} = 1700 + 930 + (111.6) L$$

For a 6-month mission, the fuel heat production will decrease by the

$$\text{decay factor } \exp\left(\frac{0.693t}{T_{1/2}}\right) = 2.45$$

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t = mission life = 210 days

$T_{1/2}$ = half-life of fuel = 162.5 days

The heat production rate is given by

$$HPR = V_f \times P.D.E. = \frac{150}{2.45} \times 68.4 \text{ L} \quad \text{Eq. (E4)}$$

V_f = fuel volume for 6 capsules

3.81 cm diameter and length $L = 68.4 \text{ L}$

P.D.E. = power density of cm fuel at

$$\text{end of life} = \frac{150}{2.45}$$

Equating the heat production rate to the sum of the heat losses and solving for L , the length of fuel capsule, we obtain

$$L = .645 \text{ cm}$$

The end of life efficiency is given by

$$\eta = \frac{\text{Power to Converter}}{\text{H.P.R.}} = \frac{275}{2701} = 0.102 \quad \text{Eq. (E5)}$$

To determine the power produced at loading time,

$$P_{\text{initial}} = P_{\text{end}} \times \text{decay factor} = 6617 \text{ watts} \quad \text{Eq. (E6)}$$

where $P_{\text{end}} = \text{H.P.R.} = 2701 \text{ watts}$

$$\text{decay factor} = 2.45$$

The excess heat to be dumped initially is simply $P_{\text{initial}} -$

$$P_{\text{end}} = 3916 \text{ watts}$$

The worst temperature gradient will be an axial gradient that occurs at the beginning of life when 3916 watts are dumped from one end of the fuel block. In this situation, the heat produced in 0.47 cm of the fuel length will flow out the heat dump ports. The remainder of the heat will flow in the opposite direction out through the diodes. Thus, the temperature gradient, neglecting the graphite and fuel capsule case which would considerably reduce the gradient, is:

$$\Delta T = \frac{SL^2}{2K} = 24^\circ \text{ C} \quad \text{Eq. (E7)}$$

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S = heat production rate = 150 w/cm

L = fuel length = 0.47 cm

K = thermal conductivity of Cm 242 = 0.7

$\frac{\text{watts}}{\text{cm} \cdot ^\circ\text{K}}$

[estimated for matrix of 3 parts
rhodium to one part curium oxide]

With a curium-fueled generator the fuel block is in the form of a squat cylinder. Therefore, the thermal shutters for the heat dump are located on the block end face rather than the lateral surface. With an emitter operational temperature of 1738° K, the dump surface must operate at approximately 1884° K. Analysis indicates that at this temperature it is possible to dump the excess 3916 watts. The heat is dumped from the port openings to a copper (clad with inconel) plate that conducts the heat radially to the generator surface. The heat then flows axially on the generator surface and is rejected to space by radiation.

The heat rejection area on the generator surface is:

$$\begin{aligned} A &= \pi (\text{diameter}) (\text{length}) \\ &= \pi (24.8) (10.8) = 842 \text{ cm}^2 \end{aligned}$$

If the surface is treated as a fin with an efficiency of .9 (assumed), the surface temperature becomes:

$$q = \sigma \epsilon A \eta T^4 = 3916 \text{ watts} \quad \text{Eq. (E8)}$$

where q = heat rejection rate

$$\begin{aligned} \sigma &= \text{Stefan-Boltzmann constant} \\ &= 5.67 \times 10^{-12} \text{ watts/cm}^2 \cdot ^\circ\text{K}^4 \end{aligned}$$

$$\epsilon = \text{surface emissivity (coated or grooved)} = .9$$

$$A = \text{surface area, cm}^2$$

$$\eta = \text{fin efficiency} = .9$$

$$T = \text{surface temperature, } ^\circ\text{K}$$

Thurs, T = 1000° K

Allowing 50° K for the copper plate, the average temperature the port openings "see" is 1050° K. The required port area is now determined by:

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$$A = \frac{q}{\sigma F [T_1^4 - T_2^4]} \quad \text{Eq. (E9)}$$

where

q = heat rejection rate = 3916 watts

σ = Stefan-Boltzmann constant
= 5.67×10^{-12} watts/cm²-(°K)⁴

F = view factor = .82

T₁ = fuel block temperature = 1884° K

T₂ = sink (generator surface) temperature = 1050° K

and the port opening becomes 73.9 cm². This is approximately 30% of the fuel block top area.

The diode analysis of the curium generator is identical to that of the cerium generator.

3. Plutonium Generator

The power densities of cerium and plutonium are comparable (6 watts/cc and 5 watts). Therefore, the generator configurations are almost identical with slight changes in dimensions. As with cerium, 22 fuel tubes will be used of diameter 2.67 cm. Forming an energy balance as with curium in Section 1 to determine the fuel length:

$$\text{Power density} + \text{fuel volume} = \text{heat to diodes} + \text{shield losses} \quad \text{Eq. (10)}$$

where power density = 5 watts/cc

shield loss, ends = 930 watts

heat to diodes = 1700 watts

shield loss, laterally = 111.6 L watts

fuel volume = $22 \times \frac{\pi D_f^2}{4} L$

D_f = fuel diameter = 2.67 cm

L = fuel length, cm

Solving, L = 5.2 cm

The thermal power developed at the end of life, i.e., the heat pro-

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duction rate (also beginning of life since plutonium's half-life is large compared to 1-5-year mission time), is the product of the power density and fuel volume, viz., 3203 watts.

The end-of-life efficiency is given by

$$\eta = \frac{\text{Power to Converter}}{\text{Heat Production Rate}} = \frac{275}{3203} = 0.086 \quad \text{Eq. (E11)}$$

The axial temperature difference through the graphite block caused by heat flow to the six diodes and end shields may be approximated by one-dimensional heat flow since 82% of the heat flows axially.

$$\Delta T = \frac{q_{\text{axial}} L/2}{KA} = 107^\circ \text{ C} \quad \text{Eq. (E12)}$$

q = axial heat flow = 2630 watts

A = graphite cross-sectional area = $A_{\text{block}} - A_{\text{fuel}} = 123 \text{ cm}^2$

L = block length = 5.2 cm

K = thermal conductivity of graphite = $0.52 \frac{\text{watts}}{\text{cm} \cdot ^\circ \text{K}}$

The radial temperature increase through the plutonium fuel is computed from the equation defining radial heat flow with heat production

$$\Delta T = \frac{Sr^2}{4K} = 72^\circ \text{ C} \quad \text{Eq. (E13)}$$

S = heat production rate = 5 watts/cc

r = fuel radius = 1.34 cm

K = thermal conductivity of plutonium oxide^{*}
= $.031 \frac{\text{watts}}{\text{cm} \cdot ^\circ \text{K}}$

This system will operate without a heat dump and, consequently, without external fins adjacent to the fuel block. The temperature of the generator surface in this area was calculated from the radiation equation

$$T = \left(\frac{q}{\sigma \epsilon A} \right)^{1/4} = 728^\circ \text{ K} \quad \text{Eq. (E14)}$$

^{*} Reference 22 on page 136.

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q = heat dumped through lateral fuel block shields
at 2 watts/cm²
= 580 watts
ε = generator surface emissivity = 0.9
A = cylindrical dump area
= π DL = 400 cm²
D = generator diameter = 24.5 cm
L = dump area length = 5.2 cm

The diode analysis is identical to that for the original cerium generator including the external diode fin for cooling the collector to 1000° K.

4. Ablative Material Requirements

The overall dimensions of a generator fueled with curium, plutonium or polonium will be appreciably smaller than the cerium generator because of the smaller fuel volume requirements of the alpha fuels. In order to obtain a gross approximation of the thickness of ablative material necessary to withstand re-entry heating, an adiabatic calculation was employed.

A cylindrical geometry was assumed with a length and diameter of 9 inches and a total weight of 100 pounds. The stagnation heating was estimated to be 35,000 Btu/ft². The thickness of beryllium, a superior ablative coating, required to preclude burnup of the system was approximately 0.75 inch.

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APPENDIX F CONVERTER DESIGN

1. Trial One

Two transistors on each side of the converter are required. Each transistor will switch 34 amps and will be selected Motorola MP500 series units. Operating frequency will be 500 cps.

$$\text{Base drive requirements} = \frac{34}{25} = 1.36 \text{ amps per unit}$$

$$\text{Base drive power} = \frac{1.36}{2} \times 1 \times 4 = 2.72 \text{ watts total}$$

$$P_S = \frac{1}{6} \left[2 V_S I_C f (T_R + T_F) \right]$$

per unit

$$= \frac{1}{6} \left[2 \times 4.14 \times 34 \times 500 (70 \times 10^{-6}) \right] = 1.64 \text{ watts}$$

$$P_S (\text{total}) = 4 \times 1.64 = 6.56 \text{ watts}$$

$$\begin{aligned} P_C (\text{per unit}) &= R_S I_C^2 \left[\frac{1}{2} - f (T_R + T_F) \right] \\ &= (.002) (34)^2 \left[.5 - 500 (70 \times 10^{-6}) \right] = \\ &1.15 \text{ watts} \end{aligned}$$

$$P_C (\text{total}) = 4 \times 1.15 = 4.60 \text{ watts}$$

$$\begin{aligned} P_B (\text{per unit}) &= 2 V_S I_{CO} \left[\frac{1}{2} - f (T_R + T_F) \right] \\ &= (2) (4.14) (5 \times 10^{-3}) \\ &\quad \left[.5 - 500 (70 \times 10^{-6}) \right] = 0.0206 \text{ watt} \end{aligned}$$

$$P_B (\text{total}) = 4 \times .0206 = .0824 \text{ watt}$$

Rectification losses

Using two MP500 series transistors for rectifiers as discussed in Appendix B:

$$I_{\text{out}} = \frac{250}{28} = 8.94 \text{ amps}$$

$$\begin{aligned} \text{Rectification loss} &= 8.94 \times 0.1 + \frac{8.94}{25} \times 1 \\ &= 0.894 + 0.358 = 1.252 \text{ watts} \end{aligned}$$

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$$\begin{aligned} \text{Total transistor losses,} &= 2.72 + 6.56 + 4.60 + \\ \text{base drive losses and} &0.0824 + 1.25 \\ \text{rectification losses} &= 15.21 \text{ watts} \end{aligned}$$

For 89% efficiency the total losses cannot exceed 31 watts. This allows approximately 15 watts' loss in the transformers which will be divided, one watt for the switching unit and 14 watts for the main unit. Referring to Figure 41, this requires a transformer of approximately 5 pounds which is somewhat heavier than originally ascertained from Figure 38. This simply means that two transistors per side is probably not an ideal choice. A recalculation is made below for three transistors per side.

2. Trial Two

Three transistors in parallel on each side of converter switching 22.7 amps each.

$$\text{Base drive requirement} = \frac{22.7}{25.0} = 0.91 \text{ amps}$$

$$\text{Base drive power total} = \frac{0.91}{2} \times 1 \times 6 = 2.73 \text{ watts}$$

$$P_S (\text{per unit}) = \frac{1}{6} \left[(2) (4.14) (22.7) (500) \right. \\ \left. (70 \times 10^{-6}) \right] = 1.1 \text{ watts}$$

$$P_S (\text{total}) = 1.1 \times 6 = 6.6 \text{ watts}$$

$$P_C (\text{per unit}) = (0.002) (22.7)^2 \left[0.5 - 500 \right. \\ \left. (70 \times 10^{-3}) \right] = 0.511 \text{ watt}$$

$$P_C (\text{total}) = 0.511 \times 6 = 3.066 \text{ watts}$$

$$P_B (\text{total}) = \text{same as approach No. 1} = 0.0824 \text{ watt}$$

Rectifier losses are the same as approach No. 1 = 1.252

$$\begin{aligned} \text{Total transistor losses,} & \\ \text{base drive losses} &= 2.73 + 6.6 + 3.06 \\ \text{and rectification losses} &+ 0.0824 + 1.252 \\ &= 13.72 \text{ watts} \end{aligned}$$

For 31 watts' total loss this allows 17.28 watts for the transformers, splitting into a ratio of 16.28 to 1 watt for the main and switching unit. This would probably be a main transformer unit of about 4.5 pounds. The curves, however, are now more readily satisfied for this approach.

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APPENDIX G

SAFETY CONSIDERATIONS

1. Cerium-144 Fallout Due to Burnup

The principal mechanisms by which removal of radioactivity from the atmosphere occurs are: gravitational settling, scavenging of radioactive particles by falling precipitation, radioactive decay and deposition by diffusion.⁴²

The basic removal relationship is:

$$dA/dt = -kA(t) \quad \text{Eq. (G1)}$$

where dA/dt = activity depletion rate

$A(t)$ = regional activity burden at time, t

k = proportionality constant = removal rate

$1/k$ = mean residence time

$0.693/k$ = half residence time

Thus, $A(t) = A(o) \exp(-kt)$ Eq. (G2)

where $A(o)$ = initial Ce-144 activity = 1.55×10^6 curies at $t = 0$.

The three atmospheric regions of interest in this analysis are:⁴³

- a. Mesosphere (160,000-250,000 ft) - 5-year
half residence time
- b. Stratosphere (40,000-160,000 ft) - 6-month
half residence time
- c. Troposphere (below 40,000 ft) - 21-day
half residence time

The activity equations for these regions and for the earth's surface are:

a. Mesosphere: $\frac{dA_1(t)}{dt} = -k_1 A_1(t) - \lambda A_1(t)$ Eq. (G3)

42. Martell, E. A., and Drevinsky, P. J., "Atmospheric Transport of Artificial Radioactivity," Science Vol. 132 No. 3439, November 1960.

43. Stebbins, A. K., "H.A.S.P. Special Report on High Altitude Sampling Program," DASA 532 B, June 1960.

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$$\text{or } A_1(t) = A(o) \exp \left(- (k_1 + \lambda)t \right) \quad \text{Eq. (G4)}$$

where λ = radioactive decay constant of cerium 144

b. Stratosphere: $\frac{dA_2(t)}{dt} = k_1 A_1(t) - k_2 A_2(t) - \lambda A_2(t)$

$$= k_1 A(o) \exp \left(- (k_1 + \lambda)t \right) - (k_2 + \lambda) A_2(t) \quad \text{Eq. (G5)}$$

$$\text{or } A_2(t) = \frac{k_1 A(o)}{k_2 - k_1} \left[\exp \left(- (k_1 + \lambda)t \right) - \exp \left(- (k_2 + \lambda)t \right) \right] \quad \text{Eq. (G6)}$$

c. Troposphere:

$$\frac{dA_3(t)}{dt} = k_2 A_2(t) - k_3 A_3(t) - \lambda A_3(t) \quad \text{Eq. (G7)}$$

$$= \frac{k_1 k_2 A(o)}{k_2 - k_1} \left[\exp \left(- (k_1 + \lambda)t \right) - \exp \left(- (k_2 + \lambda)t \right) \right] - (k_3 + \lambda) A_3(t)$$

$$\text{let } \left[k_1 k_2 A(o) / (k_2 - k_1) \right] = C_1$$

$$A_3(t) = \frac{C_1}{k_3 - k_1} \left[\exp \left(- (k_1 + \lambda)t \right) \right]$$

$$- \frac{C_1}{k_3 - k_2} \left[\exp \left(- (k_2 + \lambda)t \right) \right] + I_1 \left[\exp \left(- (k_3 + \lambda)t \right) \right]$$

where I_1 = constant of integration

$$\text{when } t = 0, I_1 = \left[C_1 / k_3 - k_2 \right] - \left[C_1 / k_3 - k_1 \right]$$

$$\text{let } C_1 / k_3 - k_1 = B_1$$

$$C_1 / (k_3 - k_2) = B_2$$

$$I_3 = B_3$$

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$$A_3(t) = B_1 \left[\exp \left(- (k_1 + \lambda)t \right) \right] - B_2 \left[\exp \left(- (k_2 + \lambda)t \right) \right] + B_3 \left[\exp \left(- (k_3 + \lambda)t \right) \right]$$

Eq. (G8)

d. Earth's Surface:

$$\frac{dA_4(t)}{dt} = k_3 A_3(t) - \lambda A_4(t)$$

Eq. (G9)

$$A_4(t) = - \frac{k_3 B_1}{k_1} \left[\exp \left(- (k_1 + \lambda)t \right) \right] + \frac{k_3 B_2}{k_2} \left[\exp \left(- (k_2 + \lambda)t \right) \right] - B_3 \left[\exp \left(- (k_3 + \lambda)t \right) \right]$$

$$+ I_2 \exp(-\lambda t)$$

$$\text{when } t = 0, I_2 = \left[k_3 B_1 / k_1 \right] - \left[k_3 B_2 / k_2 \right] + B_3$$

$$\text{let } (k_3 B_1 / k_1) = D_1, (k_3 B_2 / k_2) = D_2,$$

$$B_3 = D_3, I_2 = D_4$$

$$A_4(t) = - D_1 \left[\exp \left(- (k_1 + \lambda)t \right) \right] + D_2 \left[\exp \left(- (k_2 + \lambda)t \right) \right] - D_3 \left[\exp \left(- (k_3 + \lambda)t \right) \right] + D_4 \exp(-\lambda t)$$

Eq. (G10)

Evaluation of Constants:

$$k_1 = 0.693/1825 = 3.8 \times 10^{-4} \text{ day}^{-1}$$

$$k_2 = 0.693/183 = 3.78 \times 10^{-3} \text{ day}^{-1}$$

$$k_3 = 0.693/21 = 3.3 \times 10^{-2} \text{ day}^{-1}$$

$$\lambda = 0.693/290 = 2.39 \times 10^{-3} \text{ day}^{-1}$$

$$A(0) = 1.55 \times 10^6 \text{ curies}$$

$$C_1 = k_1 k_2 A(0) / k_2 - k_1 = 6.55 \times 10^2 \text{ curies/day}$$

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$$B_1 = C_1 / (k_3 - k_1) = 2.01 \times 10^4 \text{ curies}$$

$$B_2 = C_1 / (k_3 - k_2) = 2.24 \times 10^4 \text{ curies}$$

$$B_3 = B_2 - B_1 = 2.3 \times 10^3 \text{ curies}$$

$$D_1 = k_3 B_1 / k_1 = 1.75 \times 10^6 \text{ curies}$$

$$D_2 = k_3 B_2 / k_2 = 1.95 \times 10^5 \text{ curies}$$

$$D_3 = B_3 = 2.3 \times 10^3 \text{ curies}$$

$$D_4 = D_1 - D_2 + D_3 = 1.55 \times 10^6 \text{ curies}$$

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