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HAZARDS SUMMARY REPORT
FOR A TWO WATT STRONTIUM-90
FUELED THERMOELECTRIC GENERATOR

MND-P-2048

JUNE 1959

Technical Approval:

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Prepared by:

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Prepared by Martin Nuclear Division

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I. INTRODUCTION

The radioisotope-fueled Auxiliary Power Unit (APU) is a rather unique nuclear device in that it utilizes the decay products from 8,300 curies of Strontium-90 and its daughter, Yttrium-90, to generate thermal energy which in turn can be converted to electrical energy. The APU uses thermal energy produced when the beta radiation, resulting from the decay of Strontium-90 to Zirconium-90, is absorbed by the fuel material. Strontium-90 has relatively few gamma transitions associated with the beta decay. The majority of gamma ray emission that occurs from this source of energy is the bremsstrahlung produced as the electrons are decelerated in the fuel block. With proper design of a fuel container, the bremsstrahlung can be minimized.

The fuel technology that has been developed in the last nine months is so well advanced that the safety of a Strontium-90 thermoelectric generator can be well established. It has been demonstrated that the solubility of strontium titanate, the fuel-form of Strontium-90, is less than 10 parts per billion in any naturally occurring waters. In addition to this low solubility, it has been demonstrated that if this fuel is clad with 1/8 in. of Hastalloy C, the Strontium-90 fuel will be contained for over 500 yr under the most corrosive conditions of sea water. At the end of this 500 yr period, the 8,300 curies will be reduced to less than one curies. The remainder of the fuel will be inert zirconium.

This safe fuel-form plus the minimum radiation hazards presented by this fuel block make a contained-reentry of this fuel form the most desirable choice.

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~~SECRET~~II. THE APU DESIGN

The Strontium-90 thermoelectric generator is designed to produce 2.33 watts of electrical energy from 54 watts of thermal energy with a total efficiency of 4.3%. The generator utilizes 24 pairs of lead telluride thermoelectric elements for direct conversion to 2.86-volt electrical power. Figure shows the design of the generator.

The Strontium-90 thermoelectric generator employs a cylindrical block of strontium titanate as the material for the heat source. Strontium titanate has been chosen for its insolubility in water, compatibility with clad materials, sufficiently high power density and thermal conductivity, stability at high temperatures and feasibility of fabrication into various geometric shapes and sizes. The compound has a mass density of 4.6 gm/cc and a power density of 0.54 watt/cc. The generator will contain 1.07 lb of strontium titanate.

The primary cladding of the radioisotope fuel is Hastelloy-C, a nickel alloy. It has good corrosion resistance to a salt water environment. Approximately 0.87 lb of this material will be employed as 0.32 cm thick cladding.

The clad fuel is placed in a tungsten container having walls 0.64 cm meters thick and a total weight of 5.10 lb. The tungsten serves two purposes: as a radiation shield to attenuate bremsstrahlung and gamma radiation emitted by the fuel; and as a high temperature impact resistance shell around the fuel material.

The fuel container is placed within a graphite sphere with a radius of 6.5 cm weighing 4.41 lb. The graphite is used as a heat absorption material to resist aerodynamic heating during reentry.

The outer shell of the device is aluminum weighing 3.40 lb. The area between the outer shell and the graphite sphere, containing the thermoelectric elements, is filled with insulation.

Table 1 shows the operating characteristics of the device and Table 2 gives a weight breakdown of its components.

TABLE 1Operating Characteristics

Surface temperature (at altitude)	99°F (37°C)
Hot junction temperature (at altitude)	1000°F (538°C)
Cold junction temperature (at altitude)	113°F (45°C)
Outside diameter	23.0 cm
Radiation dose (at 80 cm)	1 r/hr
Electrical power	2.33 watts
Voltage	2.86 volts
Thermal output	54 watts
Thermoelectric efficiency	7.2%
Total Efficiency	4.3%

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HALF SCALE

1	SrTiO_3
2	CLADDING (HASTELLOY)
3	SHIELD (TUNGSTEN)
4	GRAPHITE
5	THERMO ELECTRIC INSULATION
6	SHELL
7	SPRING
8	CONTACT, OXIDE
9	THERMO ELECTRIC ELEMENT
10	CONTACT, OXIDE, SPACER
11	MOUNTING FLANGE

Fig. 1

THERMOELECTRIC POWER GENERATOR
2 WATT STRONTIUM 90

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TABLE 2

Weight of Components		(lb)
Fuel (SrTiO_2)		1.07
Cladding (Hastelloy)		0.87
Shield (tungsten)		5.10
Graphite		4.41
Thermoelectric elements (lead telluride)		1.20
Insulation		3.32
Outer shell (aluminum)		3.40
Miscellaneous		1.63
Total		21.00

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III. VEHICLE INTEGRATION

This report contains a summary of the factors that are involved in the integration of the thermoelectrical generator into the Discoverer or Sentry vehicles of the Lockheed Aircraft Corporation.

A. LOCATION

The thermoelectric unit is located in the aft portion of the booster adapter area of the vehicle at Frame Station 446.7. Figure 2 shows the missile configuration of the Lockheed nose cone and adapter mated to an Atlas booster as in the Sentry Program. No redesign is necessary if a Thor booster is substituted for the Atlas booster as in the Discoverer Program. In this position the thermoelectric unit can be mated to the adapter prior to hoisting the assembly into position atop the booster causing little, if any interference, with ground handling or static test firing of the vehicle.

B. TEMPERATURE EFFECTS

The thermoelectric unit is remotely located from any component of the vehicle that could have a temperature effect on the outer skin of the generator. As shown in Fig. 3, the unit is located above the exhaust nozzle of the rocket engine and ullage rockets but below the nozzles of the gas control rockets. During orbital flight the temperature of the mounting structure will be the same as or lower than that of the unit.

C. EMERGENCY PROVISIONS

To be readily accessible for attachment, the unit is connected directly below the structural members in the adapter. An access door built in the adapter skin would provide a quick means of removing the unit from the vehicle after the adapter is mated to the booster on the launch pad. A hand disconnect for electrical leads can be provided for quick installation and removal of the generator. For abort conditions, the unit is located as far outboard as possible so as to be thrown clear for recovery.

D. STRUCTURAL REQUIREMENTS

The thermoelectric generator can be attached to the adapter structure by means of a tube welded to the unit with a flange at one end for bolt attachment to the frame. Design criteria for the tubular structure is eight g fore and aft load with two g side loading. As the unit is supported

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Fig. 2. Missile Configuration

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Fig. 3. Booster Adapter Configuration
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from the top, the eight g loading is a tension load, therefore, not as critical as the cantilever effect produced by the two g side loading. A tubular structure is favorable weight-wise as it presents a thin cross-sectional area for the tension load but a large section modulus for the cantilever side load.

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IV. STRONTIUM-90

Since it has a half-life of about 28 yr, Strontium-90 is capable of producing usable heat for a period of 10 yr. It is a notable fission product produced from reactor wastes. In its pure form, the strontium separated from fission products will contain an appreciable amount of Strontium-89 with Strontium-90. In fuel processing, the strontium is held up to take advantage of natural decay of the Strontium-89 so that the purity of the Strontium-90 fuel form is enhanced.

A. GENERAL

The heat source contains approximately 8,300 curies or about 56.6 gm of pure Strontium-90 at launch. The fuel is strontium titanate, an insoluble compound having a power density of about 0.117 watt/gm. Since strontium titanate is a relatively scarce chemical compound, some of its physical and chemical properties are obscure. Strontium-90 has the following genetic relationships:

B. PHYSICAL PROPERTIES

Strontium titanate has a melting point of 1660°C. It is a brittle, ceramic-type material having a density of about 4.6 gm/cc.

C. CHEMICAL PROPERTIES

Strontium titanate is not soluble in water, hydrochloric acid or ammonium chloride. Its chemical composition is SrOTiO_2 . The strontium titanate ceramic is compounded by adding strontium oxide to titanium oxide accompanied by compacting and sintering.

D. NUCLEAR PROPERTIES

Strontium-90 has a half-life of 27.7 yr, decaying to Yttrium-90 by the emission of a beta-particle of maximum energy 0.54 Mev. The Yttrium-90 in turn decays by emission of a 2.24-Mev beta-particle, with a half-life of 64.2 hr. The Yttrium-90 activity builds up to saturation in a few days and

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must always be taken into account in evaluating the radiation from Strontium-90 sources. Some evidence exists for the production of a very infrequent 1.73-Mev gamma in the decay of Yttrium-90, emitted in only 0.02% of the decays. The decay scheme of Sr-90 and Y-90 is:

The beta particles will be absorbed in the source material or in the container and will not directly contribute to the external dose rate. The beta particles will, however, produce bremsstrahlung photons as they are slowed down in the absorbing medium. The dose rate due to bremsstrahlung is discussed in the section on shielding requirements. The weak 1.73-Mev gamma ray contributes much less to the dose rate than does the bremsstrahlung.

If Strontium-89 is present in appreciable quantities as an impurity, the power level of the source will be unstable because of the 54-day half-life of this isotope. It is therefore necessary to use strontium which has been separated from fission products that are old enough (preferably 18 mo or more) for most of the Strontium-89 to have decayed. Since Strontium-89 decays by beta emission, it will not significantly alter the nuclear radiation environment if the activity of the source is principally Strontium-90. Approximately 0.02% of the Strontium-89 decays to the 16-sec isomer of Yttrium-89, which in turn emits a 0.91-Mev gamma ray. This radiation is so weak that it will be masked by the bremsstrahlung from Strontium-90 and Strontium-89. Figure 4 shows the decay of 8,300 curies of Strontium-90.

E. RADIOBIOLOGICAL PROPERTIES

The ecological path of strontium is similar to that of calcium. It therefore will, through ingestion and inhalation, be deposited in the bone

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Fig. 4 Decay of 8300 curies of Strontium-90

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by replacing calcium and will act as an internal source of radiation to the blood forming organs. Strontium-90 is usually combined with its daughter, Yttrium-90, to obtain radiobiological permissible concentrations. The total permissible concentration in the body for Sr-90-Y-90 is two microcuries. The maximum permissible concentrations in air and water are 1×10^{-11} and 1×10^{-7} $\mu\text{c/cc}$ respectively for soluble Strontium-90 and 2×10^{-10} $\mu\text{c/cm}^3$ in air and 4×10^{-6} $\mu\text{c/cm}^3$ in water for insoluble Strontium-90 in unrestricted areas. Table 3 lists the properties of Strontium-90 and Strontium Titanate.

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TABLE 3

Properties of Strontium-90 and Strontium Titanate

Physical

<u>Compound</u>	<u>Molecular Weight</u>	<u>Density (g/cc)</u>	<u>Melting Point (°C)</u>	<u>Power Density (watts/cc)</u>
SrO·TiO ₂	185.84	4.6	1660	0.54

Chemical

<u>Compound</u>	<u>Oxidation State</u>	<u>Solubility</u>		
		<u>H₂O</u>	<u>HCl</u>	<u>NH₄Cl</u>
SrOTiO ₂	+2	Insol	Insol	Insol

Nuclear

<u>Nuclide</u>	<u>Half-Life</u>	<u>β Energy (Mev)</u>	<u>γ Energy (Mev)</u>	<u>Other Radiation</u>	<u>Curies/gm</u>	<u>Watts/gm</u>
Sr-90	27.7 y	0.545	No γ	X bremsstrahlung	2.00x10 ²	0.921
Y-90	64.2 h	2.26	1.7 (0.02%)	X bremsstrahlung	2.72x10 ⁵	

Radiobiological (Sr-90 - Y-90)

<u>Critical Organ Mass (g)</u>	<u>MPC</u>		<u>MPC*</u>	<u>Biological Half-Life (days)</u>	<u>Fraction In Critical Organ To Body</u>	<u>Fraction To Critical Organ By Inhalation</u>	<u>Fraction To Critical Organ By Ingestion</u>
	<u>Total Body (uc)</u>	<u>Water (uc/cc)</u>					
Bone 7 x 10 ³	2.0	1x10 ⁻⁷	1x10 ⁻¹¹	3.9x10 ³	0.7	0.22	0.25

*For soluble Sr-90 in unrestricted areas.

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V. SHIELDING REQUIREMENTS

A. RADIATION LEVELS

Since the beta particles emitted by the Strontium-90 source are absorbed in the source or container, the external dose results from bremsstrahlung produced by the slowing down of the beta particles. Because of the uncertainty of thick-absorber bremsstrahlung calculations, the radiation level due to this source has been estimated on the basis of experimental measurements made by Martin at Brookhaven National Laboratory. In the experiments, a Strontium-90 source was placed next to a strontium boride absorber and the spectrum of the resulting bremsstrahlung was measured. The half-value thickness of lead for this radiation was also determined. The bremsstrahlung production rate was 1.53×10^7 photons/curie sec and the half-value thickness corresponded to an effective energy of 1.5 Mev.

The source described in this report is estimated to emit 5.5×10^{10} bremsstrahlung photons/sec. The corresponding dose rate at three feet from the center of a bare, unshielded source is 1.6 r/hr.

B. SHIELDING

The shielding requirements are imposed primarily by weight limitations rather than by a predetermined design dose rate. The handling procedures and equipment must be designed to permit the safe storage and installation of the source.

Tungsten has been selected as the most efficient shielding material on the basis of weight; tungsten alloys such as Mallory 1000 also have better thermal and mechanical properties than lead. The maximum thickness of tungsten allowable is 0.64 cm (0.25 in.), which reduces the dose rate three feet from the center of the source to 0.9 r/hr. (This point is 80 cm from the surface of the APU.) In order to reduce the dose rate to 10 mr/hr at one meter from the center, required for shipping, the source must be shipped in a container having lead walls four inches thick.

To reduce the production of bremsstrahlung in the cladding, a layer of Hastelloy C 0.32 cm (0.125 in.) thick is introduced immediately outside the strontium titanate. Since this material is of lower atomic number than tungsten, the bremsstrahlung intensity is reduced. The shielding provided by the Hastelloy C has been included in the calculations.

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VI. HAZARDS DESIGN CRITERIA

For space application of radioisotope fueled auxiliary power units, the principal environmental hazard is that imposed by the toxicity of the radio-nuclide fuel when released to the biosphere. Aside from the relatively minor direct radiation hazard which is readily overcome by shielding, the radioisotope employed must be contained under any conceivable condition, operational or accidental, so long as its environment is the biosphere.

Absolute containment is achieved by establishing a framework of conditions to which the particular device will be subject. Once that these conditions are established, the most stringent condition, in terms of internal and external mechanical, thermal and chemical forces, serve as design criteria. The hazards design criteria are determined by extreme conditions including handling accidents, missile vehicle failures and reentry through the atmosphere and subsequent earth impact. If the device is designed for the most stringent frame of conditions conceivable, it is certain that containment will be achieved under all conditions imposed.

Handling accidents caused by the mishandling of the APU or from forces imposed by natural phenomena which would lead to a hazardous condition include impact from an aircraft crash in transit or fall from the missile vehicle to the launch pad, fires and natural phenomena.

Rocket vehicle failures can be divided into two groups, launch pad and in-flight failures. The launch pad failure would result in the complete destruction of the missile. Under this type of failure, the APU would experience:

- (1) Mechanical impact, shock waves and impact of accelerated fragments.
- (2) Thermal stress, shock and energy input.
- (3) Chemical attrition by the oxidizer of the booster vehicle.

On the other hand for in-flight failure, additional conditions to these might be imposed. For vehicle failure above 100,000 ft moderate aerodynamic heating of the APU would occur.

The reentry or post-orbit conditions imposed upon the APU include sustained aerodynamic heating and high velocity impact. In this respect several alternatives may be presented for the post-orbit fate of the APU including:

- (1) Burnup by aerodynamic heating and oxidation
- (2) Intact contained reentry
- (3) Destruct in orbit
- (4) Prolongation of orbital lifetime

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Of the alternatives only items 1 and 2 apply with certainty according to the present state-of-the-art.

Burnup is achieved by aerodynamic heating and oxidation of the incoming APU which passes into the earth's atmosphere at a high velocity. Once the APU is designed for burnup, and the radioisotope is capable of being dispersed in fine particles (several microns), the residence time of the radionuclide beyond the biosphere will resolve the hazard by natural decay.

Intact reentry and earth impact are accomplished by using ablative or heat absorbing materials to combat aerodynamic heating and by utilizing high strength high temperature containment materials for impact. For small source strengths, a contained source presents relatively minor radiation hazards even when impacting on a land mass.

A. CONDITIONS

1. Handling

The hazards involved in handling an isotopic power unit prior to launch are circumstantial under normal conditions. However, it can be inadvertently abused or mishandled; therefore, consideration must be given to determine the extreme conditions imposed on the unit during handling operations. The maximum possible incidents that can be imposed on the unit during handling, impose mechanical impact and thermal forces upon the device.

Impact - The conditions resulting in an impact of an APU are numerous. Fall from a few to many thousand feet is a conceivable accident. The unit may be dropped in transit from one area to another or when installing it on the launch vehicle. High impact loads can be imposed on it if the transportation vehicle is involved in an accident (i.e.) an aircraft crash or a train wreck.

When an object is impacted, damaging stresses are generated by the superposition of two or more tensile waves that result from the reflection of compression waves from the surface of the object away from the point of impact. The magnitude of these compression waves depend on the velocity of impact and the characteristics of the impactor and APU such as their density, strength, ductility and sound velocity in the materials. It is possible to analyze these stresses for two limiting conditions: impact of the fluid and rigid body and impact of two rigid bodies. It can be assumed that the stresses on an APU resulting from impact on any medium will more closely resemble those of cases in the impact of a fluid and rigid body. Therefore, impact analysis of the APU will be based on this condition. In this fluid impact case, the maximum stress is found by multiplying the square of impact velocity by the density of the fluid (the APU). The maximum impact velocity that the APU might attain during a handling accident is assumed to be the same as the terminal velocity of the unit on reentry. This velocity is about 400 fps which would be attained in free fall from 2,480 ft altitude.

Experiments have been conducted to determine the impact resistance of molybdenum at elevated temperatures and velocities of better than 400 fps. Results indicate that it is possible to design capsules to maintain structural integrity under stringent impact forces. However, to make a comprehensive evaluation of the hazards resulting from structural deficiency of the containment capsule under impact forces, it is felt that experimental tests on the particular configuration are necessary to evaluate the unknown constants.

Thermal Excursions - Because the APU are thermal devices, a temperature excursion within could result from forces within or from without. An evaluation of this condition is of importance when analyzing hazards because it can result in the release of the toxic radioisotope. An analysis to determine the behavior of these units during such an excursion is quite complex however, a reliable one can be made.

A thermal excursion can be imposed upon the units by external fires or by insulating. Previous analysis on a typical isotopic power generator revealed that the time required to melt down the generator by insulating varies with the age of the device. The time span for melt down was between seven hours at the beginning of operation to approximately 48 hr after one year of operation. In the same analysis it was determined that a fire releasing 10^9 calories/hr would require over one-half hour to melt down the device. This thermal release is based on an aircraft fire which was considered to be the most severe thermal excursion which the device would encounter. These calculations will not be valid for all radioisotope power units but all will fall in the same general region.

2. Missile Vehicle Failures

A complete evaluation of all conceivable types of missile failures is beyond the scope of this report. However, a brief discussion of the more important aspects of missile failures and subsequent dynamic conditions is presented. Missile failure or abort can occur on the launch pad or up to the point of orbital injection (300 mi). Since time, altitude and mode of failure are variable factors, a variety of dynamic conditions are presented.

Launch Pad Failure - The worst type of launch pad failure is that where the fuel load of the missile is either ignited or detonated on the pad or several hundred feet above it. The characteristics of this type of failure depend to a large degree upon the booster vehicle. For example, the Atlas has a fuel load of JP-4 of about 11,000 gal and an oxidizer load of liquid oxygen of 17,000 gal. The total combined fuel load is 238,000 lb (about 119 tons). Relative to the fuel load the SNAP Unit is placed in a position over the liquid oxygen tank at a height of about 70 ft above the launch pad.

Mechanical Energy - It has been demonstrated by experimentation that failures of this type can give a varying energy yield of from 12 to 77% TNT equivalent for the booster fuel load, depending upon the mixing of liquid oxygen and JP-4 and the mode of failure. The maximum shock overpressure within the exploding mixture is 7×10^5 psi (45,000 atmospheres). Here several variables come into play with respect to the object exposed:

- (1) If the object is centered in such an explosion, it will receive bulk loading (a uniform incident compression load).
- (2) If the object is at an appreciable distance from the center of the explosion it can receive differential internal tension and compression loads.
- (3) The distance from the center of the explosion will also determine the magnitude of shock overpressure.
- (4) The location of the center of the explosion with respect to the earth is critical because in some cases an air blast can yield 30% more shock overpressure than a surface blast.
- (5) The amount of fuel mixing can vary the reaction from burning to detonation resulting in a variation of the time of reaction, energy yield and peak overpressure. Molybdenum test specimens have been tested under simulated missile failure conditions without sustaining mechanical failure.

Aside from the mechanical energy imparted from the booster explosion, two other mechanical conditions are worthy of consideration. First, there is the free-fall impact of the APU upon the launch pad. From a height of 70 ft, the APU impact velocity would be about 65 fps. Free-fall, low velocity impact conditions have been simulated in tests of molybdenum specimens. Minor plastic deformation occurred but specimens did not fail structurally. Second, the impact upon the APU of fragments accelerated by the explosion could occur. Free-fall and impact upon the APU by impinging objects would present less mechanical forces than mechanical energy liberated by the exploding fuel mixture.

Thermal Energy - The thermal energy imparted from an exploding mixture of JP-4 and liquid oxygen is released in a very short period of time. The peak theoretical temperature in the center of the fireball is on the order of 5000°C . However, the total heat input into an object such as an APU would be relatively small due to the short duration of the fireball. Tests under simulated conditions show that heating from the fireball is not significant enough to affect the thermal integrity of the test specimens.

Thermal shock does not appear to affect the integrity of molybdenum test specimens. Tests have been conducted where molybdenum specimens at 816°C have been immersed in liquid oxygen at -183°C ($\Delta T = 1000^{\circ}\text{C}$) without impeding the specimen integrity.

Chemical Reaction - The possible chemical reaction that might occur on launch is that between the materials of the APU and the oxidizer (liquid oxygen). In the case of elemental molybdenum, the reaction is rapid but not explosive. However, as a safety factor, an oxidation resistant coating is applied to the exposed surface of the molybdenum isotope containers. Tests of coated molybdeum specimens indicate that the protective coating will maintain the integrity of molybdenum source capsules when immersed in liquid oxygen.

Pre-Injection Failure - Pre-injection failure of the missile can occur at altitudes varying between several hundred feet and 300 mi. In this type of abort, the conditions imposed are those of high velocity impact and moderate aerodynamic heating. The failure can occur at a range of from zero to several thousand miles.

Range of Failure - In the first few seconds after launch from a site such as Vandenberg AFB the missile, in its vertical climb, passes over land. As the range increases to several miles the missile is over the Pacific Ocean. The launch and orbital trajectory continues over water (or ice) down range for more than 15,000 mi. The most critical failure time is when the missile is above the California landmass. Range safety destruct is used to prevent a failure over inland areas downrange.

High Velocity Impact - Impact velocities following missile failure are clearly defined. The terminal velocity of about 400 fps is attained at altitudes above 2,400 ft. Below 2,400 ft. the terminal velocity is not attained. Impact at terminal velocity would create a pressure sufficient to provide penetration of media impacted with exception of consolidated and crystalline rocks. Molybdenum fuel blocks impacted at velocities appreciably beyond the terminal velocity stated were found to maintain their structural integrity (with plastic deformation) in field tests employing soil, concrete and granite target media.

3. Reentry

With the present state-of-the-art, safe reentry of an isotopic power unit can be accomplished in one of two ways; release and dispersion of the isotope at very high altitudes or random impact on the earth's surface. The determining factors as to which method is used are the size of the isotope particles after it is released from its containment capsule and the half-life of the radionuclide released. If either the particle size is greater than 10 microns in diameter or the half-life is more than two years, it would be better to design a capsule for impact. This capsule must maintain integrity throughout the aerodynamic heating cycle and impact condition. The following are the conditions imposed on the containment structure during reentry and subsequent impact.

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Conditions for Dispersing the Isotope at High Altitudes - The isotope may be released at high altitudes by burnup or mechanical destruction of the containment capsule. When considering the latter, some consideration must be given to the reliability of the mechanism. In fact, if a destruction device is incorporated into the design, it is good practice to design the unit so that the entire system will burnup should the destruct system fail.

A capsule designed for burnup must be capable of maintaining integrity under terminal velocity impact forces and of being completely vaporized by the aerodynamic heat input. The former condition is important for the accident described in Section B of this chapter.

Aerodynamic heating rates have been calculated for typical APU containment capsules. It was found that the stagnation heating rate attains a peak of between 400 and 600 Btu/sq ft sec for about 100 sec. The average structure of any APU, designed without a heat sink or ablative materials, requires about 10^4 Btu for complete melt down. Since the aerodynamic heating inputs are approximately five times greater than that required heat for melt down, it can be assured that any unit, not designed for reentry, will burnup at an altitude where the peak heat rate occurs. This altitude is generally above 15,000 ft.

Conditions for Capsule Integrity on Impact - Containment capsules designed for reentry and subsequent impact encounter two major forces, aerodynamic heating and high impact loads.

As mentioned previously, an APU reentering the earth's atmosphere at high velocities is subjected to frictional effects due to the action of the air molecules upon the unit. These effects result in high thermodynamic temperatures on the surface which tend to seriously threaten the structural integrity of the containment capsule. Two methods of combating this heating effect are to provide a heat sink or an ablative material around the unit. The heat sink absorbs the functional heat and stores it so that the unit does not experience any high temperature erosion. On the other hand ablative material removes the heat completely so that the unit does not sustain melt down. The criterion for the selection of utilizing these schemes, is by design considerations only. Because of the importance of knowing if the system will reenter without damage, a test program would have to be conducted to prove the individual design. This program will utilize plasma jet facilities where reentry conditions can be simulated.

The impact force imposed on an APU is a function of the impact velocity. For any unit reentering from a satellite orbit, the maximum velocity attained is its terminal velocity. Impact conditions resulting from terminal velocity have already been considered and require no further discussion. However, in the case of the impact from a satellite orbit, consideration must be given to the reduction of allowable stresses in the material due to the annealing effect on the metal by the aerodynamic heating.

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B. CONCLUSIONS

A perusal of the conditions imposed on an isotopic power unit, utilized in a space vehicle, reveals that it is in the realm of possibility to design a unit capable of sustaining structural integrity under the most stringent conditions. However, it must be pointed out that a test program must be conducted to prove the analytical parameters and conclusions. The following is a summary of the design criteria required for the safe operation of an isotopic unit in space.

1. Design Criteria

The design criteria must be based on the critical conditions imposed by the maximum mechanical, thermal and chemical forces on the unit. Each factor must be considered individually because the forces are not closely related. That is to say, it is possible to design a unit mechanically sound but thermally weak or vice versa.

Mechanical - Terminal velocity impact, after reentry from a satellite orbit, is the most stringent mechanical condition imposed on an isotopic power unit. If a unit can be designed and tested to maintain structural integrity under this condition, it will be mechanically safe under all conditions. Another condition that imposes a force very near that of a terminal velocity impact is the shock wave overpressure during a launch pad abort. Because the condition is a critical one, a test program will be conducted to prove the analytical parameters.

Thermal - Two conditions must be considered when thermal forces are analyzed. If the unit is to burnup on reentry, the most stringent thermal condition is an external thermal excursion. This would naturally be a launch pad abort, where the unit is subjected to a temperature of 5000°C for a short period of time.

If the unit is to impact the earth after reentry, the critical thermal condition is the aerodynamic heating.

Chemical - The critical chemical action on an APU is the accidental immersion of the unit in the rocket vehicle oxidizer.

2. Structural Integrity and Subsequent Hazards of the Strontium-90 Generator

Since the half-life of the strontium fuel is over two years and the particle size after burnup upon reentry would be in a relatively large diameter range, it was decided to impact the fuel capsule after the mission is completed. A graphite sphere is fabricated around the capsule as a heat sink material to resist aerodynamic heating during reentry. Structural integrity of the unit is dependent upon the tungsten capsule into which the strontium fuel is packed. This capsule is designed to withstand all forces to which the generator might be subjected. The following are the stresses and conditions imposed on the capsule during the lifetime of the generator.

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Mechanical -

Free-Fall Impact (70 ft) - The maximum stress imposed on the capsule by a free-fall impact of 70 ft is 610 psi. Should the device be dropped from the launch pad, the temperature of the material would be the operating temperature of the device, 1000°F.

Terminal Velocity Impact - The stress on the capsule after a terminal velocity impact is 9,300 psi. This is based on a terminal velocity of 260 fps. The temperature of the capsule at impact after reentry from a satellite orbit is approximately 1800°F.

Pressure Due to Exploding Rocket Fuel - Pressure imposed on the capsule by exploding rocket fuel have been computed from an empirical equation plotted on Fig. 5. This pressure is a function of the distance away from the center of the explosion. It is assumed that if an explosion occurs, it will originate near the booster rocket engines. This distance is more than 50 ft from the APU. Under this condition, the pressure on the capsule should not exceed 5,800 psi. Should the APU be responsible for detonating the propellant mixture, it will be in the center of the fireball. The stress on the unit in this case would essentially be zero due to the bulk loading.

Mechanical Integrity of the Designed Capsule - The tungsten capsule can withstand a maximum estimated external pressure of 14,000 psi. This pressure is estimated because it is difficult to derive a rational formula for the stresses in a cylinder under external pressure. The estimate, however, is conservative but experimental verification must be considered. All allowable stresses for the material were taken for a temperature of 1800°F.

It appears that the designed capsule is mechanically safe under the most stringent conditions imposed on it.

Thermal - Since the device is to reenter and impact, the thermal analysis was concerned only with the aerodynamic heat input. If the fuel capsule can withstand this heat, it can be assured that it will withstand any temperature excursion. The aerodynamic heat is about two times that of any other source.

A reentry analysis showed that the 3/4 in. of graphite material was a sufficient heat sink to return the fuel capsule undamaged on reentry.

Chemical - It appears at present that chemical forces will not be significant.

Hazards - Basically there are two conceivable hazards in using a Strontium-90 power unit on a space mission. These are the release of the toxic isotope to the biosphere and the external radiation dose of

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$$P = \frac{8240}{z^3} = \frac{166.67}{z^2} + \frac{49.77}{z}$$

$$z = \frac{r}{W^{1/3}}$$

r = distance from center of explosion

W = 95,000 lbs T.N.T. equivalent for the Atlas Missile

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the fuel capsule when it impacts after reentry. It has been shown that the integrity of the containment capsule is such that the probability of release of the isotope is infinitesimal. However, should an accident occur, the procedures for radiation protection given in the context of this report is applicable.

A statistical analysis on the probability of a unit impacting a populated area has been made and presented in the context of this report. It is based on an average cross-section of the earth through the north and south poles.

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VII. STATISTICAL ANALYSIS OF DATA

A. POLAR CROSS-SECTION OF THE EARTH

To establish the impact probability for a satellite in a north-south orbit, it is necessary to determine a statistical analysis for the earth based on a cross-section through the poles. This cross-section was determined by measuring the amount of land, water and ice along each five-degree meridian and averaging the total of the 36 cuts.

1. Average cross-section through the poles

(%)

Land	=	22.61
Water	=	59.37
Ice	=	18.02

2. The land can be divided into

(%)

Unconsolidated rock	=	1.42
Consolidated rock	=	8.19
Crystalline rock	=	7.01
Total	=	22.61

3. The water can be divided into

(%)

Oceans	=	58.54
Inland waters	=	0.83
Total	=	59.37

4. The ice can be divided into

(%)

Land ice	=	12.50
Water ice	=	5.72
Total	=	18.02
Earth Total	=	100

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B. REENTRY IMPACT PROBABILITY

Statistically, out of 100 APU reentering from a north-south orbit 66 will impact in water and 34 on land masses. A more detailed breakdown is as follows:

1. Of the 34 impacted on land masses

Ice Fall	12
Unconsolidated rock	7
Consolidated rock	8
Crystalline rock	7

2. Of the 66 impacted on water areas

Ice	6
Inland waters	1
Oceans	59

A further analysis of the 34 that will impact on land indicates that only a small percentage will affect populated regions. This analysis was based on the fact that unconsolidated rock supports the majority of the earth's population while consolidated rock regions are generally unfavorable to human habitation and consequently sparsely populated. The remaining land area is covered by ice or crystalline rock and virtually uninhabited. Of the 15 APU which will land on unconsolidated and consolidated rock regions approximately 1/3 will land in regions that are uninhabited or very sparsely populated because of unfavorable climate or terrain.

From this analysis, it can be predicted that of 100 APU landing on the earth's surface from a north-south satellite orbit, approximately 10 will affect populated regions. However, in regions of unconsolidated rock which supports most of the population, a source capsule will generally be buried from 6 to 10 ft upon impact, thereby providing adequate shielding from external radiation.

VIII. RADIATION PROTECTION

The use of a radioisotope source in an orbital vehicle is considered feasible only after a careful study of hazards analysis data and containment methods give assurances that the probability of anyone receiving significant direct radiation or internal exposure is remote.

The thermoelectric generator is transported to the launch site in a container designed as a shield and a pressure-tight receptacle. It is designed to contain the radioisotope in the event of leakage, should the generator structure fail and to provide sufficient shielding so that the radiation levels are within permissible limits.

When the generator arrives at the launch site, handling and emergency procedures are initiated to comply fully with the accepted regulations and standards for radiation protection. The following shows the radiation protection controls and procedures which will be in effect each time an orbital vehicle containing a radioisotope generator is launched.

A. EXPOSURE LIMITS

1. Personnel In Restricted* Areas or Monitored For Exposures

- (1) The whole body exposure during normal operations should be limited to 1.25 rem total during each calendar quarter or a total of five rem per year.
- (2) Exposure to the hands and forearms should be limited to 1.5 rem/wk.
- (3) A whole body dose of three rems will be permitted in emergencies provided this dose, when added to the previously accumulated dose, does not exceed the maximum permissible accumulated dose. The maximum permissible accumulated dose is calculated according to the following formula:

$$MPD = 5 (N-18) \text{ rems}$$

where: MPD = the maximum permissible accumulated dose
in rems N = individual age in full years.

* A "restricted area" as used in this report refers to an area in which personnel are normally monitored for radiation exposure while an "unrestricted area" is an area in which personnel are not monitored for radiation exposures.

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- (4) No individual should be exposed to airborne radioactive material in excess of the following concentrations:

	<u>Permissible Concentration</u> <u>Air (μc/mc)</u>	<u>Permissible Body</u> <u>Burden (μc)</u>
Strontium-90 (soluble)	3×10^{-10}	2
Strontium-90 (insoluble)	5×10^{-9}	

2. Personnel Under 18 years

Persons under 18 years of age should not be exposed to radiation levels that could result in an exposure in excess of 10% of the permissible dose for personnel in restricted areas.

3. Personnel in Unrestricted Areas or Not Monitored for Exposures

- (1) No individual should be exposed to radiation levels which could result in a dose in excess of two millirems in any one hour.
- (2) No individual should be exposed to radiation levels which, if he were continuously present in the area, could result in his receiving a dose in excess of 100 mrem in any seven consecutive days.
- (3) No individual should be exposed to airborne radioactive materials in excess of the following limits. The permissible body burden is the same as for restricted areas.

	<u>Permissible Concentration (μc/ml) Air</u>
Strontium-90 (soluble)	12×10^{-11}
Strontium-90 (insoluble)	2×10^{-10}

B. MONITORING EQUIPMENT

1. Personnel Monitoring Equipment

Each person working in areas where the radiation levels are sufficient to result in receiving a dose in excess of two millirems per hour should be supplied with a film badge and a self-reading dosimeter. The film badges should measure exposures up to 600 rem while the dosimeters should indicate exposures up to 200 mrem. Film badges should be developed and read routinely each week and/or whenever any of the following conditions exist:

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- (1) The dosimeter reads in excess of 100 mrem.
- (2) The dosimeter is lost, damaged or the "crosshair" is not visible.
- (3) Each time an individual is involved in an emergency such as a fire, explosion, loss of source shielding, etc.

2. Portable Monitoring Equipment

Portable instruments should be available for measuring the different types of radiation emitted by the isotope used in the thermoelectric generator. The instruments required for Strontium-90 are as follows:

- (1) Instruments of the "Cutie Pie"-type should be available to measure beta-gamma radiation up to 10 r/hr for normal operations and at least one with a range of up to 100 r/hr for emergency use.
- (2) For measuring low level contamination, instruments complete with headphones and with a range up to 20 mr/hr should be available.

C. MONITORING PROCEDURES

Experienced Health Physics personnel should be assigned to the launch site to monitor the radiation levels in all areas in which the radioisotope source is used or stored. Monitoring activities will include the following.

1. Leak Testing of the Source

The source should be leak tested immediately upon arrival at the launch site and on a daily basis until placed in the launching vehicle. Leak testing is accomplished by rubbing the outside surface of the source container with absorbent paper or a cloth dampened with alcohol and then counting with a sensitive counter.

2. Personnel Monitoring

All personnel who will handle the radioisotope unit and/or those who will work in areas where the radiation levels exceed two milliroentgens per hour should be issued a film badge and a self-reading dosimeter. There should be no exception to this rule. Records of dosimeter and film badge readings should be maintained by Health Physics personnel as permanent records.

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3. Storage of the Source

All storage areas should be clearly identified by radiation warning signs and entrance should be limited to only authorized personnel. All areas surrounding the storage area in which personnel could receive a dose in excess of two millirems per hour and/or 100 millirems in any seven consecutive days should be roped off to prevent entrance by unauthorized personnel. Health physics personnel will monitor all storage areas and if required, establish time limits that personnel may remain in these areas without exceeding permissible levels of exposure.

4. Launch Pad Activities

All activities on the launch pad that involve the radioisotope unit should be monitored by health physics personnel. This is to determine the radiation levels and the time limits that personnel may be present in the areas surrounding the launch pad without exceeding permissible levels of exposure.

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