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HAZARDS SUMMARY REPORT FOR A TWO WATT PROMETHIUM-147 FUELED THERMOELECTRIC GENERATOR

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Technical Approval:

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Prepared by Martin Nuclear Division

for the

U.S. Atomic Energy Commission

CONTENTS

I. INTRODUCTION

The radioisotope-fueled Auxiliary Power Unit (APU) for space vehicle applications is a rather unique device in that it utilizes the decay process of 1.66×10^5 curies of Promethium-147 to generate thermal energy. The thermoelectric effect is used to convert this heat to usable electric power. The APU uses the thermal energy produced when the beta radiation, resulting from the radioisotope decay of Promethium-147 to its daughter product, Samarium-147, is absorbed by the fuel material. There is no gamma radiation associated with this decay. As these beta rays are absorbed in the fuel, Bremsstrahlung gamma radiation is formed, but since the average energy beta is 0.060 Mev and the maximum energy beta is 0.223 Mev, the gammas formed by this method are easily shielded.

The use of this radioisotope as a heat source makes possible the fabrication of an auxiliary power unit that has no serious ground handling problems. Such power suppliers can answer the requirements of space for low power missions (under 10 watts electrical), supplying electrical power with a low gamma radiation background in the satellite. This isotope is an ideal heat source from the concept of reentry of the fuel in a contained form.

II. THE APU DESIGN

The Promethium-147 thermoelectric generator converts 43.5 thermal watts to 2.2 electric watts at an overall conversion efficiency of five percent. This conversion is accomplished by 24 pairs of lead telluride thermoelectric elements giving a total of 2.8 volts. Figure 1 shows the conceptual design of the generator.

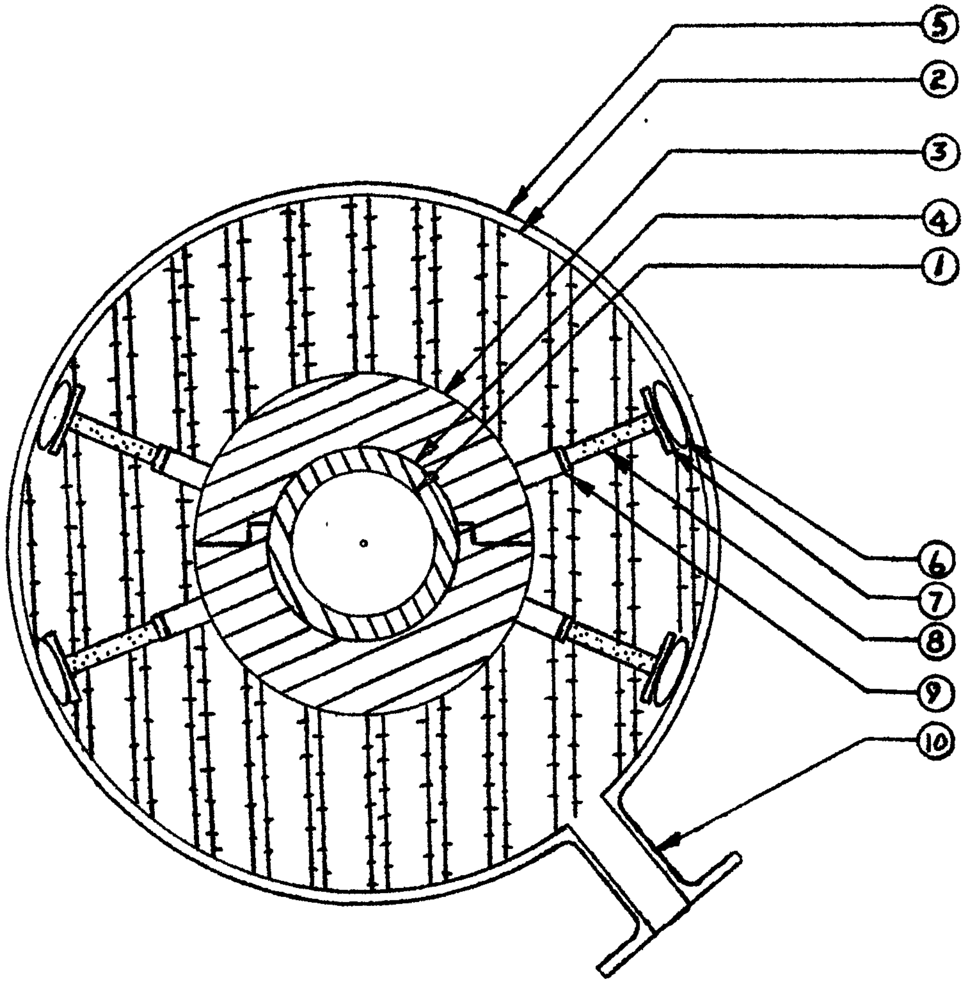
The Promethium-147 fuel is in the form of Pm_2O_3 which has a density of 6.6 gm/cc and a power density of 1.5 watts/cc. The cladding on this source will be molybdenum because of its extreme impact resistance at high temperatures and its shielding characteristics.

This entire fuel container is placed within a graphite sphere with a radius of 4.5 cm and with a weight of 1.6 lb. The graphite is used as a heat absorption material to resist aerodynamic heating during reentry.

The heat dump is an aluminum shell which has a 9.5 cm radius. Total unit weight is 9.0 lb.

The thermoelectrics are designed to operate between the temperatures of 1000 and 131°F to obtain a thermoelectric efficiency of seven percent.

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



1	Pm_2O_3
2	THERMOELECTRIC INSULATION
3	GRAPHITE
4	CLADDING (Molybdenum)
5	SHELL
6	SPRING
7	CONTACT, OXIDE
8	THERMOELECTRIC ELEMENT
9	CONTACT, OXIDE, SPACER
10	MOUNTING FLANGE

HALF SCALE

THERMOELECTRIC POWER GENERATOR
2 WATT PROMETHIUM 147

TABLE 1

Operating Characteristics

Surface temperature (at altitude)	115°F (37°C)
Hot junction temperature (at altitude)	1000°F (538°C)
Cold junction temperature (at altitude)	131°F (55°C)
Outside diameter	19.0 cm
Radiation dose (at 3 ft)	2.1 r/hr
Electrical power	2.22 watts
Voltage	2.80 volts
Thermal output	43.5 watts
Thermoelectric efficiency	7.1%
Total efficiency	5.1%

TABLE 2

Weight of Components

	(lb)
Fuel (Pm_2O_3)	0.42
Cladding (Molybdenum)	0.81
Graphite	1.56
Thermoelectric elements (Lead Telluride)	1.20
Insulation	2.02
Outer shell (Aluminum)	2.20
Miscellaneous	0.77
Total	9.00

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 the ground handling or static test firing procedures 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 Figure 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

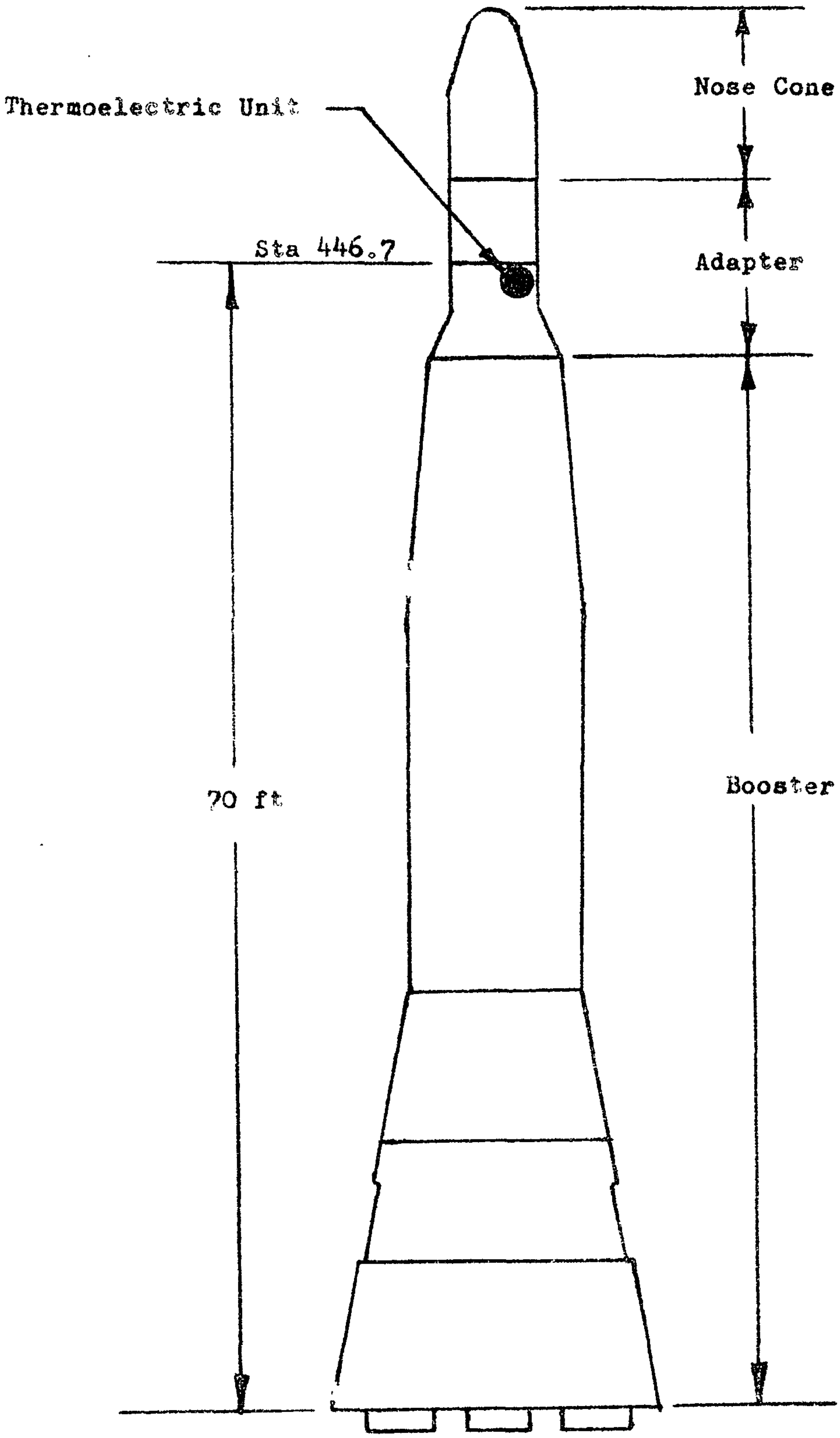


Fig. 2. Missile Configuration

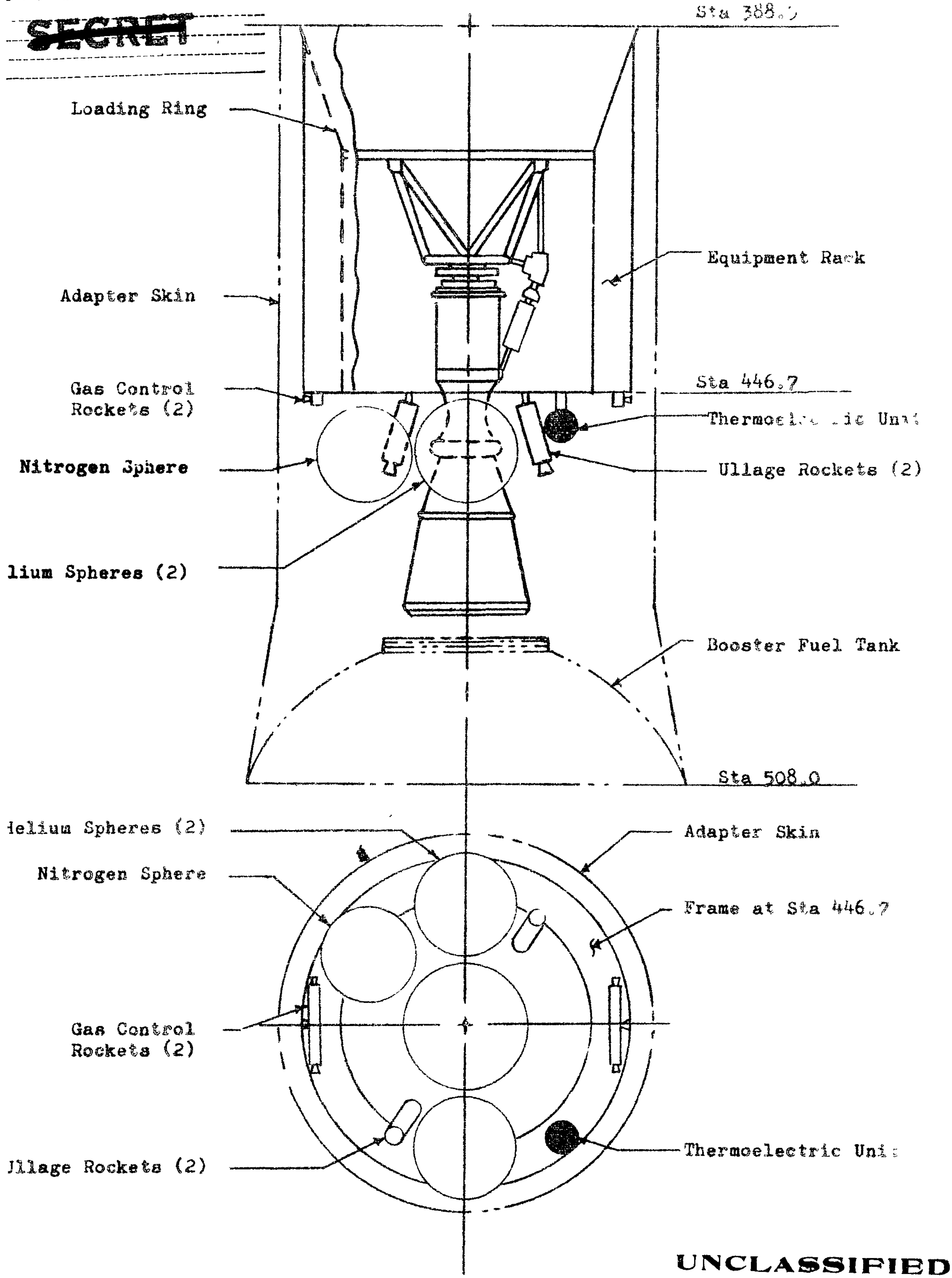


Fig. 3. Booster Adapter Configuration

structure is eight g fore and aft load with a two g side loading. As the unit is supported 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.

IV. PROMETHIUM-147

Promethium-147 is separated from the gross fission products of reactor wastes. In its pure form the promethium separated will contain appreciable amounts of Promethium-148 with Promethium-147. The material is allowed to decay for many months to reduce the quantity of Promethium-148 which has a half-life of 42 days.

A. GENERAL

The source strength at launch of 166 kc of Promethium-147 is dictated by the power requirement of 61 thermal watts which is based upon a value of 3.68×10^{-4} watts/curie. The fuel form is promethium oxide (Pm_2O_3) which has a specific power of 0.227 watts/gm. Promethium-147 has the following genetic relationships:

$$\text{Nd-147} \xrightarrow{\beta} \text{Pm-147} \xrightarrow{\beta} \text{Sm}^{147}$$

$$\text{U-235} \xrightarrow{(n,\gamma)} \text{Pm-147}$$

Figure 4 shows the decay of 166 kc of Pm-147.

B. PHYSICAL PROPERTIES

The physical properties of promethium oxide are similar to those of lanthanum oxide. It has a density of 6.6 gm/cc. Specific melting and boiling points have not been determined but it is expected that they are greater than 1000 and 3000°C respectively. It has a power density of 1.5 watts/cc. It has a molecular weight of 341.92.

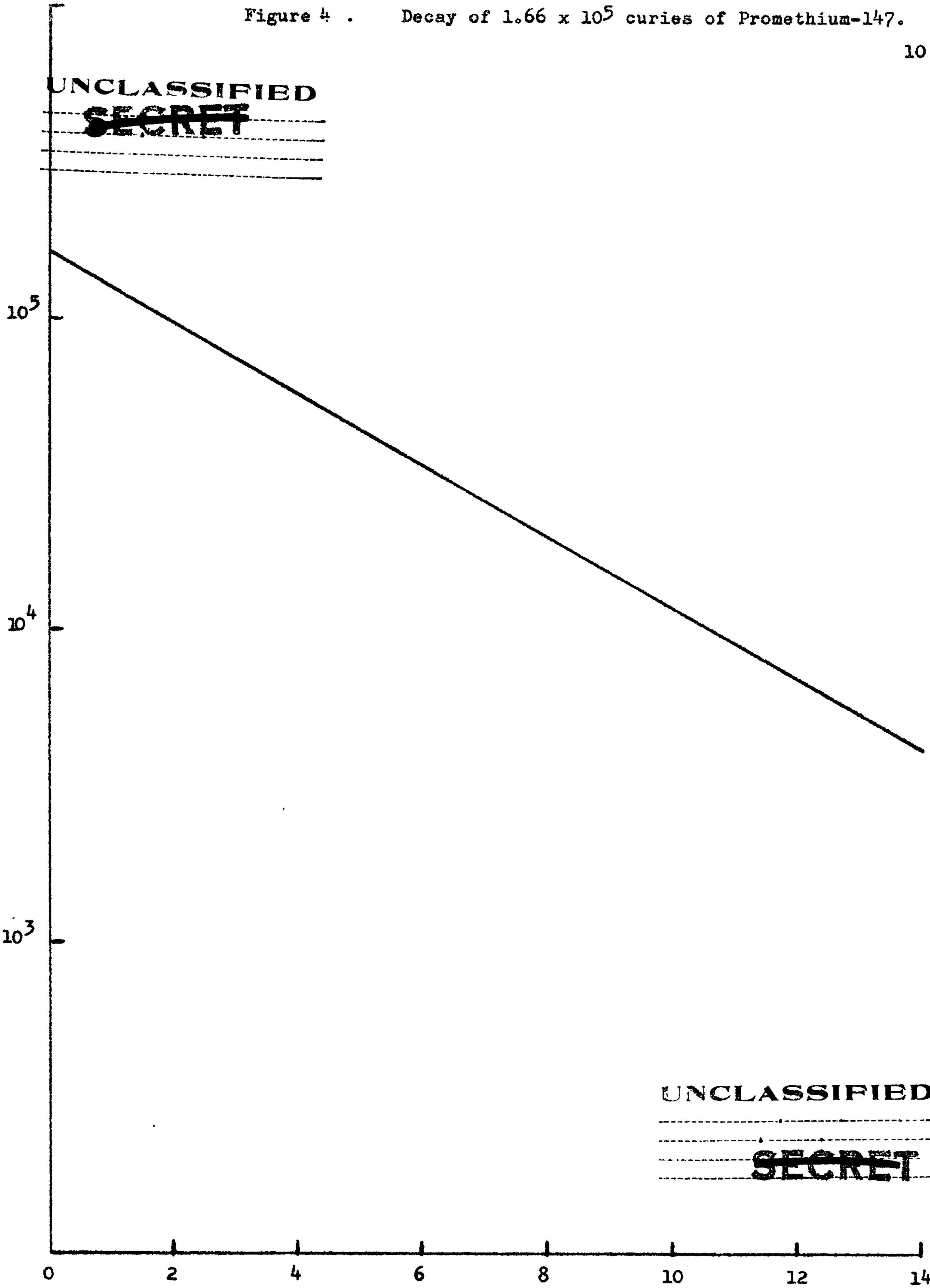
C. CHEMICAL PROPERTIES

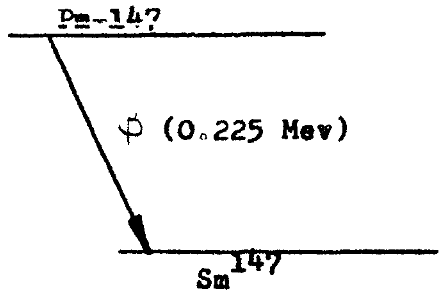
Promethium is of the lanthanide series. The oxide is only slightly soluble in cold water and forms $Pm(OH)_2$ in hot water.

D. NUCLEAR PROPERTIES

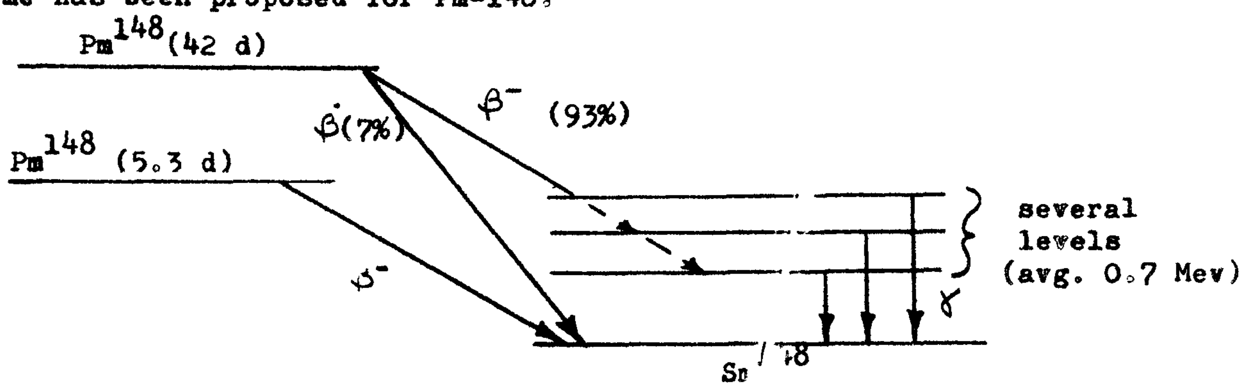
Promethium-147 has a half-life of 264 yr and decays through beta emission to Samarium-147. The beta energy is 0.225 Mev. The daughter Samarium-147 has a half-life of 1.3×10^{11} yr and decays through the emission of a 2.14 Mev alpha particle.

Figure 4 . Decay of 1.66×10^5 curies of Promethium-147.





Because the only electromagnetic radiation emitted by a pure Promethium-147 source is the weak (low intensity) and soft (low energy) Bremsstrahlung produced by the betas, the real radiological problems arise from the impurities present in a practical promethium source. The most significant impurity is Promethium-148, that has two isomers, both of which decay to stable Samarium-148. One isomer has a half-life of 42 days emitting two beta groups of maximum energies 0.6 Mev and 2.4 Mev respectively. Several gammas are also emitted by this isomer, as is described later. The spectrum of Promethium-148 gammas associated with a Promethium-147 source 14 mo old (i.e., which has been obtained from 14 mo old fission products) has been measured at Oak Ridge National Laboratory. The spectrum of the most intense radiation from an eight month old source was then calculated. In an eight month old source, there are 3.6 millicuries of Pm-148/curie of Pm-147. The spectral measurements are tabulated. The following decay scheme has been proposed for Pm-148.



Gamma Energy (Mev)	Gammas Per Pm-147 Beta (8 mo)	(14 mo)
0.290	--	1×10^{-5}
0.415	000	1.3×10^{-5}
0.560	--	6.3×10^{-5}
0.630	1×10^{-3}	6.3×10^{-5}
0.730	6×10^{-4}	2.5×10^{-5}
0.910	4×10^{-4}	1.3×10^{-5}
1.000		1.1×10^{-5}

Another impurity of potential significance is europium. Europium-155, the most troublesome isotope occurring in fission products, decays to beta and gamma emission with a half-life of 1.7 yr. To eliminate the radiological hazard due to europium, the maximum permissible amount of this element in promethium sources has been set at 10 ppm. Preliminary information from ORNL indicates that this specification can be met.

E. RADIOBIOLOGICAL PROPERTIES

The critical organ for soluble Promethium-147 is the bone, and the total permissible amount in the body is 60 microcuries. The maximum permissible concentrations of soluble Promethium-147 in unrestricted areas in air and water are 2×10^{-9} μc/cc and 2×10^{-4} μc/cc respectively. The maximum permissible concentration in restricted areas if in air is 6×10^{-8} μc/cc and in water is 6×10^{-3} μc/cc for soluble Promethium-147. Table 3 presents the properties of Pm-147.

TABLE 3

Properties of Promethium-147

Physical

Compound	Molecular Weight	Density (g/cc)	Melting Point(°C)	Boiling Point(°C)	Power Density w/cc
Pm_2O_3	341.92	6.6	1000	3000	1.5

Chemical Properties

Compound	Chemical Series	Solubility H_2O (Cold)	Solubility H_2O (Hot)
Pm_2O_3	Lanthanide	VSS	d

Nuclear Properties

Nuclide	Half-Life	Energy (Mev)	Other Radiation	Curies/gm	Watts/gm
Pm^{147}	2.64 y	0.225	Bremsstrahlung	8.62×10^2	0.345

Radiobiological Properties

Nuclide	Form	Co+&Mass(g)	MPC*TB-(uc)	MPC Air(Restricted)
Pm^{147}	Soluble	Bone 7×10^3	60	6×10^{-8} μc/cc

MPC Air (Unrestricted)	MPC Water (Restricted)	MPC Water (Unrestricted)
2×10^{-9} μc/cc	6×10^{-3} μc/cc	2×10^{-4} μc/cc

Biological Half-Life	Fraction in Co of TB
100 d	0.7

+ Critical organ   * Maximum permissible concentration   - Total body

V. SHIELDING REQUIREMENTS

A. RADIATION LEVELS

The radiation levels discussed in this section refer to a source which, at the end of the three-month mission, furnishes 57.1 watts (thermal) from the decay of Promethium-147 alone. Additional power from Promethium-148 or other active contaminants is neglected. At launch, the thermal power is 61.0 watts. The specific power has been calculated to be 0.345 watt/gm; the specific activity is 9.37 x 10^2 curies/gm, so that the source provides 3.68 x 10^{-4} watt/curie. (Ref: K. P. Johnson, "Power from Radioisotopes", Martin Nuclear Division);

In a source composed of pure Promethium-147 or one of its compounds, the radiation environment results from the weak and soft bremsstrahlung produced by the betas. A rough calculation shows that the bremsstrahlung dose rate at three feet is less than one mr/hr if the source described in this report is encased in Hastelloy C. The dose rate at the surface of the APU shell is approximately 20 mr/hr. The effective photon energy is approximately 0.15 Mev.

If the source is fabricated from eight-month old promethium, the unshielded dose rate at three feet from the center is 177 r/hr. If allowance is made for self-shielding by the source material, the dose rate at three feet is 120 r/hr and the surface dose rate is 1.1 x 10^4 r/hr. The radiation is Pm-148 gammas with a mean energy of approximately 0.7 Mev.

If the promethium oxide is made from 14-mo old fission products, the dose rate at three feet from the center is 6.15 r/hr, allowing for self-shielding and the surface dose rate is 570 r/hr. Again the mean photon energy is approximately 0.7 Mev.

The dose rates just stated refer to a freshly prepared source. At the end of a one-month of shelf life, the dose rate three feet from the self-shielded source made from eight-mo promethium is 73 r/hr. The corresponding result for the 14-mo material is 3.75 r/hr.

B. SHIELDING

The cladding material is sufficient to prevent the escape of betas from a promethium source. In the case of pure Promethium-147, no additional shielding is required.

If a tungsten shield one centimeter (0.4 in) thick is located just outside the cladding, the dose rate three feet from the eight-month promethium source is reduced to 41 r/hr and the surface dose rate is reduced to 3.8×10^3 r/hr. The dose rates from the 14-mo source are 2.1 and 19.5 r/hr respectively.

If an APU containing eight-month promethium and no tungsten shield is to be shipped, 9.2 cm (3.6 in) of lead must be provided to reduce the dose rate at one meter from the center to 10 mr/hr. In the case of 14-mo promethium, the required lead thickness is 6.5 cm (2.5 in).

In view of the results just given, it is recommended that the proposed promethium source be fabricated from at least 14-mo old fission products or that the separated material be allowed to stand until the Promethium-148 contamination has decayed to an equivalent level.

VI. HAZARDS DESIGN CRITERIA

For space applications of radioisotope-fueled Auxiliary Power Units the principal environmental hazard is that imposed by the toxicity of the radionuclide fuel when released to the biosphere. Aside fromthe 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 these conditions are established, the most stringent condition, in terms of internal and external mechanical, thermal and chemical forces, serves as a design criterion. 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 and oxidizer of the booster vehicle.

On the other hand for in-flight failure, additional conditions might be imposed. For vehicle failure above 100.000 ft aerodynamic heating of the APU would occur, but would not be sufficient to destroy capsule integrity. Also high velocity impact forces would be imposed upon the APU.

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.

Of these 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 hazard 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 determining 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. Falling from a few feet to many thousand feet is a conceivable accident. The unit may be dropped in transporting it 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 the APU. The characteristics considered are density, strength, ductility and sound velocity in the materials. It is possible to analyze these stresses for two limiting conditions: impact of a fluid and rigid body and impact of two rigid bodies. It can be assumed that the stresses on an APU Auxiliary Power Unit, resulting from impact on any medium, will more closely resemble those of case 1. 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 ft/sec, 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 ft/sec. 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 either 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. 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 the 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 in 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 ft/sec. 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 test specimens.

Thermal shock does not appear to affect the integrity of molybdenum test specimens. Tests have been conducted where molybdenum test specimens at 816°C have been immersed in liquid oxygen at -183°C (ΔT = 1000°C) without impeding the specimen integrity.

<u>Chemical Reaction</u> - 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 molybdenum specimens indicate that the protective coating will maintain the integrity of molybdenum source capsules when immersed in liquid oxygen.

<u>Pre-Injection Failure</u> - 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.

<u>Range of Failure</u> - 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 down range.

<u>High Velocity Impact</u> - Impact velocities following missile failure are clearly defined. The terminal velocity of about 400 ft/sec is attained at altitudes above 2,480 ft. Below 2,480 ft altitude, terminal velocity is not attained. Impact at terminal velocity would create a pressure sufficient to provide penetration of media impacted with the 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. <u>Reentry</u>

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 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.

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 a 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 meltdown. Since the aerodynamic heating inputs are approximately five times greater than the required heat for meltdown, 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 150,000 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 meltdown. 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.

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, 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. A unit could be designed to be 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°F 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 Promethium-147 Generator

Although the half-life of the promethium fuel is relatively short, the particle size after burnup on 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 depended upon the spherical molybdenum capsule into which the Promethium 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:

Mechanical -

Free-Fall Impact (70 ft) - The maximum stress imposed on the capsule by a free-fall impact of 70 ft is 500 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 4,500 psi. This is based on a terminal velocity of 200 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. . 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 molybdenum capsule can withstand a maximum estimated external pressure of 10,000 psi. This pressure is estimated because it is difficult to derive a rational formula for the stresses in a sphere 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 condition 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 bring in 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 Promethium-147 power unit on a space mission. These are the release of the toxic isotope to the biosphere and the external radiation dose

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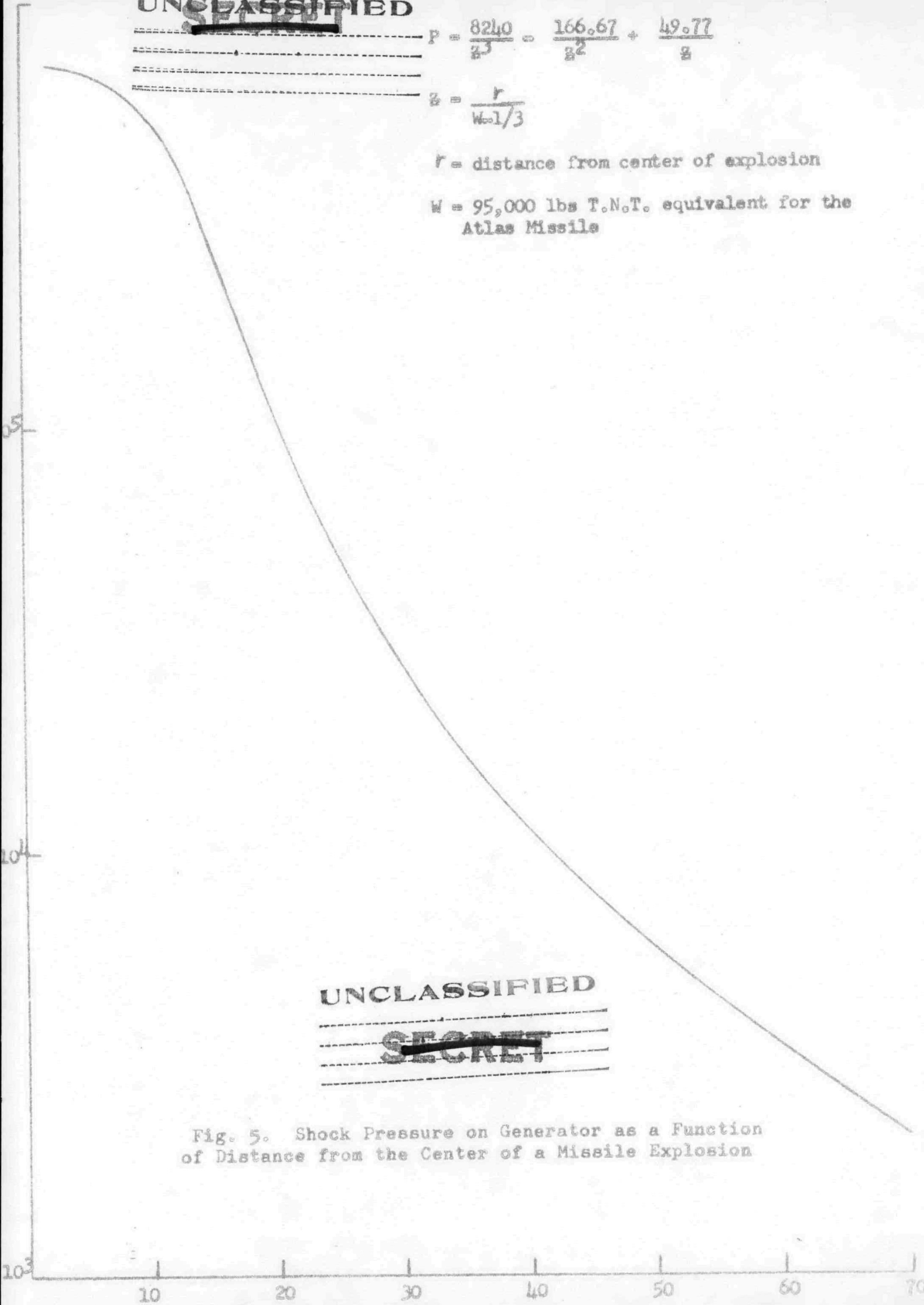

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Fig. 5. Shock Pressure on Generator as a Function of Distance from the Center of a Missile Explosion

of 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 on 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.

VII. STATISTICAL ANALYSIS FOR IMPACT

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	=	7.41
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	=	12.30
Water ice	=	5.72
Total	=	18.02
Earth total		100

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 break-down is as follows:

1. Of the 34 impacted on land masses

Ice	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 the 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 thatof 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.

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

	Permissible Concentration Air (μc/ml)	Permissible Body Burden (μc)
Promethium 147 (soluble)	6×10^{-8}	6 x 10
Promethium 147 (insoluble)	1×10^{-7}	

2. Personnel Under 18 Years of Age

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.

	Permissible Concentration (μc/ml) Air
Promethium 147 (soluble)	2×10^{-9}
Promethium 147 (insoluble)	3×10^{-9}

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:

(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 Promethium 147 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.

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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