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METALLURGY AND CERAMICS

FINAL SAFETY ANALYSIS REPORT

Snap III Thermoelectric Generator

By
W. Hagis
George P. Dix

June 1960

Nuclear Division
Martin Company
Baltimore, Maryland

UNITED STATES ATOMIC ENERGY COMMISSION • OFFICE OF TECHNICAL INFORMATION

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FINAL SAFETY ANALYSIS REPORT
SNAP III THERMOELECTRIC GENERATOR

June 1960

Prepared by: W. Hagis

George P. Dix
Nuclear Safety Analysis Unit

This report is prepared under
Contract AT (30-3)-217 with the
United States Atomic Energy
Commission

Nuclear Division
Martin Company
Baltimore, Maryland

FOREWORD

This report was prepared by The Martin Company for the United States Atomic Energy Commission under Contract AT(30-3)-217. It states the results of a safety analysis of the Polonium-210 fueled generator system developed under Subtask 5.5 during the period from July 1, 1959, through June 30, 1960.

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SUMMARY

The SNAP III thermoelectric generator produces power from the decay heat of 2200 curies of Polonium-210. This generator is to be used as a source of auxiliary power in a terrestrial satellite. For purposes of analysis, the satellite system postulated is launched from the Pacific Missile Range into a 275-statute mile polar orbit with an orbital lifetime of about one year.

Polonium-210 is an alpha emitter having a half life of 138 days and alpha and gamma decay energies of 5.3 and 0.8 mev, respectively. It is a natural component of the earth's crust, as a member of the uranium disintegration series. Sampling of polonium in the biosphere has been conducted specifically for this program, to determine background radiation levels. Since the fuel is primarily an alpha emitter, there is no direct radiation problem.

An analysis has been performed to determine the ability of the fuel container to withstand the various thermal, mechanical and chemical forces imposed upon the generator by vehicle failures. Where theoretical analysis was impossible, and where experimental evidence was desired, capsules and generators were tested under simulated missile-failure conditions. Thus, the safety limits of SNAP III in a satellite application were defined.

SNAP III is designed to be aerothermodynamically consumed on re-entry into the earth's atmosphere so that the polonium will be dispersed as aerosols in the upper stratosphere. Since heating rates will be lower for aborts occurring prior to orbiting, 65 abort cases have been considered to define the general consequences of vehicle failures. The spatial and temporal relationships of vehicle aborts are summarized in cartographic and tabular form.

I. INTRODUCTION

In this report, the SNAP III thermoelectric generator, designed at The Martin Company, is described in detail. The integration of the generator and vehicle is also presented. SNAP III will be carried on a vehicle consisting of a conventional ICBM booster mated to a final-stage injection vehicle. An eject-destruct system has been designed as a countermeasure to enhance the safety of the mission.

Polonium-210, an alpha emitter with a half life of 138 days, is used for the production of thermal energy. This isotope occurs in nature as one of the daughter products of the uranium disintegration series.

The successful mission results in the decay of the initial 2200-curie inventory of Po-210 to 356 curies before the satellite re-enters the earth's atmosphere. The aerothermodynamic history of the generator during its post-orbital re-entry is discussed. The definitions of aborted missions and forces imposed by them are presented with an evaluation of the thermal, mechanical and chemical forces imposed by launch, ascent and final-stage failures.

The report concludes with a tabular and cartographic summary of the fate of the polonium fuel for both successful and aborted missions. Sixty-five specific cases of successful and aborted missions are resolved into seven general cases.

Natural and SNAP-induced concentrations of Polonium-210 on the earth's surface are compared in the Appendix. This section includes the relative importance of stratospheric injections of Po-210, direct fallout from aborted and successful missions, deposition of natural atmospheric polonium, polonium naturally present in the biosphere, and an evaluation of soil concentrations of natural Po-210.

II. THE THERMOELECTRIC GENERATOR*

A. DESIGN

The SNAP III thermoelectric generator produces power from the heat evolved in the radioactive decay of Polonium-210. At the time of launch into orbit the generator will contain about 0.489 gram of Po-210 fuel, with an activity of 2200 curies. It will provide 69 watts of thermal power which, at a conversion efficiency of about 5%, will result in a 3.5-watt electrical power output. The activity of Po-210 falls off exponentially to half its original value in 138.4 days.

In the SNAP III the fuel is divided equally between two capsules. Both capsules are Type 304 stainless steel with a wall thickness of 0.030 inch, and each capsule is closed by a plug welded in place. The inside volume of each capsule is 0.279 cubic centimeter. The fuel occupies about 10% of this volume, leaving the remainder available for the helium gas formed in the decay process.

The two fuel capsules are placed in a stainless steel canister with a wall thickness of 0.034 inch. The canister, also, is closed by welding. A heavy vessel made of the cobalt-base alloy, Haynes-25, contains the primary capsules and canister. Figure 1 shows a cross section of the complete capsule assembly. Haynes-25 provides the mechanical strength and corrosion resistance necessary to ensure containment of the fuel under any condition encountered during manufacture, transportation and installation of the generator.

The Haynes-25 vessel has an internal diameter of 0.364 inch. Its outer wall tapers slightly; the smallest outer diameter is 0.75 inch. The plug closing this vessel is screwed into place and welded. The outer surface of the Haynes-25 vessel has a temperature of about 1100° F (593° C). The interior is at a slightly higher temperature well above the melting point of polonium.

The hot junctions of the 27 pairs of lead telluride thermoelectric elements are placed against the Haynes-25 vessel. The cold junctions are held in contact shoes which extend to the surface of the generator. The massive Haynes-25 vessel and the assembly of thermoelectric elements are held in place by rigid heat-insulating material, and voids are filled with powdered insulation (Johns-Manville Min-K).

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* C. O. Riggs

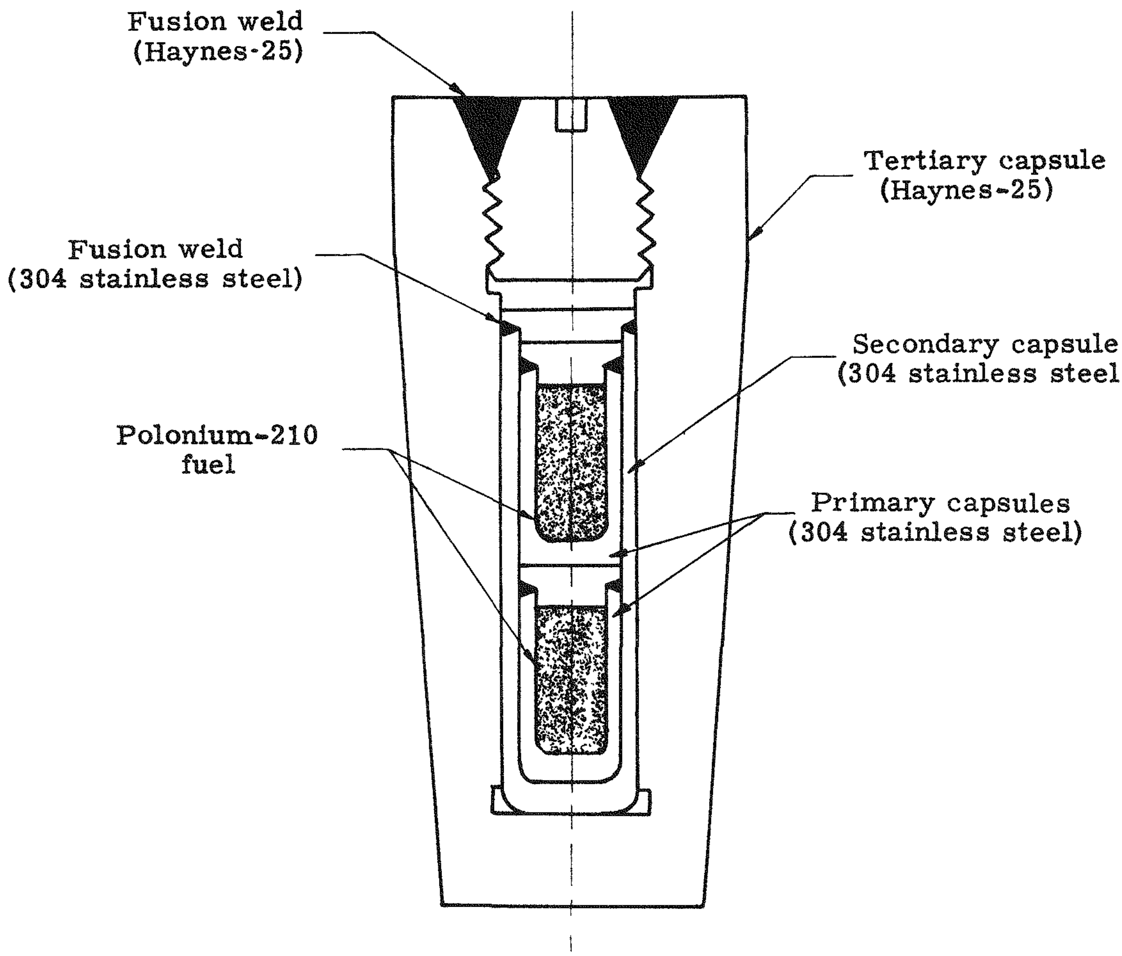

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Fig. 1. SNAP III Fuel Capsules

The generator is encased in a nearly spherical shell of copper, as shown in Fig. 2. This shell is composed of segments soldered together, so that the seams will open and allow the insulation and thermoelectric elements to fall away, exposing the core. This procedure promotes burn-up upon re-entry after an aborted satellite mission, or after orbital decay following a successful mission.

The generator shell is filled with helium (or a He-H_2 mixture) at about 1 atmosphere pressure and sealed. A controlled leak is provided. When the satellite vehicle is in orbit, where the ambient pressure is nearly zero, the helium will slowly leak out of the generator. As a result, the insulating properties of the Min-K will improve. Temperatures throughout the generator tend to fall with the decreasing activity of the Po-210 fuel; however, the improvement in insulation counteracts this tendency to some extent. The temperature, therefore, remains higher than under ordinary conditions of decreasing fuel activity; and the power output remains essentially constant (power output curve flattened). Tests indicate that the container temperature will have fallen from 1100° F (593° C) to 900° F (482° C) in 100 days. Without the helium leak and resultant power flattening, the temperature would be expected to fall to 700° F in 100 days.

At the time of encapsulation each fuel capsule will contain 0.2446 gram, or 1.165×10^{-3} mole of Polonium-210. This quantity of Polonium-210 occupies a volume of 0.027 cubic centimeter, leaving a void in each capsule of 0.252 cubic centimeter. The void is provided for the helium produced by the radioactive decay of the fuel. The pressure due to the helium can be calculated from the equation:

$$P = \frac{NRT}{V} \tag{1}$$

where:

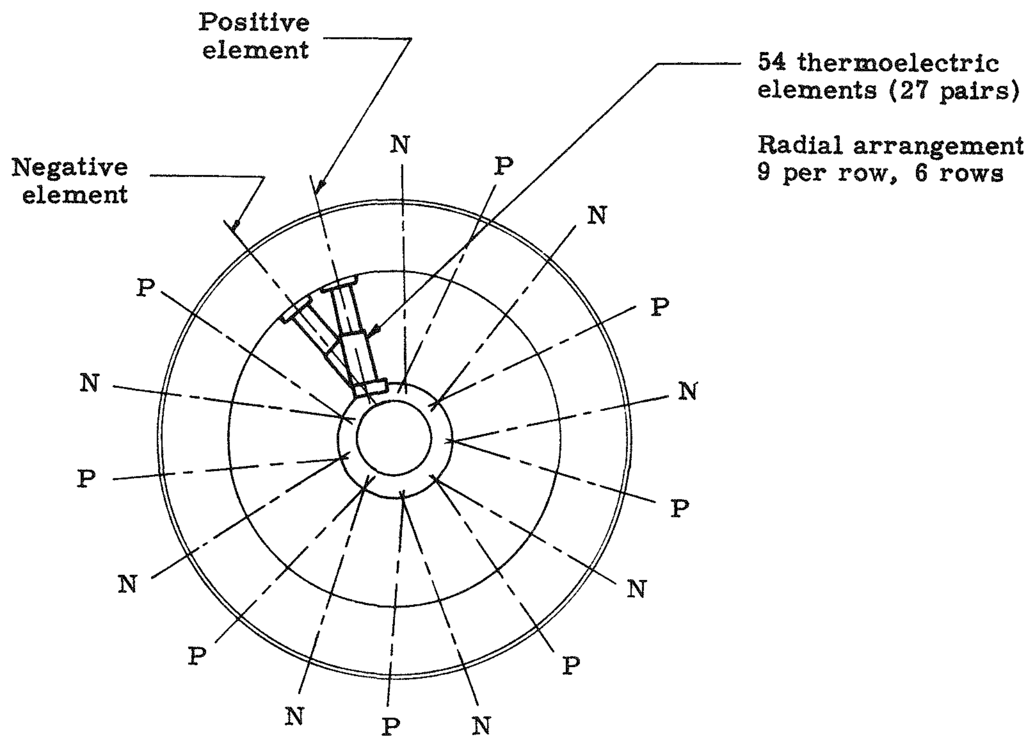
P = pressure (atmospheres)

R = universal gas constant (0.0821 l-atm/mole-°K)

T = temperature at any time (°K)

V = volume (liters)

N = moles of helium.



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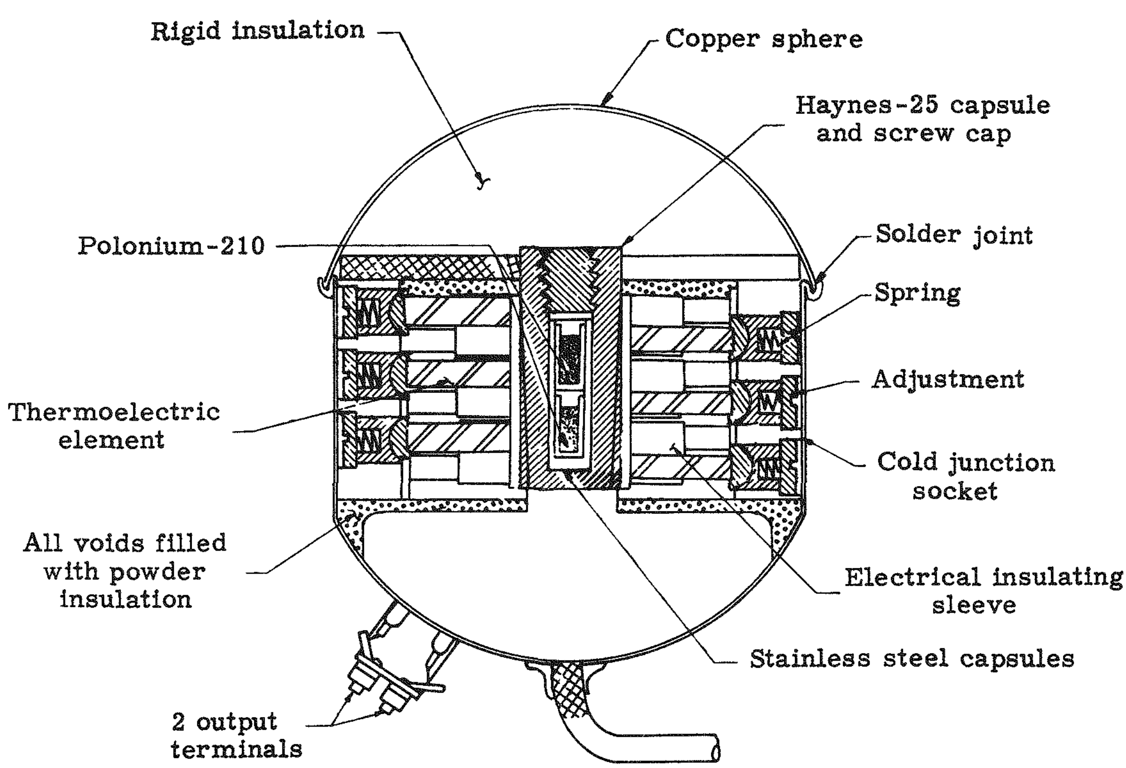


Fig. 2. SNAP III Generator

The number of moles of helium is given by:

$$N = N_o (1 - e^{-\lambda t}) \tag{2}$$

where:

N = number of moles of helium at time (t)

N_o = moles of Polonium-210 (at encapsulation)

λ = decay constant (5×10^{-3} day^{-1})

t = time from encapsulation (days).

Without the power flattening arrangement previously described, the temperature may be expected to fall in the manner expressed by the following equation:

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

where

T_o = temperature at time of encapsulation (866° K)

T_a = ambient temperature (300° K).

These equations may be combined to give:

$$P = \frac{N_o R}{V} (1 - e^{-\lambda t}) \left[(T_o - T_a) e^{-\lambda t} + T_a \right]. \tag{4}$$

The evolution of helium tends to increase the pressure within the capsule, but the decrease in temperature has the opposite effect. If Eq (4) is differentiated, and the derivative set equal to zero, the maximum pressure is found to be reached at 290 days. At this time, the temperature is 160° C and the pressure is 126 atmospheres, or 1850 psi. The variations of pressure and temperature with time according to Eqs (3) and (4) are shown in Fig. 3. In addition, the same variations are shown with temperature assumed to fall linearly from 1100° to 900° F during the first 100 days. The pressure in this time interval does not reach the maximum previously given. It is assumed that after the 100 days the power-flattening effect is exhausted. Under this condition, the maximum pressure of 2066 psi is reached in 242 days; at this time the temperature is 491° F (254° C).

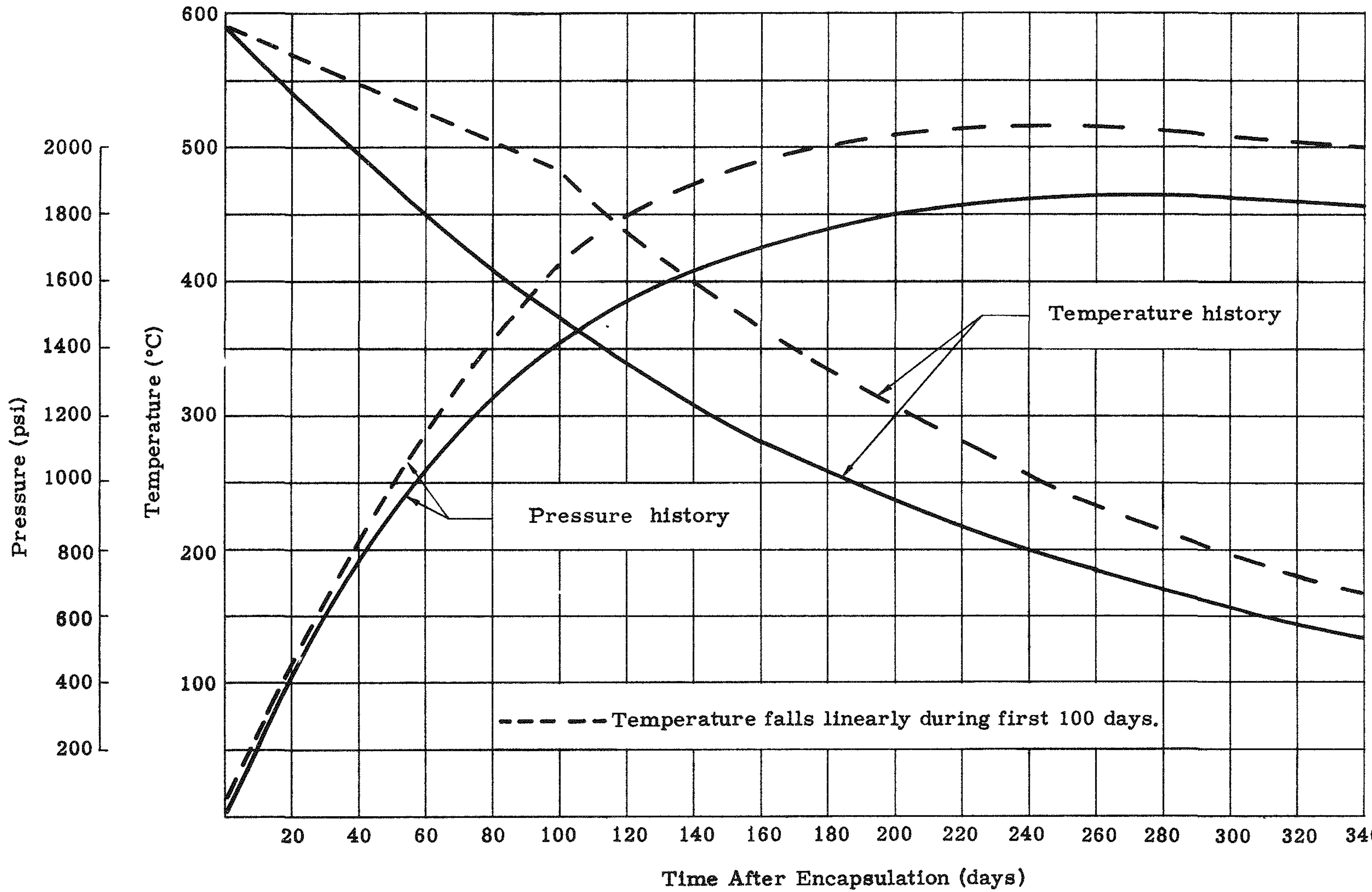


Fig. 3. Pressure-Temperature History of Fuel

The Haynes-25 containment vessel is able to withstand many times this internal pressure. When tested at temperatures from 1100 to 1700° F, it exhibited no deformation under a pressure of 30,000 psi after 640 hours. At room temperature it has withstood 95,000 psi without failure. The properties of Haynes-25 are given in Table 1.

TABLE 1

Properties of Haynes-25*

Chemical composition	Ni(9 to 11%), Cr(19 to 21%), W(14 to 16%), Fe(3%), C(0.05 to 0.15%), Si(1%), Mn(1 to 2%), Co(balance)
Physical properties	
Density	9.13 gm/cc
Melting range	1329° to 1410° C
Specific heat (28° to 100° C)	0.092 cal/gm-°C
Ultimate tensile strength	109,000 psi
Yield strength (room temperature)	70,000 psi
Corrosion	
Boiling concentrated HNO_3	0.046 inch per year
Sea water (pitting)	0.014 inch per year**

*Haynes Stellite Company, "Haynes Alloy No. 25," March 1959
**Estimated

Scale models of the complete generator and the fuel core were tested in plasma-arc tunnels to substantiate analytical results concerning consumption of the generator unit by aerodynamic heating during postorbital re-entry. It was shown that the copper shell of the generator remains intact, while the internal aluminum supporting rings melt as the unit is exposed to aerodynamic heating. The single joint near the equator of the generator shell could fail to separate properly. The result is that the interior molten aluminum acts as a heat sink and prevents proper ablation of the generator shell. Therefore, it is recommended that the copper shell be segmented into at least four parts, with the second joint normal to the existing one. Joining the segments with a low melting solder assures the release of the copper shell, insulating materials and thermoelectric elements when desired.

A second solution is to construct the generator shell of aluminum. This aids in the proper sequence of melting and does not result in the danger of prolonging the dispersion of polonium during re-entry.

III. SYSTEMS INTEGRATION

A. THE VEHICLE

The SNAP III Generator will be carried on a satellite mission by a vehicle consisting of a conventional ICBM or IRBM booster stage wedded to a final injection stage which also serves as the satellite. Typical boosters are fueled with RP-1 and liquid oxygen, whereas the injection stage is fueled with unsymmetrical dimethylhydrazine (UDMH) and inhibited red fuming nitric acid (IRFNA).

The booster for this study was assumed to be a single-stage system which accelerates the final stage to an altitude of 500,000 feet and a velocity of about 13,000 feet per second. At this point vernier rockets fire for several seconds to adjust the flight attitude of the vehicle. Then the final stage separates from the exhausted booster stage and coasts to an altitude of 1,380,000 feet. The final stage ignites and thrusts for about 120 seconds to accelerate to orbital velocity.

The satellite consists of the final-stage engine, empty propellant tanks and the payload, which is located in the forward equipment compartment. Because of inherent system weight limitations, the satellite structure is relatively light, consisting of structural members up to 0.25 inch in thickness and skins up to 0.1 inch, generally made of magnesium and aluminum.

Each major stage is equipped with a missile safety subsystem which provides:

(1) A means of transmitting location, behavior and projected missile-impact point to the range safety officer.

(2) A means of terminating powered flight and destroying the missile.

The safety subsystem hardware consists of a transponder and command receivers associated with shutdown and destruction circuitry. The vehicle is destroyed with explosive charges placed to destroy the propellant tankage, thus disintegrating the missile.

B. GENERATOR INSTALLATION

The SNAP III generator is installed in the nose cone structure of the final-stage vehicle. When the vehicle is erect on the launch pad, the generator is about 100 feet from the ground and is above the fuel tanks.

It is mounted on an approximately hemispherical structure about 6 inches in radius securely fastened to the vehicle structure.

C. THE EJECT-DESTRUCT SYSTEM

A special accessory system is provided with the SNAP III generator to throw it clear of the vehicle in case of vehicle failure during launch or to core the fuel capsule, dispersing the fuel at high altitude. This system is contained in the hemispherical shell upon which the generator is mounted. The generator is placed so that the axis of the fuel capsule makes a 45-degree angle with the longitudinal axis of the vehicle.

The eject-destruct system has, for ejection of the generator, a piston actuated by a squib of black powder. The piston is designed to project the generator at least 250 feet from the base of the missile. The mechanism for destruction of the fuel capsule uses a shaped charge of RDX with a liner; this will produce a hole about 3/8 inch in diameter through the Haynes-25 and stainless steel containment vessels, fully ejecting the fuel in its plasma.

The eject-destruct mechanism shown in Fig. 4 has three positions: a safe position, an eject position and a destruct position. While the generator is being installed and tested, the eject-destruct system is in the safe position. In this position neither the ejection nor the destruction apparatus is directed toward the generator, and neither can be set off. At an appropriate point in the launching countdown, the mechanism is placed in the eject position by a signal from ground control. A part of the mechanism rotates through 45 degrees and brings the ejection piston against a thrustor cup attached to the generator. If ejection is required while the vehicle is on the launch pad or in the ascent phase of the trajectory, the ejector will be actuated to throw out the generator. The mechanism can be returned to the safe position.

If the generator is ejected while the vehicle is on the launch pad, the fuel capsule will suffer no serious damage. A generator used several times in tests of the eject system suffered only slight case deformation. If it is ejected at a high altitude, the generator will reach a terminal velocity of 190 feet per second. Impact at this velocity on land or water will crush the case and thermoelectric elements but will not endanger the containment of the radionuclide fuel. The Haynes-25 vessel has been tested by The Martin Company in collaboration with the Aberdeen Proving Ground and has been shown to be able to withstand impact on granite at 500 feet per second.

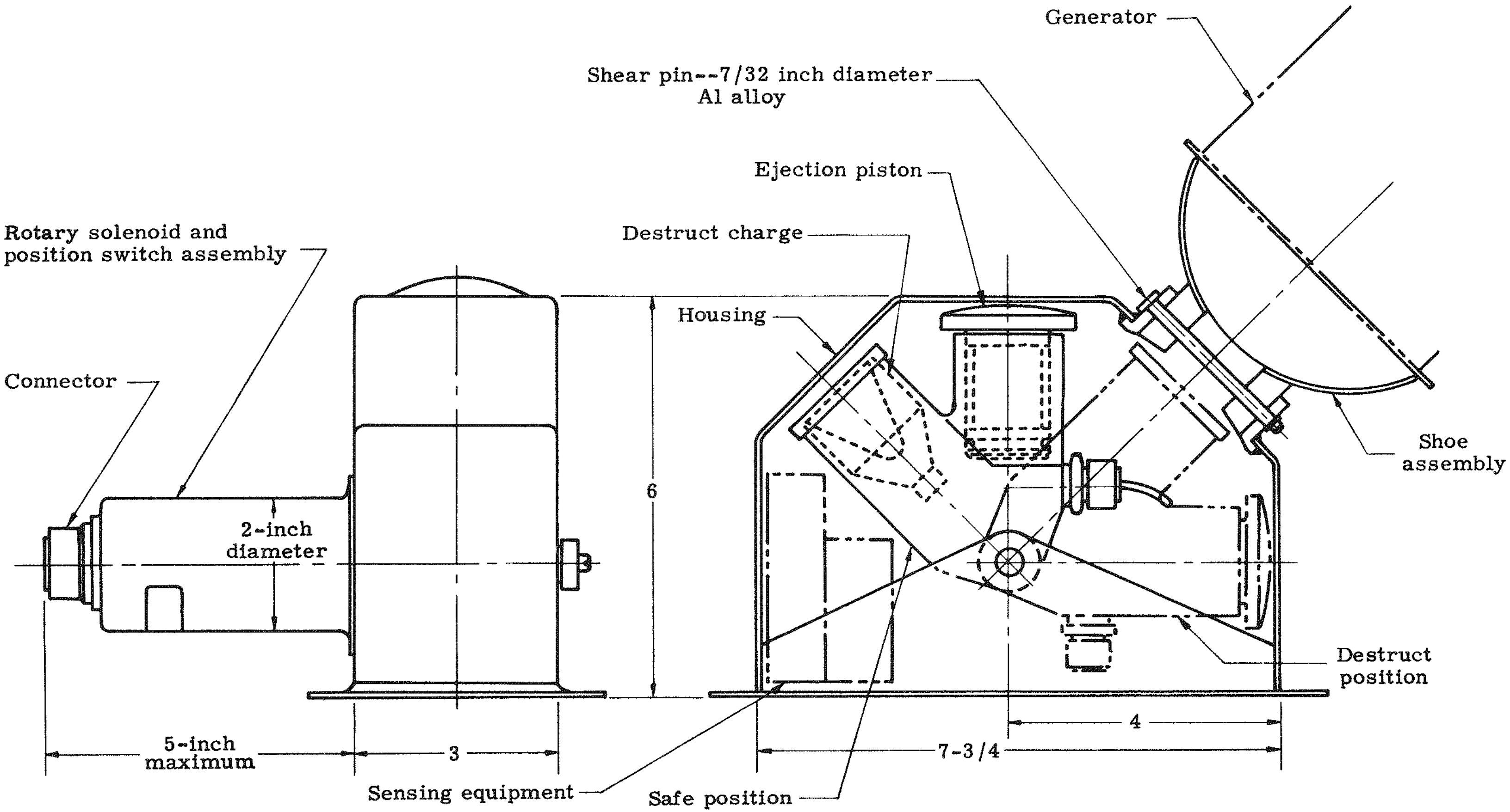


Fig. 4. Eject-Destruct Package

At or near the end of the boost phase of the trajectory, a signal will cause the mechanism to rotate through a second 45-degree angle from the eject position to the destruct position. This signal may be derived from an altimeter, an accelerometer or a timing device. The mechanism cannot be returned from the destruct position to the eject or safe positions. Subsequently, a signal derived from the increase of ambient pressure due to a decrease in altitude, or a thermal signal derived from the initiation of aerodynamic heating will actuate the destruct mechanism. The charge will destroy the fuel capsule and disperse the fuel well above 100,000 feet altitude. High altitude dispersion is thus assured either for an abort in which the vehicle fails to achieve an orbit or for re-entry after a successful mission. Figure 5 shows the effect of the destructive charge on the generator fuel container.

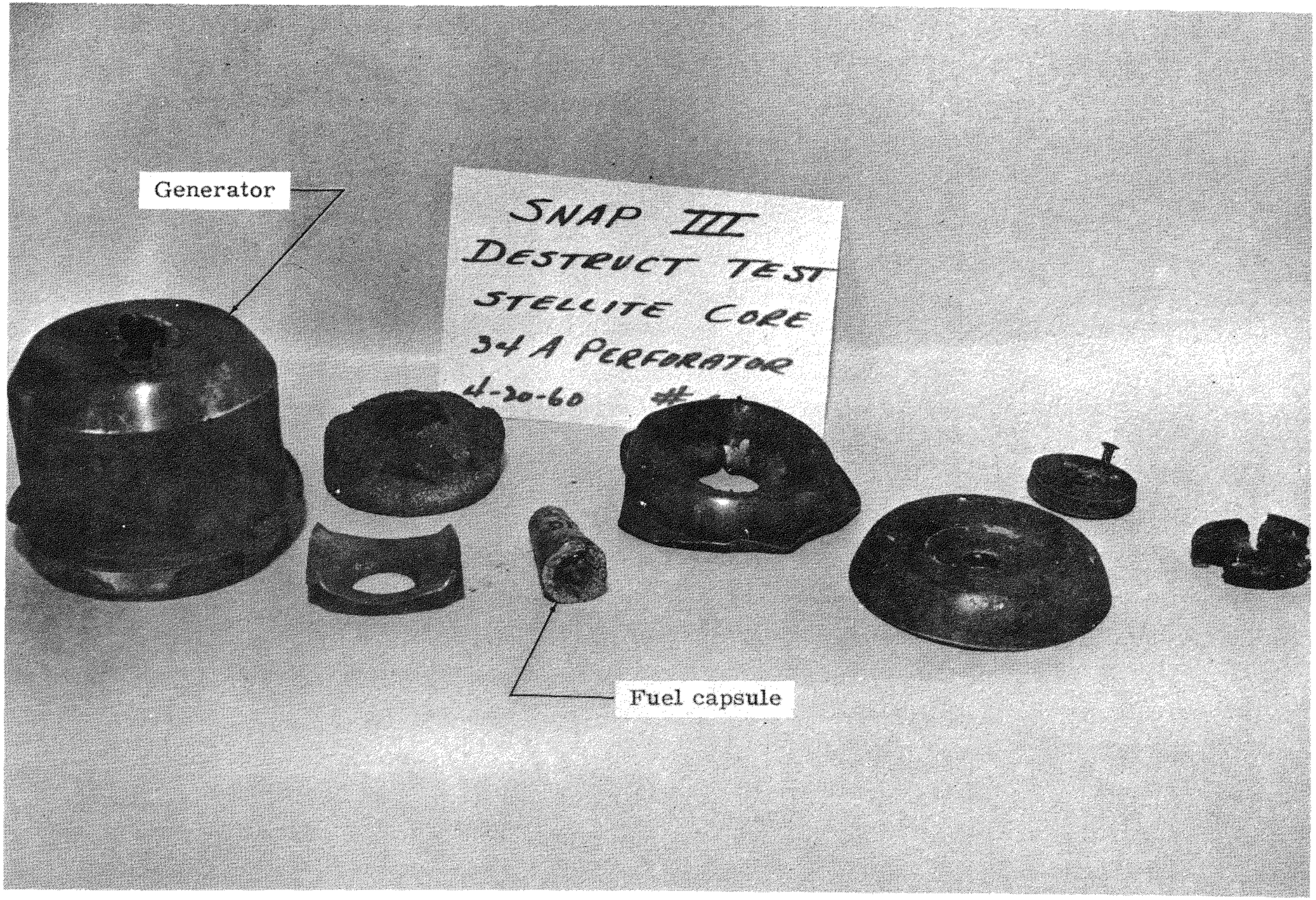


Fig. 5. SNAP III Test Core

IV. POLONIUM-210

The greatest part of the radioactivity from the material first isolated by Madame Curie is now known to have been due to the isotope Polonium-210. This isotope is a member of the naturally occurring uranium series and was first designated Radium F. The equilibrium ratio of natural uranium to natural polonium is 1.10×10^{-10}. Polonium occurs in the earth's crust at the rate of 3×10^{-10} grams per metric ton; this is equivalent to 1.3×10^{-6} microcuries per gram. Pitchblende may contain as much as 0.04 milligram of Po-210 per ton.

Because of its high power density, Polonium-210 has aroused interest as a source of thermal energy. It has been found that artificial production is more economical than isolation of the natural isotope. The Mound Laboratory, operated by the Monsanto Chemical Company for the United States Atomic Energy Commission, produces it by the neutron irradiation of bismuth in a reactor.

A. PHYSICAL PROPERTIES

Polonium is a metal which melts between 252 and 262° C and boils at about 962° C. It has a high vapor pressure at temperatures well below its boiling point. Its heat of vaporization is about 25,600 calories per mole. The solid exists in two allotropic forms. The alpha, low temperature, form has a simple cubic crystal structure. The high temperature beta form has rhombohedral structure. The inversion temperature appears to be indefinite; inversion from alpha form to beta form has been reported to begin as low as 18° C, and the reverse transition has been reported as occurring at temperatures as high as 130° C. The density of the alpha form is from 9.2 to 9.4 grams per cubic centimeter.

B. CHEMICAL PROPERTIES

Polonium usually exhibits a valence of four but forms a few compounds in which its valence is two. PoO_2 is the only known oxide. Both the dichloride and the tetrachloride have been prepared. Polonium enters into complex ions, in several cases as a constituent of the cation. The solubility of polonium oxide in common solvents varies widely, and the results found by various experiments do not always agree. The values given in the following table should be regarded only as indicating orders of magnitude.

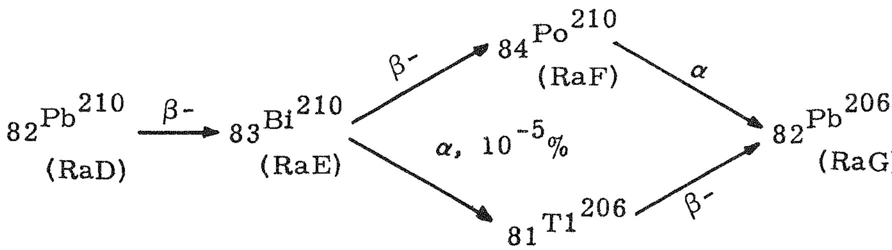
Solubility of Polonium Oxide

Solvent	Solubility (mc/cc)
HNO_3	4.35
HCl	8950
H_2SO_4	2.3
HF	2000
H_3PO_4	200
$HClO_4$	125
Citric acid	150
Oxalic acid	7.5
Tartaric acid	25
Acetic acid	100
NaOH	270
NH_4OH	1

Polonium is easily electrolyzed from solution. Most metals will replace polonium from solution without the application of a voltage. Much of the early study of polonium was carried out with films of the metal deposited on platinum.

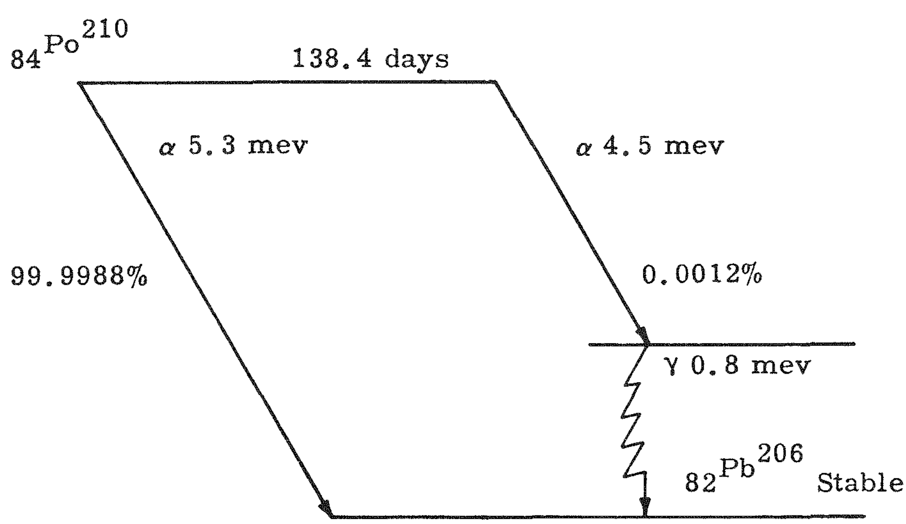
C. RADIOCHEMICAL PROPERTIES

Polonium-210, the principal isotope of the element, is a member of the naturally occurring uranium, or 4n + 2, radioactive series, which includes Uranium-238 and Radium-226, the principal isotopes of these elements. The end of the series is stable Lead-206. The last several members of the series and their relations are shown in the following chart.



Polonium-210 has a half life of 138.39 days and decays by the emission of alpha particles. In 99.9988% of the disintegrations the alpha particle has an energy of 5.3 mev. In the remaining 0.0012% of the disintegrations a 4.5-mev alpha is accompanied by a 0.8-mev gamma photon. This is the most nearly pure alpha radiation given by any radionuclide useful for power purposes. The radiation due to the gamma photons is about 0.006 milliroentgen per hour at 1 meter from a bare unshielded source of 1-curie activity.

Polonium-210 has the following decay scheme:



Pure Polonium-210 does not emit neutrons. However, if there is present in the fuel any polonium oxide or impurities containing light elements, especially beryllium, neutrons will be formed by an alpha-neutron reaction. Further, the gamma radiation will be increased by photons released in this reaction. Such effects are difficult to predict. The following table gives some results of the measurements of radiation at a distance of two inches from the surfaces of several SNAP III generators.

Radiation at Two Inches from Generator Surface

Fuel Load (curies)	Container Material	Radiation: Gamma (mr/hr)	Radiation: Neutron (mrem/hr)
1664	Molybdenum	350	2.5
1738	Molybdenum	500	15
2200	Haynes-25	400	10.6

Polonium-210 is now produced artificially by neutron irradiation of bismuth in a nuclear reactor. The isotope ${}_{83}Bi^{209}$, which constitutes practically 100% of natural bismuth, undergoes a neutron-gamma reaction to produce ${}_{83}Bi^{210}$. This nuclide, with a five-day half life, decays by beta emission, forming ${}_{84}Po^{210}$.

$${}_{83}Bi^{209} + {}_{0}n^{1} \xrightarrow{\gamma} {}_{83}Bi^{210} \xrightarrow[5\ \text{days}]{\beta^-} {}_{84}Po^{210}$$

While this reaction does not produce large amounts of Po-210, it is more feasible, economically, than the separation of the isotope from natural sources.

One curie of activity is produced by 2.225×10^{-4} gram of pure Polonium-210, and 3.14×10^{-2} watt of thermal energy is released; the specific power is about 141 watts per gram. Because it is almost exclusively an alpha emitter, requiring little shielding, and because it produces power at a high rate, Polonium-210 is an excellent source of radioisotopic power.

D. RADIOBIOLOGICAL PROPERTIES

The gamma radiation from Polonium-210 is so small that the thermoelectric elements and supporting structure attenuate its effect to tolerable levels in the SNAP III generator. Alpha radiation is almost entirely absorbed in less than a thousandth inch of the inner container. Consequently, potential radiobiological hazards can arise only if the fuel is released in a form in which it can enter the body by inhalation or by ingestion with food or water.

In the event that a soluble form of Polonium-210 enters the body by ingestion with food, the organs most likely to be critically affected are the spleen and kidneys. The potential hazard of the insoluble form arises from inhalation; in this case the organ most affected is the lung. Injury is also possible to the gastrointestinal tract (GI), particularly the lower large intestine (LLI), from insoluble material passing through it. Table 2 gives the maximum permissible body burden (MPB) and the maximum permissible concentrations in water (MPC_w) and in air (MPC_a). These are conservative limits agreed upon by Committee II, International Commission on Radiological Protection. The 40-hour week tolerances are those suggested for persons continuously employed in nuclear work. The 168-hour week tolerances are for persons not so employed. In the table, underlining indicates the critical organs and the corresponding concentrations.

Table 3 gives additional radiobiological properties and constants for Polonium-210. In this table the following terms and abbreviations are used:

T_{rad} = the radiological half life.

T_{bio} = the biological half life, the time for half the radionuclide to be eliminated by biological processes.

T_{eff} = the effective half life.

$$T_{eff} = \frac{T_{rad} \times T_{bio}}{T_{rad} + T_{bio}}$$

f_1 = fraction of the radionuclide passing from GI tract to the blood.

f_2 = ratio of the radionuclide in the critical organ to that in the total body.

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

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

$$f_w = f_1 f_2'.$$

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

Measured values for Polonium-210 in human tissues are reported later in the text.

TABLE 3

Additional Radiobiological Properties

Isotope	T_{rad} (day)	T_{bio} (day)	T_{eff} (day)	f_1	f_2	f_2'	f_w	f_a
$_{84}Po^{210}$	138.4			0.06				
Organ								
Total body		30	25		1.0	1.0	0.06	0.28
Kidney		70	46		0.13	0.07	4×10^{-3}	0.02
Spleen		60	42		0.07	0.04	2×10^{-3}	0.01
Liver		41	32		0.22	0.17	0.01	0.05
Bone		24	20		0.08	0.1	6×10^{-3}	0.03

TABLE 2

Radiobiological Properties of Polonium-210

	Organ	MPB (μc)	40-Hour Week MPC$_w$ ($\mu c/cc$)	40-Hour Week MPC$_a$ ($\mu c/cc$)	168-Hour Week MPC$_w$ ($\mu c/cc$)	168-Hour Week MPC$_a$ ($\mu c/cc$)
Soluble	Spleen	0.03	2×10^{-5}	5×10^{-10}	7×10^{-6}	2×10^{-10}
	Kidney	0.04	2×10^{-5}	5×10^{-10}	8×10^{-6}	2×10^{-10}
	Liver	0.1	7×10^{-5}	2×10^{-9}	3×10^{-5}	6×10^{-10}
	Total body	0.4	2×10^{-4}	5×10^{-9}	8×10^{-5}	2×10^{-9}
	Bone	0.5	3×10^{-4}	7×10^{-9}	10^{-4}	2×10^{-9}
	GI (LLI)	--	9×10^{-4}	2×10^{-7}	3×10^{-4}	7×10^{-8}
Insoluble	Lung	--	--	2×10^{-10}	--	7×10^{-11}
	GI (LLI)	--	8×10^{-4}	2×10^{-7}	3×10^{-4}	5×10^{-8}

V. SUCCESSFUL MISSIONS

In a successful mission a vehicle carrying a SNAP III generator will be placed in a 275-statute mile circular orbit. The vehicle will be launched from the Point Arguello complex on the Pacific Missile Range on a 183-degree azimuth so that a polar orbit will result.

The satellite can be expected to remain in orbit for approximately 365 days. Polonium-210, the fuel, has a half life of 138.4 days. Therefore, at the time of the satellite's re-entry radioactive decay will have reduced the activity level of the fuel to 16% (356 curies) of the original amount. This chapter will discuss the sequence of events during the re-entry of the satellite from orbit and the fate of the Polonium-210 fuel during this period.

A. RE-ENTRY FROM ORBIT

Orbital altitude regression is a continuous process, because aerodynamic forces are acting on the body from the time of its injection into orbit. The lifetime of the orbit is a function of the eccentricity and altitude of the orbit and the shape of the satellite vehicle. The altitude of the orbit will be slowly reduced; and when a level of 375,000 feet is reached, aerodynamic heating and dynamic pressure forces become significant. At this altitude the fuel can be dispersed as aerosols by the eject-destruct system. The shaped charge used in the eject-destruct system consists of RDX with a liner, designed so that the charge will penetrate the fuel capsule material and completely vaporize the fuel in its plasma stream. The fuel will be dispersed completely above 100,000 feet; the result will be worldwide despersion of the polonium.

B. AERODYNAMIC ANALYSIS

In the aerothermodynamic analysis it is assumed that the satellite structure is consumed by aerodynamic forces, releasing the generator to the air stream. It is also assumed that the eject-destruct device is not present in the satellite and that natural re-entry conditions prevail.

Figure 6 shows the re-entry trajectory and the aerodynamic heating rate experienced by the generator shell and fuel capsule. The generator and fuel capsule are assumed to be spinning, and the developed stagnation heating is integrated over the entire surface of the unit. A point on the

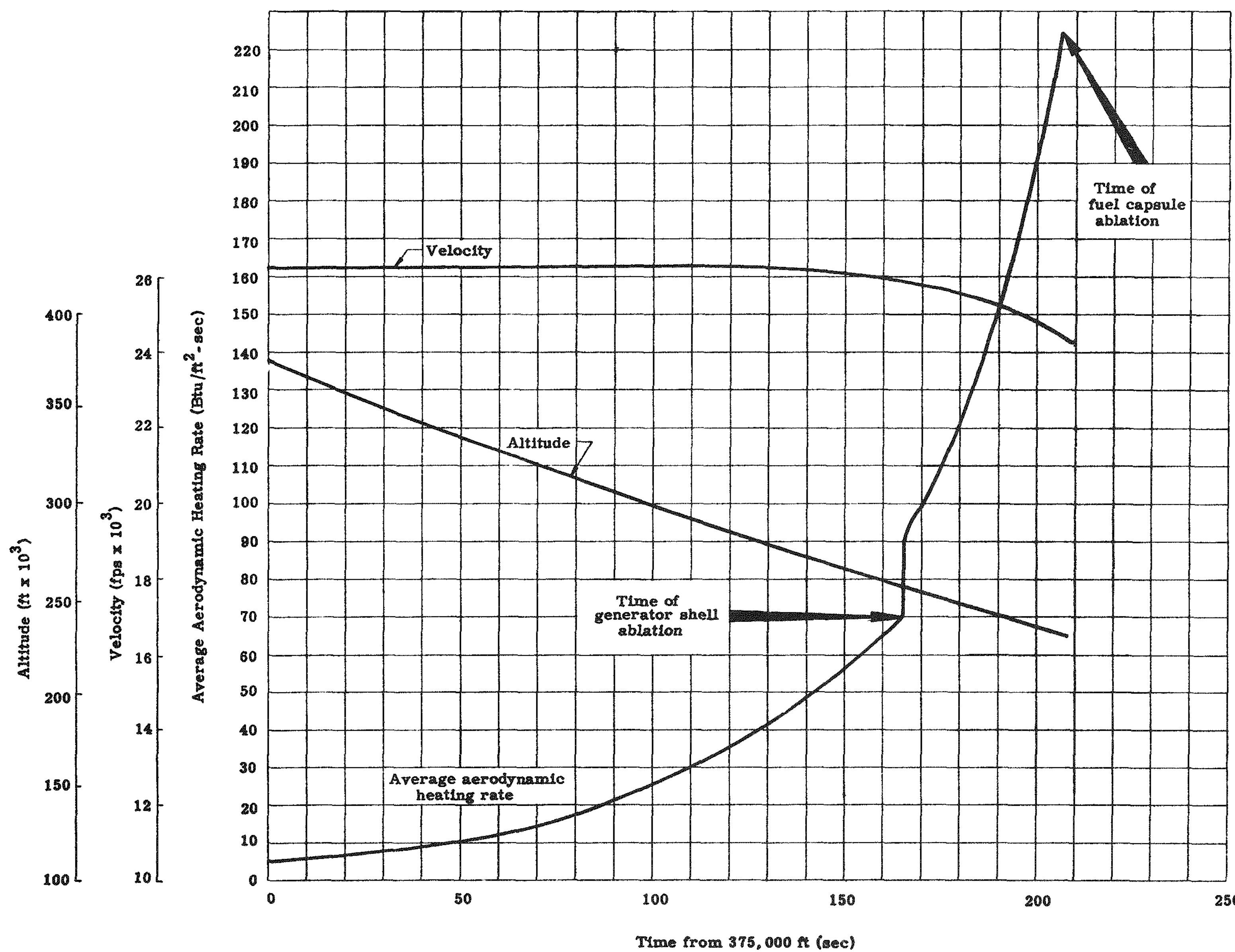


Fig. 6. SNAP III Postorbital Re-entry

surface of the spinning body heats at a rate approximately 35% of the stagnation heating rate. The generator shell is ablated at an altitude of 256,000 feet. The spinning of the unit will assist in the release of the thermoelectric elements and the surrounding insulation. The aerodynamic heating rate is inversely proportional to the square root of the radius of curvature of the re-entering body. There is therefore a steep increase in the heating rate for the smaller fuel capsule at the time of its exposure. The Haynes 25-capsule will be heated and completely ablated at an altitude of 228,000 feet. The polonium, whose boiling point of 962° C is lower than the melting point of the surrounding capsule, will be dispersed as a vapor of molecular particle size.

The satellite will have a lifetime of approximately 365 days at the design orbital altitude. Failure of the launching vehicle to yield nominal performance will make it possible for the satellite to enter into orbits having shorter lifetimes. Sixty-five re-entry trajectories resulting from malfunction of the launching vehicle have been determined for this study. Of these trajectories, 10 will produce these short-term orbits and not re-enter until after several or many orbital cycles have elapsed. Though the re-entry trajectories and the aerodynamic heating rates resulting from these postulated launch aborts are similar to those shown in Fig. 6, the polonium inventory will vary.

VI. ABORTED MISSIONS

This chapter defines aborted missions, forces imposed on the thermoelectric generator as a result of aborts, and the aerodynamic trajectories and heating rates resulting from the aborts. Summary tables and a polar projection map that gives the fate of the fuel capsule following re-entry are shown in the next chapter.

It is desired that during any re-entry, the fuel capsule will either remain intact or be aerothermodynamically consumed at high altitudes. In some aborts occurring during a limited period of the final-stage operation, however, the capsule is only partially consumed, because of an insufficient amount of aerodynamic heating. An analysis has been performed to determine the fate of the fuel and fuel capsule after malfunction of the booster vehicle or the orbital injection stage. A typical launching vehicle capable of injecting several hundred pounds of payload into a low altitude orbit has been considered for this study. The vehicle has one stage of boost and a coasting period followed by an orbital injection stage.

A. DEFINITION OF ABORTED MISSION

Potential malfunctions of the launching vehicle have been defined by analytical comparison of failure of past missile and satellite vehicles with the characteristics of the assumed vehicle. A series of tests conducted to simulate launch vehicle failures have been used to determine the destructive forces to be experienced by the SNAP IIIF generator. Additional tests have been carried out to determine the integrity of the fuel capsule under the loads that would result from impact of the capsule against the earth at high velocities (simulating the terminal velocity of the capsule during re-entry) and to determine the validity of the aerothermodynamic calculations (plasma jet experimentation).

1. Definition of Launch Failures

Launch failures are broadly defined as those failures that occur either on or directly above the launch pad. The period of launch failures begins several minutes prior to liftoff and ends approximately 15 seconds after the vehicle is airborne. This specifically excludes minor electronic and mechanical failures that interrupt the countdown. The maximum height considered for launch failures is 1000 feet. The trajectory calculations and the location of the dispersion area of vehicle remnants in case of abort are greatly simplified during this time, as the velocity of the vehicle has no horizontal component throughout this period. Launch failures are subdivided into propellant tank, propulsion and/or guidance failures.

a. Propellant tank failure

A propellant tank failure results from either overpressurization or spontaneous structural collapse of the tanks. Two failure mechanisms are possible. First, there is a possibility that rupture of the bottom of the liquid oxygen tank and the top of the RP-1 tank can cause mixing of the propellants within the missile. The second and more probable mechanism is side seam failure of the tanks and resultant mixing of the propellants on the launch pad.

b. Propulsion failure

A propulsion failure can occur at any time in the thrusting period. Large vehicles are usually tied down by explosive bolts for approximately 10 seconds after thrust is initiated, for a final check of the propulsion system. The check includes proper valve settings, sufficient propellant flow, proper thrust buildup, etc. The vehicle will be released only when thrust is at or near full power. Under satisfactory conditions, the tie-down bolts will automatically detonate and allow the vehicle to lift off. This time is considered time zero.

Failures during this period can be attributed to restricted fuel flow, incomplete combustion or other malfunctions of the booster engine during liftoff. If the vehicle is airborne, a failure will cause it to fall back on or near the launch pad. Two specific types of accidents will result. First, when the vehicle falls back on the pad, the propellants will be spontaneously ignited, causing a wide area of dispersion of debris. The second and perhaps the less serious of the two possible propulsion failures is mid-air ignition of propellants. Ignition in mid-air yields less energy than ignition on the launch pad because of poor mixing, diffusion of propellants and selective separation by gravity of missile components and propellants.

c. Guidance failures

Guidance failures during the launch sequence are rare since the vehicle is only in a vertical climb at this stage. A destruct system is incorporated in the launch booster to enable the range safety officer to destroy the vehicle if its path is significantly different from the desired path and if inflight correction is impossible. A signal will detonate charges which cause fuel tank rupture and ultimate destruction of the vehicle. Combustion of the fuel will result, producing a fire somewhat less intense than a propulsion-failure fire because of some expenditure of fuel. Also, the dispersion area on or near the launch pad will be larger than for propulsion failure because of the dissemination of the fuel due to the vehicle's motion, compounded by the force of mid-air explosion.

Debris will be distributed over a larger area, but it will be at or near the launch pad and entirely within the controlled area.

2. Definition of Ascent Failures

The ascent portion of the trajectory is that segment between the end of launch and the point of ignition of the orbital injection stage. For the vehicle under consideration, this will extend from 15 seconds after liftoff to approximately 500 seconds after liftoff, the time of final-stage ignition. This portion of the trajectory has several critical phases where failures should be considered.

a. Failure at maximum dynamic pressure

Maximum dynamic pressure occurs at an altitude of approximately 40,000 feet and a velocity of about 1500 fps. Aerodynamic loads on the vehicle are a function of the dynamic pressure and the control surfaces are subjected to the most severe loading at this time. Several past missile firings have failed during this period, and their points of impact were within a distance of less than five miles from the point of launch. At the Point Arguello complex this distance is well within the land area where recovery of the SNAP unit will be possible.

b. Failure at booster separation

The point of booster separation is a major area of trajectory malfunction. The danger of interaction between the two stages is great; it would result in damage to the second-stage engine, propellant tankage and/or guidance system. A severe "bump" between the stages can damage the nozzle of the second-stage rocket or cause the attitude of this stage to be misaligned, so that large control moments may be necessary to return the vehicle to the programmed course. Dynamic instability may occur, and structural failure of the latter stage will result. A failure at booster separation will cause the complete vehicle to impact downrange at approximately 2000 miles.

c. Failure during coast

A coasting period is generally used between booster burnout and final-stage ignition. This period allows the vehicle to achieve the proper altitude and attitude for final-stage ignition. The orbital injection stage is fired at a zero angle of attack; i.e., the vehicle axis is parallel and coincident to the velocity vector. An optimum energy expenditure program requires that for large boosters and orbit altitudes of 275 miles the burnout of the booster occur at approximately 500,000 feet. Thus, the remaining 800,000 feet will be achieved by coasting.

During the separation and coasting sequences, the attitude of the vehicle is defined by gyro references which energize the attitude control system, if the vehicle deviates from the prescribed attitude. It is possible to drive the gyro systems of the vehicle to their limits by large disturbing forces resulting from booster burnout and bumping of the final stage during separation. It is doubtful, though, that this would go unnoticed since the gyro position is telemetered back to the launch control center. If an undesirable impact is predicted, the vehicle will be destroyed on ground command. Failure of vehicle destruction at any time during the coasting sequence will result in impact approximately 2000 miles downrange.

3. Definition of Final-Stage Failure

Failure during final-stage ignition and during its thrusting period is critical because of the generation of aerodynamic heating on the re-entering bodies. Failures are generally restricted to two separate categories:

(1) Propulsion failure, either failure to ignite or failure after ignition

(2) Guidance failure.

The probability of occurrence of these malfunctions is discussed in the next chapter.

a. Propulsion failures

A complex sequence of events must occur for final-stage ignition. As will be shown, the probability of failure of the final stage will be greater at this time than at any other period during its operation. Thrust terminations were assumed at various times from the time of ignition of the final stage. They were at 0, 28, 58, 88, 98, 108 and 113 seconds (Cases 15a, 15b, 15c, 15d, 16a, 16b and 15e, respectively, Table 5).

The following specifications and initial conditions for the final-stage rocket system are estimates of actual values expected for this mission.

Weight at ignition (lb)	8244
Weight of fuel consumed (lb)	6524
Specific impulse (lb/lb/sec)	282
Burning time (sec)	118
Initial flight path angle (deg)	7.5
Initial altitude (ft)	1.38×10^6

Initial velocity (fps)	10,990
Initial latitude (deg)	16.46 N
Initial longitude (deg)	121.31 W

b. Guidance failures

Failures in the guidance system during final-stage operation will produce the greatest deviation from the planned trajectory. Though most large final-stage rocket systems include redundant destruct systems having a high reliability of operation, all possible re-entries resulting from this failure were investigated for this study. The probability of such failures requires that this analysis be conducted.

The final stage was analyzed for both pitch and yaw misalignments during stage operation, as a means of duplicating actual re-entry trajectories. Misalignment was simulated by instantaneous deflecting of the vehicle in the pitch and yaw directions at various times from ignition, with continuous thrusting of the rocket after the misalignment. Thus, the widest possible impact area for this vehicle was achieved. The cases considered are shown in Table 4.

B. FORCES IMPOSED ON GENERATOR BY ABORTED MISSIONS

The forces imposed on the generator by aborts along the launching trajectory can be categorized as resulting from three sources. They are thermal, mechanical and chemical reactions. Their degrees of effect on the generator depend on the time of malfunction of the vehicle.

1. Forces Imposed by Launch Failures

A failure during launch will result in the spillage of propellant on the launch pad and the surrounding area. Present day large boosters use liquid oxygen and RP-1 (kerosene) as propellant. Upon detonation, enough thermal and mechanical energy is released to create a possible Po-210 release mechanism.

a. Thermal forces

The oxidizer from the basement booster will quickly vaporize, but a severe fire will result from the fuel. A distinct fireball will form and will be aggravated by the release and combustion of final-stage fuel. After a short period of time, the structural members of the vehicle may ignite and burn at a much higher temperature than the fuel fire. If the SNAP III generator is located in the center of the wreckage, it will

TABLE 4

Final Stage Guidance Failures

Case	Time of Misalignment (sec)	Misalignment Pitch (deg)	Misalignment Yaw (deg)
14a, b, c, d	0	+5, +30, +45, +90	0
17a, b, c	0	-5, -30, -90	0
10a, b, c, d	28	+5, +30, +45, +90	0
18a, b	28	-5, -30	0
16c	38	+5	0
11a, b, c, d	58	+5, +30, +45, +90	0
16d	78	+30	0
12a, b, c, d	88	+5, +30, +45, +90	0
16f	98	+45	0
16e, g, h	103	+30, +45, +90	0
16i	108	+90	0
13a, b, c, d	113	+5, +30, +45, +90	0
20a, b, c, d	0	0	±5, ±30, ±45, ±90
21a, b, c, d	28	0	±5, ±30, ±45, ±90
22a, b, c, d	58	0	±5, ±30, ±45, ±90
23a, b, c, d	88	0	±5, ±30, ±45, ±90
25a, c	98	0	±30, ±45
25b, e	103	0	±30, ±90
25d, f	108	0	±45, ±90
24a, b, c, d	113	0	±5, ±30, ±45, ±90

experience the thermal effects of the fire for a period of 20 minutes. A test program was conducted to determine the effects of both thermal and mechanical forces on the thermoelectric generator and fuel capsule in the event of launch aborts.

b. Mechanical forces

Components of the thermoelectric generator will be subjected to several forces of a mechanical nature. The maximum height considered for the launch portion of the trajectory is 1000 feet, but a fallback to the launch pad, as caused by an abort, does not cause damage to the fuel capsule. The destruct-eject system releases the generator from the vehicle for free fall from this altitude. The capsule was designed to withstand impact on rigid target media of speeds up to 500 fps; the design was substantiated by high speed rocket-sled tests. This limiting impact speed is greater than the terminal velocity of the capsule in free fall from high altitudes (in excess of 10,000 feet). Therefore, a fall from 1000 feet, cushioned by the generator shell, has a negligible effect on the capsule.

The impulsive force resulting from shock-pressure waves originating from the ignition of liquid oxygen and RP-1 has been determined analytically by methods derived from tests involving TNT. Initial analyses showed that shock loads from these fuels will produce the forces of 77% TNT equivalent. Later studies by STL developed empirical relations for the prediction of shock overpressures from LOX-RP-1 at radial distances from the point of origin. The relation for the predicted average pressure is:

$$P = \frac{593}{Z^3} - \frac{28.8}{Z^2} + \frac{20.7}{Z}. \qquad (1)$$

For an upper 98% confidence level, the relation takes the form:

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

where

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

R = Distance from explosion (ft)

W = Total weight of propellant (lb).

Typical values for present day large boosters are:

R = 35 feet (approximate distance of generator from source of explosion).

W = 250,000 pounds (typical weight of large booster propellant).

Substitution of these values in Eqs (1) and (2) gives

P = 157.5 psi, from Eq (1)

P = 1527 psi, from Eq (2).

The SNAP III generator was tested under simulated vehicle-abort conditions at Aberdeen Proving Ground. In these tests, fuel cores and generators were subjected to a shock overpressure of 1020 psi at an appropriately scaled distance from a 1650-pound TNT charge. Mechanical integrity of the cores was maintained in all cases. The generator was also subjected to a missile-fire test in which a thermal excursion equivalent to that of a large-stage missile abort on the pad was simulated. Effects were measured on eight specimens, and in all the samples the integrity of the fuel core was maintained.

c. Chemical forces

A malfunction during the launch portion of the trajectory will cause the vehicle and thermoelectric generator to impact downrange at a distance of less than five miles from the point of launch. This will cause impact of the fuel capsule in ground within the PMR range safety zone. During the fire test previously summarized, the fuel capsule was exposed to nitric acid and liquid oxygen; it withstood these attacks with no noticeable damage. Concentrated nitric acid will corrode Haynes-25 at the rate of 0.046 inch per year, but it is inconceivable that the capsule will be immersed in the acid for a period longer than a few days. Therefore, it is not expected that ground impact will result in significant corrosion damage to the fuel capsule.

2. Forces Imposed on Generator by Ascent Failures

The types of failures that occur during the ascent period are very similar to the types of launch failures described in the preceding section and to the types of final-stage failures yet to be outlined. The amount of propellant available for thermal energy during abort is rapidly decreasing, and the effect of the high velocity at the time of the abort will cause dissemination of the fire from the capsule. The fuel cores will impact at their terminal velocity at distances of up to 2000 nautical miles from the point of launch.

a. Thermal forces

The effect of thermal energy released by the detonation of the launch boosters during the ascent portion of the trajectory is not so severe as the same effect in on-pad abort. The booster is continuously expending its propellant during ascent. The effects of the velocity and aerodynamic forces will aid in the separation of the generator unit from the resulting fireball. That the fuel capsule will survive an on-pad fire has been shown in tests in which the unit was completely surrounded by the fire for periods in excess of 20 minutes. These factors all tend to make thermal-force effect during ascent failure much less severe than during on-pad failure. It therefore creates no significant hazard in ascent failure.

The aerothermodynamic effect on the generator increases during re-entries following aborts in the latter portion of the ascent phase of the trajectory but never damages the outer shell. If the generator is freed from the satellite enclosure, it will impact undamaged approximately 2000 miles downrange.

b. Mechanical forces

Aborts during the ascent portion of the trajectory will impose both shock and impulse loads on the generator and fuel capsule.

The shock pressure produced by detonation of booster propellants is less severe in ascent aborts than in launch aborts. The magnitude of the shock is lessened by the expenditure of propellant during flight. It has been shown that the capsule will withstand shock loads resulting from the detonation of all propellants in the complete vehicle. The effects of shock loads at altitudes, therefore, need not be considered further.

The impulse loads arising from impact against rigid targets have been determined analytically and proof-tested on high speed rocket-sled tests. The purpose of the tests was to determine the degree of damage and the mode of failure of the specimens. Four target materials were chosen to simulate actual targets on the earth's surface: granite, consolidated and unconsolidated rock, and water. In impact against granite, a relatively rigid material, all of the energy is absorbed by the specimen. If the specimens can survive granite impact, the other target media will not cause damage.

The tests at Aberdeen Proving Ground showed that the SNAP III fuel cores maintain their integrity in impact on granite at velocities of 500 fps, exceeding the expected terminal velocity of the capsules by 100 fps. Therefore, the cores will sustain the impulse loads arising from impact on the earth's surface.

c. Chemical forces

Like launch-pad aborts, those occurring early in the ascent portion of the launch trajectory result in vehicle impact on land, downrange from the launch site. Final-stage rockets in large booster launching systems utilize inhibited red fuming nitric (IRFNA) acid as fuel. The fuel cores could be exposed to the acid upon ground impact after a malfunction during pitchover or at maximum dynamic pressure. It is inconceivable, however, that the core would lie immersed in a pool of acid for any great length of time.

In the event of a later abort during ascent, the fuel core will impact on the Pacific Ocean and sink to the bottom. The Haynes-25 outer vessel has a thickness of 0.1875 inch. Since the sea water corrosion rate of Haynes-25 is 14.0 mils per year, more than 13 years will be required for penetration of the first wall. At this time, the activity level of the enclosed fuel will have decreased to a negligible amount. If penetration of the other two walls is considered, then the time required for fuel release by sea water corrosion is of the order of 25 years. Therefore, it can be concluded that core integrity is maintained.

3. Forces Imposed by Final-Stage Failures

Forces imposed on the thermoelectric generator by final-stage failure originate from either aerodynamic heating during re-entry or core impact on the surface of the earth. The core is designed to burn up during re-entry from a successful orbit. It is also desired that the core sustain an abort during this period and re-enter intact. These design features are not compatible, in that there are some re-entries following final-stage aborts in which the capsule is completely or partially ablated by aerodynamic heat. Ablation occurs in an area which is far downrange of the launch complex and has essentially zero population density.

a. Thermal forces

Thermal energy can be subdivided into that resulting from the combustion of the final-stage propellant and that resulting from aerodynamic heating.

The fire resulting from the final-stage abort will cause no damage to the fuel core. Thermal forces from propellant fires are most severe during on-pad failure, and it has been shown that the fuel capsule can survive this excursion. Failure at this time need not be further considered.

Aerodynamic heating during final-stage failure has a wide range of effects on the core material. It is assumed that the generator is released at 375,000 feet during its re-entry. Failure of the final stage to ignite (Case 15a, Table 5) results in undamaged-generator impact near the equator. The re-entry trajectory and the resulting aerodynamic heating are shown in Fig. 7. This type of failure has the highest probability of occurrence. The fate of the fuel core is dependent on the programmed velocity contribution of the final stage. In Case 15a, the initial velocity at final stage is 10,990 fps, too low to induce sufficient aerodynamic heating.

A propulsion failure after 98 seconds of final-stage thrusting (Case 16a), 83% of the scheduled thrusting period, results in generator melting and partial fuel core ablation. The core is 18% consumed, and the remnant impacts in the South Pacific Ocean, fracturing on contact. A propulsion failure very late in the final-stage period (Case 15e), after 96% of the total scheduled thrusting time, results in the complete melting of the fuel core and the initial dispersion of the fuel at an altitude of 147,000 feet. The consequences of altitude injection of Polonium-210 will be discussed in Chapter VIII. The re-entry trajectory and the heating rates of the generator shell and fuel core are shown in Fig. 8.

Guidance failures that cause deflection of the vehicle and/or the rocket line-of-thrust axis with respect to the velocity vector result in a complete spectrum of conditions. Thirty-two cases of pitch-deflection failure were considered. The time of guidance failure was considered from the point of final-stage ignition to near the end of the thrusting period. Of the failures studied, 4 enter into a short-lived orbit, 10 are completely melted (at altitudes above 100,000 feet), 2 impact after partial burnup and the remaining 16 impact before any melting occurs.

Failures in the yaw direction result in the widest lateral displacement of the fuel cores or their remnants. Twenty-six cases of such aborts were considered. Of these, 6 enter into short-lived orbits, 11 are completely melted at altitudes above 100,000 feet, 4 are partially consumed and 5 land intact.

b. Mechanical forces

The fuel cores do not lose their integrity in impact at terminal velocity on rigid media. No abort occurring during the final-stage period results in land impact. Of the 65 aborts considered, 33 impact either on sea water or ice; of these, 25 are not affected by aerodynamic heating. Only 8 are partially melted when impact occurs and just 2 of these land on the Antarctic Continent. This indicates the relative probability of entry of the SNAP unit on Antarctica in the event of an abort along the launch trajectory.

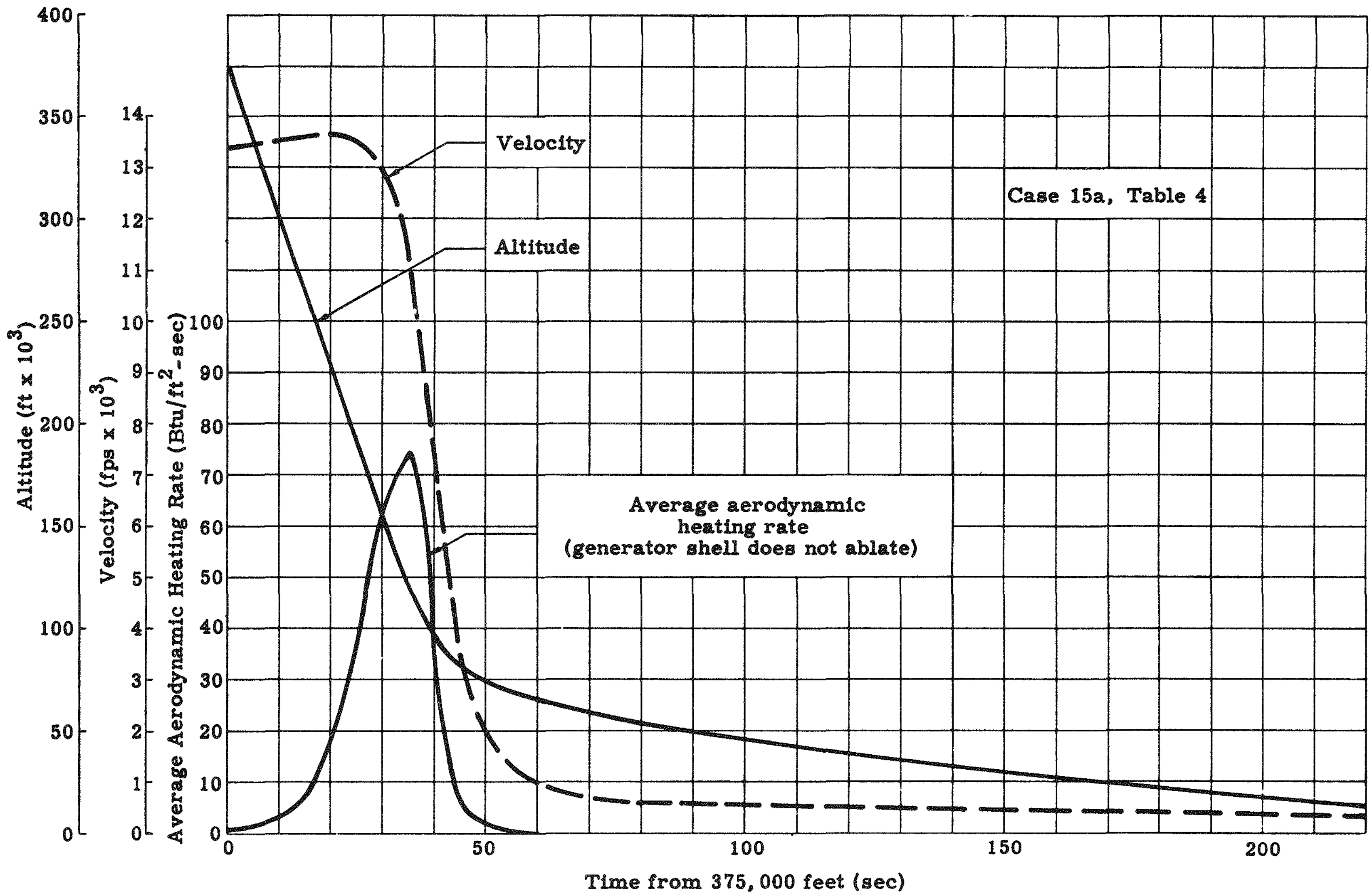


Fig. 7. SNAP III Re-entry Trajectory After Failure to Ignite Final Stage

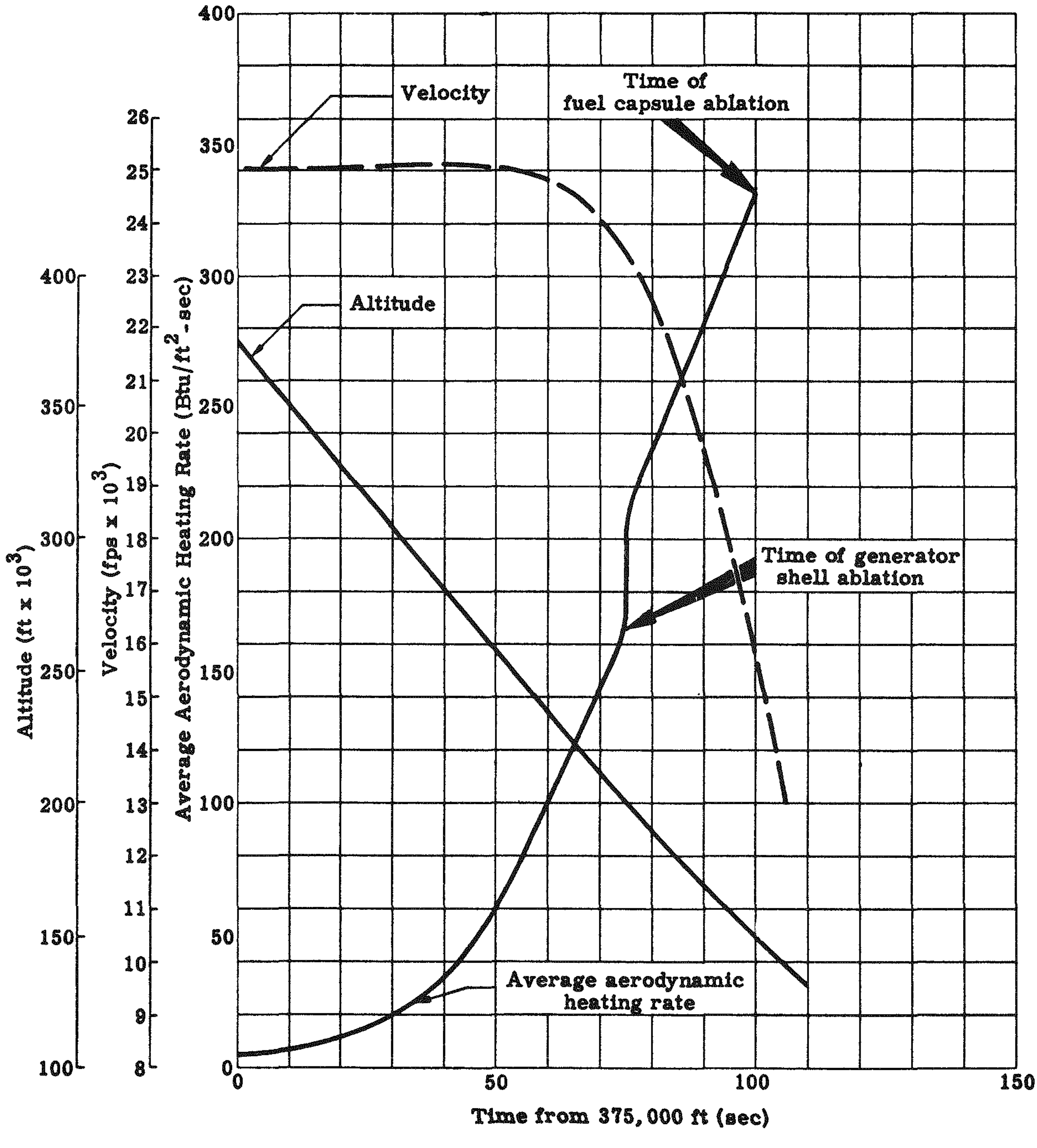


Fig. 8. SNAP III Re-entry Trajectory After Propulsion Failure Late in Final Stage (Case 15e, Table 4)

c. Chemical forces

The only chemical reaction experienced by the fuel core from a final-stage abort is sea water corrosion. It has been described for those aborts occurring during the ascent portion of the trajectory. It was shown that more than 13 years' corrosion will be necessary to completely penetrate the capsule. If the capsule is partially ablated by aerodynamic heating at the time of impact, it will either sink and begin to corrode or will fracture at impact. The activity level of the encapsulated fuel as a function of time is shown in the next chapter.

VII. CONCLUSION

This chapter summarizes the immediate and ultimate fate of the fuel for both successful and aborted missions. Since the successful missions and many of the aborted missions result in stratospheric injections of Polonium-210, a discussion of fallout and its relative importance in the biosphere is included (Appendix A).

A. SUCCESSFUL MISSION

The fate of the polonium fuel after a successful mission is clearly defined. The fuel will be ablated and dispersed as molecular particles in the upper stratosphere at an altitude of 228,000 feet or more. Re-entry will occur at a random point above the earth's surface, and the mean residence time of fallout at the altitude of release is estimated to be five years or more. For a conservative estimate of the consequences of this release, a mean residence time of eight months was employed in the fallout estimates.

After 365 days, the activity of Polonium-210 will be 356 curies. This amount will be injected into the stratosphere at a random location as fallout with a mean residence time of 240 days. It is assumed that 75% of this material is uniformly deposited in the North Temperate Zone. The resultant peak ground concentration would be 0.63 micromicrocurie per square meter, and it would occur 146 days after re-entry. The gamma dose rate in the fallout field corresponding to the peak concentration is 1.3×10^{-7} millirad per year. This level of radiation would be completely masked by the Polonium-210 which is naturally present in soils all over the world. The mechanism of fallout is discussed in detail in the next chapter.

B. ABORTED MISSIONS

The probability of failure during the ascent trajectory has been postulated for multistage vehicles, and the analytical studies and data tabulated from actual firings have been reported. It has been demonstrated that ascent failures are more prevalent than failures either at launch or during final-stage operation. The probability of failure to achieve orbit is approximately 16% of the attempts, subdivided as follows.

Phase of Trajectory	Probability of Failure
Launch	2.0%
Ascent	7.5%
Final stage	6.5%

Figure 9 shows a pictorial summary of aborts considered for this study.

1. Launch Failure

A summary of launch failures shows that the fuel cores will come to rest on or near the launch pad. Analysis of past failures indicates that the generators will probably be entangled in the vehicle wreckage, with the fuel core encased in the partially breached generator shell. The core will be intact in all cases, precluding contamination of the launch complex and environs. Launch from the Pacific Missile Range will assure land impact for failures occurring at this period, and the remnants of the vehicle will fall within several thousand feet of the launch pad. The closest body of water is more than 5 miles downrange. The core will be retrieved by the Missile Accident Emergency Team (MAET), who normally stand by for missile firings. The team consists of technicians and medical personnel and is provided with the heavy equipment necessary for removal of the SNAP generator from the wreckage. The fuel core can be retrieved with relative ease without remote handling equipment or shielding requirements since it does not pose a direct radiation hazard.

2. Ascent Failures

Ascent failures are statistically more probable than any other type considered. However, these failures do not pose potential radiation problems. In all cases, fuel cores will remain intact for the effective lifetime of Polonium-210.

Two distinct possibilities exist for the ultimate fate of the fuel following ascent aborts:

(1) Impact on land. The consequences would be essentially those described for launch failures where the generators remain intact. Location and recovery may be difficult because of low radiation levels and would probably require ground detection units.

(2) Impact on water. If the complete generator were to fall into the water without serious damage it would probably be tangled

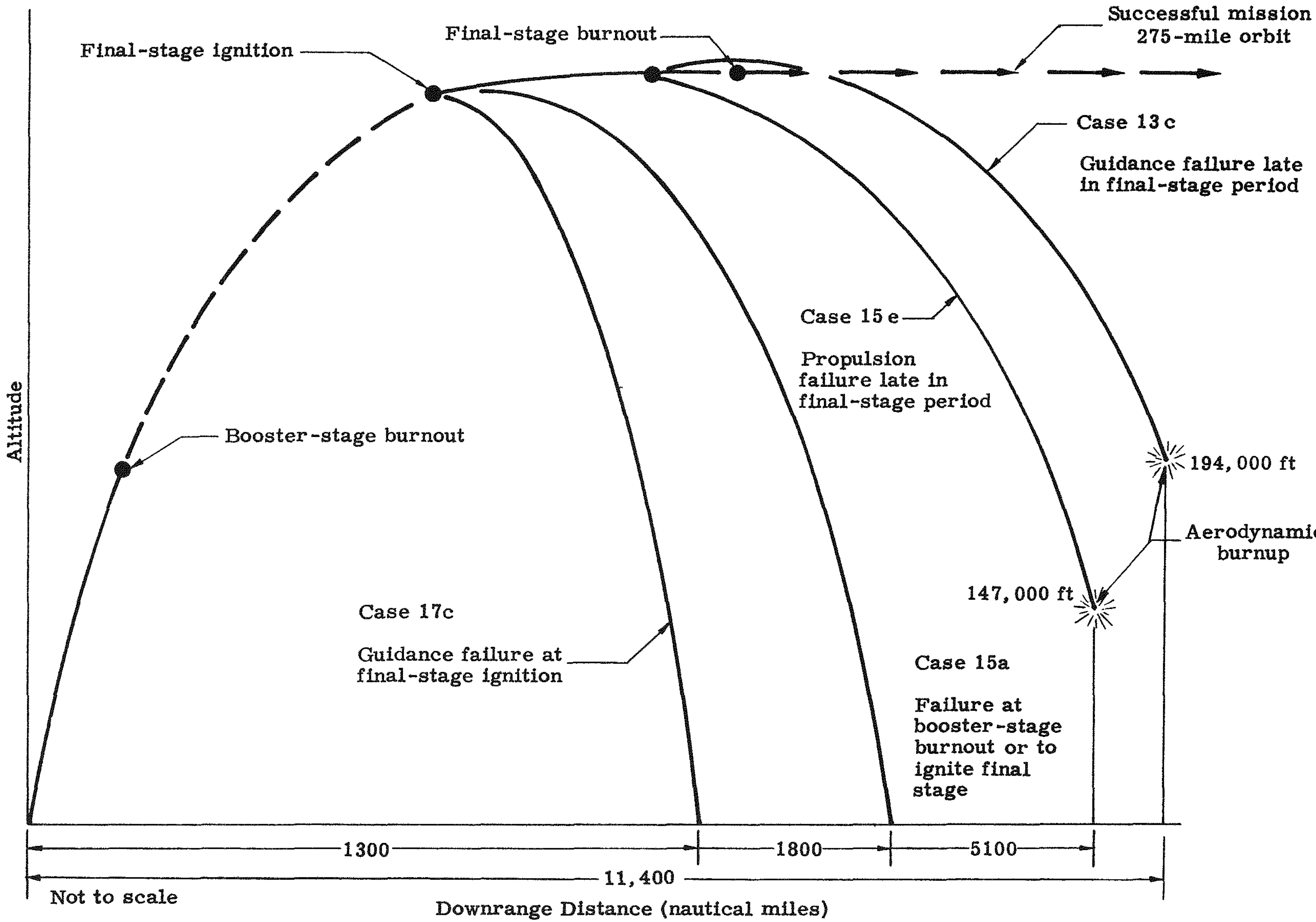


Fig. 9. SNAP III Aborted Missions

in the vehicle wreckage and retained there. However, if the fuel core is separated from the generator, it would be very difficult to locate and recover in shallow water and impossible to locate in deep water. The Haynes-25 shell containing the fuel resists corrosion well, and the fuel would be contained throughout many half lives, during which the activity will decay to an insignificant level. It appears that the majority of ascent failures would result in water impact. Therefore the sea provides an ideal place for a sealed radiation source during its decay.

3. Final-Stage Failures

Failures during final stage have been completely and systematically analyzed to include all conditions. Sixty-five cases of final-stage failures were considered and are summarized in Table 5. Those malfunctions in which the generator either burns up at altitude or impacts on the surface of the earth are shown on the polar projection map of Fig. 10. Two distinct boundaries are outlined on the map. The first, labeled Intact Impact Zone, is the area in which the generator and/or fuel core will impact and retain the integrity of the core. Superimposed on this zone, and overlapping it just south of the Equator, is the region of Open Core Landing, an area where the fuel core will be partially consumed at impact and will release some of the fuel. Local contamination of the water will result. A summary of core history resulting from the several malfunctions follows.

Partial orbit. Ten of the assumed failures enter into a partial orbit. Generally, those failures that occur in the guidance mechanism either late in the firing sequence of the final-stage rocket or at a slight angular deviation from the prescribed flight profile will not preclude orbiting. The lifetime of the orbit will range from only several cycles to nearly 1 year; lifetime is dependent upon the eccentricity and the perigee altitude of the newly formed orbit. The ultimate re-entry of the generator will be similar to the postorbital re-entry of a successful mission, and the generator will be completely ablated at 228,000 feet. Table 5 shows the activity level of the polonium at its time of release. The fuel will be dispersed largely over the entire hemisphere in which it is released, but there will be negligible ground concentration.

Burnup of fuel core at high altitude. Most of the propulsion failures that occur late in the final-stage thrusting period and most of the guidance malfunctions result in aerothermodynamic consumption of the core at high altitude. Of the cases considered, 22 are so consumed.

TABLE 5

Summary of Final-Stage Failures

Final-Stage Failures (Probability 6.5%)	Case Number *	Failure Characteristics: Time of Failure (Seconds After Final-Stage Ignition)	Failure Characteristics: Probable Cause of Failure	Misalignment of Failure (Degrees Pitch)	Misalignment of Failure (Degrees Yaw)	Probability of Failure (%)	Geographical End Points: Degrees Latitude	Geographical End Points: Degrees Longitude	Immediate Fate of Core: Consumed Aerodynamically (%)	Immediate Fate of Core: Altitude of Fuel Dispersal (ft)	Immediate Fate of Core: Impact (%)	Immediate Fate of Core: Impact Temperature (°R)	Immediate Location of Radiopolonium After Abort	Ultimate Fate of Radiopolonium	Summary of Consequences
Propulsion						4.5									
At final-stage ignition	15 a	0	Failure to ignite	0	0	3.0	4.8 N	124.0 W	0	-	100	1560	Bottom of Pacific Ocean	Exposure after 13.4 yr	Released 5 x 10^{-8} curie to water
After final-stage ignition	15 b	28	Failure of	0	0	1.5	1.8 N	124.1 W	0	-	100	1560			
	15 c	58	propulsion feed	0	0		2.7 S	124.4 W	0	-	100	1560			
	15 d	88	system, pressuri-	0	0		11.6 S	124.8 W	0	-	100	1560			
	16 a	98	zation system or	0	0		14.0 S	125.1 W	18	0	82	3200	Released at ocean surface	Marine dissemination	Released 2200 curies to water
	16 b	108	thrust chamber	0	0		27.1 S	125.9 W	35	0	65	3200			
	15 e	113		0	0		49.9 S	125.9 W	100	147,000	0	-	Injected in stratosphere	Fallout, mean residence 8 mo	Fallout in south temperate zone (2200 c injected)
Guidance	Summary					2.0									
Vehicle unstable	General					1.0									
Pitch failure (vehicle stable)	10 a	28	Failure to control	+5	0	0.5	32.1 N	43.2 E	100	214,000	0	-	Injected in stratosphere	Fallout, mean residence 5 yr	Fallout in north temperate zone (2200 c injected)
			disturbing moments,												
	10 b	28	shift of gyro reference,	+30	0		84.6 S	47.2 E	0	0	100	2037	Antarctica	Dispersion in ice	Limited contamination by 2200 curies--eventual ice burial and decay
			failure of servos,												
	10 c	28	poor separation	+45	0		61.6 S	131.1 W	0	0	100	2230	Bottom of Pacific Ocean	Exposure after 13.4 yr	Release of 5 x 10^{-8} curie to water
	10 d	28		+90	0		3.3 S	126.9 W	0	0	100	1560			
	11 a	58		+5	0		Into orbit		-	-	-	-	Into partial orbit	Re-entry after 1 day	Fallout at random (~2200 c injected)
	11 b	58		+30	0		72.4 S	47.2 E	0	0	100	2663	Antarctica	Dispersion in ice	See case 10b
	11 c	58		+45	0		74.8 S	131.0 W	0	0	100	1749			
	11 d	58		+90	0		17.7 S	127.1 W	0	0	100	1560	Bottom of Pacific Ocean	Exposure after 13.4 yr	Release of 5 x 10^{-8} curie to water
	12 a	88		+5	0		Into orbit		-	-	-	-	Into orbit	Re-entry after 78 days	Fallout at random (1500 c injected)
	12 b	88		+30	0		54.5 S	48.1 E	100	116,000	0	-	Injected in stratosphere	Fallout, mean residence 8 mo	Fallout in south temperate zone (2200 c injected)
	12 c	88		+45	0		87.3 S	48.1 E	0	0	100	3100	Antarctica	Dispersion in ice	See case 10b
	12 d	88		+90	0		35.7 S	127.4 W	0	0	100	2120	Bottom of Pacific Ocean	Exposure after 13.4 yr	Release of 5 x 10^{-8} curie to water
	13 a	113		+5	0		Into orbit		-	-	-	-	Into orbit	Re-entry after 319 days	Fallout at random (450 c injected)
	13 b	113		+30	0		Into orbit		-	-	-	-	Into partial orbit	Re-entry after 1 day	Fallout at random (~2200 c injected)
	13 c	113		+45	0		14.9 S	47.3 E	100	194,000	0	-	Injected in stratosphere	Fallout, mean residence 5 yr	Equator and south temperate zones
	13 d	113		+90	0		77.3 S	127.9 W	100	125,000	0	-		8 mo	South polar and temperate zones Fallout
	14 a	0		+5	0		16.2 N	43.9 E	100	190,000	0	-		<5 yr	Equator and south temperate zones
	14 b	0		+30	0		86.1 S	132.9 W	0	0	100	1560	Antarctica	Dispersion in ice	See case 10b
	14 c	0		+45	0		50.3 S	131.1 W	0	0	100	1560	Bottom of Pacific Ocean	Exposure after 13.4 yr	Release of 5 x 10^{-8} curie to water
	14 d	0		+90	0		8.35 N	126.5 W	0	0	100	1560			
	16 c	38		+5	0		4[illegible].8 N	42.0 E	100	228,000	0	-	Injected in stratosphere	Fallout, mean residence 5 yr	Fallout in north temperate zone (2200 c injected)
	16 d	78		+30	0		61.7 S	46.7 E	18	0	82	3200	Release at ocean surface	Marine dissemination	Release of 2200 curies to water
	16 e	103		+30	0		33.1 S	47.0 E	100	162,000	0	-	Injected in stratosphere	Fallout, mean residence 1 yr	Fallout in south temperate zone (2200 c injected)
	16 f	98		+45	0		77.3 S	48.3 E	35	0	65	3200	Antarctica	Dispersion in ice	See case 10b
	16 g	103		+45	0		69.9 S	49.2 E	100	111,000	0	-	Injected in stratosphere	Fallout, mean residence 8 mo	Fallout, south polar and temperate zones (2200 c injected)
	16 h	103		+90	0		50.3 S	128.1 W	0	0	100	2250	Bottom of Pacific Ocean	Exposure after 13.4 yr	Release of 5 x 10^{-8} curie to water
	16 i	108		+90	0		59.2 S	128.5 W	0	0	100	2710			
	17 a	0		-5	0		36.9 S	125.1 W	100	190,000	0	-	Injected in stratosphere	Fallout, mean residence <5 yr	Fallout in south temperate zone (2200 c injected)
	17 b	0		-30	0		6.2 N	123.5 W	0	0	100	1560	Bottom of Pacific Ocean	Exposure after 13.4 yr	Release of 5 x 10^{-8} curie to water
	17 c	0		-90	0		13.1 N	123.2 W	0	0	100	1560			
	18 a	28		-5	0		53.0 S	126.1 W	100	212,000	0	-	Stratospheric injection	Fallout, mean residence ~5 yr	Fallout in south temperate zone (2200 c injected)
	18 b	28		-30	0		3.9 N	123.7 W	0	0	100	1560	Bottom of Pacific Ocean	Exposure after 13.4 yr	Release of 5 x 10^{-8} curie to water

TABLE 5 (continued)

Final-Stage Failures (Probability 6 5%)	Failure Characteristics: Case Number *	Failure Characteristics: Time of Failure (Seconds After Final-Stage Ignition)	Failure Characteristics: Probable Cause of Failure	Misalignment of Failure (Degrees Pitch)	Misalignment of Failure (Degrees Yaw)	Probability of Failure (%)	Geographical End Points: Degrees Latitude	Geographical End Points: Degrees Longitude	Immediate Fate of Core: Consumed Aerodynamically (%)	Immediate Fate of Core: Altitude of Dispersal (ft)	Immediate Fate of Core: Impact (%)	Immediate Fate of Core: Impact Temperature (°R)	Immediate Location of Radiopolonium After Abort	Ultimate Fate of Radiopolonium	Summary of Consequences
Yaw failure (stable)	Summary					0.5									
	20 a	0	Failure to control disturbing moments; shift of gyro reference, failure of servos	0	±5		Into orbit		-	-	-	-	Into orbit	Re-entry after 6 days	Fallout at random (2150 c injected)
	20 b	0		0	±30		50.9 S	142.1 W/109 8 W	100	162,500	0	-	Injected in stratosphere	Fallout, mean residence >1 yr	Fallout in south temperate zone (2200 c injected)
	20 c	0		0	±45		26.1 S	143.5 W/108.0 W	74	~100,000	26	3200	Injected in stratosphere	Fallout, mean residence 8 mo	Fallout, south polar and temperate zones (2200 c injected)
	20 d	0		0	±90		3.9 N	137.6 W/110.6 W	0	0	100	1560	Bottom of Pacific Ocean	Exposure after 13.4 yr	Release of 5 x 10^{-8} curie to water
	21 a	28		0	±5		Into orbit		-	-	-	-	Into orbit	Re-entry after 17 days	Fallout at random (2000 c injected)
	21 b	28		0	±30		43.7 S	138.2 W/112.7 W	100	164,000	0	-	Injected in stratosphere	Fallout, mean residence >1 yr	Fallout in south temperate zone (2200 c injected)
	21 c	28		0	±45		24.9 S	140.1 W/114.1 W	88	~100,000	12	3200		Fallout, mean residence 8 mo	
	21 d	28		0	±90		0.9 N	136.5 W/112.1 W	0	0	100	1560	Bottom of Pacific Ocean	Exposure after 13.4 yr	Release of 5 x 10^{-8} curie to water
	22 a	58		0	±5		Into orbit		-	-	-	-	Into orbit	Re-entry after 7 days	Fallout at random (2150 c injected)
	22 b	58		0	±30		42.7 S	135.1 W/115.5 W	100	166,000	0	-	Injected in stratosphere	Fallout, mean residence >1 yr	Fallout in south temperate zone (2200 c injected)
	22 c	58		0	±45		26.6 S	137.1 W/114.3 W	97	~100,000	3	-		Fallout, mean residence 8 mo	Fallout in south temperate zone (2200 c injected)
	22 d	58		0	±90		3.17S	134.7 W/114.2 W	0	0	100	1560	Bottom of Pacific Ocean	Exposure after 13.4 yr	Release of 5 x 10^{-8} curie to water
	23 a	88		0	±5		Into orbit		-	-	-	-	Into orbit	Re-entry after 73 days	Fallout at random (1500 c injected)
	23 b	88		0	±30		59.0 S	133.2 W/119.4 W	100	186,000	0	-	Injected in stratosphere	Fallout, mean residence >1 yr	Fallout in south temperate zone (2200 c injected)
	23 c	88		0	±45		36.8 S	133.1 W/117.0 W	100	142,500	0	-		Fallout, mean residence ~1 yr	Fallout in south temperate zone (2200 c injected)
	23 d	88		0	±90		11 3 S	132 2 W/117.4 W	0	0	100	1860	Bottom of Pacific Ocean	Exposure after 13.4 yr	Release of 5 x 10^{-8} curie to water
	24 a	113		0	±5		Into orbit		-	-	-	-	Into orbit	Re-entry after 320 days	Fallout at random (450 c injected)
	24 b	113		0	±30		Into orbit		-	-	-	-	Into orbit	Re-entry after 32 days	Fallout at random (1900 c injected)
	24 c	113		0	±45		55 9 S	48.3 E/ 51 1 E	100	237,000	0	-		~5 yr	South temperate zone
	24 d	113		0	±90		36.3 S	127.5 W/122 7 W	100	111,000	0	-		8 mo	South temperate zone
	25 a	98		0	±30		78.8 S	46.3 E/ 56.1 E	100	207,000	0	-	Injected in stratosphere	Fallout, mean residence ~5 yr	South polar and temperate zones Fallout (2200 c injected)
	25 b	103		0	±30		59.6 S	45 0 E/ 54.8 E	100	224,000	0	-		~5 yr	South temperate zone
	25 c	98		0	±45		57.4 S	133.5 W/119.0 W	100	158,000	0	-		>1 yr	South temperate zone
	25 d	108		0	±45		81.6 S	132.0 W/123 5 W	100	186,500	0	-		~3 yr	South polar and temperate zones
	25 e	103		0	±90		24.9 S	131.3 W/119 3 W	0	0	100	2700	Bottom of Pacific Ocean	Exposure after 13 4 yr	Release of 5 x 10^{-8} curie to water
	25 f	108		0	±90		33.1 S	130.7 W/121.4 W	35	0	65	3200	Bottom of Pacific Ocean	Exposure after 8 7 yr	Release of 3 x 10^{-4} curie to water

* Refers to machine run and map plot points.

** Symbol c stands for curies.

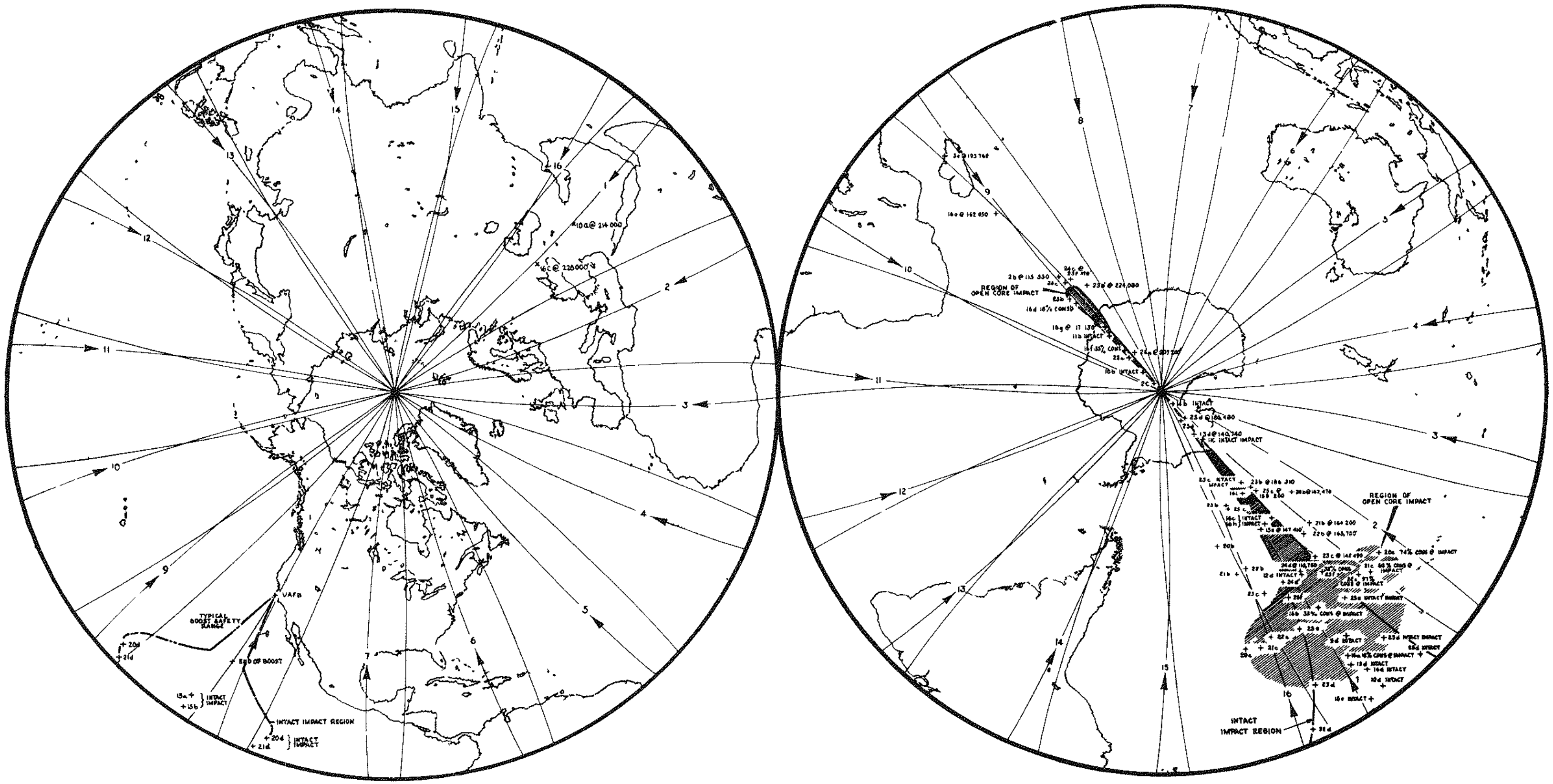


Fig. 10. SNAP III Impact Areas

Partial ablation. The design philosophy, requiring either (1) that the fuel core be completely melted and dispersed at high altitude for a post-orbital re-entry or (2) that the core return intact following an abort, creates a condition in which the core may be only partially melted at the end of the heating period (at approximately 100,000 feet). This occurs in eight of the cases considered. The fate of the fuel will depend on the degree of damage to the core. A core that has been only slightly affected by ablation will impact and probably fracture on the surface of the earth. In all of these cases, the core lands on water or on Antarctica. Local contamination of the sea will result but will be negligible because of the vast volume of available water. Contamination of Antarctica will be confined to a local area. The fuel will eventually be buried in the ice, where it will decay. A core severely but not completely ablated will fail at altitude because of the internal pressure exerted by the encapsulated gases (Po-210, He) produced during the natural decay of the element. Fracture of the core will result in the release of the fuel at the base of the stratosphere and its dispersal throughout the world, but mainly in the hemisphere of release.

Impact in undamaged condition. Table 5 shows that 25 of the cases considered are intact at impact. A failure of the destruct-eject mechanism, an abort, or a severe guidance malfunction occurring early in the thrusting portion of the final stage results in impact without rupture of the fuel core. In Case 12d, an abort caused by a guidance failure results in the complete melting of the outer generator shell. The shell, along with the insulating material and the thermoelectrics surrounding the fuel core, is discarded at an altitude of 90,000 feet. Continued aerodynamic heating of the fuel capsule does not seriously damage the core, but the ambient surface temperature of the capsule is raised by 517° F.

The majority of cases considered impact upon the South Pacific Ocean at a terminal velocity of approximately 300 fps. In cases of this type the core easily sustains the impact loads and sinks to the bottom of the ocean. Sea water corrosion releases the polonium after 13 years; by this time the activity level of the fuel has been reduced by radioactive decay to 5.0×10^{-8} curie.

4. Summary of Aborted Missions

The large number of cases considered for final-stage abort makes possible a comprehensive safety and evaluation screening. The outlines on the map of Fig. 10 show that the fate of the fuel core can fall into seven broad categories (Table 6).

TABLE 6

Fate of Fuel

Category	Type of Failure	Fate of Fuel	Fuel Recovery
Impact on land	Launch, ascent	Contained	Yes
Impact in shallow water	Ascent	Contained	Yes
Impact in deep water	Ascent, final stage	Contained effectively	No
Partial ablation of fuel core impact on surface of ocean and fracture, releasing fuel	Final stage	Hydrospheric dissemination	No
Partial ablation of fuel core fracture at high altitude due to internal gas pressures	Final stage	Stratospheric dissemination	No
Prompt re-entry, burnup	Final stage	Stratospheric dissemination	No
Into orbit	Final stage	Stratospheric dissemination	No

VIII. BIBLIOGRAPHY

1. SNAP Hazards Subcommittee, "Minutes of Meeting," March 10 and 11, 1959 (Unpublished).

2. SNAP Hazards Subcommittee, "Minutes of Meeting," June 24 through 26, 1959 (Unpublished).

3. SNAP Hazards Subcommittee, "Committee Statement of Policy," August 7, 1959 (Unpublished).

4. Suess, H. E. and May, H. C., Rev. Mod. Phys., XXVIII, 53 (1956).

5. Moyer, H. V., Polonium, U. S. Atomic Energy Commission, 1956.

6. Dix, G. P., "Preliminary Operational Hazards Summary Report for the Task 2 Generator," The Martin Company, MND-P-2184, December 1959. SECRET-RESTRICTED DATA

7. Dix, G. P., Dobry, T. J., and Guinn, P., "SNAP III Thermoelectric Generator Radiological Safety Analysis," The Martin Company, MND-P-2513, February 1959.

8. Dobry, T. J., and Guinn, P., "SNAP III Thermoelectric Generator Safe Handling Procedures," The Martin Company, MND-P-2514, April 1959.

9. Wilson, R. J., "Operational Testing of SNAP III," The Martin Company, MND-P-2368, July 1960.

10. Oehrli, R., Hagis, W., and Milewski, C., "Preliminary Aero-thermodynamic Analysis of SNAP III," The Martin Company, MND-P-2142, October 1959 (Unpublished). SECRET-RESTRICTED DATA

11. Broadview Research Corporation, "An Investigation of the Integrity of Certain Test Assemblies Under Missile Failure Forces--Explosive Shock, Temperature and Oxidation Test Program," RD-58-2, 1035-9, July 1958.

12. Quarterly Statement of Fallout by the U. S. Atomic Energy Commission, October 1959.

13. Joint Committee on Atomic Energy, Fallout from Nuclear Weapons Tests, May 1959.

14. Supplement No. 17 (A/3838), Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, 13th Session, New York, 1958.

15. Joint Committee on Atomic Energy, Fallout from Nuclear Weapons Tests, August 1959.

16. Arnold, J. R. and Martell, E. A., "The Circulation of Isotopes," Scientific American, CCI, No. 3, September 1959.

17. Eisenbud, M., Private Communication (letter), New York University, Institute of Industrial Medicine, May 16, 1960.

18. Nuclear Science and Engineering Corporation, "Polonium-210 in the Biosphere," NSEC-25, May 1960.

19. Burton, W. M. and Stewart, N. G., "Use of Long-Lived Natural Radioactivity as an Atmospheric Tracer," Nature, CLXXXVI, No. 4725, May 21, 1960.

20. Faul, H., Editor, Nuclear Geology, John Wiley and Sons, New York, 1954.

21. International Commission on Radiological Protection, Report of Committee II on Permissible Dose for Internal Radiation--1958 Revision.

APPENDIX A

COMPARISON OF NATURAL AND SNAP-INDUCED POLONIUM CONCENTRATIONS

The uniform deposition of fallout and resultant radiation effects due to a stratospheric injection of polonium is presented and compared with that naturally present in soil and that deposited by fallout of naturally occurring Polonium-210 in the atmosphere.

To establish a basis for the fallout calculations, recent measurements of high-yield nuclear weapon fallout were used. Deposition measurements of fission products from high yield explosions indicate that 75% of the fallout occurs over the hemisphere in which the tests are conducted, with nearly all of it falling in the corresponding temperate zone. This relationship will be assumed in computing fallout deposition due to stratospheric injection of Polonium-210, where the injection might occur over either the Northern or Southern Hemisphere. The fallout due to an injection over the equator or poles will deposit somewhat differently; however, the relation will be assumed to be applicable in computing a conservative estimate over this area.

It has been estimated that particles injected in the lower stratosphere (below 125,000 feet) at temperate and polar latitudes will remain in the stratosphere for less than one year. A mean residence time of 8 months, which has been suggested for both temperate and polar injections in the vicinity of 100,000 feet, is used in the fallout calculations. The suggested mean residence time for equatorial injections at an altitude of 100,000 feet is approximately 2 years.

A. RELATIVE IMPORTANCE OF A STRATOSPHERIC INJECTION OF POLONIUM-210

The direct measurements of radon and its disintegration products and elemental Polonium-210 taken in various parts of the world serve as a basis upon which the relative importance of the air and soil concentrations resulting from an injection of Polonium-210 into the stratosphere can be evaluated. The data used in the comparisons represent both past and current levels of radon and Polonium-210 content in the environment, and its transport through the food chain. Mean values obtained by measurement of Polonium-210 concentration due to natural sources are compared with maximum values of concentration due to a stratospheric injection to yield conservative estimates of the relative importance of the injected radioisotope.

The maximum soil concentration of 7.7×10^{-5} $\mu\mu c$/gram due to fallout deposited after a stratospheric injection of 2200 curies of Polonium-210 is approximately 10^{-5} times the value of 6.5 $\mu\mu c$/gram for the soil concentration of naturally present Polonium-210 reported by Nuclear Science and Engineering Corporation (NSEC).

The external radiation due to the 5.3-mev alpha particles of the injected-deposited Polonium-210 is insignificant, since the range in air is only 3.8 cm and the critical layer of human tissue is not reached by any naturally occurring alpha particles (alpha particle penetration depth in human tissue is approximately 45 microns). External gamma radiation in the fallout field is negligible because of the extremely small percentage of disintegrations resulting in gamma energy release.

Potential radiobiological hazards arise only if the fuel enters the body by inhalation or by ingestion with food and/or water. Martin Company tests, which yielded a great deal of valuable information concerning launch pad aborts, definitely indicate that damage to a fuel core would not result in the dispersion of the fuel. Therefore, in the event of a maximum credible accident while the vehicle is on the launch pad, no serious hazard would exist; however, the area should be restricted until the fuel core is properly recovered.

The equilibrium value determined for an accumulated deposition of naturally present Polonium-210 in air is 1.23×10^{-2} $\mu\mu c/cm^2$, and the maximum value of deposition due to a stratospheric injection is 3.86×10^{-4} $\mu\mu c/cm^2$. By comparison, high altitude injections of Polonium-210 result in a deposition 30 times less than the deposition that occurs naturally.

Calculations performed on NSEC measurements indicate that the eventual total body and critical organ concentration of naturally present Polonium-210 is negligible when compared with the maximum permissible total body burden, permissible critical organ burden and MPC_w as suggested by ICRP-Committee-II (see Tables 2 and 3 and Summary of NSEC Measurements).

B. DIRECT FALLOUT FROM ABORTED AND SUCCESSFUL MISSIONS

Following final-stage high altitude abort, Polonium-210 is injected directly into the stratosphere. A conservative analysis assumes all the Polonium-210 to be released as fine particles at an altitude of 100,000 feet at 35° N and 120° W. The total accumulated deposition of Polonium-210 due to fallout is given in Fig. A-1 for a maximum injection of 2200 curies and for 356 curies (this value corresponds to the generator source

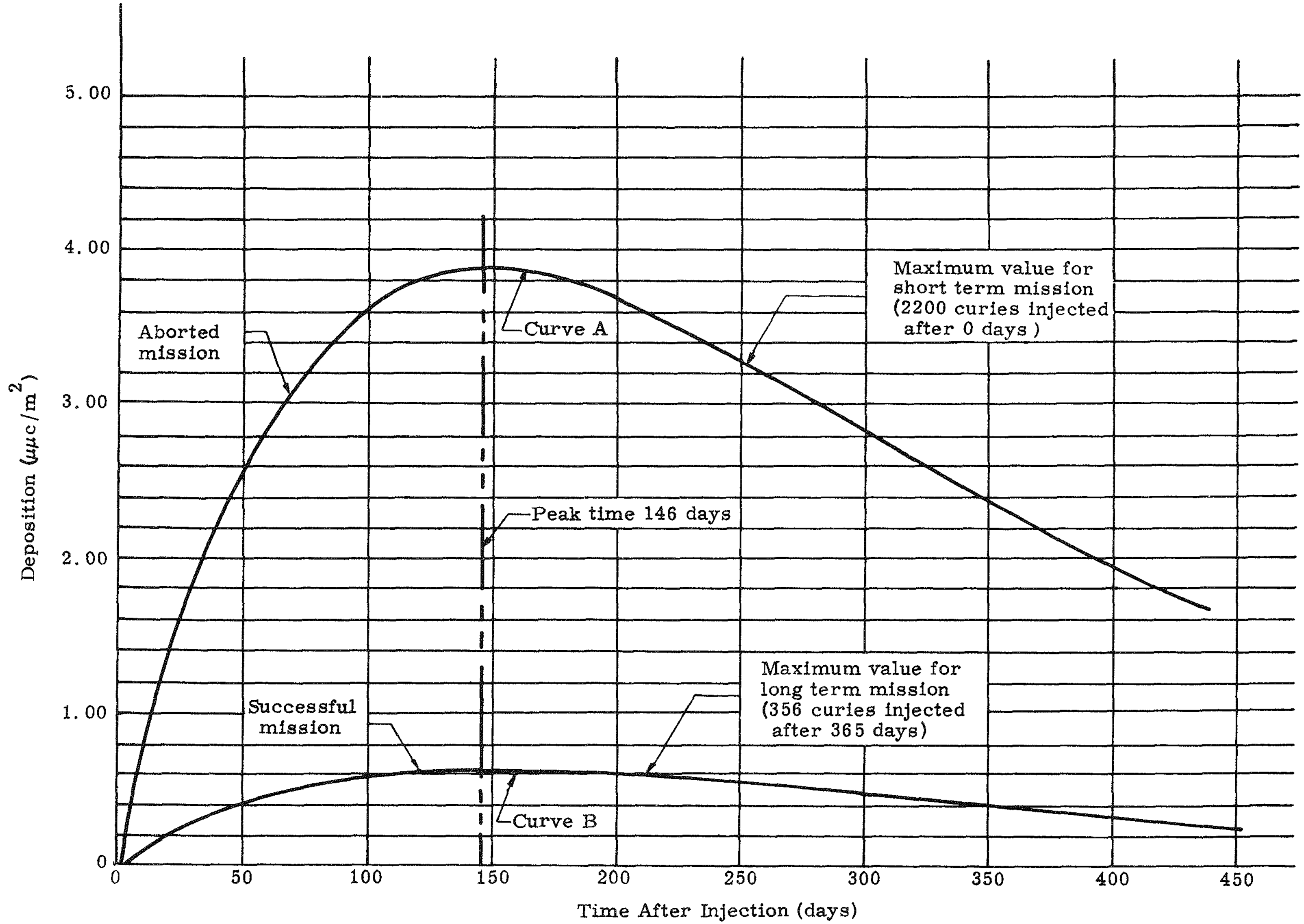


Fig. A-1. Polonium-210 Deposition in the North or South Temperate Zone from a Stratospheric Fuel Injection activity at the end of a successful mission). The maximum value of deposition due to a stratospheric injection after an immediate final stage abort is 3.86×10^{-4} $\mu\mu c/cm^2$. Other values for short term (< 365 days) and long term ($\geq$ 365 days) missions can be computed by use of Figs. A-1 and A-2. Figure A-2 shows the radioactive decay of Polonium-210 versus time after the initial source of 2200 curies has been launched. The deposition over the area of injection at any time after orbit is attained can be determined by selecting from Fig. A-2 the value of activity corresponding to the time, dividing it by the original activity (2200 curies) and multiplying the appropriate deposition value from curve A in Fig. A-1 by the ratio.

The accumulated deposition was computed from the following equation, which considers stratospheric injection of radioactive material.

$$X_0 = \frac{N_0 Z}{A} \left[e^{-\lambda_r t}\right] \left[1 - e^{-\lambda_f t}\right]$$

X_0 = total deposition ($\mu\mu c/m^2$)

N_0 = amount of radioactivity initially injected ($\mu\mu c$)

Z = fraction deposited in area considered

A = area of deposition (m^2)

λ_r = decay constant of Polonium-210 (day^{-1})

λ_f = reciprocal of mean residence time (day^{-1}).

The half life of Polonium-210 is 138.4 days, and the mean residence time for particles injected at an altitude of 100,000 feet is 240 days. The area of deposition is assumed to be the North Temperate Zone (30 to 60° N), which occupies 3.6×10^7 square miles. The fraction deposited in this area is taken to be 0.75.

C. DEPOSITION OF NATURAL ATMOSPHERIC POLONIUM-210*

The mean rate of exhalation of radon from the earth's surface is 7.7×10^4 $dpm/m^2/day$. Since land occupies 39.3 percent of the surface of the Northern Hemisphere, the mean radon exhalation rate in the

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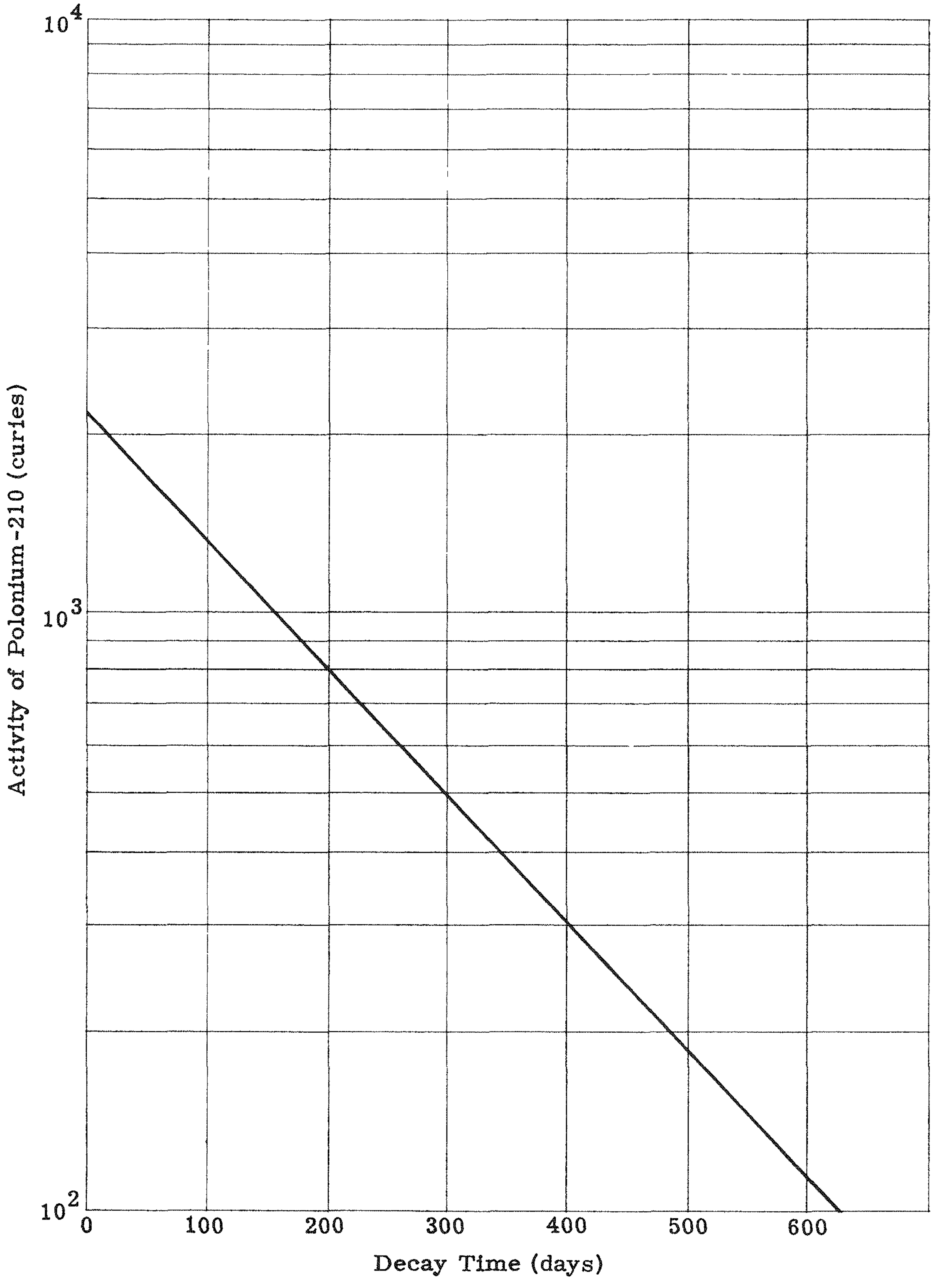

Fig. A-2. Radioactive Decay of a 2200-Curie Source of Polonium-210

Northern Hemisphere is 1.35 x 10^{-8} curie/m^2/day. This is equivalent to a production rate of 6.76 x 10^{-12} curie/m^2/day of Radium-D. If the ratio of Polonium-210 (Radium-F) to Radium-D, 0.10 (average value), is applicable in estimating the production rate of Polonium-210, then the production rate of Polonium-210 is 6.76 x 10^{-13} curie/mi^2/day.

To estimate the material balance of Polonium-210 in the troposphere it is necessary to set up the following differential equations.

$$\frac{dP}{dt} = Po - \lambda P - \gamma P$$

$$\frac{dX}{dt} = \gamma P - \lambda X$$

where

Po = the production rate of Po-210 in the atmosphere ($\mu\mu c/cm^2$-day), considered to be uniform over the Northern Hemisphere

P = the Po-210 content in the troposphere ($\mu\mu c/cm^2$)

λ = radioactive decay constant of Po-210 (day^{-1})

γ = reciprocal of mean residence time (day^{-1})

X = average accumulated deposition of Po-210 ($\mu\mu c/cm^2$).

These equations can be integrated on the basis of the following hypotheses:

(1) All the natural Po-210 fallout comes from the troposphere.

(2) The fallout rate is proportional to the tropospheric content.

(3) The production rate of Po-210 is constant.

The solutions are:

$$P = \frac{Po}{(\lambda + \gamma)} \left[1 - e^{-(\lambda+\gamma)t}\right]$$

$$X = \frac{Po}{(\lambda + \gamma)} \left\{\frac{\gamma}{\lambda} \left[1 - e^{-\lambda t}\right] + e^{-(\lambda+\gamma)t} - e^{-\lambda t}\right\}$$

At equilibrium, the value determined for deposition, X, is 1.23×10^{-2} $\mu\mu c/cm^2$. The deposition is assumed to take place in the first inch (2.54 cm) of soil, and the average soil density is 2.0 gm/cc. Therefore, the soil concentration at the earth's surface due to fallout of natural atmospheric Polonium-210 is 2.5×10^{-3} $\mu\mu c/gm$.

D. NATURAL POLONIUM-210 IN BIOSPHERE*

If the occurrence of Polonium-210 in the earth's crust were to be considered uniform, the concentration would be about 1.3 $\mu\mu c/gm$.

The Nuclear Science and Engineering Company has made some analyses of soil and plant and animal materials for The Martin Company (see Chapter VIII, Section F). In soil collected from Upper Sinclair township near Pittsburgh, four to five times the average concentration (1.3 $\mu\mu c/gm$) was found in the top inch of soil and one- to two-thirds this concentration in soil taken from eight inches below the surface. In field-grown lettuce from Florida, about 1/650 of the average concentration was found, and in wheat grown in 1959 in Westmoreland County, Pennsylvania, about 1/200. It appears to be generally true that plants differentiate against polonium. In beef liver and kidney obtained by an Allegheny County (Pittsburgh) packing house from animals raised locally, the concentrations were from 1/10 to 1/5 the average crust concentration. In milk and water from West Mifflin township (near Pittsburgh), the concentrations were 1/20 and 1/700, respectively, of the maximum permissible concentrations for water for nonoccupational exposure. Human kidney and spleen obtained in a Pittsburgh hospital were examined; these are considered the critical organs. The ratios to the maximum permissible burdens were about 10^{-4} and 10^{-5}, respectively.

The concentration in the critical organs of the human body due to naturally occurring Polonium-210 in vegetation is evaluated from data reported by NSEC. With the assumption that the intake of vegetation or vegetable products by man is 0.5 kg per day, and with the reported value of 5 $\mu\mu c/gm$ as an average concentration in vegetation and the human retention factor of 0.28 suggested by the Committee II-ICRP, the total body activity was determined to be 140 $\mu\mu c$. This value is considerably less than the 0.4 μc reported as the maximum permissible total body burden.

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E. EVALUATION OF SOIL CONCENTRATION OF NATURAL POLONIUM-210*

In an attempt to verify NSEC soil measurements, a comparison was made between NSEC results and independently measured data. The average specific activity of the NSEC soil sample taken below 20 cm of earth was found to be 0.65 $\mu\mu$c/gm (average based on two samples); that computed from independently measured data at a depth of 25 cm was found to be 0.1 $\mu\mu$ c/gm with a peak value at 0.5 $\mu\mu$c/gm. The independently determined values agree favorably with the NSEC measurement. The independent results were determined from measurements of radon content in soil air at a depth of 25 cm overlying bedrock, taken by Fordham University in New York in 1944 and 1945. If it is assumed that the disintegration products of radon are in secular equilibrium, the values measured for radon content are the same as for Polonium-210. The range of radon content varied from 0.1 to 0.88 $\mu\mu$ c/cc with a probable average at 0.2 $\mu\mu$ c/cc. The concentration was converted to specific activity by dividing by the soil density.

In testing of topsoil, NSEC found that the specific activity had increased by a factor of 10. Fordham University found that the concentration of radon increases with depth, indicating that Polonium-210 does also. That activity should increase with depth seems more natural, but near the surface the radon content of soil air is highly variable and is largely affected by meteorological factors. In general, the discrepancy in the measurements is probably indicative of the variability of Polonium-210 activity in soil, due to the variation of radon content in soil and rock and the exhalation rate of Po-210. More important, however, is the fact that NSEC measurements indicate that the concentration of Polonium-210 naturally occuring in soil is considerably greater by several factors of 10 than that due to deposition as a result of a stratospheric injection of Polonium-210 from SNAP III.

F. SUMMARY OF NSEC MEASUREMENTS

The results of a survey of Polonium-210 in the biosphere performed by Nuclear Science and Engineering Corporation are presented in Table A-1. The size sample taken for analysis, total Polonium-210 activity found in the sample, and the specific activity are shown. Discussions of the samples assayed, the procedures used and the results obtained are given in the references.

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TABLE A-1

Results of Polonium-210 Assays

	Sample	Sample Size		Total Po-210* ($\mu\mu c$)	Specific Activity	
Soil	A1(Top 5 cm of	10.7	grams	50	5	$\mu\mu c$/gram
	A2 soil)	11.1		80	7	
	B1(Below 20 cm	10.4		8	0.8	
	B2 of soil)	10.9		5	0.5	
Water	1	100	liters	0.7	0.007	$\mu\mu c$/liter
	2	100		0.6	0.006	
Lettuce	1	2000	grams wet	4	2	$\mu\mu c$/kg wet
	2	2000		4	2	
Wheat	1	1000		6	6	
	2	1000		7	7	
Beef kidney	1	1023		250	240	
	2	756		120	150	
Beef liver	1	924		230	250	
	2	915		260	280	
Milk	1	1	gallon	0.05	0.01	$\mu\mu c$/liter
	2	1		1.0	0.3	
Human bone	1	43	grams wet	0.1	0.002	$\mu\mu c$/gram wet
	2	46		0	0	
Human kidney	1	224		2.5	0.011	
	2	340		3.3	0.010	
Human spleen	1	37		0.05	0.001	
	2	59		0.3	0.005	
Reagent controls	1	--		0.1	--	
	2	--		1.1	--	

*Sensitivity: 0.4 $\mu\mu c$ at the 5% level of significance.
Precision: ±50% at the 95% confidence level.
Accuracy: ±50% at the 95% confidence level.