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PHYSICS AND MATHEMATICS

CURIUM FUELED GENERATORS FOR LUNAR AND SPACE MISSIONS

Preliminary Safety Analysis Report

By
Cecil O. Riggs

June 1960

**Martin Company
Baltimore, Maryland**

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PRELIMINARY SAFETY ANALYSIS REPORT

CURIUM FUELED GENERATORS
FOR LUNAR AND SPACE MISSIONS

June, 1960

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FOREWORD

This report was prepared for the United States Atomic Energy Commission under Contract AT(30-3)-217 by The Martin Company. It covers the preliminary safety analysis for curium-fueled generators.

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SUMMARY

Two thermoelectric generators, using the radioisotope Curium-242 as the heat source, are described.* The first, designed for a lunar mission, is fueled with 3.76 grams of Curium-242 with an activity of 12,480 curies. The second, designed for a satellite or space probe mission, is fueled with 6.28 grams having an activity of 20,400 curies. Either generator will be launched within 60 days after encapsulation of the fuel. The lunar mission generator is designed for a useful life of 60 days after launch and the satellite mission generator will have a life of 180 days. Either will have an electrical output of 13 watts at the end of life. The satellite mission generator requires a heat dump during the first part of its life.

Containment of the Curium-242 is by a vessel of Hastelloy C lined with tantalum. Hastelloy C has excellent resistance to oxidation and to corrosion by salt water or acid; it also has good mechanical properties and a high melting point. The lunar mission generator has additional containment from a beryllium shell.

Curium-242 is an alpha emitter with only a small amount of gamma and neutron radiation. Consequently, the principal radiobiological hazard is from ingestion or inhalation. For soluble Curium-242, the critical organs are the liver and lower large intestine; for insoluble Curium-242, the lungs and lower large intestine are the critical organs. Consideration is also given to the daughter, Plutonium-238, which is a long-lived alpha emitter.

It is assumed that these generators would be launched by a typical ICBM vehicle combined with a final orbital injection stage. Vehicle failure in the later part of the final stage would result in burnup of the Curium-242 from aerodynamic heating upon re-entry. The resulting fallout, assumed to take place between 30 and 60 degrees of latitude in one hemisphere, would be insignificant. If a failure occurred during the ascent phase, the intact fuel capsule would drop into the ocean and containment would be assured. In the later part of the ascent phase or early part of the final stage, incomplete burnup of the generator could occur, with the possible fuel dispersal in the ocean. Within 48 hours, dilution would reduce the fuel concentration in the water below the

*Detailed design and analysis information on the two generators is presented in Martin Company Reports MND-P-2373 and MND-P-2374.

maximum permissible for general public use. In the early part of the ascent phase, there is a possibility that the generator might impact on land. The lunar mission generator is expected to withstand this without jeopardizing containment of the Curium-242. In the scarcely credible event of the fuel capsule separating from the generator, there is a possibility that the capsule may be broken. However, the capsule is designed to fail in a manner that will not compromise the containment of the Curium-242. Even if the containment were violated, impact in the ocean would result in harmless dispersion. Impact on land would be handled in the same way as a launch pad fire. Launch failures are less probable than other vehicle failures. In case of a launch pad fire, there is a very remote possibility of violation of the containment due to the effects of the fire or nitric acid corrosion. Any release of the Curium-242 would take place within a controlled area where the fuel could be recovered or buried.

I. INTRODUCTION

The Martin Company has made a study of the potential hazards that may arise in the use of a radionuclide-powered thermoelectric generator for an extraterrestrial mission. The isotope used was Curium-242 and two modifications of the conceptual design have been prepared. The majority of the attention has been given to a generator designed for a lunar mission to include a landing. The second modification is to be used in a space probe or terrestrial satellite. It is assumed in both cases that launch of the vehicle will take place about 60 days after the encapsulation of the radionuclide fuel. After launch, the generator for the lunar mission should have a useful life of 60 days and that for the space mission should have a life of 180 days. In either case, the design output at the end of life is 13 electrical watts.

Preparation of the fuel, the assembly of the generator and the launching of the vehicle are considered. Accidents which may occur in the launching of the vehicle are analyzed and the fate of the fuel in the event of an aborted mission or upon re-entry of the vehicle after the completion of a mission is determined.

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II. THE THERMOELECTRIC GENERATOR

A. LUNAR GENERATOR CONFIGURATION

In the lunar mission generator, a rectangular block of Hastelloy C provides the principal containment of the Curium-242 fuel and serves as the heat accumulator for the hot junctions of the thermoelectric elements. The configuration is shown in Fig. 1. The Hastelloy C block is 2 by 2 by 5/8 inches. Four 1/4-inch holes, drilled alternately from opposite 2 by 5/8-inch faces, contain the radionuclide fuel. These holes are closed by plugs screwed into place and welded. The holes are lined with tantalum. This lining is to prevent corrosion of the Hastelloy C by the plutonium which is formed in radioactive decay of of the Curium-242. Provision must be made in the fuel space for the accumulation of helium produced by the alpha decay of Curium-242.

The thermoelectric elements are arranged in two-inch square modules for placement against the 2 by 2-inch sides of the heat accumulator. Each module contains 64 elements in a square array. The individual elements have a square cross section and are 1 inch long. A thin electrical insulation is provided between the elements by a thermosetting material applied in liquid form. The required straps for electrical connections are welded or soldered to the ends and the assembly is held between thin electrically insulating plates formed by flame spraying metal plates with aluminum oxide. The thermoelectric elements are composed of cobalt silicide and can be used at temperatures as high as 1800° F.

The configuration of the generator as a unit is shown in Fig. 2. The two parts of the outer case are held together by aluminum bolts. Spring washers are used to exert pressure on the modules of the thermoelectric elements to hold them firmly against the heat accumulator and to allow for thermal expansion and contraction. The two parts of the generator case serve as the cold junctions. The case is made of beryllium. After the generator is assembled, the case is filled with thermosetting insulation.

A radiator is to be attached to the upper part of the case, and a conical, thin-walled metal bellows is attached to the lower part. The bellows contains helium gas under a pressure of about 100 psi. This structure is intended to take up some of the shock of landing on the moon and also serves as a radiator. Design objectives require that the generator be able to withstand landing on the moon at a velocity of 500 fps.

Fig. 1. Fuel Capsule

Output: 13 watts
 Weight: 4 lb
 Efficiency: 5.3%

Fig. 2. Basic 13-watt Generator Unit--Subtask 5.8 (Full Scale)

B. LUNAR GENERATOR CHARACTERISTICS

The thermoelectric generator for the lunar mission is designed to produce 13 watts at the end of the mission (120 days after the fuel is encapsulated). It will be placed on the moon approximately 60 days after encapsulation. Assuming an overall efficiency of 4.8% when converting the heat to electrical energy, the unit will be fueled initially with 3.76 grams of Curium-242, producing 451 thermal watts from an activity of 12,480 curies. The temperature reached by the fuel shortly after encapsulation will be about 1850° F.

The subsequent temperature history of the fuel cannot be determined exactly. The temperature will fall in an essentially exponential manner, but at a rate dependent upon the ambient temperature. Before launch, the ambient temperature is considered to be about 85° F. During flight to the moon, the ambient temperature will depend upon the relative position of the generator with respect to the vehicle. It is expected that the generator will be exposed so that the ambient temperature is practically that of space. Upon reaching the moon, the generator will be exposed to a cycle of light and dark intervals, each of about 14 days duration. The ambient temperature is expected to vary between 250 and -250° F. For considerations of potential hazards, the fuel temperature at the time of launch is of most interest; it is discussed in Chapter VI.

C. PROPERTIES OF GENERATOR COMPONENTS

Beryllium, used for the outer container of the generator, has very good resistance to chemical action. Like aluminum, it forms a thin protective film of oxide. The oxide formed in air above 825° C is adherent and highly refractory. The Brush Beryllium Company is conducting long term tests on beryllium which indicate good corrosion resistance to sea water. It is attacked, however, by hydrochloric acid.

Beryllium melts at 1285° C (2345° F) and the oxide melts at about 2530° C. It has good mechanical properties which are retained to fairly high temperatures. Various significant properties are given in Table 1.

Hastelloy C, the material used for the fuel containers, is a nickel alloy which melts at about 1288° C. It is highly resistant to oxidation to about 1150° C. The International Nickel Company has conducted extensive corrosion tests over a period of several years at the Harbor

Island Test Station, Wrightsville Beach, North Carolina. From the behavior of specimens exposed to sea water for 10 years, the corrosion rate is estimated to be 0.0001 inch per year. It will withstand strong reducing or oxidizing conditions such as those encountered with nitric acid, aqueous solutions of ferric or cupric salts, or with wet and dry chlorine gas. The various properties are listed in Table 1.

Tantalum is used for the lining of the fuel container because of its excellent resistance to corrosion by plutonium and other metals. Its melting point is 2996° C. While its elastic properties are not as good at room temperature as those of many other metals used for structural purposes, it maintains a fairly high tensile strength to about 1650° C.

Tantalum oxidizes in air at elevated temperatures. The oxide is extremely adherent but porous; it is not volatile below 1400° C (Ref. 1). Tantalum is not attacked by most acids.

D. SPACE MISSION GENERATOR CONFIGURATION

The configuration of the generator for the space mission is shown in Fig. 3. The radionuclide fuel is contained by a cylindrical vessel of Hastelloy C having an inside height of 1 inch, an inside diameter of 7/8 inch and a side wall thickness of 5/32 inch. This cylinder is lined with 1/32-inch-thick tantalum. The fuel, which is expected to contain about 45% Curium-242, is further alloyed with gold. This dilution decreases the power density and, consequently, the temperature of the fuel. The fuel will be fabricated into an annular ring and placed against the inner wall of the containment vessel. To hold the fuel in this position, a spring consisting of a second annular ring made of stainless steel 1/16 inch in thickness is placed against it. The steel ring will be perforated to provide a path for the helium to escape into the center of the vessel. By holding the fuel against the wall of the vessel, the path of heat flow is made more definite and constant. The central void space is 0.205 cubic inch.

The Hastelloy C vessel is surrounded by copper extending below the Hastelloy C and flared into a radiator fin which is part of a heat dumping mechanism. Because of the longer design life of this generator (240 days), it will be fueled initially with 6.28 grams of Curium-242, producing 755 thermal watts. To maintain a more nearly uniform output, part of this heat will be diverted from the thermoelectric elements in the early part of the generator life when the heat production is greatest.

TABLE 1
Properties of Generator Materials

<u>Property</u>	<u>Beryllium</u>	<u>Hastelloy C</u>	<u>Tantalum</u>
Density (gm/cc)	1.85	8.94	16.6
Melting point (°C)	1285	1288	2996
Specific heat (cal/gm °C)	0.5	0.092	0.0356
Thermal conductivity (cal/cm sec °C)	0.38	0.0270 (200 °C) 0.0408 (600 °C)	0.130
Thermal expansion (°C)	1.723×10^{-6} (25 to 700 °C)	15.3×10^{-6} (0 to 1000 °C)	6.7×10^{-6} (0 to 100 °C)
Young's modulus (10^6 psi)	44 20 (1400 °F)	30.9 27.6 (800 °F) 24.5 (1400 °F) 20.1 (1600 °F)	27.
Ultimate tensile strength (10^3 psi)	90 (max) 75 (min) 70 (600 °F) 40 (1000 °F)	130.0 101.7 (1200 °F) 80.8 (1400 °F) 45.0 (1600 °F) 26.9 (1800 °F) 14.2 (1900 °F)	27 (1200 °F) 25 (1400 °F) 20 (1600 °F) 17 (2000 °F)
Yield strength (10^3 psi)	60 (average)	71.8 53.6 (1000 °F) 47.1 (1400 °F) 36.5 (1600 °F)	16 (1200 °F) 12 (1400 °F) 8 (2000 °F)

Fig. 3. Space Mission Generator Configuration 6

At the upper end of the vessel, the Hastelloy C and copper are fastened to a block of tungsten that serves as part of a shadow shield for the instrumentation that will be placed on the axis of the generator.

The thermoelectric elements used in this generator are lead telluride. The melting point of this material is about 1690 °F, but it sublimates rapidly at temperatures below this. It is desirable to keep the design maximum hot junction temperature at 1325 °F. To do this, it is necessary to have a radiation step in the heat transfer path and a variable shunt path or heat dump. The central heat accumulator block, consisting of the Hastelloy C, copper and tungsten, radiates heat 3/4 inch to a stainless steel shell covered on the outside by a thin electrical insulating sheet. The hot junctions of the thermoelectric elements are placed against this sheet. A small portion of the space between the heat accumulator and the steel shell is occupied by a ring bellows containing an alloy of sodium and potassium (NaK). The thermal expansion and contraction of this material actuates a lever system which opens and closes an insulated door opposite the copper radiator. Initially, when the heat production of the fuel is high, a great deal of the heat will be radiated directly out of the generator. Later, as the door closes, more heat will flow through the thermoelectric elements.

The thermoelectric elements are arranged radially about the stainless steel shell in four rings, each containing eight pairs of elements. An aluminum shell holds the cold junctions and serves as the outer covering of the generator. Space between the thermoelectric elements and across the top of the generator is filled with Min-K thermal insulation.

E. CHARACTERISTICS OF THE SPACE MISSION GENERATOR

The thermoelectric generator for the space mission is designed to produce 13 watts electrical output at the end of the mission, 240 days after the fuel has been encapsulated. It is expected that it will be launched approximately 60 days after encapsulation. Assuming an overall efficiency of 4.8% in the conversion of heat to electrical energy, the unit will be originally fueled with 6.28 grams of Curium-242, producing 755 thermal watts from an activity of 20,400 curies. The temperature reached by the fuel shortly after encapsulation is expected to be 1660 °F if the generator is assembled.

Subsequently, the temperature of the fuel in the generator will fall in an essentially exponential manner at a rate dependent upon the ambient temperature. If the ambient temperature before launch is taken as 85 °F, the fuel temperature at that time will be about 1310 °F. After launch, the generator will probably be exposed in such a way that it is radiating into space.

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III. SYSTEM INTEGRATION

A. VEHICLE

It is expected that the modified 13-watt, Curium-242-fueled generator will be carried on a satellite or lunar mission by a typical vehicle (perhaps Atlas-Agena B) which consists of a conventional ICBM missile wedded to a final-stage injection vehicle. A typical ICBM vehicle is designated as a one and one-half stage vehicle. It may be fueled with RP-1 and liquid oxygen. The injection stage vehicle has a Bell Hustler engine. It carries unsymmetrical dimethylhydrazine (UDMH) as fuel and inhibited red fuming nitric acid (IRFNA) as an oxidizer. The fuel is hypergolic, that is, it ignites spontaneously upon contact with the oxidizer. The mixture is not subject to detonation.

The ICBM has two booster engines and a main sustainer engine fed from common tankage. From launch, the engines boost the vehicle to an altitude of about 250,000 feet and a velocity of about 10,000 fps. At this point, an outboard skirt holding the booster engines separates and falls away. The sustainer engine continues to fire until the vehicle reaches an altitude of about 860,000 feet and a velocity of 18,500 fps. If required, vernier rockets burn for about 10 seconds to adjust the flight attitude. The final stage separates from the exhausted booster-sustainer stage and coasts to the injection altitude of about 1,584,000 feet. The final stage ignites and burns for about 100 seconds, accelerating to orbital velocity.

The satellite consists of the final-stage engine, empty propellant tanks and the payload. The satellite structure is necessarily relatively light, consisting of structural members up to 0.25 inch in thickness and skins up to 0.1 inch, mostly of magnesium and aluminum.

Each major stage is equipped with a missile safety subsystem which provides a means of transmitting location, behavior and projected missile impact point to the range safety officer, plus a means of terminating powered flight and destroying the missile. The safety subsystem hardware consists of a transponder and command receivers associated with shutdown and destruction circuitry. Vehicle destruction is achieved by explosive charges placed so as to destroy the propellant tankage, thus terminating the rocket thrust.

B. RELATIVE PROBABILITY OF FAILURES

Possible radiological hazards may arise from aborted missions. To fully determine these hazards, it is necessary to know the configuration of the generator and its location in the lunar vehicle and to

study, by means of a digital machine program, several variations of the trajectory that may occur. Although this information is not available at present, it is possible, from the results of previous analyses, to classify the potential hazards that may occur.

Aborted missions can be broadly divided into launch, ascent and final-stage failures. These different failures do not have equal probabilities of occurring. Ascent failures are somewhat more probable than final-stage failures, and either has greater probability than launch failures. Failures frequently occur at separation of the stages. If the separation is imperfect, or if the parts bump, torques may be imposed upon the vehicle that the guidance system cannot correct.

Failures may also be classified as guidance or propulsion failures. In the final stage, the latter is more than twice as probable as the former. In propulsion failures, failure to ignite is twice as probable as failure after ignition.

In the final stage, guidance failures cannot produce a gross deviation of the vehicle from its projected path over the earth's surface. In an extreme case, the guidance servomotors will command a maneuver which the vehicle cannot execute. This will cause it to break up or tumble.

C. LAUNCH FAILURES

Launch failures may be broadly defined as those failures which occur either on, or directly above, the launch pad. These failures occur within an altitude range of 0 to 1000 feet and within a time range of several minutes before launch to 15 seconds after launch. They may be divided into propellant tank, propulsion and guidance failures.

1. Propellant Tank Failure

A propellant tank **failure results from** either overpressurization or spontaneous structural failure of the propellant tanks. Two failure mechanisms are possible. First, there is a possibility that the bottom of the liquid oxygen tank of the booster will fail and the top of the RP-1 tank will rupture, mixing the propellants within the missile. Second, the worst probable failure is to have the side-seams of the tanks fail and the propellants mix on the launch pad.

The mixture of liquid oxygen and RP-1 fuel can be ignited by sparks and, in some cases, spontaneously. The liquid oxygen will vaporize rapidly and some of the RP-1 fuel will soak into the launch pad or drain into the flame bucket of the launch pad. Any likely fire will be gravity fed until the collapse of the missile structure allows it to reach the unexpended fuel in the tanks.

In observed failures of multistage vehicles, two distinct fireballs have been observed. These have resulted from the combustion of the first-stage fuel and the subsequent ignition and combustion of the final-stage fuel. Since the final-stage fuel is hypergolic, its combustion is quite probable, though subsequent to, rather than simultaneous with, the first-stage combustion. It has been estimated that the liquid oxygen will be entirely vaporized in about five seconds. The fireball caused by the RP-1 fuel will rise at a velocity of 15 to 20 fps. After a short time, the second fireball from the Hustler engine fuel will form. It will be smaller than the first but will probably last longer. After the fireball rises, the remaining fuel and some of the structural metals will burn on the launch pad. This fire can be expected to persist for about 20 minutes with rapidly diminishing intensity.

The Martin Company, in conjunction with the Aberdeen Proving Ground, conducted a fire test to simulate a missile failure on the launch pad. The flame temperature rose to a maximum of 5060° F at 5 seconds after ignition. It fell to 1720° F at 90 seconds and subsequently rose to near 4000° F, where it remained for several minutes. Thermocouples were placed at several points in the simulated missile structure. The maximum temperature recorded by any of these was 4200° F at 25 seconds after ignition. The temperature of this thermocouple fell back to 720° F at 50 seconds. The subsequent maximum temperature shown by any of the thermocouples was 1920° F at 145 seconds. From that time, the temperature indicated by each of the thermocouples fell gradually. After 20 minutes, the maximum recorded was 900° F.

2. Propulsion Failure

A propulsion failure during the launch phase can result from some malfunction of the fuel pumps, valves, pressure system, or booster engines. It will take place directly above the launch pad at an altitude of 0 to 1000 feet. Combustion of the fuel can be expected. If the failure takes place at a low altitude, the progress of the fire will be substantially the same as that previously described. As the altitude at which failure occurs increases, the intensity of the resulting fire will decrease because of the smaller amount of fuel available and its dispersion by the motion of the vehicle. Debris from the vehicle and the satellite, including the generator, will fall back upon the launch pad or in its immediate vicinity.

3. Guidance Failure

If significant perturbations in the vehicle trajectory appear during the launch phase, a self-destruct command will be given either by the vehicle's own guidance system or manually from the ground. This signal detonates charges which cause fuel tank rupture and ultimate destruction of the vehicle. Combustion of the fuel will result, producing

a fire somewhat limited in intensity because of the previous expenditure of fuel and its dispersion by the motion of the vehicle. Debris will be distributed over a slightly larger area than in the case of a propulsion failure, but will fall near the launch pad, entirely within the controlled area or in nearby water.

D. ASCENT FAILURES

Ascent failures are those occurring in the ascent trajectory between about 1000 feet altitude and final-stage ignition at 1,570,000 feet. These failures can occur at any time from about 15 seconds to 585 seconds after launch. In a previous study (Ref.2), analyses have been carried out for certain significant points in the trajectory. The points selected are: pitchover, maximum dynamic pressure, booster separation, sustainer burnout, vernier burnout and final-stage ignition.

1. Failure at Pitchover

Pitchover is the point at which the program places the missile in a ballistic turn. At this point, the missile is tilted from its vertical launch trajectory and programmed into the ascent trajectory. The initial conditions at pitchover are an altitude of about 1000 feet, an attitude of 90 degrees, a velocity of about 200 fps and a range of zero.

The results of a failure at this point will be essentially the same as for a propulsion failure on the launch pad. Containment of the radionuclide fuel will not be endangered.

2. Failure at Maximum Dynamic Pressure

Maximum dynamic pressure is applied to the missile on the ascent trajectory 60 seconds after launch. At this point, the angle of attack of the missile is reduced to zero, thus starting a zero-lift trajectory. The initial conditions at this point are an altitude of 38,000 feet, an attitude of 54 degrees, a velocity of 857 fps, and a range of about 0.1 nautical mile.

If failure occurs at this point, the missile will coast to an apogee at 41,000 feet altitude and about one nautical mile downrange. The missile will impact about two nautical miles downrange. If fire occurs, it will be less intense than one occurring during the launch phase and will not violate the containment of the radionuclide fuel. Any detonation will produce a shock wave of smaller magnitude because of the lower density of the air.

3. Failure at Booster Separation

Booster burnout and separation occur at the end of the zero-lift trajectory and at the beginning of the sustainer pitch program, 147 seconds after launch. The skirt and booster engines separate and fall away. The conditions are an altitude of 250,000 feet, a velocity of 10,890 fps, an attitude of 23 degrees and a range of 60 nautical miles.

If there should be a propulsion failure at this point, the vehicle would coast to an apogee of 586,000 feet at a range of 320 nautical miles. It would ultimately impact 780 nautical miles downrange. The RP-1 fuel would be largely expended, minimizing any possible fire or detonation.

It is assumed that the launch takes place at the Cape Canaveral complex with an azimuth that directs the vehicle down the missile range over the Caribbean and the Atlantic Ocean. In an abort that occurs at booster separation, the vehicle impacts at high velocity in the sea.

An abort which takes place at this point introduces aerodynamic heating as another factor to be considered. There is re-entry from an altitude of 586,000 feet. The resultant heat is relatively low, so the fuel capsule will remain intact. Since the capsule does not burn up, it enters the sea intact as a contained source.

4. Subsequent Failure in the Ascent Phase

Sustainer burnout occurs 260 seconds after launch. At this time, the altitude is 720,000 feet, the attitude 14.8 degrees and the range 340 nautical miles. Vernier burning does not increase the velocity of the vehicle but corrects attitude errors. Vernier burnout occurs 289 seconds after launch. The booster-sustainer vehicle separates from the final stage and drops away. If the final stage fails to ignite, it will coast to an apogee at 1,584,000 feet and ultimately impact 2500 nautical miles downrange. Final-stage ignition should take place 585 seconds after launch and shortly before this altitude is reached.

At this time, the quantity of RP-1 fuel remaining is small and is exhausted after vernier burnout. Consequently, the hazard of fire is minimized and a detonation shock wave cannot form at these altitudes. Aerodynamic heating upon re-entry after a vehicle failure will depend principally upon the velocity attained. As a consequence of this, there can result a spectrum of heating effects upon the generator ranging from no damage to complete ablation of the generator shell. The fuel capsule is expected to remain intact and finally fall into the ocean.

E. FINAL-STAGE FAILURES

The final stage is required to give the vehicle, at 1,584,000 feet (300 miles), sufficient velocity to achieve the desired orbit. At this altitude and an attitude of zero degrees, a circular orbit about the earth is attained by a velocity of 25,024.1 fps and escape into an orbit about the sun is attained at 35,389 fps. A lunar impact can be attained at any velocity above about 35,092 fps if it is properly oriented and timed. It must be understood that only very slight deviations from the design velocity and flight path angle can be tolerated if the lunar mission is to be successful.

For velocities equal to, or greater than, the escape velocity, the vehicle will become a permanent satellite of the sun if it misses the moon. Recapture by the earth after many years is possible but extremely unlikely. For velocities between that required for a circular orbit and the escape velocity, the vehicle becomes a satellite of the earth in an orbit which may persist for many years. Re-entry will take place after many half-lives of the curium isotope. Meanwhile, there will be a buildup of activity due to the daughter nuclide, Plutonium-238. This will reach a maximum in about seven years.

The potential hazards after final-stage ignition are consequently those that accompany re-entry.

IV. PROPERTIES OF THE FUEL

Curium is an artificial element which can be produced in various ways from other transuranic elements. Several isotopes are known. The one of interest in isotopic power technology is Curium-242.

A. NUCLEAR PROPERTIES

Curium-242 is most easily obtained by the neutron irradiation of Americium-241. This irradiation produces a metastable isotope, Americium-242 m, which decays by beta emission with a 16-hour half-life to Curium-242. There are competing disintegrations of Americium-242 m, but the transition to Curium-242 takes place for about 80% of the atoms. Curium-242 decays by alpha emission with a half-life of 162.5 days. The product is Plutonium-238. Curium-242 also undergoes spontaneous fission but with a half-life of 7.2×10^6 years. The daughter element, Plutonium-238, decays by alpha emission with a half-life of 86 years and by spontaneous fission with a half-life of 3.8×10^{10} years. These various transformations are shown by the following chart:

Curium-242 decays with the emission of highly energetic alpha particles. 73.7% of the disintegrations go directly to the ground state of Plutonium-238, with the alpha particle having more than 6 mev energy. The decay scheme is represented in the following chart:

The alpha radiation energies and approximate percentage are given in the following table.

Alpha Emission of Curium-242

<u>Energy (mev)</u>	<u>Approximate Percentage</u>
6.110	73.7
6.066	26.3
5.965	
5.535	
5.502	

The alpha particles are completely absorbed in the fuel or near the inner surface of the fuel container.

A small fraction of the alpha disintegrations of Curium-242 is accompanied by the emission of gamma photons. There is also a small production of gamma radiation in the spontaneous fission and in neutron-gamma reactions in the surrounding materials. The gamma energies and

the corresponding fractions of the disintegrations which produce gammas are listed in the table which follows. The gammas with energy less than 0.2 mev are assumed to be absorbed in the source fuel. The others will escape with some attenuation by the materials of the generator structure. The dose rate from an unshielded source with the fuel loading proposed for this generator at a distance of one meter is also given in the table.

Gamma Radiation from Curium-242

<u>Energy(mev)</u>	<u>Gammas per Disintegration</u>	<u>Dose Rate at 1 meter (mr/hr)</u>
0.044	4.1×10^{-4}	absorbed
0.102	6.0×10^{-5}	absorbed
0.158	2.7×10^{-5}	absorbed
0.210	2.0×10^{-7}	0.286
0.562	1.8×10^{-6}	7.56
0.605	1.4×10^{-6}	6.40
0.890	9.0×10^{-8}	0.572
1.010	1.0×10^{-7}	0.754
	Fission	11.5

The spontaneous fission of the Curium-242 produces neutrons at an average rate of about 2.65 neutrons per fission. Consequently, the 3.76 grams of fuel at encapsulation will produce 2.02×10^4 neutrons per second. If it is assumed that the neutrons have energies between 1 and 2.5 mev, this neutron production will produce a dose rate of 71 millirem per hour at a distance of one meter from the unshielded source.

In addition to those due to fission, there will also be neutrons from alpha-neutron reactions with light elements which may be present as impurities in the fuel. It is not possible to determine exactly the number that will be produced in this way but it has been estimated that this neutron flux will be equal to about two-thirds that from fission. Consequently, the total dose rate at one meter from the unshielded source due to neutrons will be about 120 millirem per hour. The neutrons will also tend to increase the gamma radiation by taking part in neutron-gamma reactions in the fuel and in the materials surrounding

the fuel. Adequate biological shielding for ground handling of the space mission generator is necessary.

For a long-range analysis of the lunar mission generator fueled with Curium-242, some consideration must be given to the daughter element, Plutonium-238, since it is also radioactive. After one half-life of the Curium-242 (162.5 days), the masses of the two nuclides will be essentially the same. After 1250 days, their alpha activities are equal at 62 curies, compared with the original loading of 12,480 curies. The gamma radiation from Plutonium-238 is weak. The neutron flux is also quite low.

B. PHYSICAL PROPERTIES

Curium is a silvery white malleable metal. Its density is 13.5 grams per cubic centimeter and it melts at approximately 950° C.

The specific activity of Curium-242 is 3.31×10^3 curies per gram and the specific power is 120 watts per gram.

C. CHEMICAL PROPERTIES

Curium (atomic number 96) is a member of the actinide series of elements. In its chemical properties, it is a representative member of this series and resembles the members of the lanthanide series, in which its homologue is gadolinium. The principal valence of curium is three; an oxide and a fluoride are the only known compounds in which it exhibits a valence of four and this oxidation state has not been found in solution.

Plutonium has a much more complex chemistry than curium and exhibits all the positive valence states from three to six. A fact of great significance is that metallic plutonium alloys with most other metals except tantalum. Therefore, it is desirable to use a tantalum lining in any vessel which is to contain plutonium.

D. RADIOBIOLOGICAL PROPERTIES

The gamma and neutron radiation from the curium-fueled generator set the requirements for the biological shielding while the generator is being transported and installed in the vehicle. The alpha particles are absorbed in the fuel itself and in the first few thousandths of an inch of the container. Potential radiological hazards from the alpha radiation can only arise if the fuel is released in a form whereby it can enter the

body by inhalation or by ingestion with food or water.

In the event that a soluble form of Curium-242 enters the body by ingestion with food, the organs most affected are the liver and the gastrointestinal tract, particularly the lower large intestine [GI(LLI)] For the insoluble form of the radionuclide, the potential biological hazard arises from inhalation, in which case the organ most affected is the lung. Injury also occurs to the gastrointestinal tract from insoluble Curium-242 passing through it.

The biological course of plutonium is different. For soluble material, the bone is the critical organ. For insoluble material, the critical organs are the lung and the lower large intestine. Because of its long effective half-life, Plutonium-238 is considered a greater potential hazard than Curium-242 and the maximum permissible concentrations in air and water are smaller.

Table 2 gives the maximum permissible burden, MPB, and the maximum permissible concentrations in water, MPC_w , and in air, MPC_a . These are conservative limits agreed upon by Committee II, International Commission on Radiological Protection. The 40-hour week tolerances are those suggested for persons occupationally employed in nuclear work. The 168-hour week tolerances are for persons not so employed. In the table, underlining indicates the critical organs and the corresponding concentrations.

Table 3 gives additional radiobiological properties and constants for Curium-242 and Plutonium-238. In this table, the following terms and abbreviations are used:

T_{rad}	The radiological half-life.
T_{bio}	The biological half-life; the time for half the radionuclide to be eliminated by biological processes.
T_{eff}	The effective half-life, $T_{eff} = \frac{T_{rad} \times T_{bio}}{T_{rad} + T_{bio}}.$
f_1	Fraction of the radionuclide passing from GI tract to the blood.
f_2	Ratio of the radionuclide in the critical organ to that in the total body.

f_2' Fraction of the radionuclide passing from the blood to the critical body organ.

f_w Fraction of the radionuclide taken into the body by ingestion that is retained in the critical organ. For soluble compounds,

$$f_w = f_1 f_2'.$$

f_a Fraction of the radionuclide taken into the body by inhalation that arrives in the critical organ.

TABLE 2
Radiobiological Properties of
Curium-242 and Plutonium-238

$^{96}\text{Cm}^{242}$	Organ	MPB (μc)	40-hr week		168-hr week	
			MPC_w ($\mu\text{c/cc}$)	MPC_a ($\mu\text{c/cc}$)	MPC_w ($\mu\text{c/cc}$)	MPC_a ($\mu\text{c/cc}$)
Soluble	<u>GI(LLI)</u>		7×10^{-4}	2×10^{-7}	2×10^{-4}	5×10^{-8}
	<u>Liver</u>	0.05	3×10^{-3}	1×10^{-10}	9×10^{-4}	4×10^{-11}
	Bone	0.09	5×10^{-3}	2×10^{-10}	2×10^{-3}	8×10^{-11}
	Kidney	0.2	9×10^{-3}	4×10^{-10}	3×10^{-3}	1×10^{-10}
	Total Body	0.2	0.01	6×10^{-10}	5×10^{-3}	2×10^{-10}
Insoluble	<u>Lung</u>			2×10^{-10}		6×10^{-11}
	<u>GI(LLI)</u>		7×10^{-4}	1×10^{-7}	2×10^{-4}	4×10^{-8}
$^{94}\text{Pu}^{238}$	<u>Bone</u>	0.04	1×10^{-4}	2×10^{-12}	5×10^{-5}	7×10^{-13}
	<u>Liver</u>	0.2	6×10^{-4}	8×10^{-12}	2×10^{-4}	3×10^{-12}
	Kidney	0.3	8×10^{-4}	1×10^{-11}	3×10^{-4}	4×10^{-12}
	<u>GI(LLI)</u>		8×10^{-4}	2×10^{-7}	3×10^{-4}	6×10^{-8}
	Total Body	0.3	1×10^{-3}	1×10^{-11}	4×10^{-4}	5×10^{-12}
Insoluble	<u>Lung</u>			3×10^{-11}		1×10^{-11}
	<u>GI(LLI)</u>		8×10^{-4}	1×10^{-7}	3×10^{-4}	5×10^{-8}

TABLE 3

Nuclide	T _{rad} (day)	T _{bio} (day)	T _{eff} (day)	f ₁	f ₂	f ₂ ¹	f _w	f _a
⁹⁶ Cm ²⁴²	162.5			< 10 ⁻⁴				
Organ								
Total Body		2.4 x 10 ⁴	161.4		1.0	1.0	1 x 10 ⁻⁴	0.25
Bone		7.3 x 10 ⁴	162.1		0.3	0.3	3 x 10 ⁻⁵	0.075
Kidneys		2.4 x 10 ⁴	161.4		0.02	0.02	2 x 10 ⁻⁶	0.005
Liver		3 x 10 ³	154.3		0.38	0.4	4 x 10 ⁻⁵	0.1
⁹⁴ Pu ²³⁸	3.3 x 10 ⁴			3 x 10 ⁻⁵				
Organ								
Total Body		6.5 x 10 ⁴	2.2 x 10 ⁴		1.0	1.0	3 x 10 ⁻⁵	0.25
Bone		7.3 x 10 ⁴	2.3 x 10 ⁴		0.83	0.8	2.4 x 10 ⁻⁵	0.2
Liver		3 x 10 ⁴	1.6 x 10 ⁴		0.11	0.15	4.5 x 10 ⁻⁶	0.038
Kidneys		3.2 x 10 ⁴	1.6 x 10 ⁴		0.015	0.02	6 x 10 ⁻⁷	0.005

V. FUEL PREPARATION

Americium-241 in solution is obtained from the Dow Chemical Company at Rocky Flats, Colorado. It will be sent to Oak Ridge where the Americium-241 will be converted to the oxide, principally AmO_2 , but probably containing some Am_2O_3 . The oxide, in powder form, will then be sent to The Martin Company at Baltimore, Maryland. The Martin Company will mix the americium oxide with aluminum powder and encapsulate it in aluminum. Each capsule will contain approximately 3.57 grams of americium oxide and 160 grams of aluminum. These capsules will be sent to the Materials Testing Reactor operated by Phillips Petroleum Company at Arco, Idaho, where they will undergo neutron irradiation. They will remain in the reactor for about 100 days and will be allowed to cool for 30 days. During the cooling, there is additional transformation of Americium-241 to Curium-242, accompanied by considerable decay of fission products. Approximately 43% conversion of the original Americium-241 to Curium-242 will be attained. The capsules will then be returned to The Martin Company for the final fuel preparation.

The aluminum-encapsulated slugs, returned from the Materials Testing Reactor, will contain aluminum, various isotopes of americium, principally Am^{-241} , various isotopes of curium, principally Cm^{-242} , and fission products. In The Martin Company Heavy Element Processing Facility, chemical processing will separate the curium from all the other components of the mixture except the americium. It is not fully determined at this time to what extent the americium can be removed from the mixture. After processing, there will be a buildup of Plutonium-238 from the decay of the Curium-242 so that the final fuel form at encapsulation will contain Plutonium-238 and americium as well as the Curium-242. While both of these contaminants are radioactive, their specific activities are low and they do not add significantly to power production or to shielding requirements. On the other hand, they are not disadvantageous. The power density of the Curium-242 is so high that it has been found desirable to dilute it by the addition of nickel or gold. The plutonium and americium serve as additional diluents.

The transportation of Americium-241 presents no serious potential hazards or severe shielding problems. The americium oxide will be shipped from Oak Ridge to The Martin Company at Baltimore in a returnable shipping cask. For the transportation of the aluminum-encapsulated slugs of americium oxide and aluminum, a special shipping cask has been designed and has been approved by the Bureau of Explosives. A drawing of this container is shown in Fig. 4. Fourteen

capsules will be placed in this container for one shipment. The capsules will have been carefully cleaned by sandblasting to avoid the buildup of dangerous contamination on the surface during irradiation.

After irradiation, the situation with regard to potential hazards and **shielding** is greatly changed. For the transportation of 14 irradiated capsules, a 12,000-pound shipping container is being designed and will be fabricated by The Martin Company. A rack for holding the capsules will be contained in a steel chill block surrounded by lead and water. Transportation will probably be by means of trucks.

Further details concerning the processing of the Curium-242 fuel are given in Refs. 3 and 4.

Fig. 4. Drawing of Shipping Container for Aluminum Encapsulated Americium Oxide

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VI. HAZARDS ANALYSIS

An evaluation was made of the hazards that may be encountered in the assembly and use of the two modifications of the Curium-242-fueled generator under normal circumstances and in any credible accident that may take place. The hazards considered arise from mechanical, chemical and thermal stresses that may occur. The objective is to contain the radionuclide completely in all circumstances.

A. MECHANICAL INTEGRITY

1. Internal Pressure

As the Curium-242 decays, helium is evolved and the containing vessel becomes subject to internal pressure. The pressure due to the helium can be calculated by the equation

$$P = \frac{NRT}{V} \quad (1)$$

where

P = pressure (atmospheres)

R = universal gas constant (0.0821 liter atmospheres per mole degree)

T = temperature at any time (°K)

V = volume (liters).

The moles of helium is given by

$$N = N_0 (1 - e^{-\lambda t}) \quad (2)$$

where

N_0 = moles of Curium-242 at encapsulation

λ = decay constant ($4.24 \times 10^{-3} \text{ day}^{-1}$)

t = time from encapsulation (days).

Shortly after encapsulation and assembly of the generator, the container will be at its maximum temperature and the Hastelloy C of which it is composed will have its minimum strength. While the mass of helium increases with time, the temperature decreases and the strength of the Hastelloy C increases. The temperature may be expected to fall in the manner expressed by the following equation:

$$T = (T_o - T_a) e^{-\lambda t} + T_a \quad (3)$$

where

T_o = temperature at time of encapsulation

T_a = ambient temperature.

These equations may be combined to give

$$P = \frac{N_o R}{V} (1 - e^{-\lambda t}) (T_o - T_a) e^{-\lambda t} + T_a \quad (4)$$

Lunar mission generator. In the graph in Fig. 5, the temperature of the fuel block of the lunar mission generator is plotted against time. The conservative assumption has been made that the fuel initial temperature is 1850 °F and that the ambient temperature is 85 °F for the first 60 days and 275 °F after launch.

Since the exact fuel form and the void volume available have not been determined for this generator, there has been plotted, on the same figure, the value of PV at the corresponding values of the temperature. In this way, the void volume that must be provided with any desired safety factor can be calculated quite simply. The void volume calculated in this manner will be the total void for the Curium-242 load of 3.76 grams. Since there are four chambers, the calculated volume may be divided equally between them.

The internal pressure that the Hastelloy C vessel can withstand is calculated approximately (and conservatively) by assuming that each of the fuel chambers is a hollow cylinder with an internal diameter of 1/4 inch and a wall thickness equal to half the minimum separation of the chambers, 5/48 inch. The equation for the pressure that a hollow cylinder can withstand is given by:

$$P = \frac{b^2 - a^2}{b^2 + a^2} \sigma \quad (5)$$

Fig. 5. Lunar Generator

where

P = pressure (psi)

b = external radius (inch)

a = internal radius (inch)

σ = yield strength (psi).

From this equation, it is found that the pressure resistance required of the vessel is 0.541 times its yield strength.

The yield strength and other elastic properties of Hastelloy C vary with temperature. Typical data for these properties are shown in Fig. 6.

In Table 4, pertinent data have been considered to determine the minimum void volume.

TABLE 4

Temp (°F)	Time (days)	Hastelloy C Yield Strength (psi)	Available Resistance 0.541 (psi)	PV (psi x in. ³)	Required Void (10 ⁻³ in. ³)
1600	21	36,500	19,760	185	9.38
1500	52	43,700	23,620	250	10.59
1400	72	47,100	25,500	310	12.12
1300	93	48,500	26,220	370	13.76
1200	118	49,800	27,000	420	15.60

The void volume requirement determined in this way is a limiting value, without consideration of any safety factor. Thus, if a volume of about 0.016 cubic inch were provided in each chamber, there would be a safety factor of four. Temperature excursions above the expected values could be endured. The yield strength of Hastelloy C has been used in these calculations. The ultimate tensile strength, which is greater, would result in values for pressures which could be endured without violating the containment of the radionuclide fuel; however, the fuel block and generator would be permanently distorted.

Fig. 6. Properties of Hastelloy C at Elevated Temperatures

Satellite mission generator. Similar calculations for the satellite mission generator have been made in a somewhat simpler manner. In the design, a void volume of 0.2046 cubic inch has been provided. In Fig. 7, the temperature and the helium pressure developed have been plotted against time after encapsulation. An initial temperature of 1650 °F with an ambient temperature of 85 °F for the first 60 days and absolute zero thereafter has been assumed. In this case, the pressure developed rises to a maximum of about 3000 psi at one half-life, 162.5 days. Even if the temperature were 1600 °F at the end of the mission, the pressure would be about 8000 psi. The temperature at the time of maximum pressure is about 670 °F. The yield strength of Hastelloy C at this temperature is 53,000 psi. Equation 5, considering only the Hastelloy C vessel, indicates that it is able to withstand a pressure of about 16,000 psi. In addition, the tantalum within the Hastelloy C vessel and the copper surrounding it make a contribution to the strength. Consequently, the helium pressure is safely contained, by a wide margin.

2. External Pressure

If a failure of the vehicle should occur in certain phases of the launch trajectory, it is probable that the generator would fall into the ocean intact. The generator and the fuel capsule would consequently become subject to external pressure dependent upon the depth of the water into which they sank. The pressure exerted at the greatest ocean depth is approximately 14,000 psi.

The external pressure which a hollow cylinder can withstand is given by

$$P = \frac{b^2 - a^2}{2 b^2} \sigma \quad (6)$$

where

P = pressure (psi)

b = external radius (in.)

a = internal diameter (in.)

σ = yield strength or ultimate tensile strength.

Lunar mission generator. With the same assumption for the fuel capsule of the lunar mission generator as in the calculation of internal pressure (that is, that it can be considered as a hollow cylinder with an internal radius of 1/8 inch and an external radius of 11/48 inch),

Fig. 7. Generator for Satellite Mission

Eq (6) can be applied. The fuel capsule will be cooled by the ocean water and distortion of the block is not important, so the ultimate tensile strength of Hastelloy C at room temperature is used. This calculation shows that the fuel capsule has the capacity to withstand about 45,600 psi, or more than three times the external pressure it will experience.

Satellite mission generator. Equation 6, applied to the Hastelloy C vessel of the satellite mission generator, indicates that it will withstand an external pressure of 29,700 psi. This is more than twice the maximum pressure it can encounter submerged in the ocean.

3. Impact

It is extremely difficult to predict the stresses to which a vessel will be subjected in case of impact on a surface at high velocity. An equation for the stress developed in impact on a rigid body such as granite is

$$P = \rho V^2 \quad (7)$$

where

P = stress developed (lb/ft²)

V = velocity (fps)

ρ = bulk density of the impacting body (slugs per cubic foot).

This equation has some theoretical basis and is confirmed by tests, but it is often difficult to interpret in terms of strain, or damage produced. For impact on any surface not completely rigid, the stress developed will be less. In any case, the angle of impact and the orientation of the impacting body will significantly affect the results.

If a vehicle failure were to take place in some phase of the ascent trajectory, it may be expected it would fall back and impact on the ground.

Lunar mission generator. It is a design objective for the lunar mission generator that it shall be able to withstand a landing on the moon at a velocity of 500 fps without damage that would render it inoperative as a generator. It is not strictly within the province of this report to determine whether this requirement is met, since there is no hazard to personnel involved in an accident on the moon. It does appear desirable to avoid release of radioactive material on the moon's surface. If this design objective is met, there is no danger of release of the radionuclide in impact at this velocity on the earth's surface.

Applying Eq (7) to the generator as contained in the beryllium vessel, neglecting the radiator fin and the gas-filled bellows, it is found that the stress developed is about 6000 psi. It would seem reasonable that the vessel could withstand this stress. The point of greatest weakness appears to be the aluminum bolts. The design contemplates impact being made on the bellows in the lunar landing; deformation of the bellows will absorb some of the stress. If the impact were to take place on the earth's surface, the orientation would be random. Even if the generator does not survive as a functioning unit, the containment of the Curium-242 fuel is assured.

The terminal velocity of a body falling freely through the lower part of the earth's atmosphere is given by

$$V^2 = 841 \frac{W}{C_D S} \quad (8)$$

where

V = velocity (fps)

W = weight of body (lb)

S = surface area (ft²)

C_D = drag coefficient, a function of the shape and attitude of the falling body.

Using appropriate data for the beryllium-enclosed generator, again neglecting the radiator and bellows, the terminal velocity is found to be about 80 fps. With the radiator and bellows giving greatly increased surface area and poorer aerodynamic shape and only about 50% increase in weight, the terminal velocity is less. Consequently, any impact on the earth's surface will be much less severe than the moon landing at 500 fps.

If the fuel block were to become separated from the rest of the generator and impact at 500 fps on a rigid surface, it is probable that it would be broken up. Application of Eq (7) indicates an imposed stress of about 30,000 psi. The block is scored with three notches on each of the 2 x 2-inch sides, parallel to and between the fuel holes. In this way it is intended that the stress may be partly relieved by breaking along these lines without exposing the Curium-242.

The separation of the fuel block from the generator is highly improbable. It might occur in case of an abort at such an altitude that partial burnup exposes the fuel block but without sufficient aerodynamic heating to consume it.

The satellite mission generator. If the satellite mission generator, not including the external shadow shield, were to impact on a rigid surface at 500 fps, the stress imposed would be about 6250 psi. The generator would be crushed, but without violating the containment of the radionuclide fuel. The terminal velocity of the generator in free fall would be about 80 fps.

The fuel core, consisting of the Hastelloy C containment vessel, copper radiator and tungsten block, may become separated from the rest of the generator. If it were to make impact on a rigid body at 500 fps, the stress imposed would be 46,000 psi. With some orientations of the block upon impact, this stress might result in rupture of the containment vessel. Generally, the structure of the block would absorb a great deal of this stress; the copper radiator fin would be distorted and the tungsten portion may break away from the rest of the block.

Exposure of the fuel core of this generator may take place under the same circumstances as for the lunar generator; i.e., an abort in which there is incomplete burnup. The core of the satellite generator is initially more exposed than that of the lunar generator.

In addition to the fire tests which have been mentioned, The Martin Company, in collaboration with Aberdeen Proving Ground, has conducted a number of impact tests with typical generator fuel cores. Cores, at a high temperature, have been caused to impact at velocities up to 500 fps on various kinds of surface, including granite. While the cores used in these tests have had a different configuration from the cores proposed for use in the Curium-242-fueled generator, a great deal has been learned about impact in general.

A series of tests should be made with the core for the lunar mission generator and with the generator itself in order to assist in selecting the optimum design.

B. CHEMICAL INTEGRITY

Either the lunar generator or satellite generator, or their fuel containers, may fall into the ocean from an abort which might take place in a certain phase of the launch trajectory. Hastelloy C has excellent resistance to corrosion by sea water and is not subject to pitting. With either generator, the Curium-242 will be safely contained for hundreds of years. In each generator fuel capsule, there is a tantalum liner which resists internal corrosion by the plutonium and is also highly resistant to sea water corrosion.

The lunar generator provides some secondary containment of the fuel by means of the beryllium case. Beryllium has good resistance to sea water corrosion. The weakest element in this structure is probably the aluminum bolts holding together the beryllium structure.

In the generator for the satellite mission, the Hastelloy C vessel is covered with copper, which provides additional resistance.

In the event of a launch pad fire, the generator cores may be exposed to the action of nitric acid. At room temperature, the penetration rate for Hastelloy C in concentrated nitric acid is 0.001 inch per year, but for boiling acid, it increases to 0.01 inch per year for dilute acid and becomes very high for concentrated acid. Since, in any launch pad fire, the acid present is likely to be both hot and concentrated, the Hastelloy C vessel cannot provide containment of the radionuclide for a long period of time. However, any nitric acid not consumed in the fire will be rapidly drained away and evaporated, so that any exposure of the Hastelloy C to acid corrosion has the probability of short duration. Sufficient acid to corrode the Hastelloy C vessel will only collect in random pockets among the debris, and the probability that the Hastelloy C vessel will escape any contact with the acid is high.

The tantalum liners of the fuel capsules are impervious to nitric acid. However, the tantalum, if unsupported, may be ruptured by the internal gas pressure.

The fuel capsule of the lunar generator is further protected by the generator shell. Beryllium is not attacked by concentrated nitric acid at room temperature, but is attacked by hot acid. Aluminum is not attacked by nitric acid.

The Hastelloy C fuel capsule of the satellite mission generator is surrounded by copper. Copper is rapidly attacked by both dilute and concentrated nitric acid.

In all cases of possible corrosion where there are present more than one metal, there should be an experimental examination of electrolytic effects.

In the fire test carried out by The Martin Company in collaboration with The Aberdeen Proving Ground, several fuel cores were exposed to the fire and the possibility of nitric acid corrosion. Only one of these showed any indication of corrosion. The configuration of the cores tested was not the same as that of the ones being considered here, but the result gives some indication of the probability of attack. In the simulated missile fire, the nitric acid persisted longer than it could in an actual missile fire, since there was less opportunity for it to drain away.

It is concluded that, while the release of the radionuclide by the action of nitric acid in the event of a launch pad fire is a possibility, it is highly improbable.

C. THERMAL INTEGRITY

In a vehicle failure during launch, there is, of course, the potential hazard of the release of the radionuclide fuel due to the fire itself. The time history of launch pad fires, especially of the simulated launch pad fire, has been given in Chapter III. Except for an initial excursion which lasted less than a minute, the indicated temperature in the fire did not reach the melting point of Hastelloy C (about 2340° F) or even that of copper (about 1980° F).

Eighteen fuel containers were exposed to the simulated launch pad fire. None of these showed any effect due to the fire, other than surface discoloration. While these containers were not made of Hastelloy C, they were made of materials with similar resistance to oxidation and similar melting points.

In the case of the lunar mission generator, there is the factor of secondary containment. Beryllium has a melting point about equal to that of Hastelloy C and, in addition, it has a high specific heat and good thermal conductivity. It is subject to oxidation above 1500° F, but the oxide is adherent and tends to protect the metal underneath it. The aluminum bolts holding the two beryllium parts would probably melt.

It is concluded that the release of the radionuclide fuel by a launch pad fire is possible but that it would require an improbable combination of unfavorable circumstances.

Practical certainty of containment of the radionuclide in any launch pad accident could be attained for the lunar mission generator by a different choice of some of the components were it not for the opposing design requirement that the isotopic fuel be burned up on re-entry from an aborted mission.

D. ABORTED MISSIONS

The mechanical, chemical and thermal stresses that have been discussed arise almost entirely from vehicle failure at some point in the launch sequence. This sequence and the relative probability of failure in its various phases have been discussed in Chapter III. It is appropriate to relate the potential hazards to the various stages of the injection into orbit and to consider the burnup of the radionuclide fuel.

1. Launch Failures

In Chapter III, launch failures are defined as those which take place on the launch pad or before the missile has reached an altitude of 1000 feet. The hazard arises from fire or acid corrosion. For a launch pad fire, it has been concluded that exposure of the radionuclide is beyond the realm of probability. If failure occurs after the vehicle has gained a few hundred feet altitude, the debris will fall back upon the launch pad, but the consumption and dispersal of the fuel will have reduced the magnitude of the imposed stresses to the point where exposure of the Curium-242 is not possible.

2. Ascent Failures

In the early part of the ascent phase, the vehicle is still over land. There is no possibility of acid corrosion; a fire in the moving vehicle would not expose the isotope capsule to serious stresses, and containment would not be endangered. The hazard arises from impact on land. Breakage of the isotope container with consequent dispersion of part of the isotope is possible, but improbable.

Later in the ascent, the vehicle is over the ocean and any impact of the radionuclide container will take place on water. The mechanical stresses will not endanger the containment of the nuclide and the corrosion resistance of the container will insure containment for hundreds of years, by which time the activity will have become quite small.

In the final phase of the ascent, the vehicle will be at a high altitude, but moving with a somewhat reduced velocity (about 10,000 fps). In the event of an abort, there will be limited aerodynamic heating upon re-entry. This heating may produce some ablation of the generator shell but is expected to permit the fuel container to impact in the ocean intact.

3. Final Stage Failure

In the early part of the final stage, a vehicle failure will have the same result as in the later part of the ascent trajectory. After the vehicle has gained a high velocity, it will experience a maximum of aerodynamic heating and complete burnup is to be expected. There is, consequently, an intermediate phase in which only partial burnup may occur.

4. Burnup

For a complete evaluation of the burnup characteristics of an isotope-powered generator upon re-entry into the earth's atmosphere, it is necessary to know the configuration of the generator as well as its position in the vehicle structure and the parameters of the aborted

trajectory. Programs have been prepared for the IBM 709 digital computer whereby the problem can be studied. Plasma jet tests on models of the generator may also be required.

It is assumed that, in either the satellite mission or the lunar mission, the generator will be exposed outside the vehicle structure. In the case of the generator for the satellite mission, the outer aluminum shell, the thermoelectric elements, the insulation and the stainless steel inner shell will be consumed, exposing the fuel capsule. The copper and Hastelloy C surrounding the fuel will be consumed. The tantalum providing the final encapsulation of the Curium-242 has a high melting point, but is subject to oxidation at temperatures well below its melting point. It is said to be highly resistant to re-entry burnup, but the small quantity present would probably be consumed. Even if it is not consumed, it has purposely been made thin and it will be burst from the internal gas pressure. Thus, the Curium-242 will be released and dispersed in the stratosphere above 100,000 feet. The fate of the tungsten shield attached to the fuel capsule is uncertain but would have little, if any, effect upon the dispersion of the Curium-242. Tungsten has a high melting point, but is subject to oxidation and has a low specific heat. It is expected that the quantity present here will be consumed.

The situation with regard to the lunar mission generator is somewhat different. The radiator fin and gas-filled bellows will be consumed. The behavior of the beryllium cover is uncertain. Beryllium does not have an unusually high melting point (2345°F). It does have a high specific heat and thermal conductivity, giving it the attributes of a good heat sink. It oxidizes above 1500° F, forming an adherent and protective oxide. In case the beryllium is not consumed, it is expected that the aluminum bolts will melt, allowing the two parts of the beryllium cover to be separated by aerodynamic forces, exposing the interior of the generator. The insulation will have been separated into two parts; consequently, the Hastelloy C fuel block will be exposed and consumed. There is also a tantalum containment to which the same considerations apply as in the case of the satellite mission generator. The Curium-242 will be released and dispersed above 100,000 feet.

5. Successful Mission

After a successful satellite mission, the satellite will eventually re-enter the earth's atmosphere. The aerodynamic heating experienced will be essentially the same as that for a final stage abort. The Curium-242 will be released and dispersed in the stratosphere.

6. Partial Burnup

If a vehicle failure occurs in the later part of the ascent phase or in the early part of the final stage, the vehicle will not have attained

sufficient velocity for aerodynamic heating to reach its maximum intensity, nor will it continue for as long a time as in a re-entry from a successful mission or a later abort. In this circumstance, the complete sequence described above may not take place. The effect of the aerodynamic heating will be terminated at about 100,000 feet altitude. If the generator has not been completely consumed, the radionuclide may have been exposed with the result that some of it is released into the troposphere. The generator will be quite hot and may have been weakened by partial ablation so that, upon impact on water, it may be broken open, releasing the Curium-242 locally in the ocean, where it would be rapidly diluted. The satellite mission generator, at the time of launch, contains 15,900 curies of Curium-242. If this activity were dispersed in 0.08 cubic kilometer, the concentration would be less than the maximum permissible concentration for drinking water for the general public. It is estimated that this amount of dilution by normal ocean movement would take place in less than 48 hours (Ref. 6).

7. Stratosphere Dispersion

If the Curium-242 is dispersed in the stratosphere, it will tend to become uniformly disseminated, and after a mean residence time estimated to be at least eight months, it will fall out, principally between the 30th and 60th parallels of latitude in the hemisphere in which it was injected.

The surface deposition from such an injection may be calculated by the equation:

$$\chi = \frac{Nz}{A} e^{-\lambda t} (1 - e^{-\gamma t}) \quad (9)$$

where χ = deposition (curies per square mile)

N = curies injected

z = fraction deposited in the given area (0.75)

A = area (square miles, 3.6×10^7)

e = natural base

λ = radiological decay constant (day^{-1} , 4.24×10^{-3})

γ = residence decay constant (day^{-1} , 4.17×10^{-3})

t = elapsed time (days)

By differentiating Eq 9 and setting the result equal to zero, the time of maximum surface deposition can be found from the equation:

$$e^{-\gamma t} = \frac{\lambda}{\lambda + \gamma} \quad (10)$$

For Curium-242 with a half-life of 162.5 days, assuming a mean residence time of 240 days, the maximum surface concentration will occur at 169 days. A failure with burnup of the satellite mission generator at launch would inject 15,900 curies into the stratosphere. This would produce a maximum surface deposition of 30 micromicrocuries per square meter. This is a negligible quantity compared with the average natural radioactivity of the soil. If the burnup occurs after a successful mission of 180 days, 7520 curies will be injected. The maximum deposition would occur 169 days later and would be proportionately less.

A burnup of the lunar mission generator on launch would inject 9530 curies.

For release of part of the Curium-242 in the troposphere due to partial burnup, the deposition will be less widely disseminated, will take place more rapidly and will be somewhat heavier. From the nature of the trajectory, it will be principally over the ocean.

8. Range Safety

The only situations in which a ground release of the radionuclide fuel is possible are: (1) fire on the launch pad, and (2) impact from an abort in an early phase of the ascent trajectory. In either case, the release would be in a strictly controlled area, a government reservation including the launch complex.

At the time of a vehicle firing, a "fall-back" area is established from which all personnel are excluded, except those necessary to the operation; these persons are confined to the blockhouse. The fall-back area extends at least 2500 feet from the launch area and includes the projection, along the ground, of the expected trajectory. Road blocks are set up to deny access to this area. Presumably, the procedure at Cape Canaveral is similar to the present practice at the Vandenburg-Point Arguello complex, where a missile accident emergency team (MAET) stands by in the fall-back area during each launching. The team is presently equipped with an M-246 wrecker, 20-ton crane, D-8 bulldozer, fire truck and H-19 helicopter. For missions in which radionuclides are involved, certain equipment revisions have been recommended to include airborne search equipment with radiation detectors, a remotely operated or heavily shielded handling vehicle, TV equipment, remote cutting tools and a water pool for shielded storage.

If the Curium-242 should be released in this controlled area, it would be immediately isolated and steps would be taken to recover it or bury it. The Curium-242 is primarily an alpha emitter so the hazard to personnel is principally from ingestion and inhalation. The neutron dose rate from an unshielded source equivalent to the loading of the lunar mission generator is about 120 millirem per hour and that from gamma radiation is about 27 millirem per hour at one meter distance. Trained personnel would be able to work for several hours, if required, in proximity to the radionuclide source without exceeding the emergency dose of 3 rems. Shielding would not be required; the fuel capsule can be handled with tongs.

If the fuel capsule fell on land, it would probably be desirable to institute an aerial search, in addition to ground search. If it were not in plainly visible debris, the absence of penetrating radiation would make it hard to locate. If it fell in water, the shielding effect of the latter would make it almost impossible to locate.

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