HAZARDS SUMMARY REPORT
FOR A THREE WATT POLONIUM-210 FUELED
THERMOELECTRIC GENERATOR

MND-P-2047

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Technical Approval:

[Signature]
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</table>
I. INTRODUCTION

The radioisotope-fueled Auxiliary Power Unit (APU) for space vehicle applications is a rather unique nuclear device as it utilizes the decay process from 1,570 curies of Polonium-210 to generate thermal energy. The thermoelectric effect is used to convert this heat to usable electrical power. The APU uses thermal energy produced when the alpha radiation, resulting from radioisotope decay of Polonium-210 to its daughter product, Lead-206, is absorbed by the fuel container. Only 0.0012% of all alpha disintegrations are accompanied by a gamma of 0.203 Mev; therefore, no serious handling problems are encountered with this thermoelectric power supply.

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. The design of a Polonium-210 fueled isotope will be a safely contained unit in the event of a launch pad abort and makes an ideal fuel to dissipate in space when reentering. Polonium-210 was chosen because of its high volatility at operating temperatures and the extremely long time that will be required for the condensed form to reach ground level. Since polonium has such a low temperature of condensation, and at these altitudes there is so little extraneous material to serve as condensation nuclei, the particle size of condensed material will be very small. Thus a large percentage of the Polonium-210 will decay to stable Lead-206 by the time the particle reaches ground level.
The Polonium-210 thermoelectric generator is designed to produce 2.92 watts of electrical energy from 50.2 watts of thermal energy with a total efficiency of 5.82%. The generator utilizes 27 pairs of lead telluride thermoelectric elements for direct conversion to 2.95 volt electrical power. Figure 1 shows the design of the generator.

The 1,570 curies of Polonium-210 source material is encapsulated in four successive containers to prevent the release of contamination to the atmosphere. First, the polonium source is encased in two stainless steel capsules with welded tops and each contains 785 curies. These capsules are 0.290 in. in diameter and 0.590 in. long with an inside volume of 0.279 cubic centimeters. Second, these two capsules are encased in a single steel canister 0.360 in. in diameter and 1.30 in. in length with a welded top. Third, this canister is placed in a stainless steel block which is capped by a welded steel plug. Fourth, this block and the 27 pairs of semiconductor thermoelectric elements are encased in an aluminum container which is hermetically sealed. As an added safety precaution, the container is evacuated so that a negative pressure exists within it. This negative pressure allows air to enter if a leak should occur during ground handling operations.

Because of the high volatility of the Polonium-210 fuel at operating temperature, and the extremely long time that will be required for the condensed Polonium-210 to reach ground level, it was decided to burnup the generator on reentry. Therefore, no ablative or heat sink materials are incorporated into the design. Table 1 shows the operating characteristics of the device and Table 2 gives a weight breakdown of its components.
Fig. 1. Polonium-210 Generator
MND-P-2047
### TABLE 1

**Operating Characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface temperature (at altitude)</td>
<td>130 °F</td>
</tr>
<tr>
<td>Hot junction temperature (at altitude)</td>
<td>950 °F</td>
</tr>
<tr>
<td>Cold junction temperature (at altitude)</td>
<td>223 °F</td>
</tr>
<tr>
<td>Outside diameter</td>
<td>4.875 in.</td>
</tr>
<tr>
<td>Length</td>
<td>5.5 in.</td>
</tr>
<tr>
<td>Radiation dose (at 1 meter)</td>
<td>8 mr/hr</td>
</tr>
<tr>
<td>Electrical power</td>
<td>2.92 watts</td>
</tr>
<tr>
<td>Voltage</td>
<td>2.95 volts</td>
</tr>
<tr>
<td>Thermal output</td>
<td>50.2 watts</td>
</tr>
<tr>
<td>Total efficiency</td>
<td>5.87%</td>
</tr>
</tbody>
</table>

### TABLE 2

**Weight of Components**

<table>
<thead>
<tr>
<th>Component</th>
<th>(lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel (Po-210)</td>
<td>0.001</td>
</tr>
<tr>
<td>Stainless steel capsules</td>
<td>0.600</td>
</tr>
<tr>
<td>Thermoelectric elements</td>
<td>1.200</td>
</tr>
<tr>
<td>Insulation</td>
<td>0.500</td>
</tr>
<tr>
<td>Outer shell</td>
<td>1.000</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>0.600</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.9</strong></td>
</tr>
</tbody>
</table>

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**MND P-2047**

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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 provides 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.
Fig. 2. Missile Configuration
.adapter Skin

Gas Control Rockets (2)

Helium Spheres (2)

Nitrogen Spheres

Gas Control Rockets (2)

Ullage Rockets (2)

Equipment Rack

Thermoelectric Unit

Ullage Rockets (2)

Booster Fuel Tank

Sta 44.67

Frame at Sta 44.67

Thermoelectric Unit

Fig. 3 Booster Adapter Configuration

MNF P 20-7
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 from the top, the eight g loading is a tension load and therefore is 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.
The radionuclide selected for the power source of this unit is Polonium-210. The source strength at launch of 1,570 curies is dictated by the power requirement of three electrical watts (50.2 thermal watts), which is based upon a value of 0.032 thermal watt/curie and a thermoelectric efficiency of five percent. However, because of source fabrication, installation and transportation time requirements, which cause a reduction of source strength by natural decay prior to launch, an initial source strength in excess of 1,570 curies will be required.

A. GENERAL

Polonium-210 occurs in nature as one of more than 50 natural radionuclides. It has been estimated that approximately 10,000 tons of the element polonium are disseminated in the earth's crust, most of which is Polonium-210. In 1898, the natural radioactivity of Polonium-210, extracted from uranium ores, drew M. Curie to the discovery of the element polonium. At present, Polonium-210 is produced artificially by the neutron irradiation of bismuth according to the following reaction:

\[
\text{Bi}^{209}(\gamma \gamma) \rightarrow \text{Bi}^{210} \rightarrow \text{Po}^{210} \]

It then undergoes radiochemical separation and is prepared and encapsulated by the Mound Laboratory of the Atomic Energy Commission (AEC). Aside from power source applications, the other uses of Polonium-210 include applications for heat standards, alpha particle absorption studies, biological irradiation studies and neutron sources.

B. PHYSICAL PROPERTIES

Polonium is a milvery grey metal with a melting point of 254°C and a boiling point of 962°C. It has a relatively high density of 9.4 gm/cc. Polonium is quite volatile at elevated temperatures, and its condensation from the vapor phase is preferential on some metals such as platinum and palladium. Since the Polonium-210 source capsule is approximately 600°C, the polonium contained will be approximately 50% liquid and 50% volatile.

C. CHEMICAL PROPERTIES

Polonium forms both soluble and insoluble compounds. Elemental polonium will oxidize rapidly to form polonium oxide (PoO₂) at elevated temperatures and halide compounds of polonium are known. It is soluble in both hot concentrated and dilute nitric acid and...
in dilute hydrochloric and sulfuric acids. It is slightly soluble in water and very slightly soluble in potassium hydroxide.

D. NUCLEAR PROPERTIES

Polonium-210 has an atomic number of 84 and an atomic mass of 210.049. It has a half-life of 138.39 days and decays according to the following scheme.

\[
\begin{align*}
\text{Po}^{210} & \quad \text{half-life 138.39 days} \\
4.5 \text{ MeV } \alpha & \quad (0.0012\%) \\
5.3 \text{ MeV } \alpha & \quad (99.9988\%) \\
\text{Pb}^{206} & \quad \text{(Stable)}
\end{align*}
\]

The radioisotope decays with a 5.3 MeV alpha particle with a very minor contribution from a 4.5 MeV alpha particle. An 0.8 MeV gamma is essentially coincident with the 4.5 MeV alpha emission. The alpha particles have a range of 3.84 cm and a velocity of \(1.59 \times 10^9\) cm/sec in air.

The alpha particles resulting from the radioactive disintegration of Polonium-210 collect orbital electrons and become helium atoms. At 40°C, under standard pressure, the helium production is about 0.0259 cc/curie or about 40.7 cc for 1,570 curies. Polonium-210 decays to Lead-206 with a lead buildup rate of about 0.5%/day. Figure 4 shows the source strength in curies with respect to time for a 1,570 curie Polonium-210 source.

From Los Alamos Scientific Laboratory data, the neutron emission for a bare unshielded source is expected to be from 100 to 200 neutrons/sec/curie depending upon the impurities (usually oxygen) contained. Based upon these data, a 1,570 curie source would emit \(1.5 \times 10^5\) to \(3.1 \times 10^5\) neutrons/sec. Measurements made on a prototype SNAP-III unit, where neutrons were attenuated by the molybdenum capsule and external structure of the generator, showed a flux of 41.7 neutrons/sec/curie. If this is extrapolated for a 1,570 curie source, the expected flux is about \(0.65 \times 10^5\) neutrons/sec.

E. RADIOBIOLOGICAL PROPERTIES

1. External Radiation Hazard

Polonium-210 sources emit penetrating gamma and neutron radiation. The radiation due to the 0.8 MeV gamma from a bare unshielded source
Fig. 4. Decay of 1.570 Curies of Polonium-210
at one meter is 0.0065 mR/hr/curie or 10 mR/hr at one meter for the
1.570 curie source. As Polonium-210 decays, the gamma radiation will
progressively decrease to 10.1 mR/hr at one meter from the source
after one half-life (138.39 days). The neutron radiation from a
1.570 curie source at 0.89 meters would be about 3.25 mrem/hr. The
alpha radiation emitted does not constitute as significant an
external biological hazard as the neutron radiation because of its
short range and low penetration. In summary, the penetrating radia-
tion from Polonium-210 is significant but does not constitute an acute
radiation hazard.

2. Internal Radiation Hazard

Polonium-210 is quite toxic when ingested or inhaled and there-
fore constitutes a serious internal radiation hazard. The high
specific ionization of an alpha particle impinging upon internal
body tissue results in a very rapid dissipation of energy.

The maximum permissible concentration of Polonium-210 for the
total body is 0.03 microcuries for soluble polonium. The maximum
permissible concentration in air is 2 x 10^-11 microcuries/cc for
soluble polonium and 7 x 10^-12 microcuries/cc for insoluble polonium
for unrestricted areas. The maximum permissible concentration in
water is 3 x 10^-5 microcuries/cc for insoluble Polonium-210 and
7 x 10^-7 microcuries/cc for soluble Polonium-210 in unrestricted
areas. The critical organ for soluble Polonium-210 is the spleen
when it is ingested or inhaled. The critical organs for insoluble
Polonium-210 are the lungs.

Table 3 presents the physical, chemical, nuclear and radiobiological properties of Polonium-210.
**TABLE 3**

Properties of Polonium-210

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Atomic Number</td>
<td>Atomic Weight (g/cc)</td>
<td>Density</td>
<td>Melting Point (°C)</td>
<td>Boiling Point (°C)</td>
<td>Volatility (From Platinum Surface after 10 Minutes)</td>
<td></td>
</tr>
<tr>
<td>84</td>
<td>210.096</td>
<td>9.4</td>
<td>254±5</td>
<td>962±2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>In O₂ at 690°C (%)</td>
<td>In Air at ~ 700°C (%)</td>
<td>In Vacuum at 625°C (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>~100</td>
<td>50</td>
<td></td>
<td></td>
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<table>
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<tr>
<th>Chemical Properties</th>
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<th></th>
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<tbody>
<tr>
<td>Purity (%)</td>
<td>Oxidation State</td>
<td>Solubility</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥ 90</td>
<td>±2.3,4</td>
<td>H₂O</td>
<td>KOH(Dilute)</td>
<td>HNO₃(Hot, Conc)</td>
<td>HNO₃(Dilute)</td>
<td>HCl(Dilute)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SS</td>
<td>VSS</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nuclear Properties</th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-Life (sec)</td>
<td>γ Decay Energy (MeV) (%)</td>
<td>Other Energy (MeV)</td>
<td>γ Radiation (mr/hr/curie)</td>
<td>gm/curie/ cm</td>
<td>watts/ curie/hr</td>
<td>cal/ curie/hr</td>
</tr>
<tr>
<td>138.59 (1)</td>
<td>5.3</td>
<td>99.9988</td>
<td>--</td>
<td>n(α, n) (100-200 n/sec/cur)</td>
<td>0.0055(at 1m)</td>
<td>4.460</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radiobiological Properties (1)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Form</td>
<td>CO⁺ &amp; Mass (gms)</td>
<td>MPC°-TB (µc)</td>
<td>MPC Water (µc/cc)</td>
<td>MPC Air (µc/cc)</td>
<td>Biological Half-Life</td>
<td>Fraction In Co of TB</td>
</tr>
<tr>
<td>Soluble</td>
<td>Spleen 150</td>
<td>0.03</td>
<td>7x10⁻⁷</td>
<td>2x10⁻¹¹</td>
<td>57d</td>
<td>0.06</td>
</tr>
<tr>
<td>Insoluble</td>
<td>Lungs 1000</td>
<td>0.02</td>
<td>3x10⁻⁵</td>
<td>7x10⁻¹²</td>
<td>40d</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*+CO = Critical Organ*

*MPC = Maximum Permissible Concentration*

*°-TB = Total Body*

(1) MPC air and water for unrestricted areas.
V. SHIELDING REQUIREMENTS

A. RADIATION LEVELS

In view of the close similarity between the polonium-fueled APU described in this report to the SNAP-III generator, estimates of radiation levels encountered with the proposed device are based on measurements of the levels created by the SNAP-III generator. (Ref. MND-P-2513, "SNAP-III Thermoelectric Generator Radiological Safety Analysis"). The proposed APU is to be fueled with 1,570 curies of Polonium-210 which provides 50.2 watts (thermal). This fuel activity and the dose rates based upon it refer to the time of launch. If the APU is prepared one month earlier, the given dose rates should be increased by 16% in order to obtain the dose rates from the freshly prepared source.

Electromagnetic radiation from the APU is due entirely to the 0.803 Mev gamma ray emitted in 1.2 x 10^-3% of the decays of Polonium-210. The gamma flux at the surface of the aluminum vessel, 4.875 in in diameter, is 2.25 x 10^5 photons/sq cm/sec. The corresponding dose rate is 360 mrem/hr. At a distance of three feet from the center of the source, the gamma flux is 1.0 x 10^4 photons/sq cm/sec, corresponding to a dose rate of 16 mrem/hr.

Neutrons are produced in a polonium source by (α, n) reactions which occur when alpha particles emitted by Polonium-210 interact with the nuclei in the containing vessel or in certain impurities (i.e., beryllium) which may be present in the fuel. The neutron emission of the SNAP-III generator was measured by counting the neutron multiplication by the ERDL reactor in a subcritical condition; it was 41.2 neutrons/curie/sec. The neutron flux at the surface of the aluminum vessel is 1.40 x 10^5 neutrons/sq cm/sec, at three feet from the center it is 7 neutrons/sq cm/sec. The energy spectrum of the neutrons has not been measured, but if it is assumed that the effective energy is 4.5 Mev, as in the case of a Po-Be source, the neutron dose rates are 205 mrem/hr and 1.0 mrem/hr respectively.

The total (gamma plus neutron) dose rates are 0.56 rem/hr at the vessel and 17 mrem/hr at three feet from the center.

B. SHIELDING REQUIREMENTS

Because of the low radiation levels expected from the proposed APU, no biological shielding has been included in the design. In order to reduce the dose rate to 10 mrem/hr at one meter, required for shipping the source 0.7 cm (0.39 in.) of lead must be provided.
in the shipping container. Since most of the dose rate is due to gammas, this thickness has been determined so that the gamma dose rate at one meter is 9.0 mr/hr, and the attenuation of neutrons has been neglected.
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 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 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 re-entry 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 an 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 container 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 radionuclide 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, 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 resis-
tance 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 meltdown 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 109
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 fail-
ures 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 57-4 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 $7 \times 10^5$ 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 specimens at 816°C have been immersed in liquid oxygen at -183°C (ΔT = 1000°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 molybdenum 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 down range.

High Velocity Impact - 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.

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 burn up 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 10^6 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 burn up 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°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 Polonium-210 Generator

The Polonium-210 source material is encapsulated in four successive containers. Of these, the Type 316 stainless steel block is structurally most important, and it will be analyzed as being the ultimate for containment of the toxic fuel. The following are the stresses and conditions imposed on this capsule during the lifetime of the generator.

Mechanical -

Internal Pressure - Since helium gas is generated within the inner capsule by the alpha decay of the fuel, it is necessary to determine the internal gas pressure in the capsule. Each inner capsule contains 785 curies or 5.01 x 10^20 atoms of Polonium-210. The helium generated and the temperature of the device vary with time; therefore the pressure
is a function of the age of the device. Figure 5 shows a plot of the pressure buildup with time. The maximum pressure exerted upon the inner walls of the capsule is 1,310 psi and this occurs 289 days after encapsulation.

**Free-Fall Impact (70 ft)** - The maximum stress imposed on the capsule by a free-fall impact of 70 ft is 400 psi. Should the device be dropped from the launch pad the temperature of the material would be the operating temperature of the device or 900°F.

**Terminal Velocity Impact** - Should there be a pre-orbital, post launch abort of the device, a terminal velocity impact stress would be imposed on the capsule. This stress is equal to 18,000 psi. It is based on a terminal velocity of 470 fps. The temperature of the capsule on impact would be approximately 1200°F.

**Pressure Due to Exploding Rocket Fuel** - Pressures imposed on the capsule by exploding rocket fuel have been computed from an empirical equation plotted on Fig. 6. 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 APU in this case would essentially be zero due to bulk loading.

**Mechanical Integrity of the Designed Capsule** - The Type 316 stainless steel capsule can withstand a maximum internal pressure of 27,000 psi and an estimated external pressure of 20,500 psi before mechanical failure occurs. The external 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 corrected for temperature variations.

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

**Thermal** - Since the device is to burn up on reentry, the thermal analysis was concerned with determining if there was enough aerodynamic heat input to destroy the capsule and the thermal integrity of the device during ground handling.

A reentry analysis showed that the device will vaporize completely at an altitude of about 150,000 ft. This is based on an orbital decay-type reentry.

Thermal integrity of the device has been assured under the maximum handling thermal excursion possible. It has been analytically determined that the device will sustain both a rocket vehicle and an aircraft fire.
Fig. 5. Helium Pressure Buildup in Polonium-210 Capsule
Chemical - Test will have to be conducted to determine the integrity of the device when it is immersed in liquid oxygen or any other oxidizer that may be employed in the booster vehicle. It appears at present, that chemical forces will not be significant.

Hazards - Basically, there are two conceivable hazards in using a Polonium-210 power unit on a space mission. These are the release of the toxic isotope to the biosphere and the rate of fall-out of the isotope after burnup on 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 this report are applicable.

A cursory fall-out analysis has been made to show the rate of fall-out of the Polonium on the earth's surface. Because the half-life of Po-210 is relatively short and the particle size is small, the fall-out hazard does not appear to be significant.
VII RADIOISOTOPE DISPERSION

The average altitude for burnup of the Polonium-210 units is estimated to be 150,000 ft. Contamination below 70,000 ft is not desired. Therefore, a layer of the atmosphere 80,000 ft thick is a suitable residence volume for Polonium-210.

Before reentry, it has been estimated that the polonium in the source capsule will be 50% volatile and 50% liquid. During reentry the source capsule will be beyond the melting point of polonium (962°C), hence all of the polonium will be vaporized. According to the investigations of C. Chemie, as reported by Gmelin, the diameter of polonium atom groups is smaller than one micron, based upon measurements of alpha stars.

Figure 7 shows the fall-out velocity of polonium as a function of particle size. If the particle size is one micron the fall-out velocity will be $9.1 \times 10^{-4}$ fps. The time required for the polonium particles to fall from 150,000 to 70,000 ft according to Stokes' Law will be:

$$
\frac{8 \times 10^4}{9 \times 10^{-4}} = 0.88 \times 10^8 \text{ sec}
$$

$$
= \frac{8.8 \times 10^7}{8.64 \times 10^4} = 1.02 \times 10^3 \text{ days}
$$

$$
= 1.02 \times 10^3 = 7.4 \text{ half-lives.}
$$

$$
= 1.38 \times 10^2
$$

Assuming an orbital lifetime of one half-life and a fall-out time of 7.4 half-lives for a total of 5.4 half-lives of the 1570 curie source,

$$
C_t = C_0 e^{-0.693t/\text{half-life}}
$$

Where $t = 8.4$ half-life

$$
C_t = C_0 e^{-0.693(8.4)}
$$

$$
= 1570 \times 10^3 e^{-5.82}
$$

$$
= 1570 \times 10^3 (3 \times 10^{-3})
$$

$$
C_t = 4.7 \text{ curie}
$$

Approximately 4.7 curies would reach the 70,000 ft-altitude level.
Fig. 7. Fallout Velocity of Polonium-210
As a Function of Particle Size
This analysis is based upon conservative assumptions and does not include high altitude wind flow, mixing and Brownian movement. Particles smaller than five microns in diameter are seriously affected by Brownian movement, resulting from collisions with air molecules, so that some of them remain suspended for very long periods. The rate of fall of larger particles is affected by turbulence of the air. This analysis neglects the adhesion of polonium particles to metal particles of the disintegrating satellite component metals which are of larger micron size.
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:

\[ MPD = 5 \times (N-18) \text{ rems} \]

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

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

<table>
<thead>
<tr>
<th>Permissible Concentration in Air (Bq/ml)</th>
<th>Permissible Body Burden (Bq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polonium 210 (soluble)</td>
<td>( 5 \times 10^{-10} )</td>
</tr>
<tr>
<td>Polonium 210 (insoluble)</td>
<td>( 2 \times 10^{-10} )</td>
</tr>
</tbody>
</table>

* 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. 
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 those for restricted areas.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Permissible Concentration (µC/ml) Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polonium 210 (soluble)</td>
<td>$2 \times 10^{11}$</td>
</tr>
<tr>
<td>Polonium 210 (insoluble)</td>
<td>$7 \times 10^{12}$</td>
</tr>
</tbody>
</table>

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 Polonium-210 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 up to 100 r/hr for emergency use. For measuring low level contamination, instruments complete with headphones and with a range up to 20 mr/hr should be available.

(2) Portable Proportional Alpha Survey Meters, complete with headphones, should be available to measure alpha contamination up to 20,000 counts/min. Although Polonium-210 does emit neutrons, it will not be necessary to provide neutron monitoring since the dose rate is relatively low when compared with the gamma levels. Neutron exposures are controlled by keeping the gamma exposures within permissible limits.

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.

D. EMERGENCY PROCEDURES

Extreme precautionary measures have been taken to virtually remove the probability of an individual receiving an excessive radiation dose due to use of a radioisotope in an orbital vehicle. To further reduce this probability, emergency conditions that could occur, even under the most remote circumstances, must be considered and emergency procedures presented to cope with any condition. Listed are some of the potential emergency conditions together with a general outline of the remedial action that must be taken.


Hazards Present: High level airborne and surface contamination.

Remedial Action: Evacuate all personnel from vicinity of source. While wearing self-contained respirators, rope off area and place source in shipping container. Clean up all contaminated areas. Check personnel for exposures and contamination.

2. Condition: Fire

Hazards Present: Moderately high external radiation and possible high airborne and surface contamination.

Remedial Action: Evacuate all personnel from vicinity of source. Firemen should wear self-contained respirators and approach fire as directed by health physics personnel. When fire is out, source should be approached only when radiation levels have been determined by health physics personnel. Monitor all personnel for contamination.
<table>
<thead>
<tr>
<th>Condition</th>
<th>Hazards Present</th>
<th>Remedial Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explosion on launch pad</td>
<td>Moderately high external radiation levels and possibly high airborne and surface contamination.</td>
<td>Personnel should evacuate the area but take no further action until source has been located and radiation levels checked. Rope off area around source. Follow up by covering source with sand, place behind barricade, etc. Clean up contaminated areas if necessary. Determine personnel exposures and contamination.</td>
</tr>
<tr>
<td>Reentry into ocean</td>
<td>Probably none.</td>
<td>Monitor radiation levels surrounding reentry location.</td>
</tr>
</tbody>
</table>