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MND-P-2356

PHYSICS AND MATHEMATICS

**PRELIMINARY OPERATIONAL SAFETY REPORT
FOR THE TASK 5.6 THERMOELECTRIC GENERATOR**

By
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May 1960

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Baltimore, Maryland

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Printed in USA. Price \$1.50. Available from the Office of Technical Services, Department of Commerce, Washington 25, D. C.

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FOR THE
TASK 5.6 THERMOELECTRIC GENERATOR

May 1960

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FOREWORD

This report was prepared by The Martin Company Nuclear Division under Atomic Energy Commission Contract AT (30-3)-217.

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SUMMARY

This report evaluates the operational hazards associated with the use of a plutonium-fueled thermoelectric generator in a terrestrial satellite. It is a preliminary report which discusses the hazards problems by extrapolating analytical and test data from previous final analyses performed for similar isotopic power devices. A final report for a Task 5.6 mission will refine and resolve the areas of uncertainty, based upon specific vehicle characteristics, detailed aerodynamic calculations, and safety test data.

It appears that the plutonium fuel can be consumed and dispersed at high altitude during re-entry, following a successful mission.* As an alternative, however, since the fuel (Pu-238) is an alpha emitter with a long half-life, it appears that random intact re-entry following a successful mission is also feasible.** However, as a precaution against aborted missions, the launch azimuth should be over water as much as possible to avoid impact or dispersion in areas of significant population density.

It is recommended that the fuel and generators be transported by air carrier to preclude local restrictions of ground transport and to provide better statistical safety. The transport phase poses a very minor safety problem.

*SNAP Hazards Subcommittee recommends this alternative as a general rule for isotopes employed in satellites.

**NASA favors this alternative for alpha emitters (NASA Nuclear Space Hazards Report, March 1960).

I. INTRODUCTION

The use of isotopes for satellite power has been proposed and investigated for many missions. The Subtask 5.6 MOD-1 generator produces 1.5 electrical watts from 33 thermal watts created by the absorption of 5.5 Mev alpha particles emitted by Plutonium-238. The advantages inherent in this device are constant power output, reliability, low weight, and the ability to operate in the absence of solar energy.

The safety problems involved with the MOD-1 generator are not novel, and initial criteria for operational safety have been set forth (Refs. 1, 2, 3, and 4). The fuel loading of the generator is small compared to other generators analyzed (e.g., 1017 curies versus 10^6 curies), but the fuel has a substantially longer half-life (e.g., 86 years versus 285 days). Therefore, as the isotope inventory is small, dispersion of the fuel on re-entry appears favorable, but the long half-life and low radiation levels of the fuel favor intact re-entry. This indicates that either alternative is acceptable for successful missions, and that the problems previously encountered for aborted missions are comparably minimized.

The purpose of this report is to weigh the various safety criteria, alternatives, and countermeasures in terms of the design of the MOD-1 generator as defined in Report MND-P-2354, the final report for Subtask 5.6. The design employed as the analytical model for the safety analysis varies to a very minute extent from the MOD-1 final design. This, however, will not substantially affect the results of this safety analysis.

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II. MOD-1 THERMOELECTRIC GENERATOR*

An isotopic thermoelectric generator uses radionuclide fuel to provide a heat source for a bank of thermoelectric elements. The thermoelectric elements are composed of semiconductor materials which produce electrical power in proportion to the difference in temperature between the hot and cold junctions

A. GENERAL DESIGN OF GENERATOR

The generator utilizes Plutonium-238 as the power source. This material is encapsulated in three successive containers to prevent the release of radioactive material into the atmosphere. Two separate containers formed of Haynes-25 alloy are provided. These are lined with a thin inner shell of tantalum to prevent alloying of the plutonium with the Haynes alloy. The Haynes-25 capsules are designed to have sufficient strength to withstand the forces generated by the helium formed during the radioactive decay of the plutonium fuel over long periods of time. The two fuel containers are housed in a single block of Hastelloy C which forms the entire hot junction and provides a flat face at the point of contact for the 18 pairs of thermoelectric elements. The Pu-238 fueled thermoelectric generator provides 1.5 watts of electrical power for operation of certain components within a satellite. The power density of the Pu-238 fuel form is 0.032 thermal watts per curie and 0.565 thermal watts per gram of Pu-238. The 1017-curie source will produce a total of 33 thermal watts. Of the total thermal energy available, 4.3% is converted to 1.5 electrical watts by the 36 thermoelectric elements. The remaining heat is lost by radiation to the outside and to the surrounding structure.

The outside configuration of the generator is roughly rectangular with rounded ends. It is 9 inches long and 4-1/2-inches wide on each side. The unit weighs approximately 10 pounds and requires no shielding other than the materials of the capsule itself. The configuration is shown in Fig. 1.

The outer shell of the generator is fabricated from 6061 aluminum, 0.032-inch thick and operates at 307° K. The radiator is also fabricated from aluminum alloy and is operated at a mean temperature of 398° K. The thermoelectric elements operate at a hot junction temperature of about 811° K and at a cold junction temperature of about 422° K. The operating temperature of the fuel capsule of 860° K is well below the melting point of the encapsulating material.

* William Hagis

Fig. 1. MOD-I Thermoelectric Assembly Generator and Assembly Details

The fuel capsule is insulated from the inner skin by alternate layers of silica mat and gold foil for about one-fifth the interval between the fuel capsule and the outer shell. Beyond this point, fiberglass insulation is used exclusively. In the area of the thermoelectric elements, a Min-K type insulation is used.

B. FUEL FORM

The Task 5.6 generator is fueled with approximately 58.4 grams of Pu-238 which has a source strength of 1017 curies. Plutonium-238 has the following genetic relationships:

The fuel is in the form of two metallic slugs 0.968 inch long and 0.48 inch in diameter, having a total volume of 5.7 cc. Table 1 presents the physical, chemical, nuclear, and radiobiological properties of Pu-238.

1. Physical Properties

The Pu-238 fuel is at a temperature of 1090° F, well below the melting point of plutonium (1202° F). Solid-state plutonium has a density of approximately 16.5 grams per cc.

2. Chemical Properties

Elemental plutonium is subject to mild corrosion by oxygen. This reaction is accelerated by an increase of moisture; therefore, if plutonium metal is exposed to water in the presence of free oxygen the corrosive attack is vigorous. While such reactions cannot occur within the source capsule because of the absence of both free oxygen and water, they could occur if the core impacts after partial burnup.

Plutonium has four oxidation states (+3, 4, 5 and 6) with the +4 state essentially the most stable one (i.e., PuO_2). The metal is insoluble in sulfuric acid and is soluble in both hot concentrated and dilute nitric acid. Plutonium has a tendency to alloy itself with conventional metals at elevated temperatures. Tantalum is used to encapsulate the fuel since it does not readily form an alloy with plutonium.

TABLE 1
Properties of Plutonium-238

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A. Physical Properties

<u>Isotope</u>	<u>Atomic Weight</u>	<u>Density (gm/cc)*</u>	<u>Melting Point*</u>
Pu-238	238.124	19.7 (25° C) 16.5 (500° C)	640° C 1185° F

B. Chemical Properties

<u>Oxidation State</u>	<u>HNO₃</u>	<u>Solubility HCl</u>	<u>H₂SO₄</u>
+3, 4, 5, 6	S	S	I

C. Nuclear Properties

<u>Half-Life (yr)</u>		<u>Decay Energy</u>				<u>Other Radiation</u>	<u>He Production (cc at STP/ curies decayed)</u>
Decay	Spontaneous Fission	<u>α (Mev)</u>	<u>α (%)</u>	<u>γ (Mev)</u>	<u>γ (%)</u>		
86.4	3.8 x 10 ¹⁰	5.49	72	0.143	10 ⁻³	n (α,n)	6.03
		5.45	28	0.099	8 x 10 ⁻³	n (n, γ)	
		5.35	0.09	0.043	0.38		
<u>(curies/gm)</u>		<u>(gm/curie)</u>	<u>Thermal Watts/curie</u>				
17.4		0.0575	0.0354				

D. Radiobiological Properties

				<u>Restricted Area MPC</u>		<u>Unrestricted Area MPC</u>	
<u>Critical Organ</u>	<u>MPC Body</u>	<u>Biological T_{1/2}</u>	<u>Form</u>	<u>Water</u>	<u>Air</u>	<u>Water</u>	<u>Air</u>
	(μ c)	(yr)		(μc/cc)	(μc/cc)	(μc/cc)	(μc/cc)
Bone	0.04	200	Sol	1 x 10 ⁻⁴	2 x 10 ⁻¹²	5 x 10 ⁻⁵	7 x 10 ⁻¹³
Lung	--		Insol	--	3 x 10 ⁻¹¹	--	10 ⁻¹¹
GI(LLI)	--		Insol	8 x 10 ⁻⁴	10 ⁻⁷	3 x 10 ⁻⁴	5 x 10 ⁻⁸

*Principles of Nuclear Reactor Engineering, pp 461

3. Nuclear Properties

Plutonium-238 has an atomic number of 94, an atomic mass of 238.124 and a half-life of 86.4 years. It decays by alpha emission to U-234 and has a spontaneous fission half-life of 3.8×10^{10} years.

Plutonium-238 has the following decay scheme:

The decay of Pu-238 is characterized by the emission of high energy alpha particles having an average energy of 5.48 Mev. The velocity of the particles in air is 1.78×10^9 centimeters per second, and their range in air is 3.96 centimeters. Accompanying the alpha radiation is infrequent low-energy gamma radiation of from 0.043 to 0.143 Mev. The daughter, U-234, has a long half-life (2.48×10^5 years) and decays through alpha emission to Th-230.

Neutron radiation from the fuel capsule comes from (α , n) reactions and from spontaneous fission. The latter contributes an insignificant number of neutrons, since the spontaneous fission half-life is 10^{10} years.

Since the fuel decays primarily by alpha emission, helium gas is formed within the capsule as the alpha particles pick up orbital electrons. The helium gas production at standard temperature and pressure is about 6 cc per decayed curie or 1266 cc (0.2 gram) of helium after one half-life, and 48 cc after 1 year. The helium gas generated by the daughter U-234 is not significant within one half-life of Pu-238.

4. Radiobiological Properties

The direct radiation from the fuel does not constitute a significant radiation hazard. The gamma dose rate is 59 milliroentgens per hour at the outer shell, while the neutron dose rate is 130 millirems per hour at the same location.

There is no internal radiation hazard as long as the plutonium is retained inside the fuel capsule. When released to the biosphere, high energy alpha emitters constitute a significant biological hazard if ingested or inhaled. The critical organ for soluble Pu-238 is the bone, and the maximum permissible concentration for soluble Pu-238 in the human body is 0.04 microcuries. Table 1 presents the maximum permissible concentrations of Pu-238 in water and air.

C. FUEL CAPSULES

The isotope fuel capsules will be fueled with 1017 curies of Pu-238. The capsule design has been dictated by the thermodynamics of the generator and by the consequences of the potential failures of the missile system which places the generating system in orbit.

The analysis shows that these requirements can be met (Refs. 5, 6, 7 and 8). A detailed analysis of the mechanical characteristics of the capsules is found in Appendix A.

1. Design

The fuel capsule design shown in Fig. 2 incorporates three separate containers, constructed of different material, to prevent the release of the fuel under various conditions. The total fuel load is divided into equal parts and loaded into two capsules constructed of Haynes metal with a thin tantalum inner liner. Both the tantalum and Haynes-25 capsules are closed by welding. The main functions of the Haynes-25 capsule are to contain the resulting helium buildup from alpha decay and to prevent fuel dispersion at impact.

These inner capsules are assembled into a block of Hastelloy-C metal. The block of Hastelloy-C serves as a hot junction for the thermal elements and provides good corrosion resistance should the unit impact in sea water.

NOTE:

All dimensions in inches.

Fig. 2. Pu-238 Fuel Capsule

2. Materials

The present concepts of an intact capsule following aborted missions and burnup in the upper atmosphere upon re-entry imposes the following requirements:

- (1) Impact resistance at elevated temperatures.
- (2) Corrosion resistance in sea water.
- (3) Low melting and vaporization temperatures.

Haynes-25. Haynes-25 melts at 2425° F to 2570° F and is an alloy of nickel, cobalt, chromium, tungsten, iron, silicon, and manganese. At the capsule operating temperature of 1100° F, Haynes-25 has an ultimate tensile strength of 125,000 psi. It has a specific heat of 0.092 and relatively good thermal conductivity (142.2 Btu-in./ft² hr-°F at 1100° F). It is resistant to oxidation and carburization to 1040° C and will resist hydrochloric and nitric acids at certain concentrations and temperatures. In addition, tests have shown a penetration of less than 0.6 mils per year in wet chlorine at room temperature.

Hastelloy C. Hastelloy C melts at 2460° F. It is highly resistant to oxidation up to about 1150° C and will withstand strong reducing or oxidizing conditions such as those encountered with nitric acid, aqueous solutions of ferric and cuprous salts, or with wet or dry chlorine gas. It exhibits excellent corrosion resistance, having an estimated corrosion rate of 0.0001 inches per year in sea water. Its specific heat is the same as Haynes-25 (0.092) and its thermal conductivity is 114 Btu-in./ft²-hr-°F. Its ultimate tensile strength is 94,000 psi at 1100° F.

D. SHIELDING CHARACTERISTICS*

Isotopes of transuranic elements are, in general, members of long decay chains. In some cases subsequent decay products cause a significant increase in radiation hazards. To determine long-time biological dose rates, a study was made of the growth of the successive decay products of Pu-238.

*A. M. Spamer, Shield Analysis Unit

Table 2 shows the decay chain of which this isotope is a member. Its decay was traced through one million years. Figures 3 and 4 show the growth of the decay products per original gram of Pu-238 from 10^{-2} to 10^2 , and 10^2 to 10^6 years, respectively. Figure 5 shows the variation of dose rate with time per original gram. Inspection of this figure shows that the total dose rate decreases for about 300 years and then increases. This increase is due to the growth of Radium-226. About 1000 years are required for the dose rate to build up to its original value. The dose rate continues to increase until a peak is reached at about 200,000 years.

When Pu-238 is used for satellite applications in which burnup re-entry is planned, the dose rates at the start of life are sufficient for determining ground handling shielding requirements. Dose rates for the generator were determined for an initial fuel loading of 1017 curies. The locations at which dose rates were determined are shown in Fig. 6, and the dose rates are tabulated in Table 3.

The dose rate at the capsule surface was included to evaluate radiation hazards in event of an accidental intact re-entry. If the capsule becomes exposed, the dose rate at its surface is higher than acceptable tolerances allow. However, since the temperature of the capsule will be above 100° F, it is improbable that a person would hold it long enough to receive an excessive dose.

If the capsule or complete generator is held in the hands, the allowable dose for the hands is 1500 millirems per week. Consequently, the fuel capsule alone can be held for 1.8 hours before the weekly dose is exceeded, and the complete generator could be held for eight hours per week.

Dose rates at one foot and at one meter are more applicable to the whole body allowance of 100 millirems per week. Thus a person could stand one foot from the generator for 25 hours per week without exceeding the allowable dose. At one meter, the dose rate is so low that a person could stand at this distance for an unlimited time--the total weekly dose would be only 60 millirems.

TABLE 2

Decay Products of Cm-242 and Pu-238

Isotope	Gamma Rays		Neutrons per Second per Gram from Spontaneous Fissioning
	Energy (Mev)	Fraction of Disintegrations in Which γ -ray is Produced	
Pu-238	0.0438	3.8×10^{-4}	4.4×10^3
	0.099	8×10^{-5}	
	0.150	1×10^{-5}	
	0.203	4×10^{-8}	
	0.760	5×10^{-7}	
	0.810	$\sim 10^{-7}$	
	0.875	2×10^{-7}	
U-234	0.050	0.283	7.08×10^{-3}
	0.118	0.003	
	0.450	2×10^{-7}	
	0.500	1×10^{-7}	
Th-230	0.068	0.0059	9.6×10^{-4}
	0.110	1×10^{-6}	
	0.142	7×10^{-4}	
	0.184	1.4×10^{-4}	
	0.206	5×10^{-8}	
	0.235	5×10^{-8}	
	0.253	1.78×10^{-4}	
Ra-226	0.184	0.012	
	0.26	7×10^{-5}	
	0.42	2×10^{-6}	
	0.61	2×10^{-6}	
Rn-222	0.51	0.0007	
Po-218	None Listed		
Pb-214	0.241	0.115	
	0.294	0.258	
	0.350	0.450	
Bi-214	0.607	0.658	
	0.766	0.065	
	0.933	0.067	
	1.120	0.206	
	1.238	0.063	
	1.379	0.064	
	1.761	0.258	
	2.198	0.074	
Po-214	None Listed		
Pb-210	0.0465	0.04	
Bi-210	None Listed		
Po-210	0.803	1.8×10^{-5}

Fig. 3. Decay of Pu-238 and Growth of Decay Products (10^{-2} to 10^2 years)

Fig. 4. Decay of Pu-238 and Growth of Decay Products (10^2 to 10^6 years)

Fig. 5. Dose Rate from Pu-238 and Its Decay Products (10^{-1} to 10^6 years) at One Meter

Fig. 6. Location of Dose Points

TABLE 3

Dose Rates in mrem/hr for Task 5.6 Generator

<u>Source of Radiation</u>	<u>Capsule Surface</u>	<u>Generator Surface</u>	<u>One Foot</u>	<u>One Meter</u>
Neutrons	676	130	3.13	0.290
Decay gammas	143	58	0.80	0.074
Gammas from spontaneous fission	4.7	1.3	0.005	0.0004
Total	824	190	3.9	0.36

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III. TRANSPORTATION OF GENERATORS

The shipment of the isotopic power generator to the Government is divided into two specific phases: (1) shipment of the loaded fuel capsules from the AEC facility in Los Alamos, New Mexico, to The Martin Company and (2) shipment of the complete generator from The Martin Company to the launch site. The following discussion includes a description of the transportation containers, the mode of shipment and shipping hazards.

A. THE SHIPPING CONTAINERS

The shipping containers for the fuel capsule and the complete generator are designed to provide adequate cooling and for containment of the radio-isotope fuel during any credible transportation accident.

Since the generator fuel is primarily an alpha emitter, the requirements for biological shielding are not so stringent. The purpose of the shipping container is simply to protect the source and to facilitate handling. Stainless steel will be used in the construction of the container, which will be designed to have surface temperature less than 150° F.

The case is designed so that the fuel capsule is sandwiched rigidly between the top and bottom of the container while separators surrounding the capsule maintain the proper air gap between the capsule and the container wall.

For the purpose of analyses, the container was arbitrarily chosen as a hollow cylinder with the outer dimensions of 3 inches in diameter and 6 inches in length. Considering both convection and radiation heat losses and assuming the ambient temperature to be 100° F, the surface temperature to dissipate the required 33 watts is 204° F. Fins were used to reduce the surface temperature to a tolerable level. Six stainless steel fins, 0.8-inch long and 0.125-inch thick located axially on the sides of the above-mentioned cylinder will provide sufficient supplementary cooling to lower the surface temperature to 150° F. The surface temperature of the contained isotope capsule when carried in this container is calculated to be 366° F. This is considered to be a reasonably low and safe temperature level.

The complete generator shipping container is similar to the fuel capsule container except that it is larger, it does not require fins and it provides for shock mounting of the generator during shipment. Figures 7 and 8 show the encapsulated fuel shipping container.

Fig. 7. Shipping Container, Mod-I Fuel Capsule

SECTION B-B

Material: SS AISI 316

Fig. 8. Shipping Container, Mod-I Fuel Capsule

B. MODE OF SHIPMENT

The decay rate of the fuel is not a contributing factor in determining the mode of shipment. Because of its relatively long half-life (about 86 years), the output of the generator will remain approximately constant for the operating life time of 2 to 5 years. Therefore, the mode of transportation need only be selected from a safety and convenience standpoint.

The following safety statistics have been compiled from Sandia Corporation and ICC data for commercial carriers.

<u>Mode of Transportation</u>	<u>Chances of Accident Per 1000 Miles*</u>
Air (commercial cargo)	1/5550
Truck	1/230
Rail	1/3300

The serious accident statistics compiled by H. A. Knapp of the AEC are as follows:

<u>Mode of Transportation</u>	<u>Fraction of Accidents Resulting in A Serious Accident</u>	<u>Chance of a Serious Accident Per 1000 Miles**</u>
Air (commercial cargo)	1/8	1/42,000
Truck	1/500	1/115,000
Rail (freight)	1/25	1/82,000

The following is a discussion of the relative merits of each mode of shipment.

*Based on involvement of different carriers that might be used for transporting hazardous materials within the U.S. for an average haul between two points 1000 miles apart.

**Based on the overall chance of a serious accident for various methods of transporting a hazardous cargo between two points 1000 miles apart.

Air shipment. Air shipment of the fuel capsule is the preferable mode of transport for several reasons. First, although the potential radiation hazard is extremely low, air transport will minimize human contact with the shipment. Secondly, although the probability of a serious accident for air transport is higher than other modes of transportation, based upon commercial cargo shipments, the probability for a single accidental event is lower.

Truck shipment. Such a shipment might involve local restrictions, selective routing, and delays due to weather and road conditions. The frequency of truck accidents is higher than for air or rail for a single event, but the frequency of serious accident is lower than the other two modes of transportation.

Rail shipment. In addition to requiring a long transit time for shipment, the frequency of accidents when shipping by rail is intermediate between air and truck shipment. Approximately 50% of freight car derailments occur at speeds greater than 35 mph with 24% at speeds greater than 45 mph.

C. SHIPPING HAZARDS

Certain potential hazards would be present in air shipment of the fuel capsules. These would include ground* and air transport and can be readily divided into thermal and mechanical forces.

1. Thermal Forces

It is estimated that 10^9 calories per hour of heat would be released in an aircraft fire which would burn at 2000°F for approximately half an hour. Of the external heat available (5×10^8 calories), only a portion, perhaps 1% (5×10^6 calories) of this heat would be available to the fuel capsule and its container. This would be a factor of 10^3 greater than the approximately 5×10^3 calories required for melting. If it is assumed that the Pu-238 fuel is vaporized and conveyed to a surrounding area of four acres,** this would produce a concentration of 6.14 microcuries per square centimeter. However it is conceivable that the heat available could not be absorbed by the capsule and container by virtue of the emissivity, absorption and conduction conditions about the body and a release would probably not occur. Also, the material of the innermost portion of the fuel capsule is fabricated of tantalum, which has a melting point of 5160°F , considerably in excess of the fire temperature of 2000°F .

An aircraft fire of the magnitude described here would be more severe than any credible ground transport fire.

*From the point of origin to the airport.

**Area of concentration of aircraft fire.

2. Mechanical Forces

An in-flight accident might release the fuel capsule and container and allow them to fall from a 10,000-foot altitude with a resulting impact velocity of about 500 feet per second. In this case, the capsule and container would probably be buried several feet below ground.

The capsules are designed to survive impact at their terminal velocity of 500 feet per second, so they could withstand impact conditions from an in-flight accident. Any conceivable ground accident would impose lower mechanical forces than those imposed during terminal velocity impact.

IV. AERODYNAMICS

This section includes an analysis of the aerodynamics involved with the present design, methods of solution of trajectory and aerothermodynamic problems and various possible schemes for the solution of the more outstanding problem areas.

All phases of the ascent and re-entry trajectory should be analyzed to establish the fate of a fueled thermoelectric generator when carried in an orbiting vehicle. One extremely critical phase occurs when the vehicle, near orbital velocity, re-enters the atmosphere. This could occur upon natural decay of the satellite from orbit or during an aborted final-stage operation. One important aspect of this problem is the severe aerodynamic heating that the generator will experience and the ultimate fate of the plutonium fuel.

The problem is further complicated because of the alternatives regarding the fate of the isotope after postorbital re-entry. It has been recommended in one case that the fuel should be dispersed at high altitudes as minute particles by aerothermodynamic means. One design condition that is not completely compatible with this philosophy is the requirement that the fuel capsule should land intact upon the earth's surface for all vehicle aborts. An immediate dilemma will result in that during an abort, late in the final-stage booster and just prior to orbital injection, the present fuel capsule would be partially consumed at the time of impact. These types of failures will result in an impact area downrange of the launch site which will have plutonium exposed at ground level. This area is commonly referred to as a "gray zone." The present effort was conducted along the originally imposed alternatives, but information is given to present a method of eliminating the hazards associated with the gray zone. This general scheme would be to design the fuel capsule to sustain the re-entry heating for all types of re-entries as recommended by NASA for alpha emitters. This discussion will be elaborated on in more detail in a later section.

A. TECHNICAL DISCUSSION (Refs. 10 and 11)

Trajectory data (Refs. 12 and 13) was obtained using the General N Stage Two-Dimensional Powered Trajectory Program and the Vanguard Three-Dimensional Program. The data used for this preliminary study have been extrapolated from Task 2 and Task 5 analyses. The basic equations for the two-dimensional program are shown in Fig. 9.

where

$\bar{x}, \bar{y}$ = Inertial axis

r_E = Radius of earth

r = Radius of vehicle from center of earth

ϕ = Range angle

α = Vehicle angle of attack

γ = Local flight path angle

$\bar{\gamma}$ = Inertial flight path angle

δ_p = Engine gimbal angle

μ = Earth gravitational constant

m = Mass of vehicle

V = Velocity

$$\ddot{\bar{x}} = - \left[\frac{T \sin (\alpha + \delta_p) + L}{m} - \frac{\mu}{r^2} \cos \gamma \right] \sin \bar{\gamma} + \left[\frac{T \cos (\alpha + \delta_p) - D}{m} - \frac{\mu}{r^2} \sin \gamma \right] \cos \bar{\gamma}$$

$$\ddot{\bar{y}} = \left[\frac{T \sin (\alpha + \delta_p) + L}{m} - \frac{\mu}{r^2} \cos \gamma \right] \cos \bar{\gamma} + \left[\frac{T \cos (\alpha + \delta_p) - D}{m} - \frac{\mu}{r^2} \sin \gamma \right] \sin \bar{\gamma}$$

Fig. 9. Two-Dimensional Trajectory Equations

Aerodynamic heating on a body is a function of shape, Mach number, atmospheric pressure and nose radius. The method of analysis has been that of an IBM-709 digital program (Ref. 14). The Martin ablation program handles the incoming aerodynamic heat and determines its effect on the re-entering body. The scheme is to break the body into various thin layers and to determine the amount of heat necessary to heat, melt and ablate each layer. Heat losses to other layers and to the atmosphere by conduction and radiation are determined and considered throughout the process. The number of layers into which a specimen may be subdivided is a function of the specimen size, shape, thermodynamic properties of the material, etc. Shown in Fig. 10 is a summary of the equations and a graphical discussion of the process. The heat conducted out of the first layer is equal to the heat conducted into the second layer. This procedure is followed throughout the entire program. An integration of the heating values around a tumbling or rolling re-entering body indicates that an average of 35% of the stagnation heating rate will be seen at any point on the surface.

1. Trajectory Data

A detailed evaluation of each re-entry condition requires an exact trajectory and specific model size and shape to determine the flight path and resulting aerodynamic heating rates. Unfortunately, this could not be done on this project, and these parameters had to be either extrapolated from other tasks or estimated without the benefit of digital programs. Shown in Fig. 11 is a trajectory that can be expected for a post-orbital re-entry. Although the trajectory will depend on the size and weight of payload, type of mission, etc., the trajectory shown will give a good indication of the fate of the isotope-powered generator.

2. Aerothermodynamic Data

The fuel capsule and generator housing were initially limited in design by several factors; among these were:

- (1) The ability to withstand internal temperature and pressure variations during the operational life of the unit.
- (2) The ability to withstand impact upon the earth's surface after unit separation during launch abort.
- (3) Heat transfer characteristics of the generator.
- (4) The ability to burn completely from aerodynamic heating following postorbital decay.

<u>Element</u>	<u>Aerodynamic</u>	<u>Radiated</u>	<u>Conducted</u> <u>In</u> <u>Out</u>	<u>Stored</u>	<u>Phase Change</u>	$\approx$
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$$\begin{aligned}
 \textcircled{1} \quad & \dot{q}_{in} - \sigma \epsilon (T_1^4 - T_\infty^4) - \frac{K}{\Delta X} (T_1 - T_2) = \rho C_p \frac{\Delta X}{\Delta t} \Delta T_1 + \rho \frac{\Delta X}{\Delta t} L_F \\
 & = \rho C_p \frac{\Delta X}{\Delta t} (\Delta T_1 + \frac{L_F}{C_p})
 \end{aligned}$$

$$\textcircled{2} \quad + \frac{K}{\Delta X} (T_1 - T_2) - \frac{K}{\Delta X} (T_2 - T_3) = \rho C_p \frac{\Delta X}{\Delta t} (\Delta T_2)$$

$$\textcircled{3} \quad + \frac{K}{\Delta X} (T_2 - T_3) - \frac{K}{\Delta X} (T_3 - T_4) = \rho C_p \frac{\Delta X}{\Delta t} (\Delta T_3)$$

etc.

ΔT_1 = increase in T_1 for time increment Δt

Fig. 10. Heat Transfer Scheme

Fig. 11. Re-entry Trajectory Post-orbit Decay

The desire to have the entire unit consumed by the aerodynamic heat is a means of alleviating the critical problem of having the capsule impact on the earth's surface. Three approaches were considered for the solution of this problem. They were:

- (1) Generator released from the satellite by aerodynamic heat (separation).
- (2) Generator released from the satellite by mechanical means at an altitude where the aerodynamic forces are significant (eject).
- (3) Fuel released from the satellite and generator (destruct) at high altitude. Each case was considered as a probable solution and a summary of the discussion concerning each case is presented below.

Generator released from satellite by aerodynamic means. The design of having aerodynamic heat as the only means of separating the thermoelectric generator from the satellite will require a definite orientation of the satellite during re-entry. Assuming that the unit was placed at the rear of the satellite as it traveled through the atmosphere, only a small amount of aerodynamic heat will be applied to the generator in an attempt to separate it from the satellite structure. The satellite body would act as a heat shield for the generator, thereby preventing the unit and fuel capsule from properly ablating. A possible solution would be to have aerodynamic surfaces mounted on the satellite or to have the satellite shaped in such a fashion so that, in either case, the satellite re-enters with the generator mounted at its stagnation heating region. An aerodynamic study is required if it is decided that a mechanical means of generator separation is impractical or undesirable.

Generator released from satellite by mechanical means. A direct and more practical solution for generator release would be by mechanical ejection of the generator from the satellite structure. If generator burn-up is desired for postorbital re-entry, its release will only be necessary at this time. An intact impact landing is required for any other type of re-entry. Any other structure surrounding the fuel core at the time of impact will only aid the core to withstand the impact loads. The generator can be attached to the satellite structure by means of an explosive actuator, designed so that the generator will be forcibly separated from the satellite. Sensing devices for detonation of the separation device can be one or a combination of the following sources. They could be operated by variation in atmospheric pressure, temperature changes on the surface of the satellite caused by aerodynamic heating, or after an elapsed time from launch.

The design for the isotopic unit could use a modification of devices presently under consideration (Task 5.5). After the operational life-time is reached (approximately five years), sufficient power is still being generated by the thermoelectric generator to detonate the explosive actuators. A ground activation signal would be the most positive and most easily controlled method of initiating detonation. This will enable positive control over the position and time of re-entry.

Release of the generator from the satellite will occur at an altitude where aerodynamic heating becomes significant (approximately 375,000 feet). Figure 12 shows the typical aerodynamic heating rate experienced by a tumbling generator and fuel capsule as they pass through the atmosphere along the trajectory shown in Fig. 11. The break in this curve at 120 seconds represents the point of burnup of the generator shell and its structural material and the initial exposure of the fuel capsule. Heating rate is inversely proportional to the square root of the radius of curvature of the body. Thus, an immediate increase is apparent at the point of capsule release. It has been assumed that all of the initial heat was applied to the generator housing because of the presence of the insulating material between it and the fuel capsule. By use of previous analyses from Tasks 2 and 5, an estimate of capsule and solid fuel material showed that complete consumption will occur prior to 200,000 feet.

Fuel capsule destruction at high altitude. Extensive testing and methods of application of shaped charges have been in practice for a number of years and have been tested under Subtask 5.5. The shaped charge is oriented to fire through the fuel; on detonation, a plasma stream is passed through the capsule wall, vaporizing the fuel into small particles and ejecting the fuel through the satellite skin. Ground control signals for initiating detonation of the shaped charges can be employed. Dispersion of minute particles of plutonium at high altitudes will cause the best possible diffusion and subsequent infinitesimal ground concentrations per square mile.

B. SUMMARY AND CONCLUSIONS

Several recommendations can be made for successful fulfillment of the design criteria of having acceptable radiation levels on the ground when the capsule is returned either due to an abort condition or from post-orbital re-entry.

Fig. 12. Aerodynamic Heating Rates for Generator and Capsule Re-entry

The mechanical means of separating fuel capsule or generator from the satellite have been elaborated upon in previous sections. Considering that the satellite can re-enter from orbit and act as a heat shield for the generator, it is apparent that the units might separate from the satellite structure by means other than aerodynamic heating. Design modification of the satellite unit will be required to ensure that it will re-enter with the generator unit at the satellite's stagnation point.

The necessary design changes are either the installation of aerodynamic control surfaces or a modification of the configuration of the satellite. It is felt that aerodynamic surfaces might significantly affect the performance of the satellite, which would make them undesirable. An oblate shape is required so that aerodynamic forces on the satellite will align it so that the attached generator will enter ahead of the satellite. Both of these modifications are extensive and, perhaps, undesirable at this time.

Explosive actuators used to separate the generator from the satellite or shaped charges placed so that they fire through the fuel capsule appear to be a necessity for ensuring that the fuels dispersed at high altitude with the present design. Either method will fulfill the requirement, but both have inherent disadvantages. There are many complications involved in placing these devices in satellites, although both methods have been extensively tested and used for many years. First, additional unproductive weight will be required. The firing mechanism, radio-receiving equipment, attachments, etc., will all contribute excessive, nonuseful weight to the payload. Some minor structural modifications to the design of the satellite will be required. Secondly, and probably the biggest drawback to mechanical separation, is the reliability of detonating charges by remote signals received from ground.

Serious consideration should be given to having the fuel capsule re-enter intact for all possible conditions. There will always be a gray zone associated with the design philosophy of having intact re-entry for vehicle aborts and burnup requirements for postorbital re-entry. Again, the gray zone is defined as that area of the abort trajectory where the fuel capsule is sufficiently heated or partially ablated so that the fuel capsule will fail at impact. This will result in an area having plutonium free on the surface of the earth.

Summarized in the shielding analysis section is the dose rate at the surface of the capsule and at various distances from it. Temperature at the surface of the capsule exceeds 100° F, making it improbable that a person would hold it long enough to receive an excessive dose. Studies conducted recently by Government-sponsored groups have resulted in recommendations that isotopes which are alpha emitters and are used for space missions should be returned intact. The plutonium isotope, as used for the Task 5.6 mission, seems to be ideally suited for an intact re-entry.

If a random re-entry is assumed, the aerodynamic heat available to heat and separate the generator from the satellite will be reduced because of the large diameter of the satellite. Aerodynamic heat is inversely proportional to the square root of the radius of curvature of the nose of the re-entering body. The satellite will traverse most of the heating region before a sufficient amount of it is accumulated to separate the generator from the satellite.

Further study is required, but it can be assumed at this point that an insufficient amount of heat will remain to completely melt the generator housing, fuel capsule and fuel element. If needed, additional insulation can be placed around the fuel capsule to ensure a minimum of heat transfer from the surface of the generator to the fuel.

An intact re-entry is most feasible if all of the recommended steps are employed.

A postorbital re-entry of the generator from a polar orbit can impact anywhere on the earth's surface. Shown below is the statistical analysis of the earth's surface for comparative purposes:

<u>Surface Covering</u>	<u>Area (sq mile)</u>	<u>Percent of Earth's Surface</u>
Total area of earth	196.9×10^6	100.00
Water area	144.9×10^6	73.59
Water ice area	12.9×10^6	2.08
Land area	52.0×10^6	26.41
Land ice area	8.8×10^6	4.47

V. FALLOUT PATTERNS

Worldwide fallout from bomb testing serves as a good example for the fallout pattern derived from an injection of radioisotopes into the stratosphere. From the total yield (90 to 92 megatons) of bomb tests to date, 140 pounds or 9.2 megacuries of Strontium-90 have been produced. Of this amount approximately 5 megacuries were injected into the stratosphere, most of it above the Northern Hemisphere. Figure 13 shows the present and predicted soil levels of Sr-90 and demonstrates that fallout tends to concentrate selectively between certain latitudinal bands in the Northern and Southern Hemispheres. Material injected into the stratosphere above the higher latitudes of a given hemisphere will deposit almost entirely in that hemisphere. Weapons debris injected into the stratosphere will fall out in an average time of 1 to 3 years, depending upon the latitude of injection. The lowest half-residence time suggested lately is about six months. Half-residence time is defined as that time when half of the debris placed in the stratosphere will be deposited on the earth's surface. This conservative estimate of six months has been used as a basis for the calculations presented in this report.

A. DIRECT FALLOUT FROM ABORTED MISSIONS

Following final-stage high altitude aborts, plutonium could be injected directly into the stratosphere above the Southern Hemisphere. Wherever burnup occurs, either partially or entirely, and results in a release of some fuel as very large particles, fallout will be prompt over regions of the Southern Hemisphere.

Fallout Pattern

Amount Pu-238 released	1017 curies
Half-residence time	180 days
Half-life Pu-238	31,536 days
Deposition zone	30° to 60° latitude
Pu-238 deposited in zone*	75%
Area of zone	3.6×10^7 square miles

*It is assumed that the remaining 25% is deposited elsewhere on the earth's surface.

Fig. 13. Present and Predicted Soil Levels of Sr-90 (Fallout from Nuclear Weapons Tests, May 5 to 8, 1959, Joint Committee on Atomic Energy)

The half-residence time of 180 days used in the calculations is representative of southerly launched trajectories; actually injections occurring above the Southern Temperate Zone would probably have a half-residence time of about one year or longer.

The ground concentration can be calculated by the following expression:

Total deposition (ψ_0) in millicuries per square mile is equal to

$$\frac{N_0(Z)}{A} \left[e^{-\lambda_r t} \right] \left[1 - e^{-\lambda_f t} \right]$$

where

N_0 = number of curies released initially = 1.017×10^6 millicuries

Z = percent deposited in zone 30° to 60° = 75%

A = area of zone = 3.6×10^7 square miles

λ_r = radioactive decay constant = $2.2 \times 10^{-5} \text{ day}^{-1}$

λ_f = residence decay constant = $385.0 \times 10^{-5} \text{ day}^{-1}$

t = time after release, days

$$\psi_0 = \frac{1.017 \times 10^6 \times 0.75}{3.6 \times 10^7} \left[e^{-2.2 \times 10^{-5} t} - e^{-387.2 \times 10^{-5} t} \right]$$

and

$$\frac{d\psi_0}{dt} = 0.0212 \left[-2.2 \times 10^{-5} e^{-2.2 \times 10^{-5} t} + 387.2 \times 10^{-5} e^{-387.2 \times 10^{-5} t} \right]$$

ψ_0 is a maximum when $\frac{d\psi_0}{dt} = 0$.

Then $t_{\max} = 1343$ days

and $\psi_{0_{\max}} = 0.0205$ millicurie/square mile.

Figure 14 shows the Pu-238 deposition in the Southern Hemisphere as a function of time after injection of 1017 curies.

The following table compares this dose with the doses received from various natural and man-made sources of radiation.

Estimated Dose from Different Radioactive Sources*

	30-Year Genetically Significant Dose (millirad)
Natural sources	3000
Fallout from nuclear weapons	50**
Medical sources	500 to 5000
From 1017 curies of Pu-238	$\sim 5 \times 10^{-6}$

*"External Radiation Doses," Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, 1958, p 15.

**"Fallout from Nuclear Weapons Tests," JCAE, May 1959, Table IV, p 40.

B. ULTIMATE RANDOM FALLOUT FROM ORBITAL DECAY

For cases where a successful mission is accomplished or an abort occurs late in the final-stage firing sequence, aerodynamic burnup of the generator and the fuel capsule will result in having 1017 curies injected into the stratosphere. These conditions will conceivably occur in a region over the Northern Hemisphere for a near-successful mission and over either hemisphere for a perfect launch and, as shown in Fig. 13, concentration of fallout will be between 30 and 60 degrees latitude. Therefore, an estimated peak ground accumulation of Pu-238 of 0.0205 millicurie per square mile would be expected.

For a case where orbital decays occur at 86.4 years, the half-life of Pu-238, 508.5 curies will be injected randomly into either hemisphere. This would yield a peak ground concentration of about 0.01025 millicurie per square mile in the area from 30 to 60 degrees N or S latitude.

Fig. 14. Plutonium-238 Fallout in 30°-to-60°-Latitudinal Band Following Post-orbital Re-entry or Final Stage Abort Under Complete Burnup

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APPENDIX A

MECHANICAL INTEGRITY OF FUEL CAPSULE*

A. INTERNAL PRESSURES

An analysis of the mechanical integrity of the device must encompass the helium pressure accumulation within the source capsule, the structural integrity of the container under various operating conditions, and other external environmental factors which might affect the integrity of the capsule.

The following rules have been established to govern the scope of the analysis:

- (1) After the successful injection into orbit, the fuel capsule must sustain the effects of the evolution of helium for a period of five years.
- (2) In the event of an aborted launch, it is assumed that the free fuel capsule will impact and bury itself in dry soil which will lower the capsule temperature to the order of 370° K. The successful containment of the radioactive isotopes is predicated on this temperature as the datum point.

Helium pressure accumulation. After the generator is fueled and thermal equilibrium is achieved, the capsule temperature is 866° K. As the Pu-238 decays by virtue of alpha emission, the alpha particles absorb electrons from the surrounding media to form helium atoms. This mechanism continues to operate until the α -emitting fuel is exhausted. Since the capsule is not vented, the pressure within rises with time, resulting in high internal pressures. Under an operating condition in space over the initial five-year period, the resulting helium production and the drop in operating temperature are negligible. After this time, the operational life of the power supply is ended, and there is no longer any requirement for containment from an operational point of view.

In the case of a missile abort, the generator would impact the earth at some point either in a media of water, ice, soil or rock. In examining the pressure equation:

$$P = \frac{mRT}{VM}, \quad (1)$$

*C. D. Waring

where

- V = free volume of the container = 1.568×10^{-3} liter
- R = gas constant = 0.08207 liter-atmosphere per mole, °K
- M = molecular weight of helium = 4.002
- T = absolute temperature of the capsule, °K
- m = mass of helium gas generated, grams

only m and T are time-dependent variables and only T, the capsule temperature, is a function of its surroundings. This can be demonstrated in the following manner:

let

- Q_0 = initial heat transfer flux
- Q = transfer flux at some later time
- λ = decay constant of the fuel
- t = time
- T_0 = initial capsule temperature
- T_a = ambient temperature
- T = core temperature at some later time
- K = some transfer constant.

Then, initially

$$Q_0 = K (T_0 - T_a)$$

but, at a later time, $Q = Q_0 e^{-\lambda t}$ and

$$Q = K (T - T_a), \text{ equating } Q\text{'s}$$

$$Q_0 e^{-\lambda t} = K (T - T_a) \text{ but,}$$

$$Q_0 = K (T_0 - T_a)$$

so,

$$K (T_0 - T_a) e^{-\lambda t} = K (T_0 - T_a)$$

$$T = (T_0 - T_a) e^{\lambda t} + T_a. \quad (2)$$

Surveying this equation it can be seen that the ambient temperature T_a plays an important role in determining T . The highest possible value of T_a for an abort condition was a value of 300° K which is representative of an impact in dry soil. An initial stabilized capsule temperature was calculated to be 370° K for these conditions and its decay is plotted in Fig. A-1.

In returning to Eq (1), it is necessary to determine the mass m of helium gas generated at time t in order to completely define the equation. The radioactive decay of Pu-238 can be described by the equation

$$\frac{dN}{dt} = -\lambda N$$

where

N = the number of atoms remaining at time t

λ = decay constant of Pu-238 = $2.54 \times 10^{-10} \text{ sec}^{-1}$.

Solving the equation and determining the constant of integration the equation becomes

$$N = N_0 e^{-\lambda t}$$

where N_0 = number of atoms in 470-curie source = 7.12×10^{22} .

The number of the atoms that have decayed N_1

$$\text{is } [N_0 - N_0 e^{-\lambda t}] \text{ and } N_1 = N_0 [1 - e^{-\lambda t}].$$

This quantity becomes the mass of the liberated helium when multiplied by the mass of a single helium atom (6.646×10^{-24} grams) or

$$m = m_{\text{He}} N_0 [1 - e^{-\lambda t}].$$

Therefore equation (1) becomes

$$P = \frac{R}{VM} \left[m_{\text{He}} (1 - e^{-\lambda t}) \right] \left[(T_0 - T_a) e^{-\lambda t} + T_a \right] \quad (3)$$

In the above argument, the contribution by the decay of the daughter element U-234 is neglected by virtue of its long half-life of 2.48×10^5 years.

In applying this equation it is assumed that the perfect gas law applies. It is also assumed that:

- (1) No diffusion of the helium through the capsule wall takes place.
- (2) There is no absorption of the helium atoms by the impurities in the source.
- (3) Total conversion of alpha particles to helium takes place.

Capsule strength required by helium pressure buildup. In order to determine the stresses in the capsule walls after an abort, it is assumed that the Hastelloy C outer capsule will not contribute to the containment because of the possibility of partial aerodynamic burning. The peak stress in the capsule wall will occur at the time of maximum capsule pressure. By examining Eq (3) and letting $t \rightarrow \infty$ it is found that the limit of the capsule pressure is 27,200 psi.

The radial stress in the capsule wall is expressed by the equation

$$S_t = \frac{PD}{2t} \quad (4)$$

where

- P = pressure = 27,200 psi
- D = internal diameter = 0.48 inch
- t = 0.125 inch.

This yields a value of 52,100 psi for the maximum radial stress, S_t . The stress buildup with time is plotted in Fig. A-1.

Fig. A-1. Capsule Pressure Buildup Stress and Temperature Decay upon Impacting on Dry Soil

The longitudinal stress is given by the equation

$$S_t = \frac{PD}{4t} . \quad (5)$$

Since the equation shows it to be one-half the value of the radial stress, it is not considered to be of importance.

In comparing the maximum radial stress with the properties of the Haynes-25 capsule material, Table A-1, the safety factor using the yield value is $\frac{70,000}{52,100} = 1.34$, while the value based on the ultimate strength is $\frac{150,000}{52,100} = 2.78$. Thus the fuel capsule will easily support the required pressure forces.

Impact forces. If a satellite launch attempt does not result in a successful orbit, the isotopic generator will either be consumed by aerodynamic heating or will impact on the earth. For the latter case, the capsule will reach a terminal velocity which is a function of its weight (W), shape (C_D), area normal to its flight path (A) and the angle γ with which it falls with respect to the local horizontal. This can be derived as follows:

$$D = C_D q A \quad (6)$$

where

D = drag

C_D = drag coefficient

q = dynamic pressure = $1/2 \rho V^2$

A = area.

Solving for terminal velocity, where drag equals weight:

$$V = \sqrt{\frac{841 W}{C_D A}}$$

The velocity is indirectly proportional to the drag area, and the drag area of the falling capsule can vary, depending on the orientation of the body. Thus, for the low drag case ($A = 7.5 \times 10^{-3}$ square foot), the terminal velocity, V , of the fuel capsule is

$$\sqrt{\frac{841 \times 1.8912}{(1.0) (7.5 \times 10^{-3})}} = 460 \text{ ft/sec.}$$

The impact pressure that the fuel capsule will be subjected to is calculated from the equation $P = \rho V^2$, the method of Rinehardt and Pierson, where ρ is the bulk density of the capsule and V is the velocity in feet per second. Thus, for $V = 460$ feet per second,

$$P = 27,750 \text{ lb/in.}^2$$

The impact parameters are summarized below:

	<u>High Velocity Case</u>
Weight (capsule), lb	1.8912 lb
Area	$48 \times 10^{-3} \text{ ft}^2$
Velocity (max)	460 ft/sec
C_D	1.0
Impact pressure	27,750 psi

Stress in the capsule as a result of impact. Impact can take place against many types of surfaces and with such a variation in the velocity and orientation of the impacting body that a complete analytical investigation does not appear possible. However, the resistance to load that can be sustained by a solid cylinder resting on a flat plate can be calculated by the equation:

$$P = \frac{d\theta^2}{0.349 E} \quad (7)$$

where

- P = load in pounds per linear inch
 θ = maximum pressure at center of contact (psi)
 E = modulus of elasticity
 d = outer diameter of the capsule (inches)
 S_p = stress at impact (psi)

It has been demonstrated that for impact conditions the value of E can be doubled. Therefore, Eq (7) can be written

$$P = \frac{d\theta^2}{0.698 E} \quad (8)$$

The contact area (b) over which the impact load is distributed can be calculated from the equation

$$b = 2.15 \sqrt{\frac{Pd}{E}} \quad (9)$$

Again, it is permissible to double the value of E and the equation becomes

$$b = 2.15 \sqrt{\frac{Pd}{2E}} \quad (10)$$

$$\text{and } S_p = \frac{P}{b} \quad (11)$$

For the case with the inner core of Haynes-25,

- θ = 27,750 psi
 d = 0.75 in.
 E = 24×10^6

Equation (8) results in

$$P = 34.5 \text{ pounds per inch}$$

and from Eq (10),

$$b = 1.592 \times 10^{-3} \text{ inches.}$$

Therefore,

$$S_p \text{ (impact)} = 21,700 \text{ psi.}$$

For the outer core of Hastelloy C,

$$P = \frac{d\theta^2}{0.698 E} \quad (8)$$

where

$$d = 1.125$$

$$\theta = 27,750 \text{ psi}$$

$$E = 20 \times 10^6 \text{ (best estimate)}$$

$$P = 62.2 \text{ lb/in.}$$

The value of b is 2.84×10^{-3} inches;

therefore,

$$S_p = \frac{P}{b} = 21,900 \text{ lb/in.}^2$$

These equations give approximate values and are only suggestions of the performance of the capsule design. Should the design be accepted for hardware production, these values should be substantiated by a comprehensive test program. The values are summarized in Table A-1.

TABLE A-1

<u>Material</u>	<u>Haynes-25</u>	<u>Hastelloy C</u>
Density (gm/cm ³)	9.13	8.94
Thermal conductivity Btu-in/ft ² -hr-°F	142.2	114
Thermal expansion (in/°F)	7.58×10^{-6}	7.44×10^{-6} (70°F to 1000°F)
Specific heat Btu/lb-°F	.092	0.092
Tension modules (psi)		$26 \text{ to } 22 \times 10^6$
Poisson's ratio	0.30	0.30
Ultimate tensile strength (538°C) (psi)	109,000	81,000
(590°C) (psi)		67,000
Yield strength (psi)	70,000	50,000