NUCLEAR DIVISION

MARTIN

BALTIMORE 3, MARYLAND

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PRELIMINARY SAFETY ANALYSIS

LOW POWER CERIUM-144 GENERATOR

MND-P-2363

June 1960

PREPARED BY:

Nuclear Safety Analysis Unit

The Martin Company

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FOREWORD

This report was prepared for the U.S. Atomic Energy Commission in fulfillment of Task 5.5 of Contract AT(30-3)-217 by The Martin Company.

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SUMMARY

Two configurations of small, Cerium-144 fueled thermoelectric generators have been designed at The Martin Company for use in terrestrial satellite systems. In both, the radiocerium fuel is enclosed in a tapered cylindrical capsule of Haynes-25, to provide containment during the various launch accidents. The capsule temperature is 580° C during operation, well below the melting point of Haynes-25 (1329° C). Lead telluride thermoelectric elements surround the capsule and are contained within an outer stainless steel shell. One configuration incorporates a second shell which is filled with mercury for biological shielding.

The typical vehicle employed to inject the payload into orbit consists of a booster stage fueled with liquid oxygen and RP-1 (a kerosene) and a final injection stage fueled with unsymmetrical dimethyl hydrazine. The final stage is also the satellite.

Cerium-144 produces thermal energy in its beta decay to Praseodymium-144 and Neodymium-144. It has a half life of 285 days and a power activity constant of 0.0074 watt per curie. Each generator uses 9900 curies of ceric oxide with silicon carbide additives, the mixture weighing 37 grams. Since the daughters of Cerium-144 have different oxidation states, oxygen is evolved within the fuel.

The biological shield reduces the direct radiation dose rate from decay gammas and bremsstrahlung to 90 mr/hr at 3 feet (two generator units). When the unshielded generators are mounted on the vehicle, the dose rate at ground level is 1240 mr/hr.

The integrity of the fuel capsule under the spectrum of launch failure forces is considered in this report. These forces include internal pressure, external forces from shock overpressures and impact, corrosion and propellant fires.

Following successful missions, the fuel will be released in the stratosphere at a time when the source strength is about 4000 curies. The result for Temperate Zone releases will be a ground concentration of 2 x 10^{-9} curie per square mile. For prompt stratospheric releases, resultant ground concentrations will be 0.053 millicurie per square kilometer.

I. INTRODUCTION

The Martin Company has prepared this preliminary safety report to discuss the safety measures adopted in the use of small, Cerium-144 fueled thermoelectric generators in terrestrial satellite systems. The Cerium-144 generator has been evaluated by comparison with similar isotopic power systems, specifically, the Task II and Snap III generators.

Two generators employing a total Cerium-144 inventory of 19,800 curies have been designed to produce an auxiliary power output of 3.2 electrical watts after six months of operation. Two alternate generator configurations are described: one mercury-shielded to facilitate ground handling, and the other unshielded for remote installation in the launch vehicle.

The generators are designed so that the radiocerium fuel will be consumed by aerothermodynamic forces on re-entry into the atmosphere. The ultimate fate of the fuel after both successful and unsuccessful missions is treated in this report. Since many of the cases considered result in dispersion of the fuel as aerosols in the stratosphere, a postulation of the fallout mechanism is also made. Aborted missions are refined into the following general cases:

(1) Impact of fuel on land with recovery.

(2) Impact in shallow water with recovery.

(3) Impact in deep water without recovery.

(4) Partial ablation of fuel,impact of remnants in remote areas.

(5) Prompt re-entry, total ablation and dispersion of fuel in stratosphere as aerosols.

(6) Orbital injection of short duration with ultimate ablation and dispersion of fuel in stratosphere.

II. GENERATOR

Each satellite utilizes two thermoelectric generators, each supplying 1.6 watts at the end of six months for a total system output at that time of 3.2 watts. The thermal energy output is converted to electrical energy by a series of thermoelectric elements.

In one design, a biological shield surrounds the generator to protect launch operations personnel. A fill and drain system is attached to the biological shield for remote draining of the mercury biological shield to reduce liftoff weight prior to the launching of the missile. Figure 1 shows a thermoelectric generator encased in its biological shield. In the other design the generator is the same, but the biological shield is not utilized. Instead, a remote handling mechanism is used to install the generator, which is encased in a lead cask prior to installation.

A. THERMOELECTRIC GENERATOR

Each Cerium-144 heat source has an activity of 9900 curies and is contained in a tapered cylinder of Haynes-25 material. Physical details of the containment of the fuel are reported in a later section of this report. At initial loading, the 9900 curies of ceric oxide will produce 73 thermal watts at a capsule temperature of 580° C. The lead telluride thermoelectric elements are located between the capsule and a stainless steel sphere. The fuel capsule maintains the hot junction temperature of the thermoelectric elements, and the stainless steel sphere maintains the cold junction temperature by radiating excess heat to the outside. Environmental tests indicate that the cold junction temperature will vary from 110° C at initial loading to 74° C after six months of operation. Thermal insulation surrounds the capsule and thermoelectric elements, to maintain the necessary temperature differential across the elements. The elements are electrically insulated, to allow for a continuous series connection.

The thermoelectrics consist of doped lead telluride arranged in pairs of P- and N-type elements. A screw and spring attachment at the cold junction permits thermal expansion of the elements. Electrical leads are attached to the generator and connected to output terminals at the top of the biological shield, to produce electrical power for the satellite.

B. BIOLOGICAL SHIELD

A biological shield designed to reduce direct radiation doses to permissible levels surrounds the generator. The shield is a stainless steel sphere approximately 17 inches in diameter, containing liquid

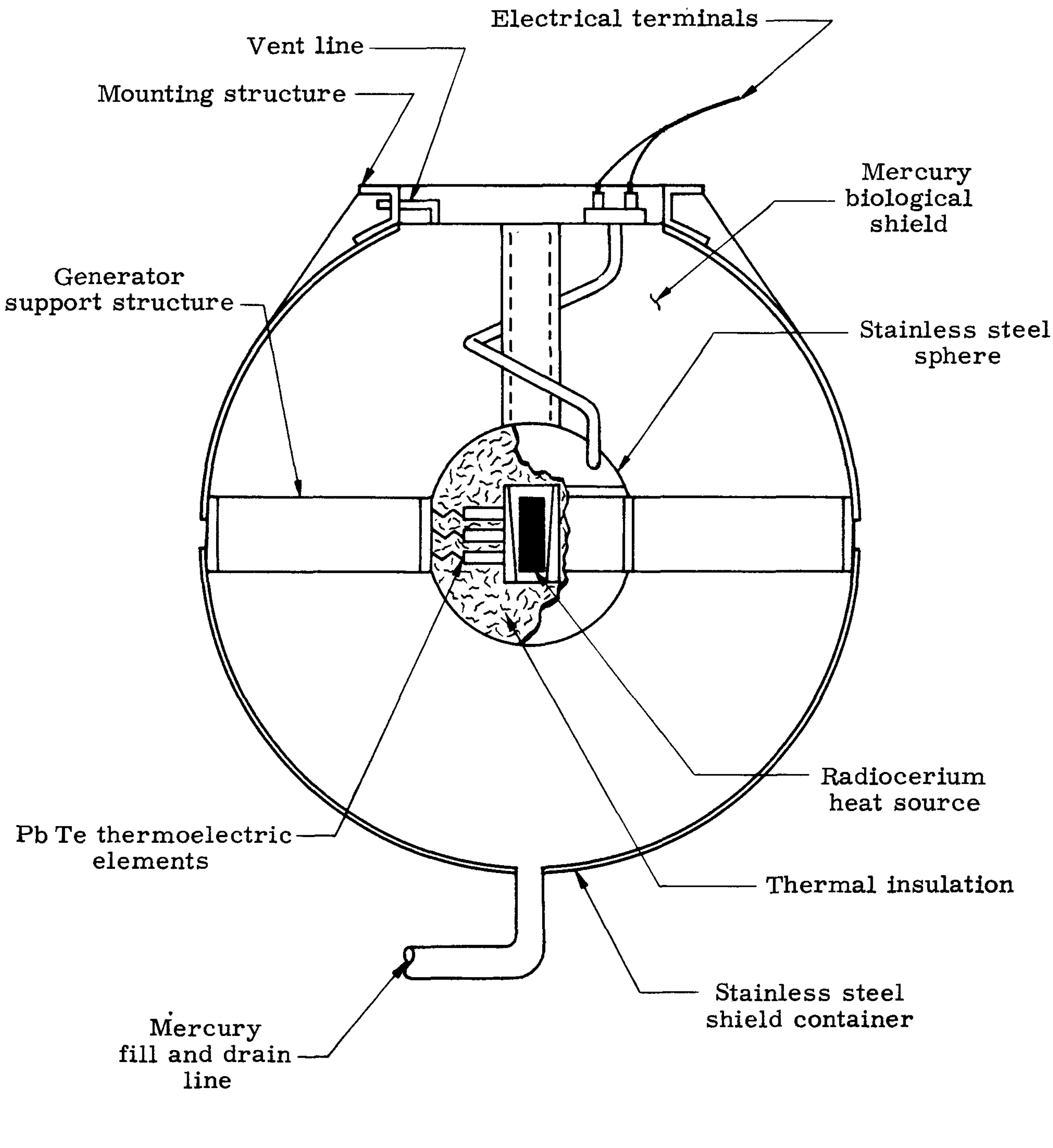


Fig. 1. Shielded Generator Configuration

mercury. A circular ring support structure holds the generator in place. At the top of the sphere is an opening, to permit the insertion of the fueled generator in the biological shield container.

Mercury flows in or out of the biological shield through a built-in fill and drain system. The inlet and drain line is located at the lowest point on the biological shield shell, to ensure complete mercury drain prior to launch; the vent line is located at the uppermost point on the sphere, to prevent air voids from forming as the sphere is being filled. The mercury shield of one generator weighs 1250 pounds but is drained remotely prior to the launching of the missile. The actual flight weight of each unit, including the biological shield container, is 25 pounds.

III. INTEGRATION OF VEHICHLE AND GENERATORS

Two concepts have been developed for the installation of the units in a typical satellite. In one concept, the generator and biological shield unit previously described is manually installed in the satellite. This design requires an auxiliary fill and drain system to install and remove the mercury shield when required. The other concept considers remote installation in the missile of a generator without a biological shield. This method reduces the weight by 50% and does not require a fill and drain system. However, modification of the gantry crane is required, and added restrictions are imposed upon working personnel in the launch area after installation of the generators in the vehicle.

A. INSTALLATION OF SHIELDED GENERATORS

The generators encased in biological shields are located in the aft position of the satellite vehicle and are bolted to a frame at the skin separation plane of the booster and final stage. After final stage separation, the units are exposed to the environment. The aft equipment rack of the satellite is located directly above the units, and the booster propellant tanks are directly below the generators. The two units are 180° apart, on opposite sides of the final stage rocket engine.

A mercury fill and drain system accompanies the generators as they are transported to the site and integrated with the missile. The completely assembled units are placed in a lead cask for transportation. At the launch site, personnel can remove the units and bolt them directly to the satellite vehicle at ground level. The generators can be checked out at ground level with the satellite components. The satellite is then raised into its position atop the basement stage. At this location, the units are 75 feet from ground level.

Fill and drain lines are attached manually to disconnectors after the final vehicle stage is placed in position. At five minutes prior to launch, the mercury is drained from the units. Should a hold occur after this time, the mercury can be returned to the biological shield container. The disconnectors attached to the shield container are remotely operated by a lanyard arrangement as the missile leaves the launch pad.

B. REMOTE INSTALLATION OF GENERATORS

The location of the unshielded generators is similar to that of the shielded generator, the position of the generators around the final stage rocket depending upon the structure of the gantry crane.

The units are shipped in a lead cask smaller than but similar to that of the shielded generator. At the launch site the casks are placed in position on the gantry platform, and the area is cleared of personnel. The arrangement of equipment is shown in Fig. 2. As an actuator raises the lid of the cask, the manipulator swings into place, grasps the generator and rotates it 90°. The manipulator carriage positions the generator through an opening in the missile skin into a fitting attached to the satellite frame. The carriage is moved back, and a panel closes the missile access hatch. Limitations which must then be placed on working personnel are defined by the shielding requirements listed in a later section of this report.

C. PROPELLANT LOADS

The generators are located five feet below the final stage propellant tanks and two feet above the booster propellant tanks. Figure 3 shows the position of the units with respect to both the booster and final stage fuel tanks.

The final stage of a typical satellite vehicle utilizes UDMH (unsymmetrical dimethyl hydrazine) fuel, with IRFNA (inhibited red fuming nitric acid) as an oxidizing agent. If accidentally ignited, the final stage propellants will release only thermal energy.

A typical booster propellant load contains RP-1 fuel with liquid oxygen as the oxidizing agent. Unlike the final stage propellants, when ignited en masse, the booster propellants will release some mechanical (shock) energy, as well as a large amount of thermal energy.

Tests were conducted to determine the thermal energy effect on similar generators and are reported in Ref. (1).

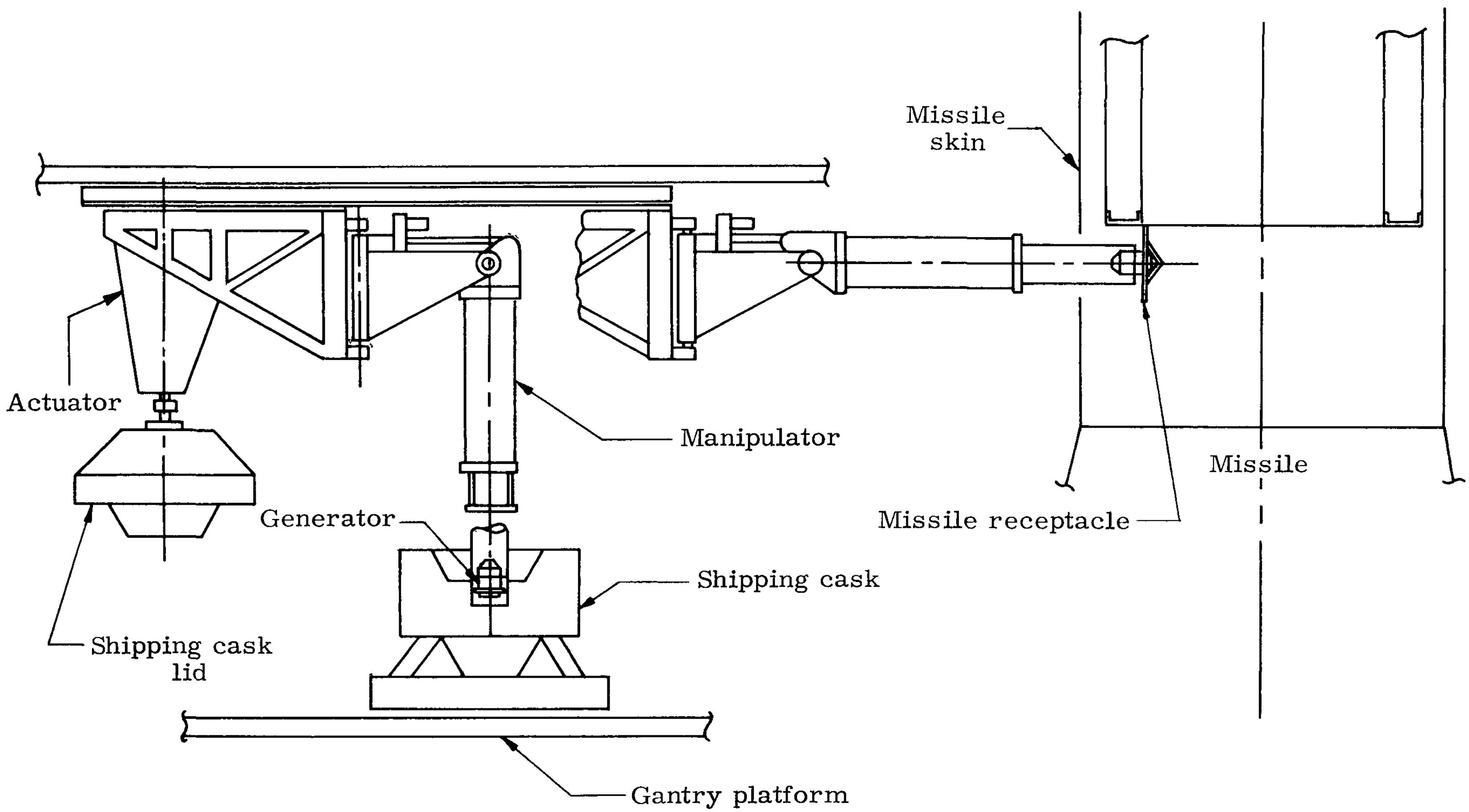


Fig. 2. Manipulator Carriage for Remote Handling of Unshielded Generators

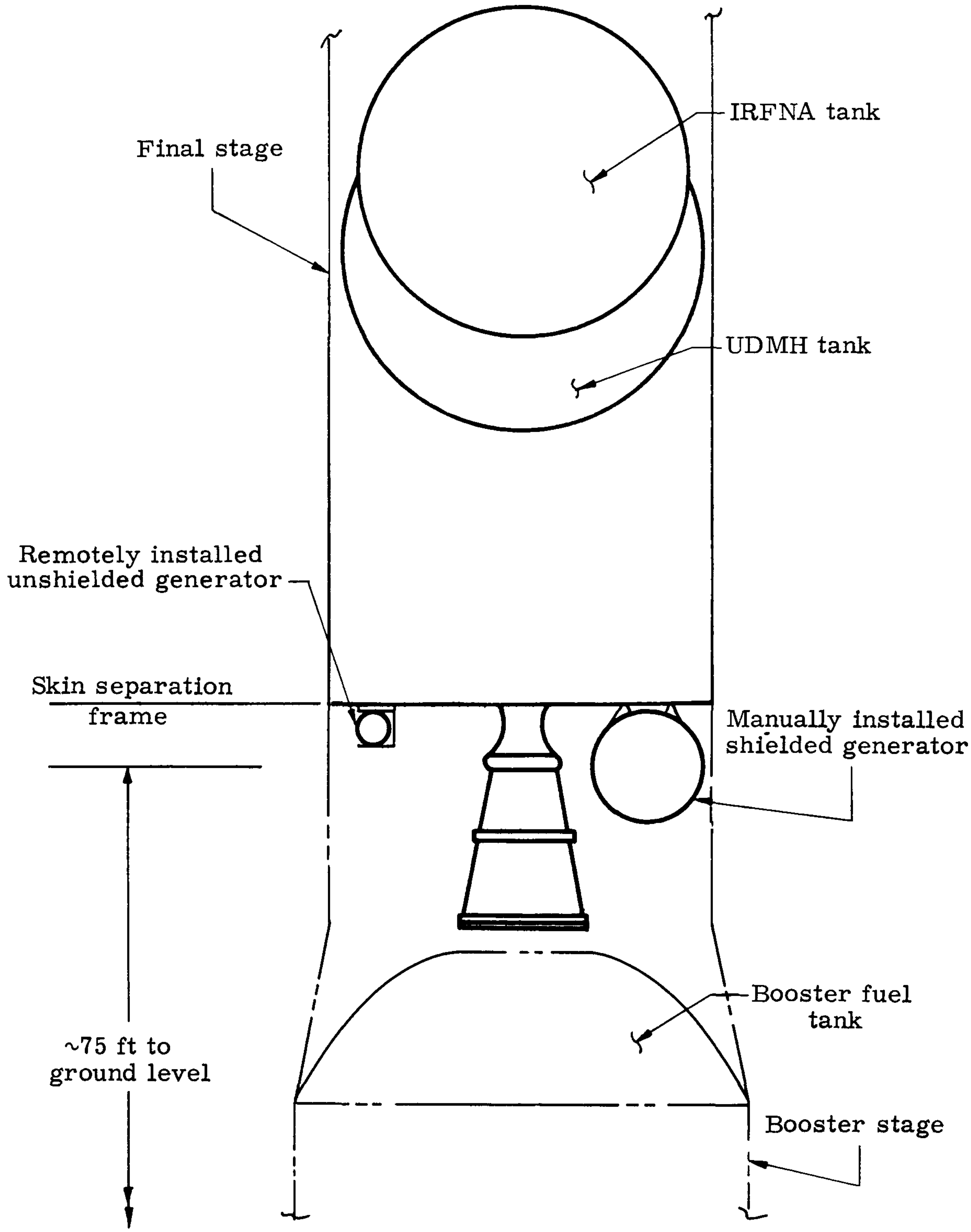


Fig. 3. Integration of Both Generator Concepts in the Missile

IV. CERIUM-144

The thermal energy required of a Task 5 generator is 73 thermal watts. Since the power activity constant of Cerium-144 is 0.0074 watt per curie, 9900 curies are required to fuel each generator. The fuel form, ceric oxide with 10% SiC and 0.5% CaO additives, has a specific power of 1.96 watts per gram; hence, the fuel weight is about 37 grams. The fuel is compacted into right cylindrical pellets under 25 tons per square inch (tsi) pressure and sintered, to produce uniform grain structure. Table 1 presents the chemical, physical, thermal and nuclear properties of the fuel. Further data on the fuel may be found in Ref. (2).

A. CHEMICAL PROPERTIES

Ceric oxide is insoluble in water and dilute acid solutions, but it is soluble in concentrated nitric and sulfuric acids. Because of the additives, some CeC_2 and $CeSi_2$ will be formed in the fuel in minor amounts.

As a result of the different oxidation states of the isotopes of the Cerium-144 decay chain, an evolution of oxygen within the fuel pellet will occur according to the following reaction chain:

$$12\ CeO_2 \xrightarrow{(\beta)} 2\ Pr_6O_{11} + \underline{O_2} \uparrow$$

$$2\ Pr_6O_{11} \xrightarrow{(\beta)} 6\ Nd_2O_3 + 2\ \underline{O_2} \uparrow$$

Over an infinite decay time, a maximum of 1.7 grams of oxygen will be produced; this is equivalent to 1.2 liters of O_2 gas at STP.

B. PHYSICAL PROPERTIES

The fuel has a bulk density of 5.4 gm/cc, and the corresponding cerium density is about 4 gm/cc. Pure ceric oxide melts at 2600°C; however, decrepitation of the fuel induced by additives occurs at 1800°C.

C. THERMAL PROPERTIES

The fuel form has a specific power of 1.96 watts per gram and a corresponding specific activity of 265 curies per gram. Ceric oxide has a thermal conductivity of 0.01 cal/cm/sec °C, a specific heat of

TABLE 1

Properties of Ce-144 O_2 + 10% SiC

Chemical Properties

Compound	Cold H_2O	Hot H_2O	Dilute Acids	HNO_3	H_2SO_4
CeO_2 + SiC	Insoluble	Insoluble	Insoluble	Soluble	Soluble

Physical Properties

Molecular Weight	Melting Point (°C)	Crystalline Structure	Bulk Density (gm/cc)
~ 140	1800 (d)	Face-centered cubic	5.4

Thermal Properties

Thermal Conductivity (cal/sec-cm/°C)	Specific Heat (cal/gm/°C)	Thermal Linear Coefficient of Expansion (cm/cm/-°C STP)	Specific Activity (curies/gm)	Specific Power (watts/gm)	Power Activity Constant (watts/curie)
0.01	0.1	12.1×10^{-6}	265	1.96	0.0074

Nuclear Properties

Radionuclide	Half Life	Mode of Decay	β Energy Mev	β Energy %	γ Energy Mev	γ Energy %	Other Radiation
Ce-144	285 days	β, γ	0.327	75	0.054	10	X from Bremsstrahlung
			0.258	5	0.080	10	
			0.16	20	0.134	15	
Pr-144	17.5 min	β. γ	3.01	98	0.69	1.6	X from Bremsstrahlung
			2.30	~1.3	1.50	0.25	
			0.79	1.0	2.18	0.8	
Nd-144	1.5×10^{15} yr	α	None		None		α 1.9 Mev

0.1 cal/g °C, and a thermal linear coefficient of expansion of 12.1×10^{-6} cm/cm-°C.

D. NUCLEAR PROPERTIES

Cerium-144 is a fission product which is separated from reactor wastes. Some of the radiation and resultant thermal energy associated with radiocerium originates in the beta decay of Cerium-144, but a majority of the thermal energy is derived from the beta decay of Praseodymium-144 to Neodymium-144. Aside from the gamma radiation which is emitted instantaneously upon decay of radiocerium, a large portion of X-ray photons (Bremsstrahlung) is emitted during the slowing down of the energetic beta particles. Although Cerium-144 is formed directly by fission, a minor amount is formed from fission product decay, as shown by the following genetic relationship:

$$\text{Xe-144} \xrightarrow{\beta} \text{Cs-144} \xrightarrow{\beta} \text{Ba-144} \xrightarrow{\beta} \text{La-144} \xrightarrow{\beta} \text{Ce-144} \xrightarrow{\beta} \text{Pr-144} \xrightarrow{\beta} \text{Nd-144}$$

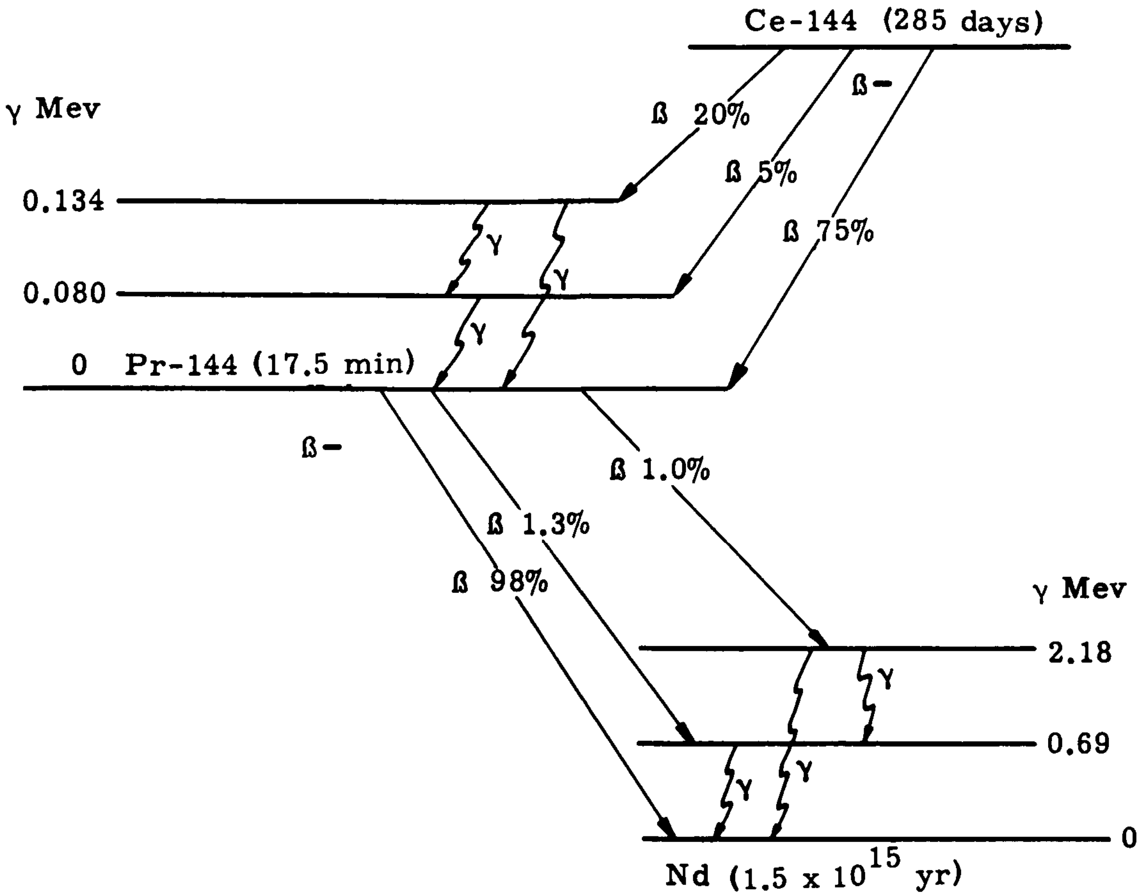
$$\text{U-235} \xrightarrow{(n,\ \gamma)\ \text{Fission}} \text{Ce-144}$$

Cerium-144 has a half life of 285 days and decays by beta emission to praseodymium. The beta energies associated with Ce-144 and their percents of abundance are 0.30 mev (75%), 0.25 mev (~5%) and 0.16 mev (20%). The gamma radiation energies range from 0.012 to 0.134 mev.

Praseodymium-144 has a half life of 17.5 minutes and decays by beta emission to Neodymium-144. The Praseodymium-144 beta energies and their percent abundance are 3.0 mev (98%), 2.3 mev (~ 1.3%) and 0.79 mev (1.0%). The 3.0 mev beta particles are the major source of thermal power and the predominant cause of Bremsstahlung emission from the radiocerium fuel.

Neodymium-144 has a half life of 1.5×10^{15} years and decays by the emission of ~1.5 mev alpha particles. Because of its long half life, Neodymium-144 is considered to be stable.

The following diagram represents the decay scheme of Cerium-144 and Praseodymium-144.



E. RADIOBIOLOGICAL PROPERTIES

The radiobiological properties of Cerium-144 are shown in Table 2. The critical organs for soluble radiocerium are the large lower intestine, the skeleton and the liver; for insoluble radiocerium, the lungs and large lower intestine. The maximum permissible total body burden is 5 microcuries. The total internal radiation dose from one microcurie of Cerium-Praseodymium-144 inhaled is 1160 millirems.

TABLE 2

Radiobiological Properties of Cerium-144 and Daughters

Radionuclide and Type of Decay	Form	Critical Organ	Maximum Permissible Burden = Total Body (μc)	Maximum Permissible Concentration: 40-Hr Week (water) (μc/cc)	Maximum Permissible Concentration: 40-Hr Week (air) (μc/cc)	Maximum Permissible Concentration: 168-Hr Week (water) (μc/cc)	Maximum Permissible Concentration: 168-Hr Week (air) (μc/cc)
$_{58}$Ce-144 (β, γ)	Soluble	GI	-	3×10^{-4}	8×10^{-8}	10^{-4}	3×10^{-8}
$_{59}$Pr-144 (β, γ)		Bone	5	0.2	10^{-8}	8×10^{-2}	3×10^{-9}
$_{60}$Nd-144 (α)		Liver	6	0.3	10^{-8}	0.1	4×10^{-9}
		Kidney	10	0.5	2×10^{-8}	0.2	7×10^{-9}
		Total Body	20	0.7	3×10^{-8}	0.3	10^{-8}
	Insoluble	Lung	-	-	6×10^{-9}	-	2×10^{-9}
		GI	-	3×10^{-4}	6×10^{-8}	10^{-4}	2×10^{-8}

Biological half life--500 days
Effective half life--180 days
Dose per single inhalation--1160 mrem/μc

V. SHIELDING REQUIREMENTS

In one of the designs a biological shield surrounds the generator. to provide adequate protection for personnel working in the area of the generator for extended periods of time. The physical characteristics of the biological shield were explained in Section II. Although the radiation level around the generator is high after the mercury has been drained, personnel can work at ground level for short periods of time. Radiation levels for the unshielded (remotely handled) design will be similar to those of the shielded generator with its mercury shield drained. Further consideration is given to the shielded generator.

A. SHIELDED SOURCE

The radiation dose rates at a point one meter from a geometrical source of 9900 curies were calculated for various thicknesses of mercury shielding interposed between the source and the point in question. The rates obtained represent those from the initial source, disregarding radioactive decay; therefore, they are maximum dose rates. Table 3 lists the results of the calculation.

TABLE 3

Hg Shield Thickness (inches)	Dose Rate at 1 Meter (mr/hr)
6	40
5	154
4	616

Maximum permissible exposure times and corresponding dose rates were determined for different separation distances, for the case in which the mercury biological shield thickness around each generator is 6.0 inches. The dose rates stated apply to the combined source strength of two generators. A maximum permissible total dose of 3 roentgens was used in the analysis. Table 4 summarizes the maximum permissible exposure times and corresponding dose rates for various distances from the generators.

TABLE 4

Distance from Source (feet)	Dose Rate (mr/hr)	Maximum Permissible Exposure Time (hours)
2	206	14.6
3	90	33
4	52	45
5	34	88
10	8	375
20	2	1500

B. UNSHIELDED SOURCE

Since the mercury is drained from the units before the vehicle is launched, it is desirable to know the radiation levels from an unshielded source near the ground. In this evaluation, the source is located approximately 75 feet above ground level. From an unshielded generator source, the dose rate at a separation distance of 100 feet will be 1240 mr/hr. This radiation level permits an individual to remain in the vicinity of the vehicle for 2.4 hours before receiving a total dose of 3 roentgens. At a distance of 50 feet from an unshielded source, the radiation dose rate is 5000 mr/hr. An individual in this vicinity, adjacent to the missile and 25 feet above the pad, would receive the total maximum permissible dose of 3 roentgens in 36 minutes. For launch pad aborts after the generators have been separated from the biological shields, remote equipment will be required to recover the fuel.

VI. SAFETY DESIGN CRITERIA

The safety design requirement for the generator is absolute containment of the fuel, except in cases of high velocity re-entry into the earth's atmosphere. The radiocerium is sealed in a primary capsule as shown in Fig. 4. Actually, three containment structures are inherent in the shielded design of the generator: the fuel capsule; the secondary shell of the generator, which holds the thermoelectric elements and insulation; and the tertiary shell, which encloses the mercury biological shield.

A. CONTAINMENT

Containment must be maintained against a variety of external and internal forces. To ensure this, an analysis was made to establish limiting values of internal and external pressures, corrosion and temperature effects.

1. Internal Pressure

The source of internal pressure within the fuel capsule is the free oxygen which evolves from the fuel during radioactive decay. The mechanism by which oxygen is liberated from the fuel matrix is not well known, but it appears that not all of the oxygen produced in the fuel would migrate to the free void volume of the capsule and contribute to the buildup of internal pressure. However, because of this uncertainty, and for a conservative analysis, it is assumed that all of the oxygen that evolves goes into the free void volume. Figure 5 shows the pressure due to oxygen accumulation in the void volume during the first 350 days after encapsulation. The maximum pressure is 34,000 psi.

By use of the following relationship, the mass of oxygen at any time after encapsulation can be calculated:

$$m_t = m_\infty (1 - e^{-\lambda t})$$

where

m_t = mass of oxygen at time t (grams)

m_∞ = mass of oxygen at infinite time (grams)

λ = decay constant (2.43×10^{-3} day^{-1})

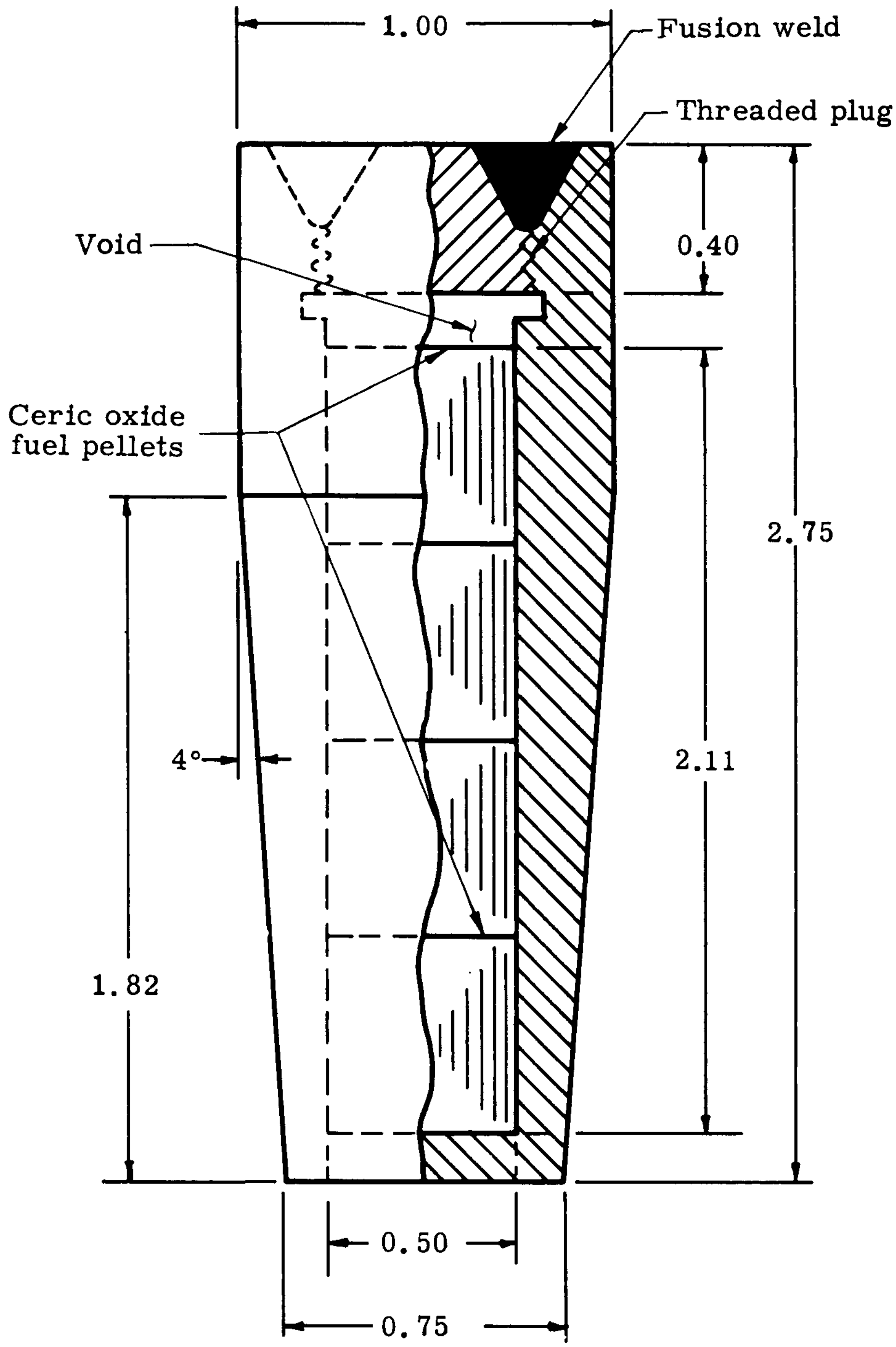


Fig. 4. Cerium Capsule Configuration

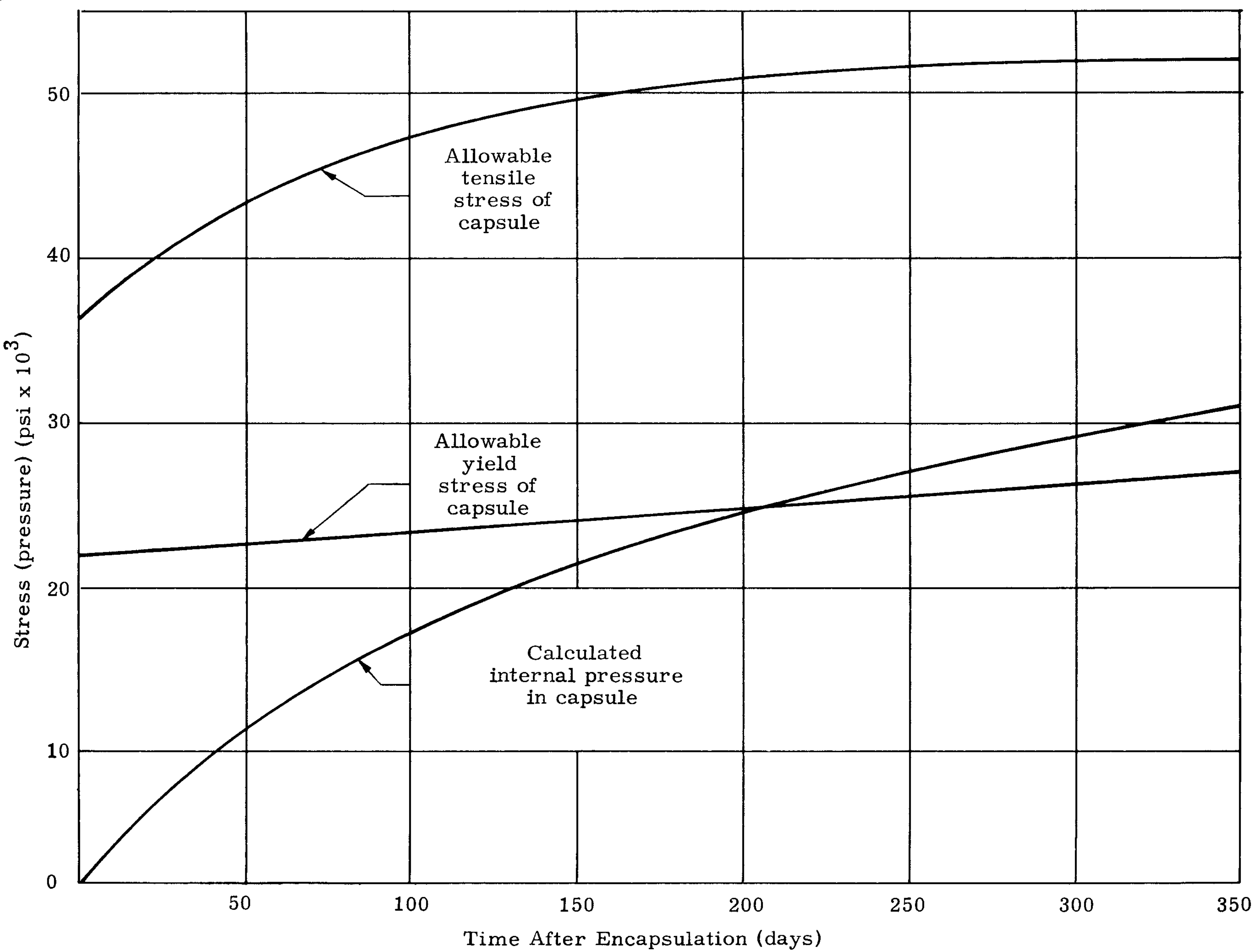


Fig. 5. Mechanical Integrity of Haynes-25 Capsule

t = time (days after encapsulation).

Based upon the ideal gas law, the following expression was derived and used to determine the pressure at any time after encapsulation:

$$P_t = \frac{m_t \; RT_t}{VM}$$

where P_t = pressure at time t (atmospheres)

R = ideal gas constant (0.0821 liter-atmosphere per mole-°K)

T_t = temperature at time t (°K)

V = void volume (5×10^{-4} liter)

M = molecular weight of oxygen (32 grams/mole)

m_t = mass of oxygen at time t (grams).

Table 5 shows capsule temperatures at several times after encapsulation.

TABLE 5

Fuel Capsule Temperature

Time (t) (days)	Capsule Temperature (°K)	(°C)
0	855	582
63	794	521
178	639	366
348	483	210

To determine the integrity of the capsule when it is subjected to internal pressure, the following equation is employed:

$$P = \frac{S\,(R^2 - r^2)}{R^2 + r^2}$$

where

P = allowable pressure (psi)

S = ultimate yield or tensile stress (psi)

R = outside capsule radius (0.375 inch)

r = inside capsule radius (0.25 inch).

Then, the tensile stress needed to rupture the capsule at the end of 6 months is 50,000 psi, well above the internal pressure exerted at this time. The capsule material will, however, begin to yield gradually after 7 months and may eventually rupture. The capsule has been tested at 870° C and 30,000 psi without failure. Since the material will yield in a ductile manner, the void volume will increase and a lower pressure will result. Though a somewhat marginal case of integrity exists after 7 months, release of fuel at this time will not jeopardize the safety of the mission, since the generator is designed to completely ablate on re-entry induced by orbital regression.

2. External Pressure

In the event of missile failure, the generator will be subjected to external dynamic pressures from shock and impact loads.

The failure of the booster propellant tanks containing liquid oxygen and RP-1 can yield a low order detonation. The resultant shock over-pressure is approximately 1000 psi at the location of the generators. This shock load was experimentally simulated with scaled-down specimens at a proportionate distance from a known quantity of TNT. The integrity of the fuel capsules was maintained in this test environment.

The maximum impact force imparted to the fuel capsule during a vehicle failure is attained at terminal velocity impact on a rigid medium. For an average terminal velocity of 302 fps, the maximum impact pressure is 12,000 psi. Impact experiments were conducted in which fuel capsules were heated to the expected operating temperatures and impacted at terminal velocity on target media simulating the earth's surface. Capsule integrity was maintained in all cases.

Since discrete fuel capsules were tested individually, a safety factor is introduced by the clamping effects of the actual generator structure. The structure will serve to reduce the impact velocity and absorb a portion of the energy imparted by impact and shock loads.

3. Corrosion

The minimum wall thickness of the primary capsule is 0.125 inch. Corrosive agents anticipated are salt water, in cases of impact at sea, and nitric acid, in cases of launch failures releasing second-stage propellants (IRFNA). The pitting corrosion rate of Haynes-25 is about 0.014 inch per year in salt water and about 0.046 inch per year in boiling concentrated nitric acid. The anticipated exposure time to nitric acid is less than one week, whereas marine exposure will occur over an infinite period of time.

4. Propellant Fires

A propellant fire releases a great deal of thermal energy over 20 to 30 minutes, a relatively long period. The initial fireballs will be of short duration, but of high thermal potential. However, their effect upon capsule integrity is negligible, since only a small fraction of the available total thermal energy would be imparted to the fuel capsule. Following the initial violent release, there is a sustained propellant and metal fire which has a temperature profile varying from 4500° to 1500° F. Discrete fuel capsules (3) were exposed to this environment along with (5) capsules enclosed in the generators. Integrity was maintained in all cases.

VII. FATE OF FUEL

The fate of the fuel can be generally defined for both successful and aborted missions.

A. SUCCESSFUL MISSION

A successful mission is defined as one where the satellite is injected into a 300-statute mile polar orbit having a lifetime of about 600 days. At this time, the Cerium-144 inventory of the generators will have decayed from the initial source strength of 19,800 to about 4000 curies. As the orbit continues to regress, the satellite will re-enter the sensible atmosphere. Aerodynamic heating will separate the satellite from the generator, and the generator shells will melt to expose the fuel capsule. Continued re-entry of the fuel capsule at high velocity will provide enough aerodynamic heat to melt and disperse the capsule and its radiocerium at an altitude of approximately 200,000 feet.

Since satellite re-entry will be at random, the release of fuel will occur at a random location. The following assumptions are made:

(1) The mean stratosphere residence time of the fallout released is 285 days.*

(2) Seventy-five percent of the material will be uniformly deposited in the Temperate Zone (30° - 60° latitude).

Therefore, at the end of the mean residence time (2.5 years after launch), 1000 curies are deposited on the earth's surface, 750 curies in the Temperate Zone.

$$\frac{\text{Amount deposited } (30\text{-}60°)}{\text{Area } (30\text{-}60°)} = \frac{750 \text{ curies}}{3.6 \times 10^7 \text{ sq miles}} =$$

$$2 \times 10^{-9} \text{ curie/sq mile}$$

The ground deposition will be about 2000 micromicrocuries per square mile at the end of one mean residence time. This corresponds to an individual dose rate in the Temperate Zone of about 10^{-9} millirad per hour, which is not measurable.

*This is conservative; estimated mean residence time for material released at 200,000 feet is about five years or more.

B. ABORTED MISSION

If the launch vehicle travels on a due south azimuth down the Pacific Missile Range, it will pass over 14,000 miles of ocean and across the Antarctic Continent before passing over a populated land mass (Madagascar). Malfunctions of the vehicle will result in projected impact points along this azimuth, except for failures in yaw, which will yield projected impact points at a varying lateral distance from this azimuth. The fate of the fuel as a consequence of aborts falls into six categories as follows:

(1) Impact on land

(2) Impact in shallow water

(3) Impact in deep water

(4) Partial ablation, impact of capsule remnants

(5) Prompt re-entry, total burnup and dispersion

(6) Into orbit.

1. Impact on Land

The fuel capsules will impact on land from failures occurring immediately after launch. Since the launch azimuth is over a controlled range safety area, the resultant hazard will be small. The linear segment of the projected launch azimuth is approximately five miles in length. As the fuel capsules will be in an undamaged condition, the fuel will be retrieved as a sealed source.

2. Impact in Shallow Water

The linear segment of the projected launch azimuth that represents shallow water is from five to ten miles downrange, a total length of five miles. In this case, undamaged capsules would probably be connected to vehicle debris. The capsule would be recovered, and safe disposal of the fuel would follow.

3. Impact in Deep Water

For failures both before and after final-stage ignition, the fuel could impact in deep water downrange. The subsequent immersion of the undamaged fuel capsule in salt water would introduce the capsule into a corrosive environment. Based upon a pitting rate of 0.014 inch per year and a minimum capsule wall thickness of 0.125 inch, the fuel would be exposed in eight years. At this time, the Cerium-144 inventory for two generators would be 20 curies. This does not represent a safety problem, since the fuel is insoluble, and the source is removed from human contact.

4. Partial Ablation, Impact of Capsule Remnants

For some aborts occurring after final-stage ignition, aerodynamic heating on re-entry will destroy the generator shells and partially ablate the fuel capsule and/or fuel. Therefore, at impact, the fuel will be exposed. The linear segment of the projected launch azimuth for this condition ranges from south of the Equator to midway on the Antarctic Continent, a length of about 6000 miles. The amount of Cerium-144 exposed at impact varies from about 1 to 19.8 kilocuries with the remainder dispersed by aerodynamic heating above 100,000 feet altitude.

The consequences of 19.8 kilocuries of exposed cerium on the floor of the Pacific are not significant. If all of this material were dissolved immediately, contamination of less than one cubic mile of ocean would result. On the other hand, impact of exposed cerium on the Antarctic Continent would create a nuisance but would not constitute a significant biospheric injection. The dispersal of fuel at high altitudes will be discussed next. Detailed re-entry calculations may be found in Ref. 3.

5. Prompt Re-entry, Total Burnup and Dispersion

Final stage failures yielding very high re-entry velocities will result in ablation of the fuel as aerosols at various altitudes above 100,000 feet. Since most releases occur above the Southern Temperate Zone, the majority of the resultant fallout will be deposited in this zone. The material will fall out with a mean residence time of from eight months to more than five years.* The radiocerium inventory of both generators will be released without significant decay, constituting a stratospheric injection of 19.8 kilocuries.

The following relationship is utilized in determining the ground concentration at any time:

$$X_o = \frac{N_o Z}{A} \left(e^{-\lambda t}\right) \left(1 - e^{-\lambda' t}\right)$$

*A six-month mean fallout residence time is employed for purposes of analysis for conservatism.

where

X_o = ground concentration (millicuries/km^2)

N_o = amount of Ce-144 injected (1.98×10^7 millicuries)

Z = percent deposited in Southern Temperate Zone (75%)

A = area of Southern Temperate Zone (9.3×10^7 km^2)

λ = radioactive decay constant (2.43×10^{-3} day^{-1})

λ' = fallout constant (3.8×10^{-3} day^{-1})

t = time (days).

Figure 6 shows a plot of ground concentration as a function of time after release. The peak concentration is 0.053 millicurie per square kilometer, and it will occur 248 days after injection.

To determine the radiological significance of the ground concentration, the total integrated dose to individuals in the fallout field at various times can be obtained from the following expression:

$$I = CE \int_0^t X_o \, dt$$

where

I = Dose (millirad)

C = Constant (0.10 millirad-km^2/year-millicurie-Mev)

E = Average gamma energy (Mev)

t = Time (years).

Figure 6 shows the doses computed from this equation. During a lifetime, an individual would receive a dose of 0.0022 millirad.

The above results can be compared to measured ground concentrations of Cerium-144 derived from weapons debris. For example, in July 1959 the Cerium-144 concentration at 42° North Latitude was 1812 millicuries per square mile, equivalent to a dose rate of 0.0003 millirad per hour.

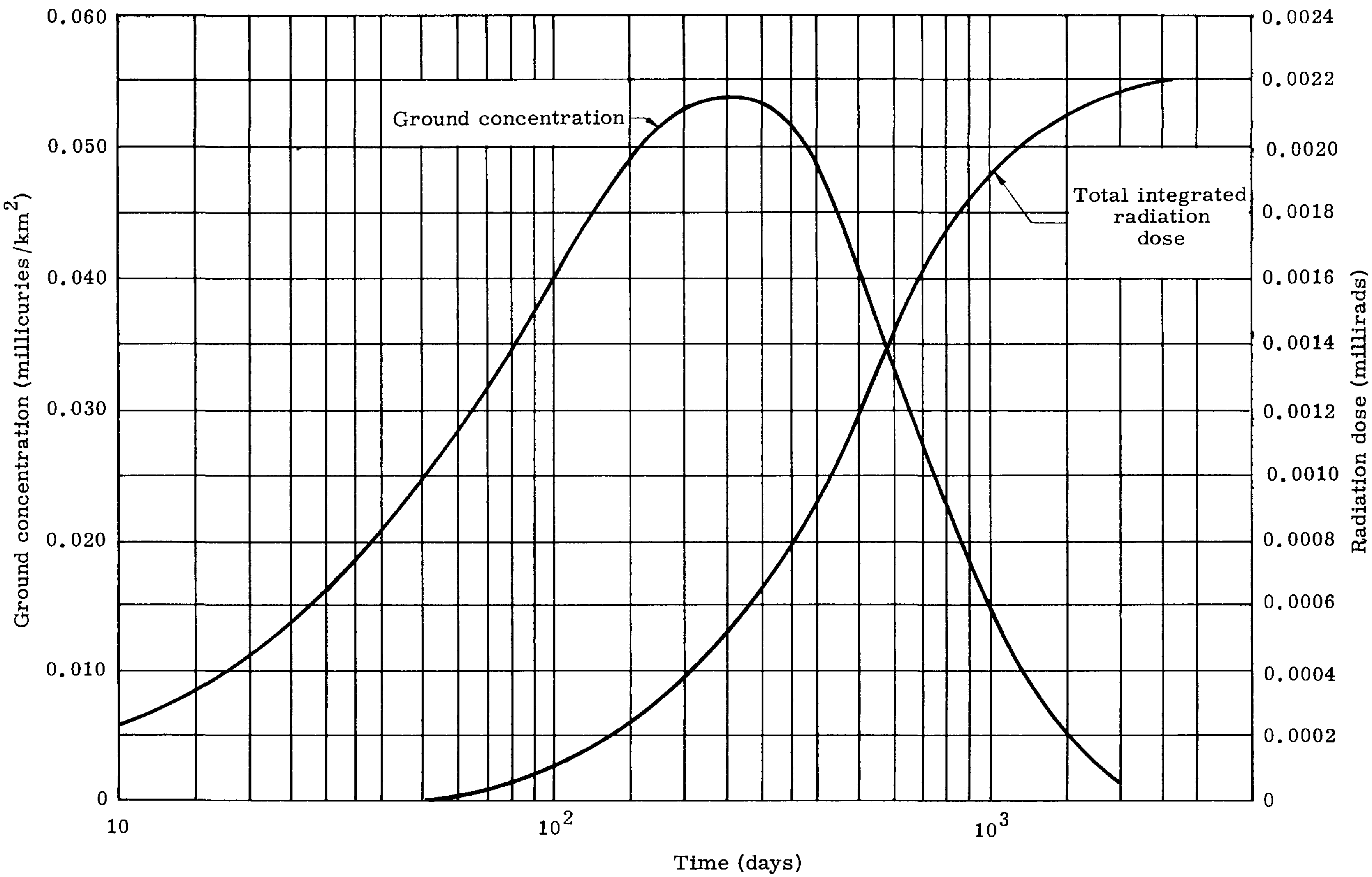


Fig. 6. Ground Concentration and Radiation Dosage

Natural sources of radiation alone will yield a 30-year dose of 3000 millirads.

6. Into Orbit

Final-stage failures occurring late in the injection phase can yield orbits which vary in lifetime from those approaching 600 days to those of several hours lifetime. Since ablation and dispersion of the fuel will result from postorbital re-entry, this case is intermediate between Case 5 and the successful mission.

REFERENCES

1. "Operational Testing of SNAP III," The Martin Company, MND-P-2368, June 1960.

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