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18 JAN 2 1962 **MASTER**
PRELIMINARY SAFETY ANALYSIS OF THE
SURVEYOR GENERATOR
SNAP Programs, Subtask 7.1

September 1961

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FOREWORD

This final report has been prepared to summarize the results of safety evaluation of a radioisotope-fueled thermoelectric generator proposed for use with the Surveyor system. It covers a portion of the work performed by Martin-Nuclear under Subtask 7.1 from December 1960 through August 1961, under Contract AT(30-3)-217 with the U.S. Atomic Energy Commission.

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SUMMARY

As originally conceived, a general safety study of SNAP-type units launched on the Atlantic Missile Range was to be conducted under Subtask 7.1. When definite mission requirements were established, the study was redirected to support specific missions. In one of these missions, the Surveyor Program, a radioisotope-fueled generator will supply power to conduct scientific experiments on the moon's surface during the lunar night. A design concept was developed for a generator which would produce 19 watts of electrical power from the decay heat of 6.9 grams of Curium-242.

Safety criteria for the ascent-to-orbit phase of the mission are satisfied by the use of a primary containment capsule of Hastelloy C material. The exceptional corrosion resistance and high temperature strength of this material provide a generous safety margin for both internal and external pressure loads anticipated. During ground handling operations, a portable polyethylene shield may be used to reduce the dose rate, allowing an individual to remain one meter from the unit for six normal working days.

Surveyor Program spacecraft will be launched from Cape Canaveral by the Atlas-Centaur vehicle system. A 100-nautical mile parking orbit will be achieved through 254 seconds of booster and sustainer firing, followed by a first Centaur firing of 259 seconds. The spacecraft will be injected into orbit approximately 537 seconds after launch. Following an unpowered orbital coast period, a second Centaur firing initiated 1289 seconds after launch will inject the spacecraft into a lunar transfer trajectory. A normal destruct system will be available for the Atlas vehicle, but no command destruct capability will exist during Centaur firing with the proposed system.

Shock overpressures and temperatures anticipated in the event of vehicle failure at launch are not sufficient to cause capsule failure. Since the data available on the yield of the Centaur fuel load are insufficient, further investigation and tests are recommended.

The consequences of vehicle failure during the ascent-to-orbit phase of the mission depend on the velocity at the time of failure. Certain critical points in the sequence of vehicle operations were selected for study, and the effects of the velocities achieved were determined. Early thrust termination of the booster or sustainer engines, or ignition failure of the Centaur engines, would result in a maximum velocity of 14,200 fps. Aerodynamic heating on a ballistic trajectory at this velocity would be insignificant. The generator would drop into the ocean in an intact condition 880 nautical miles or less downrange. The exceptional corrosion resistance of the Hastelloy C capsule assures containment of the radioisotope for a period in excess of 1000 half lives of curium.

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Following successful ignition of the Centaur stage 278 seconds after launch, velocity increases from 14,200 to 25,580 fps during a firing period of 259 seconds. Vehicle failures prior to 20,500 fps, 452 seconds after launch, would result in ocean impact with the capsule in a fully intact condition. No radioisotope release would occur. Should velocities ranging from 20,500 to those approaching 24,400 fps, 520 seconds after launch be achieved prior to failure, capsule damage prior to impact in the open ocean is probable. Radioisotope concentrations in an ocean release will decrease to less than maximum permissible within 10 days. Thrust termination at velocities from 24,400 fps to orbit injection at 25,580 fps, 537 seconds after launch, would subject the capsule, on re-entry, to sufficient aerodynamic heating to cause total destruction of the capsule and dispersion of the radioisotope at altitudes in excess of 100,000 feet. Maximum concentration has been calculated to be $3.72 \times 10^{-16} \mu\text{c}/\text{cm}^3$ of air, as compared to a permissible concentration of 4×10^{-11} curie/ cm^3 .

Guidance failures during the first firing of the Centaur stage could result in impact on land if the more southerly launch azimuths are used. It is recommended that the launch azimuth range be limited to 90 to 96 degrees and that a destruct capability be incorporated into the Centaur vehicle. Centaur guidance failures during the second firing, or lunar injection, phase could result in re-entry velocities ranging from circular to near-escape. Only a qualitative treatment was possible, and further study is recommended.

A revised generator configuration was developed through a companion design study. Approximately 8.15 grams of curium oxide will be used to produce 25 watts of electrical power. Pending more accurate data on tungsten oxidation and penetration rates, capsule conditions resulting from re-entry could range from intact to burnup, as defined for the initial configuration. Further investigations and tests are required to determine the safety aspects of this configuration.

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I. INTRODUCTION

This report, prepared by Martin-Nuclear, covers a preliminary evaluation of the earth-operational safety of a curium-fueled thermo-electric generator as a power supply in the Surveyor lunar mission. For the evaluation, the overall mission is considered to be divided into two different phases: the first, prelaunch, launch and parking orbit operations; the second, moon landing operations. This report treats the first of these phases; the second phase is covered in a separate report (Ref. 1).

The analyses contained in this report are preliminary in nature. They are intended to point out problem areas likely to be encountered in a mission of this type and to integrate safety considerations in the final design. Environmental histories of the generator are analyzed to determine the conditions under which a release of the radioactive fuel might take place, and to determine the extent of the radiological hazard involved.

Initially, two criteria defined the acceptability of the generator from a safety standpoint:

- (1) Containment of the radioisotope under all conditions which could cause a significant ingestion hazard.
- (2) Complete burnup at high altitudes following random re-entry from orbit.

Since these two criteria give rise to diverse design objectives under certain conditions, a cursory re-entry analysis was also made, using a capsule design developed under a companion configuration study. This design study was initiated to define more accurately the configuration and performance of the generator. Spacecraft power demands necessitated an increase in electrical output over that used in the previous study. Further, shielding material was incorporated around the fuel capsule to meet the stringent radiation flux limits of the scientific payload.

Since this design study was not completed until late in the period of this report, complete evaluation of the design changes, within the scope of this program, was not possible. In order to maintain report continuity, only the initial configuration is considered throughout the main body of the report. Significant effects of the revised configuration are discussed in Chapter V of this report.

For the convenience of the reader, this report is arranged so that the more important pertinent material is discussed in the main body of the report. Supporting calculations and methods of analysis are given in the appendices.

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II. SURVEYOR THERMOELECTRIC GENERATOR

The generator used for this study is an early conceptual design intended to power scientific instruments in the Surveyor lunar probe vehicle.

A. GENERATOR CONFIGURATION

The exterior configuration of the generator is that of a right cylinder with attached cooling fins. A radioactive heat source, contained at the center of the device, is surrounded by a cylindrical hot junction skin. This cylindrical surface supports 16 modules of lead telluride thermoelectric elements which convert thermal energy radiated from the source into usable electrical energy. Unconverted thermal energy is conducted to the outer radiator surface and cooling fins. The elements are held in place by a rigid insulating material (Johns-Manville Min-K). One end of the device is equipped with a movable shutter mechanism which regulates the temperature of the hot junction by controlling the amount of radiating area of the heat source exposed to the environment.

The heat source consists of Curium-242 contained successively in weld-sealed cylinders of 0.030-inch thick tantalum and 0.125-inch thick Hastelloy C. Tantalum is used to prevent combination (alloying) of any fuel products with the Hastelloy C. The heat source assembly is contained in a 0.20-inch thick copper cylinder with a spherical disc at one end, which functions as a radiator for the hot junction temperature control system. Excluding the spherical disc, the capsule is 4.37 inches long and 0.866 inch in diameter. The disc itself is 4.09 inches in diameter. The configuration of the generator is illustrated in Fig. 1.

Approximately 6.9 grams (22,800 curies) of Curium-242 generates 828 thermal watts and occupies 42.5% of the total internal volume of 0.071 cubic inch. A perforated tantalum plug positions the fuel and provides a void volume for expansion of the helium generated as a result of radioactive decay.

The generator is designed to supply 19 watts, direct current, at 3 volts, maximum. A flat power output is achieved over a 90-day period of operation on the moon by means of the temperature regulating device which controls the position of a heat dump door. Thereafter, the power decays exponentially with time, essentially following the decay scheme of the radioactive fuel. The initial fuel loading allows for an additional 10 days for shipment and 30 days for an optional hold at the launch pad.

Fig. 1. Generator for Soft Lunar Landing

B. FUEL PROPERTIES

Curium-242 is most easily obtained by the neutron irradiation of Americium-241. This irradiation produces a metastable isotope, Americium-242m, which decays by beta emission, with a 16-hour half life, to Curium-242 in about 80% of the disintegrations. After irradiation and a 30-day cooling period, the fuel is purified to remove the fission products and the curium is further processed to the desired fuel form. In this preliminary design, the fuel form was assumed to be curium metal.

1. Physical and Chemical Properties

Curium is a silvery-white malleable metal with a melting point of 1742° F and a specific power of 120 watts/gram. Because of the high specific power, the curium fuel is fabricated into a small-diameter capsule, which presents some handling problems as a result of high surface temperatures. Equilibrium temperatures in still air approach 740° F for the fuel capsule contained in the copper radiator. A loaded Hastelloy capsule without the surrounding copper radiator would be at considerably higher temperatures because of reduced radiating area. Handling and loading operations on the fuel capsule alone would require auxiliary cooling devices. A more conservative approach, in which the curium is mixed with an inert diluent to lower its specific power, would probably be adopted. Capsule temperatures have been determined to be less than 1400° F under normal operating conditions in space. At this temperature, curium will be in a solid state and the amount of plutonium present in the early phases of the mission will be insignificant.

Curium is a member of the actinide series of elements with a principal valence of 3. Chemically, it resembles the members of the lanthanide series, in which its homologue is gadolinium. Plutonium has a much more complex chemistry and exhibits all the positive valence states from 3 to 6. It forms alloys with many other metals at high temperatures, but does not form alloys with tantalum. For this reason, a tantalum liner has been incorporated in the heat source assembly to function as a barrier to any reaction between the radioactive materials and the Hastelloy C container. Additional properties of curium and plutonium are given in Table A-1 of Appendix A.

2. Nuclear Properties

Curium-242 has a half life of 162.5 days and decays by alpha emission to Plutonium-238. It also undergoes spontaneous fission, with a half life of 7.2×10^6 years. The high-energy alpha particle emission of the curium (~6 mev average), combined with the short half life, pro-

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vides a specific power of 120 watts/gram. As a consequence of the short half life, however, an initial overload of fuel is necessary to provide a constant electrical output. Decay schemes for curium and plutonium, as well as for their decay products, are given in Figs. A-1 and A-2, Appendix A.

3. Radiobiological Properties

All of the alpha particles emitted during the decay process are absorbed either in the fuel or within a few thousandths of an inch of the inner surface of the capsule. Radiological hazards arise from the gamma photons emitted with a small fraction of the alpha disintegrations. In addition, spontaneous fission produces neutrons, as well as prompt fission gammas, fission product gammas and gammas from inelastically scattered neutrons. Dose rates at one meter from an unshielded generator have been calculated to be 24 mrem/hr due to gammas, and 129 mrem/hr due to neutrons. Since neutrons contribute the major portion of the dose, a portable polyethylene shield is proposed for use during those periods when workers must remain within one meter of the fueled generator. With a polyethylene thickness of 8.4 centimeters (3.3 inches), dose rates are reduced to 10.2 mrem/hr due to gammas, and 50.2 mrem/hr due to neutrons.

Allowable dose levels for badged personnel are 1250 mrem/calendar quarter year if no attempt is made to determine the individual's previous radiation history. If a satisfactory previous radiation history is established, this level is raised to 3000 mrem/calendar quarter year (Ref. 2). Assuming the latter condition, an individual may remain at one meter from the shielded generator for approximately 50 working hours or 6 normal working days. Since the generator configuration allows the fueled heat source to be installed late in the vehicle checkout phase, this working time appears adequate for any one individual during one launch sequence. Calculated dose rates from various gamma sources, and the neutron flux, are given in Table A-2, Appendix A.

Radiobiological hazards due to inhalation or ingestion of fuel particles are not possible during the course of a normal mission, for the following two reasons:

- (1) Positive capsule integrity will be maintained under all normal operating conditions.
- (2) Successful operation of the vehicle system will land the spacecraft with the generator on the surface of the moon.

The fuel can be released only through malfunctions of the vehicle system, which are discussed in Chapter IV of this report. Permissible concentrations and the results of postulated releases are discussed in Appendix A.

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C. FUEL CAPSULE

As mentioned in the Introduction, two design criteria were used to define fuel capsule acceptability from a safety standpoint: absolute containment of the radioisotope under all conditions which could cause a significant ingestion hazard, and complete burnup at high altitudes upon re-entry. To satisfy the former criterion, capsule materials chosen were those which exhibited high strength at elevated temperatures, good impact resistance and good corrosion resistance to anticipated ambient conditions.

1. Capsule Materials

Although the capsule is composed of tantalum, Hastelloy C and copper, strength calculations are based on the capabilities of the Hastelloy C container. Tantalum is used as a barrier to any reaction between the fuel and the containment vessel; copper, with its high thermal conductivity, assures a uniform temperature distribution on the surface of the heat source and the heat dump radiator.

Hastelloy C, manufactured by the Haynes Stellite Company is an alloy composed primarily of nickel. Its melting point ranges from 2318° to 2381° F. Its ultimate tensile strength ranges from 130,000 psi at room temperature to 80,800 psi at 1400° F. Its yield strength at high temperatures is quite good--47,100 psi at 1400° F. At room temperature its impact strength averages 22 foot-pounds. (Haynes Alloy No. 25 has a strength of 120 foot-pounds.) Although the impact characteristics of Haynes 25 have been demonstrated by test to be excellent, its strength and elongation decrease rapidly above 1100° F (Ref. 3). While actual impact test data on Hastelloy C at elevated temperatures is not available, its high yield strength and typical elongation are indications of high impact resistance. Typical elongation rises rapidly to over 50% at 1400° F while the elongation of Haynes 25 decreases to 30%. The manufacturer also recommends its use where parts are highly stressed and subjected to repeated thermal shock at temperatures from 1600° to 1800° F.

Corrosion resistance is of prime importance in this application because of the long half life of Plutonium-238, the first product in the decay scheme. Hastelloy C is one of the most universally corrosion-resistant alloys available. It is resistant to oxidizing and reducing atmospheres up to 2000° F and exhibits exceptional resistance to strong oxidizing agents such as ferric chloride and cupric chloride. From the standpoint of possible ambient conditions following launch vehicle malfunction, its resistance to sea water is especially important. Corrosion test samples submerged in actual sea water for over 10 years at the Harbor Island Test Station, North Carolina, have shown only negligible weight loss and no pitting or crevice corrosion. Penetration rates of

less than 0.0001 inch/year have been estimated by the International Nickel Company (Ref. 4). With a capsule wall thickness of 0.125 inch, this penetration rate may be extrapolated to a retention time of over 1000 years. Additional material properties and corrosion rates are given in Tables B-1, B-2, and B-3, Appendix B.

2. Capsule Allowables

Allowable internal pressure loads are pertinent to capsule design for two phases of capsule life. First, no yielding should take place during the operational life of the generator. The maximum allowable internal pressure in the capsule was calculated to be 30,474 psi, using the yield strength of the Hastelloy C at 1400° F, the operating temperature. Second, it is inexpedient to permit the capsule to rupture until a significant decrease in the activity of the radioisotope--with a significant decrease in capsule temperature--has occurred through decay. The allowable internal pressure, with this condition, was calculated to be 84,000 psi, using ultimate tensile strength at room temperature.

Allowable external pressures on the fuel capsule were calculated to range from 28,400 psi at room temperature to 18,600 at 1400° F. Since external loads are of the shock or blast type following vehicle malfunction, yield strengths, more indicative of ability to withstand these transient conditions, were used for the above calculations. Detailed calculation procedures and formulae are given in Appendix B.

3. Capsule Loads

Loads imposed on the capsule may be generally classified according to origin as internal and external. During the course of a normal mission, only internal loads are significant to successful generator operation and capsule integrity. Since the discussion of radiobiological hazards in the previous section was based on absolute capsule integrity, all forces will be considered.

a. Internal pressure loads

Helium gas is generated by all radioisotopes that decay through alpha emission, when the ejected alpha particles collect electrons from the surrounding materials to form helium atoms. When the radioisotope is sealed in a capsule, the helium pressure increases with time in relation to the initial void volume in the capsule, the half life of the isotope and the temperature of the capsule. Helium pressure and assumed temperature of the fuel capsule versus time are plotted in Fig. 2. A maximum pressure of 1450 atm (21,300 psi) exists at the end of the 130-day operational constant temperature phase. This pressure is well below the previously calculated allowable of 2070 atm (30,470 psi). A decrease in pressure then occurs as the result of an assumed ex-

ponential temperature decrease to 100° F resulting from isotope decay.

Figure 2 was not carried beyond 10^4 days (approximately 270 years) because of the large margin of allowable pressure--5700 atm (84,000 psi) allowable, versus a calculated actual pressure of 1200 atm. Helium pressure calculations and formulae are given in Appendix B.

b. External pressure loads

In normal operating environments, external pressure loads on the fuel capsule will be insignificant in comparison with allowable pressure loads. Design requirements are therefore dictated by those loads resulting from launch vehicle malfunction or transportation accidents. Of these, loads resulting from vehicle malfunction are the more strenuous and consist of earth impact and shock overpressure. Since shock overpressures are dependent upon vehicle configuration, they are discussed in Chapter IV, Section A. External pressures resulting from earth impact are a function of impact velocity, which, for calculation purposes, was conservatively assumed to be the terminal velocity of a fuel capsule separated from the generator--366 fps. At this velocity, external pressure due to impact (calculated) is 16,300 psi (allowable, 18,600 psi at 1400° F). Internal pressure was neglected since it will be insignificant at the time of launch. Impact velocity and external pressure calculations are given in Appendix B.

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Fig. 2. Variation in Capsule Temperature and Internal Pressure with Respect to Time

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III. SURVEYOR MISSION

Early launchings of the Surveyor system from Cape Canaveral are planned for 1963. Prior to this time, approximately ten firings will be conducted to test the Atlas-Centaur vehicle combination. Present plans call for introduction of the radioisotope-fueled thermoelectric generator into the Surveyor Program in 1964.

A. GENERAL FLIGHT PLAN

Firing azimuths for ascent trajectories have not been definitely determined, but they will probably range from 90 to 114 degrees. It is improbable that firing azimuths greater than 114 degrees will be permitted by Range Safety, because of the proximity of the trajectory to Brazil, as illustrated by Fig. 3 (Ref. 5). The Centaur stage and its spacecraft payload will be injected into a nominally circular orbit of 100 nautical miles altitude at the locations on the map labeled "First Centaur burnout--parking orbit injection" (see Fig. 3). This ascent phase consists of approximately 153 seconds of booster firing and 101 seconds of sustainer firing of the Atlas engines, followed by a first Centaur firing of 259 seconds. Velocity, altitude and range achieved during this ascent phase on a launch azimuth of 90 degrees are plotted in Fig. 4. Detailed trajectory printout data were provided for azimuths ranging from 90 to 112 degrees (Ref. 6). These data were used for this report.

Following an unpowered orbital coast period, the spacecraft will be injected into a lunar transfer trajectory by a second Centaur firing (Ref. 7). This second burning period lasts approximately 99 seconds and spans about 9 degrees of longitude. Ignition at 1289 seconds after launch will result in burnout at the locations labeled "Second Centaur burnout--zero lunar declination injection" on the map. However, ignition may be delayed, depending upon the declination of the moon at the time of launch, so that burnout occurs at the locations labeled "Maximum lunar declination injection." During this second firing, a plus 2-degree change is programmed in the angle between the inertial velocity vector and its projection on the geocentric local horizontal plane. The spacecraft will not normally achieve escape velocity. Ignition will be initiated by ground command, following monitoring during the coast period. Should telemetered data indicate a malfunction of the orientation system during the coast phase, the second firing should not be initiated. The vehicle will then re-enter through orbit decay. A similar situation will exist if the engines fail to ignite on command. If the guidance system fails after successful ignition, a variety of flight paths

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Fig. 3. Surveyor Firing Azimuths

Fig. 4. Altitude, Range and Velocity Versus Time--Atlas Centaur System (Centaur in 100-nautical mile orbit, launch azimuth 90° E)

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is possible, depending on the mode of failure. These flight paths range from those in which escape velocity is achieved to those in which a new orbit is established (Ref. 5). Random re-entry will occur after a time in orbit determined as a function of perigee altitude and eccentricity.

B. LAUNCH VEHICLE

The Atlas-Centaur vehicle used for this mission consists of an Atlas booster and sustainer stage plus a restartable Centaur stage. The combined weight of the RP-1 (kerosene) and liquid oxygen used as propellant in the Atlas is 244,850 pounds. Liquid hydrogen and liquid oxygen are used in the Centaur stage with a combined weight of 27,740 pounds. The positions of the payload, propellant tanks and destruct units are shown in Fig. 5 (Ref. 8).

Normally, both vehicle stages are equipped with redundant safety systems which provide a means of instantaneously terminating powered flight, should the vehicle deviate markedly from the programmed flight path. Explosive charges destroy the integrity of the fuel and oxidizer tanks, causing thrust termination and spontaneous combustion of the remaining propellant. The tolerable deviation from the normal flight plan is usually ± 2.5 degrees.

For the Surveyor launch the Atlas vehicle carries redundant antennas, command receivers, destruct signal transmission paths and primers. However, the Centaur destructor control unit receives its signals from the Atlas arming device and incorporates a disabling circuit. At sustainer cutoff a disable command is sent from the Atlas autopilot programmer to the destructor control unit safetying the destructor both electrically and mechanically. Thus, no command destruct capability exists during either the first or second burning periods of the Centaur stage. Although the system described above had not been submitted for approval as of November 1960, the date of the program requirements document (Ref. 8), its use was assumed for this report. Various degrees of thrust misalignment of the Centaur stage are discussed in Chapter IV of this report.

C. GENERATOR INSTALLATION

Spacecraft mounting atop the Centaur stage will be within the envelope described in Fig. 6 (Ref. 9). A split-type fairing provides protection from aerodynamic heating during ascent. Thrusters will be actuated 206 seconds after launch to jettison the fairing, exposing the spacecraft to the ambient space environment.

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Fig. 5. Atlas-Centaur Vehicle

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Fig. 6. Surveyor Spacecraft Mounting

Spacecraft configuration is based on a triangular pyramidal tubular framework. Three landing legs extend from each apex of the triangular base to provide a landing base during the lunar touchdown phase. A large portion of the overall spacecraft weight is allotted to the landing engine system, which consists of a spherical, solid propellant retro-rocket and liquid-fueled vernier landing engines. Details of this system were not defined and are not considered in this study. Components of the scientific experiments, guidance system and power system are mounted on the external planes of the framework. A simplified version of the spacecraft with the landing engines omitted is shown in Fig. 7. An approximate position of the thermoelectric generator is indicated in both figures.

Although the spacecraft framework is designed to support the rigidly mounted components during the landing maneuver, its resistance to aerodynamic heating should be rather low. Therefore, for this study, the generator is assumed to be freed from the vehicle structure early in any aerodynamic heating process considered.

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Group A: Electronic components

Group B: Flight control components

Group C: Lunar scientific instruments

Fig. 7. Surveyor Spacecraft Arrangement

IV. ANALYSIS OF ABORTED MISSIONS

Malfunctions occurring in the course of launching the Surveyor spacecraft into a parking orbit could result in a variety of abort situations. Several possible abort situations have been chosen for study, either because they represent the type of abort that has occurred in similar systems, or because they are situations in which malfunctions are most likely to occur. Deviations from the planned flight path due to thrust misalignment during Centaur firing were also considered in an effort to determine what maximum area could be affected by an uncontrolled firing. It was assumed that destruct of the Centaur stage was not possible. Results are reported for launch azimuths of 90 to 112 degrees with the majority of cases referred to the 90-degree azimuth.

A. LAUNCH PAD ABORT

Launch failures are broadly defined as those failures that occur either on or directly above the launch pad, resulting in either fire, explosion or both. If released upon abort, propellants in the Atlas-Centaur vehicle will ignite or explode, releasing significant thermal and mechanical energy.

A launch pad explosion could result in significant shock overpressures on the fuel capsule. The proximity of detonatable fuel in the liquid hydrogen-liquid oxygen tanks of the Centaur, as opposed to the usual hypergolic fuels, increases the magnitude of the expected effects as well as the probability of an explosion (Ref. 10). Calculations made by methods given in Appendix C show that, at a distance of 15 feet, capsule overpressures of approximately 6600 psi are possible if the Centaur fuel explodes. Because of distance effects, explosion of the booster fuel would produce overpressures of only 500 psi. It is improbable that these explosions would take place simultaneously, because of the time required for mixing of the fuels into explosive concentrations. Calculations in Appendix B show that the capsule can withstand a static external pressure of 18,600 psi at 1400° F. This value is significantly above the calculated values of anticipated overpressures. However, the possible magnitude of the dynamic overpressure warrants further investigation to assure capsule integrity. Contributions from the solid propellant, main retrorocket motor and the liquid-fueled vernier engines which comprise the lunar landing system were not evaluated, because of the lack of configuration data.

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Studies of launch pad aborts of similar vehicles show that, if a fire results, it may be intense enough to cause ignition of the structural members of the vehicle. These members burn at much higher temperatures than the fuel. The effect of subjecting the generator to a missile fire was considered analytically. Initial calculations made with the simplified assumption of radiant heat transfer from an infinite surrounding body of burning gas to a body of infinite thermal conductivity gave heat transfer rates markedly different from experimental data. These data, obtained in a simulated missile fire conducted under the SNAP 1A and SNAP 3 programs (Refs. 11 and 12), indicated that capsule integrity would be maintained. Analysis was not pursued further. A complete evaluation of the situation with LOX and liquid hydrogen was beyond the scope of this preliminary report; a more complete study and test of the final configuration is recommended.

B. ASCENT ABORTS

Ascent aborts in this study are defined as those failures which occur after the vehicle is airborne and prior to achievement of planned orbital altitudes and velocities. The following critical phases of flight were considered:

- (1) Maximum dynamic pressure on the vehicle where structural breakup is most likely to occur.
- (2) Booster cutoff and subsequent sustainer failure.
- (3) Sustainer cutoff and subsequent Centaur ignition failure.
- (4) Premature thrust cutoff of the Centaur engine.
- (5) Thrust misalignment after Centaur engine ignition.

These phases are considered separately in the following text. In all cases of abort when the vehicle is airborne, the assumption is made that the generator is freed from the vehicle immediately upon abort. Therefore, all re-entry flight paths and attendant aerodynamic heating inputs are referenced to the generator alone. The method of analysis is outlined in Appendix D.

1. Failure at Maximum Dynamic Pressure

At 80 seconds after launch, a termination of the powered flight induced by vehicle breakup would result in impact in the Atlantic Ocean approximately 6.9 nautical miles downrange. The generator would impact at a terminal velocity of 240 fps in an intact condition. Aerody-

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namic heating effects on the generator would be negligible. Following impact, the generator would sink to the bottom of the ocean. At this range the ocean depth is approximately 90 feet; and since the capsule will withstand an external pressure of 28,400 psi, hydrostatic pressure alone will not breach the containment vessel. Primary containment is supplied by Hastelloy C, which will resist corrosion in seawater for an extended period of time, during which the curium would decay to plutonium.

2. Sustainer Engine Failure at Booster Burnout

At 153 seconds after launch, failure of the sustainer engine would result in a projected impact point approximately 280 nautical miles downrange in the Atlantic Ocean. A re-entry history plot of altitude, velocity, stagnation point heating rate and total heat input versus time for a 6-inch diameter cylinder representing the generator is shown in Fig. 8. The time scale starts at zero, at 400,000 feet, where the atmosphere is assumed to begin. Stagnation heating rates shown are low enough so that no significant amount of re-entry heating would take place and the generator would impact unaffected. Conclusions noted under the previous condition would apply.

3. Centaur Ignition Failure

The Centaur engine is programmed to start 278 seconds after launch. Failure to ignite would result in a projected impact point approximately 880 nautical miles downrange. A re-entry history plot for the generator is shown in Fig. 9. Stagnation heating rates shown are not high enough to cause the outer generator structure to melt off; impact of an unharmed generator would take place in the open ocean. Conclusions as noted previously would apply.

4. Premature Thrust Cutoff of Centaur Engine

As noted previously, the Centaur engine ignites at 278 seconds after launch and burns for 259 seconds. During this period, inertial velocity increases from 14,200 to 25,580 fps at first burnout and parking orbit injection. Failures resulting in premature thrust termination of the Centaur engine would cause immediate re-entry since orbital velocity would not be achieved. From the standpoint of generator safety, any of three general conditions could result, following premature thrust termination, as a function of velocity achieved:

- (1) Re-entry of the generator with the fuel capsule intact.
- (2) Partial burnup of the fuel capsule.
- (3) Complete burnup of the capsule and radioisotope.

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Fig. 8. Re-Entry History--Sustainer Engine Failure (Case 13)

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Fig. 9. Re-Entry History--Centaur Ignition Failure (Case 12)

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For calculations pertaining to the first condition, it was assumed that no significant heat inputs to the capsule can occur until the outer radiator structure of the generator has been destroyed and the insulation sloughed off. This assumption was based on thermal lag through the insulation and was found to be logical because of the short heating period. A heat input of approximately 11,000 Btu/ft² was calculated to be sufficient to cause failure of the external generator structure. This input results from re-entry heating at a velocity of 20,500 fps, with significant heating over a period of less than 120 seconds. The re-entry history of the capsule for this first condition, which occurs following thrust failure at 452 seconds after launch, is plotted in Fig. 10. Although the total heat accumulated in this case just approaches that required for external structural failure, a conservative classification of partial burnup was applied. Hence, for all thrust failures prior to 450 seconds of flight, it may be predicted that the fuel capsule will impact in the open ocean without damage at a range less than 50 degrees west longitude. Conclusions as noted for the previous cases would apply.

During the period of flight after 450 seconds, at which a velocity of 20,500 fps is achieved, more damage to the capsule will be inflicted as heating rates and total heat inputs increase. Capsule damage will range from slight to complete destruction, following a thrust termination at a velocity of approximately 24,400 fps at 520 seconds after launch. A plot of capsule temperature (versus time) after failure at a velocity of 23,700 fps shows that the Hastelloy C capsule will be almost completely consumed. This plot (Fig. 11) represents the upper boundary of the partial burnup situation. With the capsule in a weakened condition, the radioisotope may be released through impact forces, corrosion or internal pressure buildup. The conservative treatment (in Appendix A) of an ocean release shows that a concentration less than the maximum permissible 2×10^{-4} curies/meter³ H₂O is reached within 10 days. On a launch azimuth of 90 degrees, the predicted impact and possible release point will not exceed 24 degrees west longitude, approximately 400 nautical miles from the African coast. On a launch azimuth of 112 degrees, this point may approach 300 nautical miles from the Brazilian coast without an allowance for guidance errors in yaw.

As noted in the previous paragraph, complete destruction of the capsule will follow thrust termination at a velocity of approximately 24,400 fps after 520 seconds of flight. A re-entry history plot of significant parameters in this case is given in Fig. 12. A capsule temperature history for this case is given in Fig. 13. On the basis of plasma arc test results, it was assumed that the tantalum liner undergoes rapid oxidation at temperatures in excess of 2700° F in air, and that catas-

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Total Heat Input ($\text{Btu}/\text{ft}^2 \times 10^3$)

Heating Rate ($\text{Btu}/\text{ft}^2 \text{-sec}$)

Inertial Velocity ($\text{fps} \times 10^3$)

Altitude ($\text{ft} \times 10^5$)

Time from 400,000 Feet (sec)

Fig. 10. Re-Entry History--Centaur Thrust Termination at 452 Seconds After Launch (Case 8)

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Fig. 11. Temperature History of Fuel Capsule (Case 6)--Partial Burnup

Fig. 12. Re-Entry History--Centaur Thrust Termination at 520 Seconds (Case 5)

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Fig. 13. Temperature History of Fuel Capsule (Case 5)--Complete Burnup

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trophic failure releases the radioisotope. This action occurs 204 seconds from 400,000 feet at an altitude of 148,000 feet. Approximately 44 seconds remain for dispersion of the radioisotope before the capsule descends to an altitude of 100,000 feet. As the velocity approaches that required for orbit, a failure will result in earlier peaking of the heating rate and larger total heat inputs. Figure 14 presents the re-entry history following failure at 533.40 seconds at a velocity of 25,359 fps. Although failures occurring during this period result in projected impact points on the African land mass, aerodynamic heating is sufficient to cause release and dispersion of the radioactive fuel above an altitude of 100,000 feet. Calculations concerning the significance of this high altitude release are developed in Appendix A. A maximum amount of Curium-242 in the troposphere, 440 curies, would be reached 61 days after release. If the bomb debris fallout pattern is assumed, the calculated maximum activity is $3.72 \times 10^{-16} \mu\text{C}/\text{cm}^3$, well below the maximum permissible concentration in air, $4 \times 10^{-11} \text{ curie}/\text{cm}^3$. Although the particle concentration is extremely low, the possibility that an individual may inhale such a particle does exist. Based on a particle biological half life in the lung of 120 hours, a total integrated radiation dose of 4.2 rads will result. The maximum allowable lung dose is 15 rads for one year.

5. Thrust Misalignment After Centaur Engine Ignition

Various degrees of thrust misalignment after Centaur ignition were assumed in order to determine the spread of projected impact areas in the event of guidance system failure. Although the vehicle is initially flying an optimum trajectory and continues to provide thrust for its total programmed period, a significant misalignment of the thrust vector will prevent attainment of orbital injection velocity. Misalignments in yaw of 10, 30, 60, 90, 120 and 150 degrees in the thrust vector were considered. Data on the actual amount of misalignment possible, or rate of thrust vector change without structural breakup of the vehicle, were not available. However, for this study, misalignments of the thrust vector from the initial velocity vector, to the degree indicated, were assumed to be instantaneous displacements. Although full thrust over the programmed period is assumed, orbital velocity is not attained in any of the cases considered. Heating rates and total heat inputs resulting from re-entry along new trajectories defined by degree of misalignment were compared to those achieved on the nominal trajectory, to define new areas of intact re-entry, partial burnup, and total destruction. The effective result was an extension of these areas to the north and south of the nominal trajectories at reduced ranges.

An extension of these areas to the north of the 90-degree launch azimuth trajectory will not change the conclusions previously drawn as to radioisotope disposition. However, an extension of the intact

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Fig. 14. Re-Entry History--Centaur Thrust Termination at 533.4 Seconds (Case 1)

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re-entry and partial burnup areas to the south of the 112-degree launch trajectory creates a situation in which land impact or release is possible. Projected impact points in the partial burnup area include the northern coast of South America and some of the islands ringing the Caribbean. This condition could result only if misalignment in yaw approaching 60 degrees were to occur. At this angle the possibility of vehicle structural failure and early thrust termination is very high.

Although land impact with subsequent burial is a remote possibility, its consequences are investigated in Appendix A. Should the external structure of the generator be removed through aerodynamic heating, the high specific thermal energy of the capsule alone will create temperatures in excess of material melting points if burial occurs in dry sand or soil. Should the burial take place in average or damp soil, capsule materials will withstand the calculated temperatures unless severely weakened by re-entry heating.

6. Ascent Abort Summary

A pictorial summary of consequences of vehicle failure during the ascent to orbit is given in Fig. 15. The shaded portions labeled "intact impact" and "partial burnup" are the only areas in which the generator, or portions thereof, will return directly to the earth's surface following failure to orbit. The area downrange bounded by the normal trajectory trace, or locus of impact points due to thrust misalignment, defines theoretical projected impact points only. Velocities achieved prior to failure are sufficient to cause total generator destruction and radioisotope dispersion. Resulting particles will be dispersed in the stratosphere and return to earth in a manner similar to that of bomb debris. Table 1 presents a summary of important parameters for the cases investigated.

C. LUNAR ABORTS

Following an unpowered coast in orbit, the spacecraft will be injected into a lunar transfer trajectory by a second firing of the Centaur engines. Vehicle failures during this period may be divided into two general classes: failure to ignite, and failure to achieve an adequate transfer trajectory. In the former case, predicted lifetime in a circular orbit will range from one to three days prior to re-entry (Ref. 13). Aerodynamic heating on re-entry will be more than sufficient to cause total generator destruction, and radioactive material disposition will be as noted in the previous section. In the latter case, an almost infinite variety of situations may result from guidance failures or vehicle malfunction during this firing period. Monitoring of vehicle orientation during the orbital coast phase will preclude the possibility of immediate powered re-entry on ignition. Guidance failure following suc-

Fig. 15. Locus of Projected Impact Points

TABLE 1
Summary of Abort Parameters

Case No.	Time of Failure (sec from launch)	Inertial Velocity at Failure (fps)	Earth Relative Velocity at Failure (fps)	Altitude at Failure (ft)	Longitude* (degrees) (+ East)	Latitude* (degrees) (+ North)	Abort Condition	Fate of Fuel Capsule
1	533.40	25,359	23,981	613,600	+39.99	-19.26		Burnup
2	532.00	25,258	23,880	613,700	+7.39	-3.25		Burnup
3	528.00	24,980	23,602	613,800	-10.59	+7.17		Burnup
4	524.00	24,707	23,328	614,000	-19.13	+11.82		Burnup
5	520.00	24,440	23,062	614,200	-24.52	+14.50		Burnup
6	508.00	23,669	22,290	615,200	-33.87	+18.68	Premature Centaur cutoff	Partial burnup
7	488.00	22,475	21,096	617,000	-41.83	+21.68		Partial burnup
8	452.00	20,567	19,188	618,900	-50.84	+24.13		Partial burnup
9	408.00	18,570	17,191	613,100	-54.91	+25.45		Intact re-entry
10	352.00	16,444	15,069	584,800	-59.30	+26.45		Intact re-entry
11	292.00	14,586	13,221	519,100	-63.57	+27.16		Intact re-entry
12	277.90	14,206	12,844	497,500	-64.40	+27.29	Centaur ignition failure	Intact re-entry
13	152.84	9,937	8,659	205,100	-75.34	+28.43	Sustainer engine failure	Intact re-entry
14	535.34	25,495	24,117	613,600	+84.71	-19.33	Simulated random re-entry	Burnup
15	277.90**	14,206	12,844	497,500	+81.67	-27.90	10° yaw of Centaur	Burnup
16	277.90**	14,206	12,844	497,500	+17.96	+20.03	30° yaw of Centaur	Burnup
17	277.90**	14,206	12,844	497,500	+50.25	+31.51	60° yaw of Centaur	Partial burnup
18	277.90**	14,206	12,844	497,500	+60.97	+32.25	90° yaw of Centaur	Partial burnup
19	277.90**	14,206	12,844	497,500	-66.08	+31.28	120° yaw of Centaur	Intact re-entry
20	277.90**	14,206	12,844	497,500	-68.63	+29.71	150° yaw of Centaur	Intact re-entry
21	80.00	2,824	1,751	43,902	-80.01	+28.49	Failure at maximum dynamic pressure	Intact re-entry

*Projected impact location along 90-degree launch azimuth.
**Time of guidance failure followed by normal Centaur burning period.

cessful ignition may create re-entry conditions with velocities ranging from circular to near-escape, depending on the mode of failure. Entry angles may vary from zero to some maximum determined by conditions of departure from the parking orbit or by the proximity of the vehicle to the moon and its gravitational influence.

In order better to define prime parameters without a complete and lengthy analysis, re-entry trajectories were further subdivided into two classes, as illustrated in Fig. 16.

The first class is essentially two-body, or Keplerian, orbit. The right-hand boundary line in the figure represents the steepest re-entry angles possible from this type of abort. This line is the locus of entry conditions for thrust misalignment on leaving the parking orbit and establishing a ballistic-type trajectory in cis-lunar space.

The second class of aborts from a lunar mission are those which result in a near miss of the moon. Various types of unstable orbits are possible under these conditions, some of which result in earth impact or grazing re-entry. Nearly rectilinear motion is possible, resulting in very steep entry angles at near-escape speed. As indicated, this type of approach can result in intact fuel core re-entry at some random point on the surface of the earth. With steep supercircular re-entry, terrific decelerations will occur near the point of maximum temperature. It is conceivable that the radioisotope could be scattered at altitudes close to 100,000 feet where remaining aerodynamic heating would be insufficient for burnup.

The above treatment is qualitative only. Further study of the actual lunar trajectory is required to obtain more detailed information.

Fig. 16. Lunar Abort--Limiting Entry Conditions

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V. GENERATOR CONFIGURATION STUDY

A companion design study was initiated to define the configuration and performance of the thermoelectric generator beyond that data developed through the earlier conceptual design described in Chapter II of this report. Spacecraft power demands necessitated an increase in electrical output and radioisotope fuel quantity. In addition, shielding material was incorporated around the fuel capsule to meet the stringent radiation flux limits of the scientific instruments making up the vehicle payload. A complete evaluation of the revised configuration was not possible within the scope of this program. Changes significant to the safety of the unit were investigated in a cursory fashion to aid in the guidance of future programs.

A. GENERATOR CONFIGURATION

The external configuration of the generator remains cylindrical, with attached fins. Cylinder dimensions have been increased to 8 inches, diameter, and 9 inches, length. Tapered fins are attached to one side of the cylinder to form a 13- by 13-inch radiating surface which provides heat to an adjacent electronics compartment. Minor changes were made in the thermoelectric module but are not of significance to this report.

Major changes were incorporated in the configuration of the heat source. Primary containment is still provided by a Hastelloy-C capsule with a tantalum liner. The volume of the capsule was increased to retain the same relation of fuel to void volume with 8.15 grams of curium oxide. Capsule wall thickness was decreased to 0.10 inch since, in the revised design, it receives structural support from the shield material. As a result, external capsule dimensions are 1.0 inch, diameter, and 2.4 inches, length. This capsule is then inserted in a radiation shield assembly and retained by a screw plug. The shield assembly consists of a cylindrical block 4.2 inches in diameter and 2.7 inches in length, made up primarily of a tungsten alloy with an insert of beryllium. Up to a radius of 0.75 inch, the tungsten alloy is solid, completely surrounding the capsule. Beyond this radius, both the flat-sided segment of beryllium and the tungsten are drilled with 0.125-inch diameter holes parallel to the cylindrical axis in a homogeneous pattern. In the sectors where additional shielding is required, tungsten rods are inserted in the holes to give the desired effective shield thickness. Beryllium skirts are attached to both ends of the cylinder to hold the assembly together and provide a heat dump radiator surface. This arrangement is sketched in Fig. 17.

Fig. 17. Revised Generator Arrangement

Approximately 8.15 grams of curium oxide, containing 7.65 grams of Curium-242, will produce 930 watts of thermal energy at the time of encapsulation. This quantity is determined by the requirement to deliver 25 watts of electrical power in a lunar night environment after a 40-day period for shipping and optional hold and 90 days of operation on the moon. Additional details of generator construction and performance may be obtained from a companion report (Ref. 14).

B. SAFETY EVALUATION

A complete evaluation was not conducted, but changes significant to the safety of the unit were investigated.

1. Radiobiological Properties

Production of neutrons by alpha-neutron reactions is increased because of the light element oxygen in the fuel compound. However, the most abundant isotope of oxygen, O_{16} , does not contribute to neutron production as the reaction energy threshold is about 15 mev. Although the amount of radioactive material has been increased, the maximum dose rate has increased only slightly, to 144 mrem/hr 50 inches from the source, due to attenuation of the gamma flux by the tungsten shield material.

2. Capsule Allowables

Detailed calculations to determine allowable internal and external pressure loads of the revised capsule were not conducted. However, in this case, the capsule gains appreciable strength from the surrounding tungsten and the complete assembly should possess superior resistance to the anticipated loads.

3. Ascent Aborts

Configuration changes previously discussed have their greatest effect in the area of re-entry heating following vehicle failure during ascent to orbit. Two factors resulting from incorporation of the shield material are primarily responsible for differences in this area of analysis. First, the increase in size relative to weight causes a decrease in the ballistic coefficient ($W/C_d A$). As a result, the capsule follows a re-entry trajectory in which it receives an increased total heat input over a longer period. This condition is illustrated by the plot of significant parameters versus time given in Fig. 18. In order to establish maximum heating conditions, only the capsule and its tungsten shield material were used, with a trajectory typical of a re-entry from the 100-nautical mile parking orbit. A two-dimensional heat transfer analy-

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Fig. 18. Re-Entry History--Return from Orbit, Revised Capsule

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sis indicated that a maximum temperature of 4820° F would result. A plot of critical element temperature versus time is given in Fig. 19. To simplify the heating analysis, it was assumed that the total re-entry body was composed of tungsten.

The second factor is apparent through a comparison of maximum temperature and the melting point of tungsten, 6170° F. If a temperature short of melting were used as the sole criterion, intact re-entry could be predicted in this case. However, tungsten begins to oxidize in air at 752° F. Oxidation becomes more rapid, and the trioxide begins to volatilize, above 1382° F. For normal operating temperatures, increased resistance to oxidation can be obtained through alloying or protective coatings. Tests of coatings indicate that protection can be provided up to 2000° F (Ref. 15).

If the oxidation rate of tungsten after failure of the coating is catastrophic, radioisotope release through re-entry heating will be similar to the case represented by Fig. 13. In this case the Hastelloy C capsule was exposed by melting of the copper radiator after 18 seconds at temperatures above 2000° F. Thus, if destruction of the tungsten occurs within 18 seconds, the areas of impact, partial burnup and complete destruction remain essentially as previously described. At the opposite extreme, intact impact may be predicted for all abort cases and orbital re-entry if the oxidation rate is slow enough to ensure survival after approximately 1000 seconds above 2000° F. More accurate data on tungsten oxidation and penetration rates are required to define the predicted situation between these two extremes.

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Fig. 19. Time-Temperature History of Tungsten Capsule, Critical Element--Random Re-Entry from Orbit

VI. CONCLUSIONS AND RECOMMENDATIONS

Criteria defining acceptability from a safety standpoint are successfully satisfied during the ascent-to-orbit phase by the initial generator configuration, in that:

- (1) Absolute containment is assured through early phases of launch when release could result in possible ingestion of the radioisotope.
- (2) Release of the radioisotope through vehicle failures later in the ascent phase could take place only in the open ocean or at altitudes above 100,000 feet.

Guidance failures of the Centaur stage could result in land release on the more southerly launch azimuths. It is recommended that an active destruct system be incorporated in the Centaur stage, and that launch azimuths be restricted to 90 to 96 degrees to eliminate this possibility. It is further recommended that tests be conducted to determine more accurately the thermal and explosive yield of a liquid oxygen-liquid hydrogen fuel load in the event of failure on the launch pad.

Consequences of vehicle failure during injection into the lunar transfer orbit cannot be defined beyond the limiting conditions established without a more extensive study of the trajectory, control system characteristics, and statistical failure analysis.

With the revised generator configuration, more accurate data on tungsten oxidation and penetration rates are required to determine safety criteria compliance. Two approaches are possible. First, the tungsten shield material may be segmented and restrained during normal operations by bands or connectors of lower-temperature material. This arrangement would ensure that partial or complete burnup could occur only in the areas previously defined. A second approach would be to attempt to delay effects of re-entry heating through improved coatings, to the point where capsule integrity could be assured under all anticipated conditions.

It is recommended that both approaches be pursued in order to define the possibility of intact re-entry. Pending a more complete analysis of the consequences of vehicle failure during lunar transfer, intact re-entry may prove to be more desirable.

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APPENDIX A

FUEL PROPERTIES

A 15x15 grid of dots forming a stylized drawing of a person with arms raised in a 'V' shape. The figure is composed of black dots on a white background. The head is a small circle of dots at the top. The torso is a vertical line of dots. The arms are raised in a 'V' shape, with each arm consisting of a series of dots. The legs are also represented by dots, forming a base for the figure.

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I.TABLE A-1

Properties of Curium-242 and Plutonium-238

<u>Property</u>	<u>Cm-242</u>	<u>Pu-238</u>
Atomic weight	242	238.124
Density (gm/cm ³)	13.5	19.816 at 70° F 16.51 at 914° F
Melting point (°F)	1742	1183
Specific activity (curies/gm)	3.31 x 10 ³	16.77
Specific power (watts/gm)	120	0.545

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II. DECAY SCHEMES OF CURIUM-242 AND PLUTONIUM-238

Curium-242 decays to Plutonium-238 by alpha emission, with a half life of 162.5 days. Plutonium-238, with a half life of 89.6 years, decays by alpha emission to Uranium-234. Curium-242 emits highly energetic alpha particles, with 73.7% of the disintegrations going directly to the ground state of Plutonium-238.

Fig. A-1. Decay Schemes

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III.

Fig. A-2. Decay Products of Cm-242 and Pu-238

Isotope	Gamma Rays		Neutrons/sec/ gm from Spontaneous Fissioning
	Energy (mev)	Fraction of Disin- tegrations in Which γ -Ray is Produced	
Cm-242	0.044	4.1×10^{-4}	2.013×10^7
	0.100	6×10^{-5}	
	0.157	2.7×10^{-5}	
	0.210	2×10^{-7}	
	0.562	1.8×10^{-6}	
	0.605	1.4×10^{-6}	
	0.89	0.9×10^{-7}	
Pu-238	1.01	10^{-7}	4.4×10^3
	0.0438	3.8×10^{-4}	
	0.099	8×10^{-5}	
	0.150	1×10^{-5}	
	0.203	4×10^{-8}	
	0.760	5×10^{-7}	
	0.810	$\sim 10^{-7}$	
U-234	0.875	2×10^{-7}	7.08×10^{-3}
	0.050	0.283	
	0.118	0.003	
	0.450	2×10^{-7}	
Th-230	0.500	1×10^{-7}	9.6×10^{-4}
	0.068	0.0059	
	0.110	1×10^{-6}	
	0.142	7×10^{-4}	
	0.184	1.4×10^{-4}	
	0.206	5×10^{-8}	
	0.235	5×10^{-8}	
Ra-226	0.253	1.78×10^{-4}	
	0.184	0.012	
	0.26	7×10^{-5}	
	0.42	2×10^{-6}	
Rn-222	0.61	2×10^{-6}	
	0.51	0.0007	
Po-218	None Listed		
Pb-214	0.241	0.115	
	0.294	0.258	
	0.350	0.450	
Bi-214	0.607	0.658	
	0.766	0.065	
	0.933	0.067	
	1.120	0.206	
	1.238	0.063	
	1.379	0.064	
	1.761	0.258	
	2.198	0.074	
Po-214	None Listed		
Pb-210	0.0465	0.04	
Bi-210	None Listed		
Po-210	0.803	1.8×10^{-5}	

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IV.
TABLE A-2
Calculated Dose Rates Around Surveyor Generator

Contributor	Dose Rates (millirads/hr)			
	At 0.3 Meter		At One Meter	
	Without Polyethylene	With 0.084 Meter of Polyethylene	Without Polyethylene	With 0.084 Meter of Polyethylene
Decay gammas	181	64	16.8	6.0
Prompt fission gammas	40	25	3.7	2.3
Fission product gammas	37	22	3.4	1.9
Gammas from inelastic- ally scattered neutrons	0.15	0.07	0.015	
Total gammas	258	111	23	10.2
Neutrons	1376	540	129	50.0
Total dose rates	1634	651	152	60.2

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V. MAXIMUM PERMISSIBLE CONCENTRATIONS

Potential radiobiological hazards from the alpha radiation can arise only if the fuel is released in a form in which 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 critical organ is the lung. Excessive doses may also occur to the gastrointestinal tract from insoluble Curium-242 passing through it.

The biological course of plutonium is different. For soluble forms, the bone is the critical organ. For insoluble forms, the critical organs are the lung and the lower large intestine.

Table A-3 gives the maximum permissible burden (MPB), the maximum permissible concentration in water (MPCw) and in air (MPCa). These values are radiation protection guide limits agreed upon by Committee II, International Commission on Radiological Protection. The 40-hour week tolerances are those suggested for persons continuously employed in nuclear work. The 168-hour week tolerances are for the general population. In the table, underlining indicates the critical organs and the corresponding concentrations.

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TABLE A-3
Radiation Protection Guide Limits of Curium-242
and Plutonium-238

Cm-242	Organ	MPB (μc)	Maximum Permissible Concentration ($\mu\text{c}/\text{cm}^3$)			
			40-Hour Week		168-Hour Week	
			MPCw	MPCa	MPCw	MPCa
Soluble	GI (LLI)	0.05	7×10^{-4}	2×10^{-7}	2×10^{-4}	5×10^{-8}
	Liver		3×10^{-3}	1×10^{-10}	9×10^{-4}	4×10^{-11}
	Bone		5×10^{-3}	2×10^{-10}	2×10^{-3}	8×10^{-11}
	Kidney		9×10^{-3}	4×10^{-10}	3×10^{-3}	1×10^{-10}
	Total body		0.01	6×10^{-10}	5×10^{-3}	2×10^{-10}
Insoluble	Lung		2×10^{-10}		6×10^{-11}	
	GI (LLI)		7×10^{-4}	1×10^{-7}	2×10^{-4}	4×10^{-8}
Pu-238						
Soluble	Bone	0.04	1×10^{-4}	2×10^{-12}	5×10^{-5}	7×10^{-13}
	Liver	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}
	GI (LLI)		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	Lung			3×10^{-11}		1×10^{-11}
	GI (LLI)		8×10^{-4}	1×10^{-7}	3×10^{-4}	5×10^{-8}

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VI. RELEASE OF RADIOISOTOPE IN THE OCEAN

In case of failure of the booster rocket shortly after launch, it is assumed that the debris will descend into the coastal waters. Because of the containment provided, the time of release of the fuel from the capsule is remote. Later in the flight, capsule integrity may be degraded through aerodynamic heating on re-entry. The following calculations are based on the assumption that the Curium-242 fuel is released and is initially distributed uniformly in a vertical column of water. Lateral diffusion in the ocean is much greater than vertical diffusion. This situation is due to the highly stable conditions produced by the pressure and temperature gradients below the surface layer. Revelle et al (Ref. A-1) introduced fission products into the ocean at considerable depth. They were able to trace the diffusion over an area of 100 km², or more. The vertical thickness of the diffusion layer was of the order of one meter. The lateral diffusion process of the fuel is approximated by the equation (Ref. A-2)

$$P = \frac{M}{2\pi k^2 t^2} \exp \left(-\frac{r^2}{2 k^2 t^2} \right)$$

where

P = concentration (curies/meter³, or $\mu\text{c}/\text{cm}^3$)

M = linear concentration at the source (curies/meter)

t = time (sec)

r = radial distance from the source (meters)

k = diffusion velocity (meters/sec)

For the analytical model it is assumed that the total activity (22.8×10^3 curies) of the fuel is initially released in a column of water one meter high. The diffusion velocity is assumed to be 5×10^{-3} meter/sec or 4.32×10^2 meters/day. Munk et al (Ref. A-3) found this value in their study of the diffusion of fission products in Bikini Lagoon. Other sources (Refs. A-4 and A-5) report values ranging from 2×10^{-3} to 10×10^{-3} meter/sec. The concentration at a discrete distance from the source remains zero until material from the source diffuses to that point. Then the concentration will increase to a maximum at some time t_{max} and continuously decrease for all times greater than t_{max} . Figure A-3

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Fig. A-3. Diffusion of Initial Curium Released in the Ocean

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shows how concentration varies with time at four discrete points 10, 100, 1000 and 10,000 meters distant from the source. A horizontal line is drawn at the maximum permissible concentration, $2 \times 10^{-4} \mu\text{c}/\text{cm}^3$. All points above this line exceed the maximum. The concentration after 10 days is shown to be less than the maximum permissible value at all points more than 10 meters distant from the source. These results are expected to be extremely conservative because the effects of radioactive decay, currents and turbulence have been neglected.

References.

- A-1. Revelle, R. R., Folson, T. R., Goldberg, E. D., and Isaacs, J. D., "Nuclear Science and Oceanography," First Geneva Conference, Vol. 13, p 371.
- A-2. "Radioactive Waste Disposal into the Sea," TO/HS/21, April 1960, Report of the Ad Hoc Panel under the chairmanship of H. Brynielsson (Equation 52, Appendix VI, p 134).
- A-3. Munk, W. H., Ewing, G. C., and Revelle, R. R., "Diffusion in Bikini Lagoon," Transactions of the American Geophysical Union, Vol. 30(1), 1949, pp 59 to 66.
- A-4. Sverdrup, H. A., Johnson, M. W., and Fleming, R. H., "The Oceans," Prentice Hall, 1942.
- A-5. Joseph, J., and Sender, H., "Horizontal Diffusion in the Sea," Deutsche hydrographische Zeitschrift, Vol. 11(2), 1958, pp 49 to 77.

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VII. THERMAL HISTORY FOLLOWING IMPACT
AND BURIAL ON LAND

The following analysis deals with the thermal history of the generator after impact on land and subsequent insulation due to burial in the soil. For a system in which a point heat source is surrounded by concentric spherical shells, the steady-state temperature differential may be calculated from

$$\frac{dT}{dr} = - \frac{q}{KA} = - \frac{q}{4K\pi r^2}$$

or

$$T = \frac{q}{4\pi K} \left(\frac{1}{r_1} - \frac{1}{r_2} \right)$$

The heat output of the fuel capsule varies exponentially with time; therefore, the equation becomes

$$T = \frac{q \exp(-\lambda t)}{4\pi K} \left(\frac{1}{r_1} - \frac{1}{r_2} \right)$$

where

T = temperature differential (°F)

q = initial heat input (2820 Btu/hr)

K = thermal conductivity of medium (Btu/hr-ft-°F)

r₁ = radius of heat source (ft)

r₂ = radius (within medium) where temperature difference is defined (ft)

λ = decay constant of curium (2.43 x 10⁻³ day⁻¹)

t = time after encapsulation (days).

Since it is impossible to determine the thermal characteristics of the medium in which the generator might be buried, the thermal conductivities of three different media were evaluated: dry soil (8 x 10⁻² Btu/hr-ft-°F), dry sand (2.25 x 10⁻¹ Btu/hr-ft-°F), and the average

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earth crust (9.7×10^{-1} Btu/hr-ft-°F) (Ref. A-6). Figure A-4 shows the relation of time to temperature difference (between capsule or generator and surrounding medium) for the burial of the complete generator and the bare fuel core. These curves are based on a conservative assumption since r_2 is assumed to be infinite and $1/r_2$ is evaluated as zero.

It can be seen that, for some values of thermal conductivity, the generator assembly and/or the fuel capsule will melt if buried. In any case of meltdown, however, it can be justly assumed that the molten mass (the fuel, generator materials and the medium of burial) will solidify as it permeates through the surrounding medium. Since the oxide of the fuel or its decay products is relatively insoluble in water, it is improbable that the ground water or any other material which might enter into the human biological cycle would be contaminated. Also, the solidified mass, including medium of burial, will act as a semicontainment shell for the radioactive fuel material.

Reference.

- A-6. "Handbook of Chemistry and Physics," 31st Edition, Chemical Rubber Publishing Company, Cleveland, Ohio, 1949.

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Fig. A-4. Thermal History of Buried Generator

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A. REGIONAL ATMOSPHERIC MODEL RELATIONS

Present information seems to indicate that the boundary--the tropopause--between the stratosphere and the troposphere has a membrane property of resisting the passage of very small diameter particulate matter in either direction. Fallout data taken from bomb debris have shown that the mean residence times for such materials in the two atmospheric regions are different. The amount of particulate matter remaining in either region is a function of the amount initially injected, the mean residence time, and the lapsed time. These relations can be used to postulate a mathematical model for the fallout of isotopes released in the stratosphere.

A quantity of curium (A_0) introduced into the stratosphere at time t equal to zero is assumed to spread instantaneously throughout the region. This assumption is valid if the material is introduced at altitudes in excess of 100,000 feet. The loss of curium from the stratosphere will be due to radioactive decay and to the passage of curium through the tropopause into the troposphere. The following equation applies:

Rate of change of amount of curium in stratosphere	=	rate of loss of curium to tropo- sphere	+	rate of radio- active decay.
--	---	---	---	---------------------------------

$$\frac{dA_1(t)}{dt} = -k_1 A_1(t) - \lambda A_1(t) \quad (1)$$

where

A_1 = amount of curium in stratosphere

k_1 = a proportionality constant

λ = decay constant.

Equation (1) can be rewritten as

$$\frac{dA_1(t)}{dt} = -(k_1 + \lambda) A_1(t)$$

which has the solution

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$$A_1(t) = A_0 \exp \left[- (k_1 + \lambda) t \right] \quad (2)$$

If instantaneous mixing of the curium is assumed to occur in the troposphere, then

Rate of change of curium in troposphere = rate of loss from stratosphere - rate of loss due to decay - rate of loss due to deposit on earth

$$\frac{dA_2(t)}{dt} = k_1 A_1(t) - \lambda A_2(t) - k_2 A_2(t) \quad (3)$$

where

A_2 = amount of curium in troposphere

k_2 = a proportionality constant.

When combined with Eq. (2), Eq. (3) becomes

$$\frac{dA_2(t)}{dt} = k_1 A_0 \exp \left[- (k_1 + \lambda) t \right] - (k_2 + \lambda) A_2(t) \quad (4)$$

Its solution is

$$A_2(t) \exp \left[(k_2 + \lambda) t \right] = \frac{k_1 A_0}{k_2 - k_1} \exp \left[(k_2 - k_1) t \right] \quad (5)$$

where C is an integration constant.

When $A_2(0) = 0$, then $C = \frac{k_1 A_0}{k_2 - k_1}$

and Eq. (5), simplified, becomes

$$A_2(t) = \left(\frac{k_1}{k_2 - k_1} \right) A_0 \exp (-\lambda t) \left[\exp (-k_1 t) - \exp (-k_2 t) \right] \quad (6)$$

The maximum amount of curium in the troposphere will occur at $t = t_m$, as found from the equation

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$$\frac{dA_2(t_m)}{dt} = 0 = \left(\frac{k_1 A_0}{k_2 - k_1} \right) \left\{ (k_1 + \lambda) \exp \left[- (k_1 + \lambda) t_m \right] + (k_2 + \lambda) \exp \left[- (k_2 + \lambda) t_m \right] \right\}$$

Solving for t_m gives

$$t_m = \frac{\ln \left(\frac{k_2 + \lambda}{k_1 + \lambda} \right)}{k_2 - k_1} \quad (7)$$

By substituting this expression for t in Eq. (6), the maximum amount of curium in the troposphere can be calculated.

The amount of curium fallout on the earth's surface at time t can be found from the equation

Rate of change of amount on earth's surface	=	rate of addi- tion from troposphere	-	rate of radio- active decay.
---	---	---	---	---------------------------------

$$\frac{dA_3(t)}{dt} = k_2 A_2(t) - \lambda A_3(t)$$

where

A_3 = amount of curium on the surface of the earth.

The above equation can be rewritten as follows:

$$\frac{dA_3(t)}{dt} \exp(\lambda t) + \lambda A_3(t) \exp(\lambda t) = k_2 A_2(t) \exp(\lambda t)$$

and

$$A_3(t) \exp(\lambda t) = \int k_2 A_2(t) \exp(\lambda t) dt + C$$

At $t = 0$, $A_3 = 0$,

and

$$C = - \int_{t=0} k_2 A_2(t) \exp(\lambda t) dt$$

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Then

$$A_3(t) = \frac{A_0}{k_2 - k_1} \left\{ k_1 \exp \left[- (k_2 + \lambda) t \right] - k_2 \exp \left[- (k_1 + \lambda) t \right] + (k_2 - k_1) \exp (- \lambda t) \right\} \quad (8)$$

To find the time (t_m) at which the amount of curium on the earth's surface (A_3) is a maximum, A_3 is differentiated with respect to t . The results are set equal to zero, and resulting equation solved for t_m . However, this equation is found to be transcendental; t_m must be found by trial and error.

B. CALCULATED VALUES

The mean residence time for small diameter particulate matter in the stratosphere is 1000 days.

$$\text{Mean residence time} = \frac{T_{1/2}}{0.693} = 1000 \text{ days}$$

$$T_{1/2} \text{ (the half life)} = 693 \text{ days, and}$$

$$k_1 = \frac{0.693}{T_{1/2}} = \frac{0.693}{693} = 10^{-3} \text{ days}^{-1}$$

The mean residence time for the same material in the troposphere is 30 days, so that

$$k_2 = \frac{0.693}{30 \times 0.693} = \frac{1}{30} = 3.33 \times 10^{-2} \text{ days}^{-1}$$

The radioactive half life of Curium-242 is 162.5 days, so that

$$\lambda = \frac{0.693}{162.5} = 4.26 \times 10^{-3} \text{ days}^{-1}$$

Substituting these values in Eq. (7) for the time of maximum amount in the troposphere gives

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$$t_m = \frac{\ln \left(\frac{33.33 \times 10^{-3} + 4.26 \times 10^{-3}}{1 \times 10^{-3} + 4.26 \times 10^{-3}} \right)}{33.33 \times 10^{-3} - 1 \times 10^{-3}} = 60.8 \text{ days}$$

The maximum amount of Curium-242 in the troposphere (A_2) at 60.8 days is given by Eq. (6), where

$$A_0 = 22.8 \times 10^3 \text{ curies}$$

$$A_2 = 440 \text{ curies.}$$

The amount of Curium-242 in the troposphere as a function of time after capsule burnup is shown in Fig. A-5, which was obtained from Eq. (6). The amount of the isotope resting on the surface of the earth as a function of time is shown in Fig. A-6, which was calculated from Eq. (8). These curves are based on the assumption that no decay time has lapsed since the fueling of the generator. Since this assumption represents the worst possible condition, it would be comparable to failure of the booster to inject generator into orbit upon approaching orbital altitudes.

C. RADIOBIOLOGICAL HAZARDS

1. Maximum Activity in the Troposphere

If the worst possible condition is assumed, in which the SNAP generator is not injected into orbit and burned up upon re-entry, the maximum amount of Curium-242 in the troposphere would be 440 curies 60.8 days after burnup. If the bomb debris fallout pattern is followed--approximately 2/3 of the curium deposited in the northern or southern hemisphere between 30 and 60 degrees latitude, then the maximum activity per cubic meter can be approximated. The volume of the troposphere between these latitudes, to an altitude of 10,700 meters, is 7.83×10^{17} cubic meters.

$$\begin{aligned} \text{Maximum activity} &= \frac{2}{3} \left(\frac{440 \text{ curies}}{7.83 \times 10^{17} \text{ meters}^3} \right) = 37.24 \times 10^{-17} \text{ curie/meter}^3 \\ &= 3.72 \times 10^{-16} \mu\text{c/cm}^3 \end{aligned}$$

Since the MPC of Curium-242 in air is $4 \times 10^{-11} \mu\text{c/cm}^3$, the above concentration represents no hazard.

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Fig. A-5. Curium Activity in the Troposphere as a Function of Time After Re-Entry

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Fig. A-6. Curium Activity at the Surface of the Earth as a Function of Time After Re-Entry Burnup

2. Activity of a One-Micron Particle of Curium-242 at Time of Maximum Activity in the Troposphere

The total amount of curium and its decay products present in the troposphere (60.8 days) can be approximated by the equation

$$M = \frac{M_0 k_1}{k_2 - k_1} \left[\exp(-k_1 t) - \exp(-k_2 t) \right] \quad (9)$$

where

M_0 = 6.9 grams, weight of Curium-242 at time of capsule fueling

k_1 and k_2 = constants (defined previously)

M = 0.173 grams, the weight of curium and decay products present in the troposphere 60.8 days after burnup.

If it is assumed that the average diameter of the fuel material is one micron after re-entry burnup, the average particle concentration in the troposphere and the particle activity can be approximated.

$$\text{Weight of a particle (W)} = \frac{4}{3} \pi r^3 \rho$$

where

ρ = density of Cm_2O_3 = 11.75 gm/cm³

r = 0.5×10^{-4} cm

$$W = \frac{4}{3} (3.14) (11.75) (12.5 \times 10^{-14}) = 6.15 \times 10^{-12} \text{ gm}$$

Equation (9) shows that the weight of fuel material in the troposphere is 0.173 gram; thus, there are 2.81×10^{10} particles in the troposphere. If the volume of the troposphere is 7.83×10^{17} cubic meters, then there is one particle per 2.78×10^7 cubic meters, an extremely low particle concentration.

Even though the particle concentration in the troposphere is extremely low, there is the possibility that some individual may inhale such a particle. If the world population is taken as 2.85×10^9 indi-

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viduals (1958 figures) who have an average respiratory exchange of 20 m.³/day, the total volume respired by the world population in 24 hours is 5.7×10^{10} cubic meters. On this basis it is possible that 2050 individuals may each inhale a particle of Curium-242 during a 24-hour period, 60.8 days after re-entry burnup.

The radioactivity of the individual particle is of concern when it is inhaled because of the ensuing lung radiation dose. The total activity in the troposphere at the time of maximum activity was found to be 440 curies, so that the activity of each particle is 1.82×10^{-8} curie. If the biological half life of the particle in the lung is taken as 120 hours, the lung will receive a radiation dose of 4.2 rads, calculated by the method of Morgan (Ref. A-7). This radiation dose is less than one third the 15-rad dose allowable for the lungs in one year.

Figure A-5 shows that appreciable curium activity may exist in the troposphere from the twentieth to the two-hundredth day following re-entry burnup. This fact indicates that more than 180 times the 2050 individuals, or more than 369,000 persons in the whole world, could receive an organ dose approaching one third of that allowable. However, the fact that such exposure can occur only if the curium-fueled generator is not injected into orbit should be emphasized. The probability of such a failure is quite small.

3. Radiobiological Consequences of the Curium-242 Decay Products

If the power source remains in orbit for 10 half lives of the Curium-242, or 1625 days, less than 0.1% of the curium parent will exist; the remainder of the material will be Plutonium-238. The activity of this material will be 115 curies. With no decay correction for plutonium because of its long half life (89.6 years), the maximum weight of Plutonium-238 dioxide in the troposphere will be 0.185 gram, with an activity of 3.16 curies at 108.4 days. If the average plutonium particle diameter upon re-entry burnup is assumed to be one micron, the weight of such a particle will be 6.00×10^{-12} gram. The number of particles of plutonium dioxide in the troposphere becomes 3.08×10^{10} , and the activity of such particles is 1.02×10^{-10} curies. If such a particle should be inhaled by an individual, his lungs would receive a dose of 36 millirads.

Figure A-7 shows the plutonium activity in the troposphere as a function of time after re-entry burnup. Figure A-8 shows the plutonium buildup on the surface of the earth as a function of time after re-entry burnup. These curves have assumed that the Curium-242 has completely decayed.

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Fig. A-7. Fallout History of the Decay Product of Curium-242 Within the Troposphere

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Fig. A-8. Fallout History of Decay Product of Curium-242 on Surface of the Earth

Reference.

- A-7. Report of Committee II--International Commission on Radiological Protection on Permissible Dose for Internal Radiation, 1959 Revision, Unpublished.

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APPENDIX B

FUEL CAPSULE MATERIAL PROPERTIES AND STRENGTH
CALCULATIONS

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Properties of Hastelloy C (Ref. B-1)

Density (lb/in. ³)	0.323
Melting point (°F)	2318 to 2381
Specific heat (Btu/lb-°F)	0.0920
Thermal conductivity (Btu/hr-ft-°F)	
392° F	6.65
1112° F	9.88

Strength Properties with Respect to Temperature

<u>Temperature</u> (°F)	<u>Typical</u> <u>Elongation</u> (%)	<u>Ultimate Tensile</u> <u>Strength</u> (psi x 10 ³)	<u>Yield Strength</u> (psi x 10 ³)
1200	27.0	101.7	49.8
1400	51.0	80.8	47.1
1600	47.0	45.0	36.5
1800	37.6	26.9	--
1900	35.5	14.2	--
Room tem- perature	44.0	130.0	71.8

Chemical Composition

<u>Material</u>	<u>Amount by Weight</u> (%)
Ni	52.6
Cr	16.5
Mo	17.0

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TABLE B-1 (continued)

<u>Material</u>	<u>Amount by Weight (%)</u>
Fe	6.0
C	0.5
Co	2.5
V	0.4
W	4.5

Typical Penetration Rates (Ref. B-2)

<u>Media</u>	<u>Concentration (% by wt)</u>	<u>Penetration Rate (mils/yr, room temperature)</u>
Acetic acid	50	0.1
Chlorine gas	--	0.1
Chromic acid	20	0.1
Cupric chloride	10	None
Cupric chloride	10 + 10% NaCl	None
Ferric chloride	5 + 10% NaCl	None
Ferric chloride	10	None
Formic acid	89	0.1
Hydrochloric acid	37	1.0
Hydrofluoric acid	45	6.0
Nitric acid	70	1.0
Phosphoric acid	85	None
Sulphuric acid	96	0.2
Sea water*	20,000 ppm Cl ⁻ ions at a pH of 6.6	Less than 2.0

*Determined in laboratory tests.

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Corrosion test samples of Hastelloy C have been submerged in actual sea water for over 10 years at The International Nickel Company's Harbor Island Test Station, North Carolina. After this period, they have shown only negligible weight loss and no pitting or crevice corrosion under the retaining washer.

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II.

TABLE B-2

Physical Properties of Tantalum (Ref. B-3)

Atomic number	73
Atomic weight	180.95
Density (lb/in. ³)	0.599
Melting point (°F)	5425
Boiling point (°F)	10,866
Specific heat (Btu/lb-°F)	
212° F	0.03364
2192° F	0.04078
Ultimate tensile strength at 2192° F (psi)	29,000
Yield strength at 2192° F (psi)	26,000
Thermal conductivity (Btu/hr-ft-°F)	
752° F	34.59
5072° F	49.59
Latent heat of fusion (Btu/lb)	10,620
Latent heat of vaporization (Btu/lb)	324

Air Oxidation Rate

<u>Temperature</u> <u>(°F)</u>	<u>Rate</u> <u>(lb/ft²-hr)</u>
500	None
932	6×10^{-5}
1472	1.9×10^{-2}
2192	0.19

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TABLE B-2 (continued)

Corrosion Properties of Tantalum

The corrosion resistance of tantalum at 68° to 302° C to almost all corrosive media is excellent except for the following media:

Hydrofluoric acid

Fused potassium hydroxide

Fused sodium hydroxide

Fuming sulfuric acid

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III.

TABLE B-3

Physical Properties of Copper (Electrolytic) (Ref. B-4)

Atomic number	29
Atomic weight	63.54
Density (lb/in. ³)	0.322
Melting point (°F)	1982
Boiling point (°F)	4712
Specific heat (Btu/lb)	0.092
Latent heat of fusion (Btu/lb)	91.1
Thermal conductivity (Btu/hr-ft-°F)	
392° F	215
752° F	210
1112° F	206
Tensile strength (hard Cu) (psi)	55,000
Latent heat of vaporization (Btu/lb)	3150

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Material: Hastelloy C

Assumed average temperature of capsule = 1400° F

Yield strength of material at 1400° F = 47.1×10^3 psiUltimate tensile strength at room temperature = 130×10^3 psi.Allowable Internal Pressure on Cylinder Wall

$$P = \frac{b^2 - a^2}{b^2 + a^2} \sigma$$

where

 σ = strength of material (psi)

a = inside radius (0.108 in.)

b = outside radius (0.233 in.).

$$P = 0.647 (47.1 \times 10^3) = 30,474 \text{ psi} = 2070 \text{ atm (yield at 1400° F)}$$

$$P = 0.647 (130 \times 10^3) = 84,010 \text{ psi} = 5700 \text{ atm (ultimate at room temperature)}$$

Allowable Pressure on Fixed End Plate of Cylinder

$$P = \frac{4t^2\sigma}{3r^2}$$

where

t = thickness of plate (0.125 in.)

r = radius of plate (0.108 in.)

 σ = yield strength of material (psi).~~SECRET~~

$$P = 1.77 (47.1 \times 10^3) = 83,400 \text{ psi} = 5670 \text{ atm}$$

Allowable External Pressures on Fuel Capsule

$$P = \frac{b^2 - a^2}{2b^2} \sigma = 0.396\sigma$$

σ = yield strength of material (psi).

<u>External Pressure (psi)</u>	<u>Temperature (°F)</u>
28.4×10^3	80
21.2×10^3	1000
18.6×10^3	1400
14.5×10^3	1600

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SECRETV. HELIUM PRESSURE DEVELOPMENT

Curium-242 decays by alpha emission, with a half life of 162.5 days. The decay product of Curium-242 is Plutonium-238, which also decays by alpha emission and has a half life of 89.6 years. The combining of the alpha particles and free electrons accounts for the creation of helium pressure within the fuel capsule. Therefore, for the helium pressure calculation, the alphas emitted from both Curium-242 and Plutonium-238 were considered. The following conditions were assumed:

- (1) Perfect gas law applies.
- (2) Thermal conductivity of generator materials remains constant with temperature.
- (3) No diffusion of helium through the capsule wall takes place.
- (4) Constant volume within capsule.
- (5) No retention of the helium atoms by the lattice of the fuel.
- (6) Complete conversion of alpha particles to helium atoms.
- (7) Plutonium-238 decay product Uranium-234 (alpha emitter) contribution is neglected because of its long half life (2.48×10^5 years).
- (8) No density changes occur with time due to conversion of curium to plutonium.

The number of Curium-242 atoms at any time is expressed by

$$N_C = N_0 \exp (-\lambda_1 t)$$

where

N_0 = initial number of Curium-242 atoms

λ_1 = decay constant = 4.28×10^{-3} days⁻¹

t = time (days).

The number of helium atoms formed is:

$$N_{He_1} = N_0 \left[1 - \exp (-\lambda_1 t) \right]$$

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It is assumed that, for every alpha decay, a Plutonium-238 atom is formed, so that the above expression also indicates the number of Plutonium-238 atoms formed. As the parent isotope decays (Curium-242), the daughter isotope (Plutonium-238) starts contributing to the total activity.

The number of Plutonium-238 atoms at any time is:

$$N_{\text{Pu}} = N_0 \left(\frac{\lambda_1}{\lambda_2 - \lambda_1} \right) \left[\exp(-\lambda_1 t) - \exp(-\lambda_2 t) \right]$$

where

$$\lambda_2 = \text{decay constant of Plutonium-238, days}^{-1}$$

The number of helium atoms formed by Plutonium-238 decay is expressed by

$$N_{\text{He}_2} = N_0 \left[1 - \exp(-\lambda_1 t) \right] - N_0 \left(\frac{\lambda_1}{\lambda_2 - \lambda_1} \right) \left[\exp(-\lambda_1 t) - \exp(-\lambda_2 t) \right]$$

Helium from Pu decay	Amount of Pu formed	Amount of Pu present
----------------------------	------------------------	----------------------

The total amount of helium at any time is

$$H_{\text{He}_T} = N_{\text{He}_1} + N_{\text{He}_2}$$

The helium gas pressure is calculated as follows

$$P = \frac{nRT}{V} \text{ (perfect gas law)}$$

where

n = moles of helium

R = gas constant = $5.17 \times 10^{-3} \frac{\text{ft}^3 \text{-atm}}{\text{moles-}^\circ\text{R}}$

T = absolute temperature of capsule ($^\circ\text{R}$)

V = void volume of capsule = $2.51 \times 10^{-5} \text{ ft}^3$.

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The amount of Curium-242-Plutonium-238 versus time is shown in Fig. B-1. The time of maximum Plutonium-238 buildup may be calculated as follows:

$$N_P = N_0 \left(\frac{\lambda_1}{\lambda_2 - \lambda_1} \right) \left[\exp(-\lambda_1 t) - \exp(-\lambda_2 t) \right]$$

Let

$$C = N_0 \left(\frac{\lambda_1}{\lambda_2 - \lambda_1} \right)$$

$$\frac{dN_P}{dt} = C \left[-\lambda_1 \exp(-\lambda_1 t) - \lambda_2 \exp(-\lambda_2 t) \right] = 0$$

$$\lambda_1 \exp(-\lambda_1 t) = \lambda_2 \exp(-\lambda_2 t)$$

$$t = \frac{1}{\lambda_1 - \lambda_2} \ln \frac{\lambda_1}{\lambda_2} = 1240 \text{ days.}$$

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Fig. B-1. Amount of Curium-242 and Plutonium-238 Versus Time

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~~SECRET~~VI. EXTERNAL FORCES FROM IMPACT

If the satellite launch does not result in a successful orbit, the generator assembly may impact on the earth. During descent, it will reach a terminal velocity which is a function of its weight (W), shape (C_d), area normal to its flight path (A), and the angle at which it falls with respect to the local horizontal. This can be described by the following equation:

$$V^2 = 841 \frac{W}{C_d A}$$

The velocity is indirectly proportional to the drag area which varies, depending upon the orientation of the body. The terminal velocities of the generator assembly and fuel capsule, respectively, are 240 fps and 366 fps, with minimum drag area orientation and vertical descent.

The impact pressure to which the fuel capsule will be subjected is calculated from the equation

$$P = \rho V^2$$

where

ρ = mass density of the unit (slugs/ft³)

V = velocity (fps).

External pressure resulting from impact versus velocity is plotted for both the complete generator and bare fuel capsule in Fig. B-2. Mass densities of 2.95 and 17.58 slugs/ft³ were used for the generator and fuel capsule, respectively.

References.

- B-1. "Hastelloy Alloy C," Haynes Stellite Company, December 1959.
- B-2. "Corrosion Resistance of Hastelloy C," Haynes Stellite Company, November 1958).
- B-3. Schmidt, F. F., "Properties of Tantalum," DMIC Report 133, July 1960.
- B-4. Tipton, C. R., Editor, "Reactor Handbook," Vol. I, Second Edition, Interscience Publishers, Inc., 1960.

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Fig. B-2. External Pressure Versus Impact Velocity

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APPENDIX C

OVERPRESSURE CALCULATION FOR LAUNCH PAD EXPLOSION

The shock pressure originating from possible mixing and detonation of liquid oxygen and RP-1 has been determined analytically by methods derived from tests with TNT. Space Technology Laboratories (Ref. C-1) have developed an empirical relation for the prediction of shock overpressures from LOX and RP-1 fuel loads at various radial distances from the point of origin of the explosion. The predicted maximum pressure is

$$P = \frac{9862}{Z^3} - \frac{187.9}{Z^2} + \frac{52.8}{Z}$$

where

$$Z = \frac{R}{W^{1/4}}$$

R = distance of generator from explosion (ft)

W = total weight of propellant (lb).

In case of an Atlas-Centaur launch pad explosion, it is assumed that two shock waves will occur. The first is the result of the booster fuel explosion; the second results from explosion of the Centaur fuel. The booster propellant is composed of LOX and RP-1 while the Centaur propellant consists of liquid hydrogen and liquid oxygen. Since little data on the explosive yield of the Centaur fuel is available, the same equation has been applied to both cases.

The booster propellant weight considered is 244,580 pounds (Ref. C-2). The Surveyor generator will be located approximately 60 feet from the booster fuel tank. Pressures calculated from the empirical equation are shown in Fig. C-1.

The parameters used to obtain pressures resulting from the Centaur propellant explosion are: propellant weight, 27,737 pounds (Ref. C-2); and generator location, approximately 10 to 20 feet from the Centaur fuel tanks. Results are depicted in Fig. C-2.

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Fig. C-1. Shock Overpressure from Booster Propellants

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Fig. C-2. Shock Overpressure from Centaur Propellants

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References.

- C-1. Smalley, W. M., and Anderson, D. E., "The Explosive Potential of Liquid Oxygen and RP-1 Missiles," GM-TR-59000-00579, January 30, 1959. CONFIDENTIAL DEFENSE INFORMATION
- C-2. Centaur Program Requirements No. 2200, Air Force Missile Test Center, November 1960. CONFIDENTIAL DEFENSE INFORMATION

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APPENDIX D

METHOD OF ANALYSIS FOR RE-ENTRY HEATING

- (1) Velocity, altitude and flight path angle, along with dimensions of the generator, including a drag curve, are used as input a two-dimensional IBM trajectory program.
- (2) The program solves the elliptic flight equations and calculates impact parameters for a vacuum-type re-entry. The velocity, altitude and flight path angle at the time of entry into the atmosphere, assumed to begin at 400,000 feet, are then used to calculate a drag-type trajectory. Position, orientation and velocity of the generator are printed out as a function of time. The ARDC 1959 model atmosphere is used.
- (3) Chapman's equation, as given in Ref. D-3, is used to determine the heat input into the body, assuming laminar heat transfer. The particular empirical constants used are shown in the following equation:

$$\dot{q} \text{ (Btu/sec-ft}^2\text{)} = \frac{17,600}{(R_n)^{1/2}} \left(\frac{\rho_{\text{altitude}}}{\rho_{\text{sea level}}} \right)^{1/2} \left(\frac{V}{V_c} \right)^{3.15}$$

where

R_n = radius of body (ft)

ρ = density of air

V = velocity relative to earth at given altitude

V_c = velocity required for circular orbit at given altitude

Since this equation predicts heating at the stagnation point on the body only (in this case the 6-inch diameter outer structure of the generator), points remote from the stagnation point were averaged in a manner similar to the method of Ref. D-1.

- (4) For the complete generator, the outer aluminum fins, radiator structure and inner stainless steel components are assumed to undergo an adiabatic heat rise. When these elements have reached their respective melting points and received the necessary heat of fusion, it is assumed that the outer structure has burned off and the inner fuel capsule is exposed.

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(5) After the capsule is exposed to re-entry heating, heat rate, determined above, is corrected by the ratio of the square root of the instantaneous body radius to the initial radius to adjust for decreasing body size. These adjusted heat rates are programmed into the IBM one-dimensional heat flow program which calculates temperatures through the body as a function of time. Heat flow through the copper, the Haynes-25 wall and the tantalum liner into the fuel is determined by assuming that each material is divided into convenient layers. When any layer has reached its melting point and absorbed its heat of fusion, it is assumed to be melted off. Complete burnup is assumed when the tantalum layer reaches 2700° F since simulated laboratory tests with a plasma jet have shown the oxidation of tantalum to be extremely rapid at this temperature (Ref. D-2).

References.

- D-1. Lees, L., "Laminar Heat Transfer Over Blunt-Nosed Bodies at Hypersonic Flight Speeds," Jet Propulsion Laboratory, April 1956.
- D-2. Dick, P. J., "Program Summary of Transit 4-A Radioisotope Power System," Martin Company, MND-P-2628, to be published. CONFIDENTIAL RESTRICTED DATA
- D-3. Chapman, D. R., "An Approximate Analytical Method for Studying Entry into Planetary Atmospheres," NASA TR R-11, 1959.

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