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AGING EFFECTS OF U.S. SPACE NUCLEAR
SYSTEMS IN ORBIT

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1.0 INTRODUCTION

NUS Corporation, at the request of the U.S. Department of Energy (DOE), Office of Coordination and Special Projects, has prepared this report presenting information and data in support of a cost-benefit analysis being performed by Fairchild Industries (FI) on the feasibility of retrieving existing U.S. space nuclear systems in earth orbit by the Space Shuttle.^(1,2) This work has been performed under DOE Contract DE-AC01-80ET-3207, Task Order 81-7, and represents an extension of an earlier study by NUS on retrieval from orbit.^(3,4,5)

In this report NUS has evaluated for U.S. space nuclear systems presently in orbit, shown in Table 1-1, the radioisotopic inventory and external radiation field as a function of time, the effect of aging on fuel containment materials over the projected lifetime of the system, and the possible radioactive source terms should reentry eventually occur. Although the radioisotopic inventories and radiation fields have been evaluated for all systems, Transit 4A and Transit Triad have been emphasized in the evaluation of the aging effects and reentry consequences because these spacecraft have the shortest projected orbital lifetimes (570 and 150 years, respectively).

In addition to existing systems in orbit, the radioisotopic inventory, radiation field, and reentry source terms have been evaluated for a General Purpose Heat Source (GPHS) in a parking orbit due to an aborted Galileo Mission or International Solar Polar Mission (ISPM).

Chapter 2 presents the summary and conclusions of the report. Reference design information, radioisotopic inventory, radiation fields, aging of materials and reentry source terms are summarized in Chapter 3 through 8, respectively, for all systems, along with methods used in the evaluation. More detailed information on these areas is presented for each spacecraft in Appendices A through G, respectively. Appendix H presents supporting detailed information on fuel properties.

TABLE 1-1

CHARACTERISTICS OF U.S. SPACE NUCLEAR SYSTEMS
IN EARTH ORBIT AS OF LAUNCH DATE

<u>Spacecraft</u>	<u>Launch Date</u>	<u>Period min</u>	<u>Inc., deg</u>	<u>Apogee km</u>	<u>Perigee km</u>	<u>Power Source</u>	<u>Inventory of Pu-238 at Launch (curies)</u>	<u>Expected Orbital Lifetime, years</u>	<u>Disposal Mode</u>
Transit 4A	6/29/61	103.7	66.8	993	881	SNAP-3	1,700	570	Burnup
Transit 4B	11/15/61	105.7	32.4	1,103	953	SNAP-3	1,700	1,200	Burnup
Transit 5BN1	9/28/63	107.3	89.8	1,135	1,072	SNAP-9A	16,300	1,900	Burnup
Transit 5BN2	12/05/63	107.0	89.9	1,119	1,067	SNAP-9A	16,300	1,800	Burnup
SNAPSHOT	4/08/65	111.6	90.0	1,313	1,282	SNAP-10A	Reactor	3,000-5,000	Burnup
Nimbus III	4/14/69	107.3	99.7	1,135	1,074	SNAP-19	36,000	3,600	Intact Reentry
"Transit" (TRIAD-01-0X)	9/02/72	100.6	90.1	838	742	RTG	28,000	150	Intact Reentry
LES-8	3/14/76	1440.0	25.0	35,900	35,900	MHW-RTG	151,000	10 ⁶	Intact Reentry
LES-9	3/14/76	1440	25.0	35,900	35,900	MHW-RTG	151,000	10 ⁶	Intact Reentry
Galileo/ISPM ^a	3/85	-	28.0	-	-	GPHS-RTG	137,000 ^b	a	Intact Reentry

a. Applies only if mission is aborted and spacecraft goes into an earth orbit

b. Per RTG basis

Chapter 1.0 References

1. Fairchild Industries, RTG Retrieval from Orbit (Task Plan), Prepared for U.S. Department of Energy (undated).
2. Bartram, B.W., Design Control Document for Aging in Orbit Task, NUS Corporation (February 28, 1981).
3. U.S. Department of Energy, Contract to NUS Corporation for Environmental Safety Risk Assessment Support Services, Contract No. DE-AC01-80ET-32079 (September 30, 1980).
4. U.S. Department of Energy, Task Order 81-7, Aging Effects on Safety of RTG's in Earth Orbit (February 12, 1981).
5. Pyatt, D.W., The Feasibility of Retrieving Nuclear Heat Sources from Orbit with the Space Shuttle, NUS Corporation, NUS-3495 (January 1980).

2.0 SUMMARY AND CONCLUSIONS

This chapter presents the summary and conclusions of the work performed by NUS concerning the effects of aging on existing U.S. space nuclear systems in orbit related to the feasibility of retrieving such systems from orbit. This work included an evaluation for the systems presented in Table 1-1 of the following:

- o Radioisotope inventory versus time
- o External radiation field versus time
- o Effects of aging on fuel containment materials over the projected lifetime of the system
- o Potential orbital reentry radioactive source terms.

The results for these areas of investigation are summarized below.

2.1 Radioisotopic Inventory Versus Time

The radioisotopic inventory versus time for each system considered was calculated using the ORNL developed ORIGEN code, as described in Chapter 4. Inputs to the code include the initial curie activity of each radioisotope in a given fuel type and the output includes curie activity versus time for all parent and daughter isotopes, the gamma photon production rate and energy spectrum versus time, and the neutron production rate and energy spectrum versus time.

The resulting total curie activity versus time for all systems considered has been summarized in Chapter 4 and presented in detail in Section 2 of Appendices A through G for each system, respectively. The radioactivity versus time of the plutonium fueled systems is essentially dominated by Pu-238 with the other isotopes contributing in only a minor way, except after approximately 300 years. The SNAP-10A fission reactor system was shutdown after 43 days of operation in orbit after being launched in 1965. The resulting fission activity dropped

rapidly within one year following shutdown and present radioactivity levels are dominated by Cs-137 and Sr-90.

2.2 External Radiation Field Versus Time

The external radiation field dose rates versus time for each system, resulting from variations in gamma and neutron energy spectra versus time, has been calculated using an NUS modified version of the LASL developed QAD code. Gamma photon and neutron production rates and energy spectra versus time, derived from the ORIGEN output as described above, along with source geometry and materials information were input into successive QAD runs to determine the external dose rates versus time at specified distances in the axial and radial directions of each system.

The results for each system are summarized in Section 3 of Appendices A through G. In general the external dose rates from the plutonium fueled systems are dominated by spontaneous fission neutrons and (α , n) reaction neutrons from Pu-238 during approximately the first 300 years, with dose rates range on the order of 0.01 to 0.09 mR/hr at 1 m. After approximately 300 years, radon isotopes and their short-lived daughters begin to buildup resulting from plutonium isotope decay. Resulting gamma dose rates in turn begin the monotonically increase after approximately 300 years and dominate thereafter.

External dose rates from the SNAP-10A fission reactor system were quite high immediately after shutdown (approximately 60 rem/hr at 1 m due primarily to gamma photons), but fell off rapidly after that. Present dose rates are on the order of 0.8 mR/hr and are continuing to drop rapidly.

2.3 Aging of Materials and Source Terms

The radioisotope heat sources embraced by this study have represented the ultimate in materials technology, design engineering, component fabrication skills, and quality assurance efforts available over the past 20 years. All

have performed creditably in their missions, except as limited by other components of the respective spacecraft. Their short-term behavior has been adequate, lending a degree of optimism to any assessment of aging. However, the scheduling of a mission to meet the deadlines of national policy or planetary "windows" frequently required application to technology that was at a threshold of development, stimulated only by the particular mission in question. Alternatives were meager, compatibility tests were, of necessity, abridgements of actual operating conditions, and long-term experience was and still is unavailable, in many instances.

The following material aging mechanisms have been reviewed, where applicable, for each system identified in Table 1-1:

- o Radioisotope fuel: containment interactions
- o Phase changes or other thermal effects
- o Pressure effect due to gaseous decay products
- o Interaction of containment materials
- o Radiation damage - internal
- o Space irradiation
- o Evaporation - sublimation
- o Meteoroid damage.

Emphasis in the evaluation was placed on Transit 4A and Transit Triad since these systems have the shortest projected orbital lifetimes. A summary of the evaluation is presented in Table 2-1. The results, supported by the detail in Section 4 of the respective Appendices, reveals several instances of sufficient concern or sufficient uncertainty, to warrant individual study in depth, if retrieval missions are to be mounted for technical or tactical reasons.

2.4 Reentry Source Terms

A given space nuclear system in earth orbit will reenter the earth's atmosphere following orbital decay. Reentry scenarios that could release fuel include 1)

TABLE 2-1

SUMMARY OF MATERIAL AGING EFFECTS OF U.S.
SPACE NUCLEAR SYSTEMS IN ORBIT

<u>Orbiting System</u>	<u>Appendix</u>	<u>Fuel: Containment Interaction</u>	<u>Phase Changes</u>	<u>Pressure Effects</u>	<u>Interaction of Containment Materials</u>	<u>Radiation Damage - Internal</u>	<u>Space Irradiation Effects</u>	<u>Evaporation - Sublimation</u>	<u>Meteoroid Damage</u>
Transit 4A/4B	A	FF LP SMD	N	PCR	N	N	N	N	MD
Transit TRIAD-01X	B	FF,S LP SMD	SD	VPP PCR	SD	MD	N	VPP	MD
Transit 5BN1/5BN2	C	FF LP SMD	N	SD	MD	N	N	N	MD
Snapshot-10A	D	N	N	N	N	N	N	N	MD
Nimbus III	E	FF	N	VPP	N	N	N	N	MD
LES 8/9	F	FF LD	N	VPP	N	N	N	VPP	SD
Galileo/ ISPM	G	FF LD	N	?	N	N	?	VPP	?

Legend:

FF Fuel Fragmentation
 LP Liner Penetration
 SMD Strength Member Degradation
 PCR Probable Capsule Rupture
 VPP Vent Plugging Probable
 S Swelling
 LD Liner Degradation
 MD Minor Degradation
 SD Significant Damage
 N Negligible

reentry burnup, 2) land impact, and 3) ocean impact. The release mode probability and source term (percent inventory released) for each system have been summarized in Tables 2-2 and 2-3, based on the evaluation of material aging effects in Section 2.3 and Chapter 6. The results assume that reentry and associated release modes occur at the end of predicted orbit life. The expectation of source term released, representing the product of release probability and source term at the time of release, is presented in Table 2-4.

TABLE 2-2

REENTRY RELEASE MODE PROBABILITIES FOR
U.S. SPACE NUCLEAR SYSTEMS IN ORBIT

Reentry Release Mode Probabilities						
System	High Altitude Burnup					
	Vapor Release	Particulate Release Over Land	Particulate Release Over Ocean	Land Impact	Ocean Impact	Total
Transit 4A (SNAP-3)	1.0	-	-	-	-	1.0
Transit 4B (SNAP-3)	1.0	-	-	-	-	1.0
Transit Triad (RTG)	-	-	-	0.34	0.66	1.0
Transit 5BN1 (SNAP-9A)	1.0	-	-	-	-	1.0
Transit 5BN2 (SNAP-9A)	1.0	-	-	-	-	1.0
Snapshot (SNAP-10A)	1.0	-	-	-	-	1.0
Nimbus III (SNAP-19)	-	-	-	0.34	0.66	1.0
LES 8/9 (MHW-RTG)	-	-	-	0.27	0.73	1.0
Galileo/ISPM (GPHS-RTG)	-	-	-	0.27	0.73	1.0

TABLE 2-3

POSTULATED REENTRY RELEASE SOURCE TERMS FOR
U.S. SPACE NUCLEAR SYSTEMS IN ORBIT

System	Reentry Release Source Term (Percent Inventory Released)				
	High Altitude Burnup				
	<u>Vapor Release</u>	<u>Particulate Release Over Land</u>	<u>Particulate Release Over Ocean</u>	<u>Land Impact</u>	<u>Ocean Impact</u>
Transit 4A (SNAP-3)	100%	-	-	-	-
Transit 4B (SNAP-3)	100%	-	-	-	-
Transit Triad (RTG)	-	-	-	1%	100%
Transit 5BN1 (SNAP-9A)	100%	-	-	-	-
Transit 5BN2 (SNAP-9A)	100%	-	-	-	-
Snapshot (SNAP-10A)	100%	-	-	-	-
Nimbus III (SNAP-19)	-	-	-	1%	100%
LES 8/9 (MHW-RTG)	-	-	-	1%	100%
Galileo/ISPM (GPHS-RTG)	-	-	-	1%	100%

TABLE 2-4

EXPECTED REENTRY SOURCE TERMS FOR
U.S. SPACE NUCLEAR SYSTEMS IN ORBIT

Expected Radioactive Source Terms at Reentry (Curies)						
System	High Altitude Burnup			Land Impact	Ocean Impact	Total
	Vapor Release	Particulate Release Over Land	Particulate Release Over Ocean			
Transit 4A (SNAP-3)	3.65E+01	-	-	-	-	3.65E+01
Transit 4B (SNAP-3)	4.20E-01	-	-	-	-	4.20E-01
Transit Triad (RTG)	-	-	-	2.65E+01	5.15E+03	5.18E+03
Transit 5BN1 (SNAP-9A)	2.50E+01	-	-	-	-	2.50E+01
Transit 5BN2 (SNAP-9A)	2.48E+01	-	-	-	-	2.48E+01
Snapshot (SNAP-10A)	2.65E-02	-	-	-	-	2.65E-02
Nimbus III (SNAP-19)	-	-	-	1.63E-01	3.17E+01	3.19E+01
LES 8/9 (MHW-RTG)	-	-	-	1.20	3.24E+02	3.25E+02
Galileo/ISPM (GPHS-RTG)	-	-	-	3.70E+02	1.00E+05	1.00E+05

3.0 REFERENCE DESIGN INFORMATION

To provide a basis for evaluating the radioisotopic inventory and external radiation fields versus time, aging effects on materials, and reentry consequences, reference design information has been compiled for each system considered. The following reference design information was developed for each system identified in Table 1-1 and presented in detail in Section 1 of Appendices A through G for each system respectively:

- o Mission description (including launch date and orbital parameters)
- o Spacecraft description
- o Nuclear power source description (including type, layout, fuel, power level, materials of construction, and provisions for surviving reentry and impact)

Backup information on fuels and materials have been presented in Appendices H, respectively. Appendix H on fuel properties covers the following fuel types:

- o Metallic plutonium fuel (SNAP-3, SNAP-9A)
- o PuO_2 microsphere fuel (SNAP-19)
- o Plutonium molybdenum cermet (PMC) fuel (Transit Triad RTG)
- o Pressed PuO_2 (PPO) fuel (MHW-RTG)
- o Grog PuO_2 fuel (GPHS-RTG)
- o ZrHU fuel (SNAP-10A)

Information on each fuel type presented in Appendix H.

4.0 RADIOISOTOPIC INVENTORY VERSUS TIME

The initial radioisotopic fuel mix in plutonium fueled space nuclear systems will be transformed in time as the initial radioisotopes decay and daughter radioisotopes accumulate. In the case of SNAP-10A, a fission reactor system, fission products are generated during operation followed by fission product decay after shutdown. The radioisotopic mix and, therefore, the radiological hazard of each system will vary over time. The radioisotopic inventory of each system has therefore, been evaluated.

The initial radioisotopic fuel mix and the basic characteristics of each fuel type used in the systems under consideration are described in Appendix H.

The decay or buildup of a given member of a radioactive decay chain can be described by the Bateman equation: (1)

$$N_j = N_i^0 \sum_{l=1}^j \left[\frac{\left(\prod_{k=1}^{l-1} \lambda_k \right) \exp(-\lambda_l t)}{\prod_{\substack{m=1 \\ m \neq l}}^n (\lambda_m - \lambda_l)} \right]$$

where

- N_i^0 = number of i^{th} parent atoms per gram of fuel at time 0
- N_j = number of j^{th} daughter atoms per gram of fuel at time t
- λ_l = radioactive decay constant of l^{th} daughter, sec^{-1}

The number of atoms of a given isotope initially in the released fuel mix is

$$N_i^0 = \frac{P_i M A_0}{100 M_i}$$

where

- M = mass of fuel released, grams
- P_i = weight percent of isotope i initially in fuel
- M_i = mass of 1 gram-mole of isotope i, grams
- A₀ = Avogadro's number.

The activity of a given radioisotope is

$$A_j = \frac{N_j \lambda_j}{a}$$

where

- A_j = activity of isotope j at time t, curies
- a = 3.7 x 10¹⁰ disintegrations/sec-Ci.

The radioisotopic inventory versus time for each fuel type and system has been calculated using the ORNL developed ORIGEN code that uses the Bateman equation as the basis for the calculations.(2) Inputs to ORIGEN include the initial curie activity of each radioisotope in a given fuel type described in Appendix H and the output includes curie activity versus time for all parent and daughter radioisotopes, the gamma photon production rate and energy spectrum versus time, and the neutron production rate and energy spectrum versus time. Neutron production due to plutonium mix spontaneous fissioning and (α,n) reactions are accounted for.

The gamma and neutron production rates and energy spectra versus time obtained from ORIGEN are used as input to the external radiation field calculations described in Chapter 5. The radioactive decay schemes for the radionuclides in initial plutonium fuel mixes are presented in Figures 4-1 through 4-4. The results for each spacecraft are presented in Section 2.0 of Appendices A through G, respectively, for all radioisotopes from time t=0, representing the initial fueling, to at least beyond the projected orbital lifetime. The results are

Figure 4-1

Radioactive Decay of Pu-238 and Pu-242

Figure 4-2 Radioactive Decay of Pu-239

Figure 4-3 Radioactive Decay of Pu-236 and Pu-240

Figure 4-4 Radioactive Decay of Pu-241

presented in both table and graphical form. A summary of the total curie inventory for each spacecraft versus time is presented in Figure 4-5.

Total production of helium and radon gas versus time have also been estimated for each spacecraft based on the ORIGEN output by converting time integrated alpha activity into a helium inventory, and activity of all radon isotopes into radon gas inventory. The results are presented for each spacecraft in Section 2 of Appendices A through G, respectively.

Figure 4-5 Total Radiisotopic Inventory Versus Time
For U. S. Space Nuclear Systems

Chapter 4.0 References

1. Bateman, H., "The Solution of a System of Differential Equations Occurring in the Theory of Raioactive Transformations," Proc. Cambridge Phil. Soc., Vol. 15, pp. 423-427 (1910).
2. Oak Ridge National Laboratory, ORIGEN Isotope Generation and Depletion Code, Matrix Exponential Method, CCC-217 (November 8, 1975).

5.0 EXTERNAL RADIATION FIELD VERSUS TIME

The external radiation field dose rates due to a given system will change with time due to radioisotopic decay and buildup, resulting in a varying gamma and neutron energy spectra with time. The external dose rates from a given system was calculated using an NUS modified version of the QAD-P5 code, derived from the QAD code originally developed by LASL.(1,2,3)

QAD is a point kernel code system designed to calculate fast neutron and gamma-ray penetration of various shield configurations. Estimates are made of gamma-ray flux, dose rate, and energy deposition at specified detector locations, accounting for buildup within the source using Capo's parameter definitions and attenuation by shielding materials. The fast neutron dose obtained using a modified Albert-Wetton kernel was found to agree most closely with measured values.

Input data for the code consists of 1) a description of the source distribution and intensity by a number of point isotopic sources, 2) a mathematical representation of the physical geometry with quadratic surface, and 3) a tabulation of attenuation coefficients applicable to the shielding materials, buildup factors, and conversion factors.

In applying the code, equivalent cylindrical geometries were assumed for all systems considered. Thickness and material type were specified for each layer of the system. Gamma photon and neutron production rates and energy spectra as a function of time, derived from the ORIGEN runs described in Chapter 4, were input into successive QAD runs to determine the external dose rates versus time at specified distances in the axial and radial directions of each system. Measured gamma and neutron dose rates from actual systems were then used to calibrate the calculated values at time $t=0$, assuming that the measured values represented fresh fuel. Calculated values for subsequent time periods were scaled accordingly. The results indicated that the calculated and measured values at time $t=0$ were in good agreement, being within a factor of two at most.

The results of the external dose rate calculations are summarized in Section 3 of Appendices A through G for each system in Table 1-1, respectively. These results include gamma and neutron dose rates in the axial and radial directions both for a 1 m distance as a function of time and for a reference time of 10^8 sec as a function of distance. The external dose rates are for vacuum conditions. However, calculations of gamma attenuation and buildup in air indicated the vacuum-basis dose rates would decrease only slightly in air in the near-field.

The gamma dose rates appeared to be quite sensitive to impurities, especially Ac-227, reported in the literature to occur in MHW and GPHS fuel but not precisely quantified. The calculations for MHW, GPHS and Nimbus (SNAP-19 PuO_2 microsphere composition assumed to be the same as for MHW) assumed both zero and approximately a 0.12 w/o Ac-227 impurity. The gamma dose rates calculated on this basis were dominated almost entirely by Ac-227 and its short-lived daughters during a time period of approximately 1 to 30 years after loading of fresh fuel, with a rapid buildup of dose rates during the first year. Results are also presented without Ac-227 impurity. Discussions with LASL and MRC personnel indicated the Ac-227 impurity levels in these fuels were extremely small and this was not considered to be a problem. The results are included merely to show sensitivity to Ac-227 and to illustrate the need to ensure that such impurity levels are minimized in fuels.

Impurity problems may occur with earlier developed fuels such as metallic plutonium fuel. However, composition analyses for such fuels are limited, with only the major plutonium components reported.

Chapter 5.0 References

1. Malenfant, R.E., QAD: A Series of Point Kernel General Purpose Shielding Programs, Los Alamos Scientific Laboratory, LA-3573 (April 1967).
2. Oak Ridge National Laboratory, QAD, Point Kernel General Purpose Shielding Codes: QAD IV, QAD P-5, QAD-B, QAD-V, QAD-INT, QAD-HD, QAD-5K, QAD-BR, and QAD-P5A, ORNL-4181.
3. Huang, R., QAD-SQ: NUS Modified QAD-P5, NUS Corporation, NUS-TM-EC-16 (November 1973).

6.0 AGING OF MATERIALS

This section is intended to provide estimates of the significance of a number of materials degradation mechanisms that may occur during the expected orbital lifetimes of the missions detailed in Table 1-1. The postulated degradation may influence a decision to retrieve, in the near future, one or more of the radioisotopic generators while still in orbit, by use of an appropriately designed Space Shuttle subsystem. In turn, a reevaluation of the conditions to be expected at reentry, interpreted in the light of the projected technological developments and political climate, may reinforce the conclusions of the original safety analysis reports, acknowledging burnup or reentry, or may warrant a later exercise of the retrieval alternative.

The following mechanisms have been reviewed, where applicable:

- o Radioisotope fuel: containment interactions
- o Phase changes or other thermal effects
- o Containment material fatigue
- o Pressure effects due to gaseous decay products
- o Interaction of containment materials
- o Radiation damage - internal
- o Space irradiation
- o Evaporation - sublimation
- o Meteoroid damage.

The cumulative effect of the relevant degradation mechanisms is assessed and source terms are estimated accordingly.

Each generator's materials assemblage is treated in Section 4 of Appendices A through G for each system, respectively.

7.0 REENTRY SOURCE TERMS

Reentry radioactive source terms have been calculated using the methods described above for each U.S. space nuclear system considered, identified in Table 1-1, for the following release scenarios:

- o High altitude burnup (vapor)
- o High altitude burnup (particulate release over land)
- o High altitude burnup (particulate release over ocean)
- o Land impact
- o Ocean impact.

The evaluation assumes that reentry and associated release modes occur at the end of predicted orbit life. The release mode probability and source term (percent inventory released) for each system have been summarized in Tables 2-2 and 2-3. The expected source terms have been presented in Table 2-4, representing the product of the release probability and release source term. Supporting input data to the calculations are presented in Section 5 of Appendices A through G for each system, respectively.

APPENDIX A

TRANSIT 4A/4B (SNAP-3)

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A.1 REFERENCE DESIGN INFORMATION

A.1.1 Mission

Transit 4A and 4B are two navigational satellites launched on June 29, 1961 and November 15, 1961, respectively. Each is powered by a SNAP-3 plutonium fueled RTG. A summary of the orbital parameters and system design features of the SNAP-3 is presented in Table A-1 and discussed further below.

A.1.2 Nuclear Power System

The SNAP-3 RTG utilizes metallic plutonium as the heat source as shown in Figures A-1 and A-2. The plutonium is doubly encapsulated as shown in Figure A-3 with an outer capsule of Haynes-25 and an inner liner of tantalum to prevent interaction of the plutonium and Haynes-25. Since no helium venting is incorporated, the Haynes-25 capsule is designed to have sufficient strength to withstand helium pressure buildup due to alpha decay over long time periods. The fuel capsule is housed in a tapered receptacle of stainless steel.

The hot junctions of the 27 pairs of lead telluride thermoelectric elements are placed against the stainless steel receptacle while the cold junctions are held in contact shoes which extend to the surface of the generator. The Haynes-25 capsule and assembled thermoelectric elements are held in place inside a copper sphere by a rigid heat-insulating material and voids are filled with powdered insulation.

A.1.3 Fuel

The Transit generator is fueled with approximately 134 grams of plutonium metallic fuel with a composition of approximately 75% Pu-238 and 25% Pu-239, producing 55 thermal watts initially. More detailed information on the properties of metallic plutonium fuel is presented in Appendix H.

TABLE A-1

TRANSIT 4A/4B (SNAP 3) DATA SUMMARY

1.	<u>Missions</u>	Transit 4A	Transit 4B
2.	<u>Launch Dates</u>	6/29/61	11/15/61
3.	<u>Orbital Parameters</u>		
	o Period, minutes	103.7	105.7
	o Inclination, degrees	66.8	32.4
	o Apogee, km	993	1103
	o Perigee, km	881	953
	o Orbital lifetime, years	570	1200
4.	<u>System Description</u>		
	o Type	- SNAP 3 RTG	
	o Fuel	- Metallic Pu in delta phase (assumed to be 75% Pu-238 and 25% Pu-239). Core has a fuel volume of 6.4 cm ³ and a void volume of 5.6 cm ³ . Fuel mass of 134 g.	
	o Power	- 55 thermal watts	
	o Activity	- 1694 Ci Pu-238 at launch	
	o Containment	- Tantalum liner within Haynes 25 strength member	
	o Aeroshell	- None. Designed for burnup reentry with aluminum outer shell.	
	o He Venting	- No He venting. Capsule designed to withstand He buildup within the void volume. Maximum internal He pressure estimated in SAR to be 27,800 psi 187.3 years after encapsulation.

Figure A-1 Transit 4-A, Cutaway View

Figure A-2 **SNAP 3 Radioisotope Thermoelectric Generator**

Figure A-3 **SNAP 3 Fuel Capsule**

A.2 RADIOISOTOPIC INVENTORY VERSUS TIME

The radioisotopic inventory versus time for the SNAP-3 RTG onboard both Transit 4A and 4B has been calculated using the methods described in Chapter 4 of the main text. The calculations assumed an initial radioisotopic fuel mix consisting of 75% Pu-238 and 25% Pu-239 in the metallic form and other fuel properties described in Appendix H.

The results are summarized in Table A-2 and Figure A-4 that present the curie activity of the principal parent and daughter radioisotopes as a function of time.

In addition, the total production of helium and radon gas were calculated and the results presented in Figure A-5 as a function of time.

TABLE A-2

TRANSIT 4A/4B (SNAP 3) RADIOISOTOPIC
INVENTORY VERSUS TIME (EACH SPACECRAFT)

Radioactivity Inventory (Curies) at Indicated Time (Sec)						
Radionuclide	Initial	10^8	10^9	10^{10}	10^{11}	10^{12}
Tl-207	-	7.04E-15	5.69E-12	2.11E-09	2.02E-07	1.28E-05
Pb-210	-	2.38E-12	1.92E-08	5.40E-05	7.05E-03	1.38E-01
Pb-211	-	7.05E-15	5.71E-12	2.11E-09	2.02E-07	1.28E-05
Pb-214	-	9.35E-11	8.82E-08	5.40E-05	7.05E-03	1.38E-01
Bi-210	-	2.38E-12	1.92E-08	5.40E-05	7.05E-03	1.38E-01
Bi-211	-	7.05E-15	5.71E-12	2.11E-09	2.02E-07	1.28E-05
Bi-214	-	9.35E-11	8.82E-08	5.40E-05	7.05E-03	1.38E-01
Po-210	-	1.34E-12	1.92E-08	5.40E-05	7.05E-03	1.38E-01
Po-214	-	9.35E-11	8.82E-08	5.40E-05	7.05E-03	1.38E-01
Po-215	-	7.05E-15	5.71E-12	2.11E-09	2.02E-07	1.28E-05
Po-218	-	9.35E-11	8.82E-08	5.40E-05	7.05E-03	1.38E-01
Rn-219	-	7.05E-15	5.71E-12	2.11E-09	2.02E-07	1.28E-05
Rn-222	-	9.35E-11	8.82E-08	5.40E-05	7.05E-03	1.38E-01
Ra-223	-	7.05E-15	5.71E-12	2.11E-09	2.02E-07	1.28E-05
Ra-226	-	9.35E-11	8.82E-08	5.40E-05	7.05E-03	1.38E-01
Ac-227	-	7.05E-15	5.71E-12	2.11E-09	2.02E-07	1.28E-05
Th-227	-	6.96E-15	5.63E-12	2.09E-09	2.00E-07	1.27E-05
Th-230	-	2.03E-07	1.90E-05	1.05E-03	1.58E-02	1.38E-01
Th-231	-	6.30E-09	6.30E-08	6.28E-07	6.04E-06	4.16E-05
Pa-231	-	2.13E-13	2.13E-11	2.11E-09	2.02E-07	1.28E-05
U-234	-	1.48E-02	1.33E-01	5.55E-01	6.01E-01	5.56E-01
U-235	-	6.30E-09	6.30E-08	6.28E-07	6.04E-06	4.16E-05
Pu-238	1.69E+03	1.65E+03	1.32E+03	1.42E+02	3.23E-08	-
Pu-239	2.03	2.03	2.03	2.02	1.86	8.29E-01
Pu-240	-	-	-	-	-	-
Pu-241	-	-	-	-	-	-
Pu-242	-	-	-	-	-	-
Am-241	-	-	-	-	-	-
Subtotal	1.69E+03	1.65E+03	1.32E+03	1.45E+02	2.54	2.78
Actual Total	1.69E+03	1.65E+04	1.32E+03	1.45E+02	2.54	2.78

Figure A-4

Transit 4A/4B (SNAP 3) Radioisotopic
Inventory Versus Time (Per Spacecraft)

Figure A-5 Transit 4A/4B (SNAP 3) Helium and Radon Gas Production Versus Time

A.3 EXTERNAL RADIATION FIELD VERSUS TIME

The external radiation field in the vicinity of a SNAP-3 RTG has been calculated based on the methods described in Chapter 5 of the main text. The results are presented in Figures A-6 and A-7. Figure A-6 presents the gamma and neutron dose rates in the axial and radial directions at a distance of 1 m as a function of time. Figure A-7 presents the gamma and neutron dose rates in the axial and radial directions as a function of distance in a vacuum at a reference time of 10^8 sec (3.17 years) after fresh fuel loading.

Figure A-6 Transit 4A/4B (SNAP 3) External Dose Rates Versus Time at 1m Distance

Figure A-7

Transit 4A/4B (SNAP 3) External Dose Rates
Versus Distance at Time $t=10^8$ Sec

A.4 AGING OF MATERIALS

A.4.1 Introduction

The choice of plutonium-238 metal as fuel for the radioisotope generators on the Transit 4A and 4B satellites was representative of the technology available 20 or more years ago. However, this choice presents today's reviewers with a number of uncertainties that have not been resolved satisfactorily. Other fuel forms supplanted the use of Pu-238 metal; consequently, property studies and investigations of its compatibility with other materials necessarily were abridged, in order to meet the newer engineering challenges. There follows a retrospective appraisal of the Transit 4A/4B generator materials relative to varied effects of aging on their integrity.

A.4.2 Radioisotope Fuel: Containment Interactions

Plutonium metal, of the then current purity, was cast at about 1000°C into the tantalum-lined capsule shown in Figure A-3. Upon solidification at 639°C, and equilibration to the stated operating temperature of 510°C, a negative density change results in intimate contact with the containment. Data derived from studies on Pu-239 metal indicate a density of 16.5 gm/cm³ for the liquid metal, and a value of 15.9 gm/cm³ for the solid delta phase.

Compatibility tests indicate potential penetration of the tantalum capsule liner. Pu-238 metal, in contact with tantalum at 550°C for 252 days, showed intergranular attack to a depth of 0.118 cm; corresponding exposure at 600°C for 268 days showed complete penetration at the weld. A third test showed intergranular attack of about 0.076 cm depth after approximately 13 days at exposure at 1000°C, well above the melting point of the metal. It is estimated that the nominal 0.051 cm liner wall section would be penetrated completely in 1,000 days. Of course, this would be delayed slightly as temperature declines over the operational period.

Penetration rate data were not available to permit an estimate of the expected lifetime of the Haynes-25 alloy strength member. However, the existence of published phase diagrams for the plutonium-rich region of the plutonium-iron and plutonium-cobalt systems indicates that reaction rates must be rapid. At equilibrium, plutonium and the strength member alloy (primarily cobalt, chromium, nickel and manganese) would have reacted to form stable phases with an eutectic at 415 to 430°C, at a concentration of 2.25 percent (Co, Fe, etc.). It is anticipated that at the then current operating temperatures a substantial portion of the plutonium would remain in the epsilon phase and that approximately 0.0064 cm of the strength member's inner wall would have been consumed in the reaction. This represents a 2 percent reduction in wall thickness.

A.4.3 Phase Changes or Other Thermal Effects

As the plutonium-238 isotope decays, the uranium-234 isotope concentration increases. A phase diagram representing this plutonium-uranium binary system has been published. Solid solution of uranium in plutonium is indicated, with uranium appearing as a discrete phase after about 160 years of operation. As the uranium concentration increases, the liquid temperatures rise and various allotropic forms of uranium appear in appropriate temperature ranges.

The appearance of uranium adds further complexity to the degradation process. Glasstone states that "Among the elements having appreciable solubility in the solid uranium phase at elevated temperatures, mention may be made of zirconium, titanium, columbium and molybdenum." Glasstone also states that a number of elements form intermetallic compounds with uranium. However, at the progressively lower temperatures prevailing when the concentration of uranium becomes substantial, reaction rate phenomena are not likely to be rapid or extensive.

A pressure-temperature phase diagram for plutonium metal indicates that increasing pressure shifts the stability ranges of the various alpha to epsilon phases to higher temperatures. However, the temperature at which liquid appears

decreases with pressure. For example, the melting point of Pu-239 retreats from 640°C to 500°C under a pressure of 25 kilobars (363,000 psi). The maximum pressure to be sustained by the capsule and strength member was calculated as 27,800 psi, or roughly 2 kilobars. The corresponding phase changes would be insignificant.

A.4.4 Pressure Effects Due to Gaseous Decay Products

The fueled capsule provides a total volume of 12.0 cm³, with 7.1 cm³ occupied by fuel and a void volume of 4.9 cm³ filled with argon. As the plutonium-238 metal decays, this "void volume" receives and contains all helium and radon generated during the alpha-decay process.

Temperatures and pressures to be anticipated at several points in the capsule operational lifetime were calculated by Fairchild Industries as follows:

<u>Time After Loading</u>	<u>Temperature, °C</u>	<u>Pressure 10³ psi</u>
10 ⁸ seconds	579	2.0
10 ⁹ seconds	456	15.0
4.5x10 ⁹ seconds	177	27.8
10 ¹⁰ seconds	11	24.2
1.8x10 ¹⁰ (570 years)	-33	21.9
3.8x10 ¹⁰ (1200 years)	-38	21.3
10 ¹¹ seconds	-40	22.2

(1 year = 3.156x10⁷ seconds)

If the strength member was realistically designed for 27,800 psi, failure will have occurred prior to 10¹⁰ seconds.

A.4.5 Interaction of Containment Materials

In this section, one may seek for degradation mechanisms involving chemical, metallurgical, thermophysical, or frictional effects accruing solely from the juxtaposition of heat source components, exclusive of fuel material or decay product effects.

The simplicity and small size of the Transit 4A/4B capsule assembly precludes significant interaction problems. Differential expansion between metals has been accommodated by appropriate machining tolerances. Diffusion phenomena between tantalum and Haynes-25 alloy, and between the latter and 416 stainless steel, at temperatures of 500°C and below, are expected to be negligible.

A.4.6 Radiation Damage - Internal

Perhaps the most significant damage that can be postulated with reasonable certainty is that arising within the fuel, by reason of the generation of helium. Porosity within individual grains, pockets at dislocation sites, and accumulations at grain boundaries all contribute to eventual weakening and fragmentation. This does not necessarily result in poorer heat source efficiency, since helium is a good thermal conductor.

Another significant effect, localized within the fuel, is the gradual development of decay product atoms, such as uranium-234, remaining within the plutonium-238 or -239 crystalline lattice. Nominal atomic radii for plutonium and uranium are 1.64 and 1.48 Angstrom units, respectively. The replacement of a larger atom by a smaller essentially yields a solid solution. In the instance of plutonium and uranium, the size differential is less than the nominal 15 percent and the guest atom can be accommodated. The Pu-U phase diagram discussed earlier reflects this situation.

Materials in the path of alpha particles with an emitted energy of 5.5 Mev are susceptible to ionization. Since large, heavy alpha particles are readily stopped in their pathway, ionization effects would be limited to the fuel itself,

helium and other gases within the capsule, and superficial layers of atoms in the containment material. One could postulate a momentary displacement and acceleration of reaction rates between fuel atoms and ionized containment metal atoms, or vice versa. However, the continuing atom movement within the metal lattices, arising from their thermal agitation, largely negates the effect of the induced atom movement or ionization.

During the course of the decay of 98 percent of the plutonium-238 fuel in the 6.5 half-lives represented by the Transit 4A orbital lifetime, a fluence of approximately 3×10^{23} alpha particles will have been generated and absorbed. The Transit 4B orbital lifetime of 1200 years permits a yield of a slightly larger total, 3.1×10^{23} alpha particles. Additional alpha particle fluxes derived from the cascading decay of daughter products were not included in this total. The effects of alpha particle impact are not expected to be notable, since thermal annealing of limited superficial lattice damage is anticipated.

The plutonium-238 fuel also yields a spontaneous neutron flux of 2.8×10^3 per second, per gram of isotope. Over the 10^{10} to 10^{12} second lifetimes indicated, a total neutron fluence of about 3×10^{13} to 3×10^{15} would become available. The latter level, were it to be directed in one second at a square centimeter of metal at very low temperature, would be expected to produce temporary changes in resistivity in aluminum or copper, for example. Exposure to room temperature would delete substantially all of these effects.

Under the conditions prevailing in the fuel capsule for the Transit satellites, internal radiation damage is not anticipated.

A.4.7 Space Irradiation

A.4.7.1 Solar Irradiance

In June 1975, the NIMBUS-6 satellite was launched into a sun-synchronous polar circular orbit at 1,100 kilometers altitude. Every 107 minutes, on a selected schedule, measurements of the extra-terrestrial solar irradiance were made. A

value of 1392 watts per square meter was obtained, but was corrected later by data from a subsequent rocket flight. The nominal value of 1370 watts per square meter was confirmed.

No degradation is anticipated from the approximately 350 watts of solar energy falling upon the Transit satellite surface facing the sun during orbit. However, should the aluminum or copper shells become defaced by ion or meteoroid bombardment during orbital lifetimes, reverse heating effects might lead to dimensional changes and stresses at the outermost surfaces.

A.4.7.2 Space Irradiation - Ion Sputtering

The 1962 Standard Atmosphere Tables do not document the characteristics of the earth's atmosphere above 500 kilometers. However, supplementary charts, however, indicate a population of about 10^5 ions and 10^6 total particles per cubic centimeter at 1,000 kilometers altitude. Positive ion concentration appears to be 10^4 per cm^3 ; electron density approximates 3×10^4 per cm^3 . The composition of the upper atmosphere includes helium and hydrogen, and small quantities of oxygen or nitrogen, largely ionized.

The Transit 4A and 4B satellites are orbiting within or near the inner Van Allen radiation belt of the earth as shown in Figure A-8. This belt extends from about 45° north magnetic latitude to 45° south magnetic latitude; thus, during each orbit period, one-half of the orbit is spent in or near this belt of radiation, at approximately 1.15 earth radii distance. Proton isoflux contours indicate that the majority of protons to be considered appear at an energy level greater than 0.4 MeV, and up to 4 MeV. A nitrogen or oxygen atom striking at 7.4 kilometers per second has a kinetic energy of 4.3 eV. Coincidentally, the Transit 4A and 4B satellites also orbit at approximately 7.4 km per second. Thus, the impact velocity may range from 0 to 15 km per second, depending upon the relative directions of the particle and spacecraft velocity vectors.

Figure A-8 The Earth's radiation belts

For a period of sunspot minimum, the total ion population has been estimated at 1.26×10^6 per cm^3 ; during sunspot maximum, the population level drops to 1.08×10^5 per cm^3 . One average orbit period of approximately 105 minutes sweeps out 0.7×10^6 ions per cm^3 ; during one second of orbit 7.4×10^5 cm will have been traversed; the satellite surface has an area of approximately 1,000 square centimeters exposed to radiation. Thus, in one second, exposure would be:

(0.7×10^6)	x	(7.4×10^5)	x	$(1 \times 10^3 \text{ cm}^2)$	=	5.18×10^{14}
Ions per cm^3		Cm traversed in orbit in one second		Surface area		Ions contacted total

Extending this calculation:

- o Ions contacted per square centimeter of satellite per second:
 5.18×10^{11}

- o Total ions contacted in one 107 minute period:

$$1/2 \times 6420 \text{ sec} \times 5.18 \times 10^{11} = 16.6 \times 10^{14} / \text{cm}^2$$

- o Total ions contacted per day:

$$13.7 \text{ periods} \times 16.6 \times 10^{14} = 22.7 \times 10^{15} / \text{cm}^2$$

- o Total ions contacted per year:

$$(22.7 \times 10^{15} / \text{cm}^2) \times 365.2422 = 82.9 \times 10^{17} / \text{cm}^2$$

- o Total ions contacted per orbit lifetime

$$\times 570 \text{ (A)} = 4.73 \times 10^{20} / \text{cm}^2$$

$$\times 1200 \text{ (B)} = 9.95 \times 10^{20} / \text{cm}^2$$

Sputtering efficiency is reported to be less than 10^{-10} for atoms sputtered off by nitrogen or oxygen ions. At an average volume of about $5 \times 10^{-24} \text{ cm}^3$, the loss of thickness during the entire indicated orbit lifetime would be considerably less than one Angstrom unit for either Transit unit. Proton bombardment was not considered in this calculation; however, the additional contribution is considered to be negligible. The net projected material loss is essentially negligible from the standpoint of material degradation.

A.4.8 Evaporation or Sublimation

Components exposed to the vacuum of space at 1,000 kilometers altitude (7.5×10^{-11} torr) include the copper or aluminum shell or Haynes-25 capsule components. To exceed the space vacuum conditions, it is estimated that the copper shell would have to reach a temperature of at least 612°C ; the corresponding requirement for an aluminum shell would be approximately 562°C . On the assumption that the insulation surrounding the fuel capsule is open to vacuum, the stainless steel and Haynes-25 metal components would need to reach temperatures of 762° to 802°C in order for evaporation to be initiated. Design data indicates a stabilized capsule temperature on the order of 577 - 587°C . Thus, there is no apparent hazard to be attributed to evaporation of metals, nor to materials transfer within the body of the satellite.

A.4.9 Meteoroid Damage

Particles, collectively called meteoroids, include meteorites, meteors and micrometeoroids, or dust. Meteorites are generally stony fragments with masses above one gram; some are iron-nickel aggregates, and all are believed to be of asteroidal origin. Their orbits are generally circular around the sun in the plane of the ecliptic, and in a direction the same as the earth's. Velocities are about 20 km per second, occasionally up to 72 km/sec. Near the earth's orbit, the flux is so low that the probability of collision with a spacecraft is negligible.

Meteors are believed to be fragments of comets with low density and mass. Velocities relative to the earth average about 30 km/sec. Some meteors occur in showers from various constellation regions that the earth enters once a year in its orbit around the sun.

Micrometeoroids may be stony or porous; their masses may be in the range of 10^{-10} to 10^{-14} gram, and velocities are generally under 20 km per second. Sputnik 3, Explorer 1, Vanguard 3, Pioneer 1, and other spacecraft encountered micrometeoroids of this general type. In the vicinity of the earth's orbit, frequency of penetration is about one per square meter per year for sheet iron or aluminum about 0.152 cm thick. Thinner sheets are penetrated much more often; thicker sheets seldom. Back-surface spalling shows a similar frequency distribution but at a thickness of 0.10 cm.

The depth and radius of craters formed by meteoroids are proportional to the cube root of the impact momentum. The tentative annual average sporadic meteoroid environment model for the space region 1 Astronomical Unit from the sun is as follows: (9)

<u>Mass of Meteoroid</u> <u>(gram)</u>	<u>Flux</u> <u>Particles per m² per sec</u>
1.0	3.89×10^{-15}
10^{-6}	8.17×10^{-8}
4.46×10^{-9}	2.86×10^{-6}
5.0×10^{-11}	1.52×10^{-5}

Thus, the Transit satellites are susceptible to impact by meteoroids, but most probably by those in the two lower mass categories. The cratering developed by the lightest meteoroid is approximately 11 micrometers in radius and depth. In 100 years of orbit through meteoroid regions, 20,800 penetrations might be sustained over approximately $1,000 \text{ cm}^2$ of the Transit satellite. The total affected surface would comprise 8,000 square micrometers in area, 11 micrometers deep, a negligible artifact of that century in space.

With an average crater area approximately 10 square micrometers, the probability of repeated impact at the same spot is about 1×10^{-10} . Continued meteoroid impacts during the remaining 470 years of the Transit 4A orbital lifetime would essentially add another 98,000 similar craters, for a total affected area of 46,000 square micrometers, representing about 5×10^{-6} of the available surface.

Progressing to the longer orbital lifetime of the Transit 4B, and assuming that the meteoroids in this instance comprised a flux of 2.86×10^{-6} particles per second per square meter of area, and that they weighed 4.46×10^{-9} gram each, total flux over the 1200-year lifetime would amount to about 1.1×10^4 particles, leaving a cratered area of 2.2×10^6 square micrometers, or 2.2×10^{-4} of the exposed surface, with craters 20 micrometers deep, again a negligible degradation.

A.4.10 Cumulative Effects and Source Terms

The anticipated degradation mechanisms described above may be evaluated by reference to the following table. Estimated milestones and their significance to various components of the Transit 4A and 4B RTGs are indicated.

<u>Milestone</u>	<u>Component</u>	<u>Effects</u>
1000 days	Ta-Liner	Integranular attack by plutonium metal and complete intergranular penetration
1000 + days	Haynes-25 Strength Member	2% reduction in wall thickness due to reactions between plutonium, cobalt and iron
143 years	Fuel capsule	Capsule rupture due to helium pressure buildup

570 years
(Transit 4A)

RTG

Reentry burnup

1200
(Transit 4B)

RTG

Reentry burnup

Radiation damage due to alpha particles and a modest neutron fluence is expected to have little net degradation effect. Effects of sputtering or other forms of space radiation also are expected to be negligible. Evaporation effects decline with age of the satellites, corresponding to declining temperature. Meteoroid effects are limited to the most exterior of satellite surfaces, and they, too, are considered to be negligible.

A.5 REENTRY SOURCE TERMS

Reentry radioactive source terms have been calculated for Transit 4A and 4B for the following release scenarios:

- o High altitude burnup (vapor)
- o High altitude burnup (particulate release over land)
- o High altitude burnup (particulate release over ocean)
- o Land impact
- o Ocean impact.

The analysis assumes that reentry and associated release modes occur at the end of predicted orbit life (570 and 1200 years for Transit 4A and 4B, respectively). The release mode probability and associated source term (fraction of fuel released) were estimated based on the information on material aging effects developed in Chapter 4. The expected source terms were then calculated as the product of release mode probability and source term, all of which are summarized in Tables A-3 and A-4 for Transit 4A and 4B, respectively.

TABLE A-3

POSTULATED REENTRY RELEASE MODE PROBABILITIES AND SOURCE TERMS
FOR TRANSIT 4A(SNAP-3)

<u>Release Mode</u>	<u>Release Probability</u>	<u>Source Term (% Inventory Released)</u>	<u>Source Term (Curies)</u>	<u>Expected Source Term (Curies)</u>
High Altitude Burnup (Vapor)	1.0	100%	3.65E+01	3.65E+01
High Altitude Burnup (Particulate Release Over Land)	-	-	-	-
High Altitude Burnup (Particulate Release Over Ocean)	-	-	-	-
Land Impact	-	-	-	-
Ocean Impact	-	-	-	-
			Total	3.65E+01

TABLE A-4

POSTULATED REENTRY RELEASE MODE PROBABILITIES AND SOURCE TERMS
FOR TRANSIT 4B (SNAP-3)

<u>Release Mode</u>	<u>Release Probability</u>	<u>Source Term (% Inventory Released)</u>	<u>Source Term (Curies)</u>	<u>Expected Source Term (Curies)</u>
High Altitude Burnup (Vapor)	1.0	100%	4.20E-01	4.20E-01
High Altitude Burnup (Particulate Release Over Land)	-	-	-	-
High Altitude Burnup (Particulate Release Over Ocean)	-	-	-	-
Land Impact	-	-	-	-
Ocean Impact	-	-	-	-
			Total	4.20E-01

A.6 REFERENCES

1. Martin Marietta Nuclear Division, Nuclear Safety Test Report for the Space Version of the Present SNAP-3 Thermoelectric Generator, MND-P-2358 (June 1960).
2. Martin Marietta Nuclear Division, Safety Analysis for Transit Generator, MND -P-2479 (March 1961).
3. Martin Marietta Nuclear Division, Examination of a SNAP-3 Heat Source, MLM-CF-65-4-128.
4. Martin Marietta Nuclear Division, Program Summary for the Transit 4A Radioisotope Power System, MND-P-2628 (August 1961).
5. Martin Marietta Nuclear Division, SNAP-3: Final Safety Analysis Report, MND-P-2364.
6. Martin Marietta Nuclear Division, Helium Pressure Buildup in SNAP-3, MND-P-1726.
7. Westinghouse, SNAP-3 Thermoelectric Generator, WEC-F-6930-19-1 (April 30, 1960).
8. Glasstone, S. and A. Sesonske, Nuclear Reactor Engineering, Van Nostrand Company, New York (1967).
9. Valley, S.L., Handbook of Geophysics and Space Environments, U.S. Air Force Cambridge Research Laboratory (1965).
10. Jaffee, L.D. and J.B. Rittenhouse, Behavior of Materials in Space Environments, Jet Propulsion Laboratory, Technical Report 32-150 (1961)
11. Rittenhouse, J.B. and J.B. Singleton, Space Materials Handbook, NASA-SP-3051 (1969).
12. Espe, W., Materials of High Vacuum Technology, Pergamon Press (1968).
13. Heide, E. (Translated by E. Anders and E. du Fresne) Meteorites, University of Chicago Press (1964).
14. Mound Laboratory, MRC, Plutonium-238 Isotopic Power Sources: A Summary Report, MLM-1270.

APPENDIX B

TRANSIT TRIAD 10-1X (RTG)

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B.1 REFERENCE DESIGN INFORMATION

B.1.1 Mission

The Transit Triad 10-1X spacecraft shown in Figure B-1 is a navigational satellite with which naval vessels can obtain around-the-clock fixes of location with extremely high accuracy. The Transit Triad was launched from Vandenberg AFB on September 2, 1972 and placed into a polar, circular orbit by a Scout vehicle as shown in Figure B-2. The spacecraft is powered by a plutonium fueled RTG. A summary of the orbital parameters and system design features of the Transit Triad RTG is presented in Table B-1 and discussed further below.

B.1.2 Nuclear Power System

The Transit Triad RTG has two major components, the heat source and the converter, as shown in Figure B-3. The heat source, shown in Figure B-4, is cylindrical and consists of the radioisotopic fuel, the fuel capsule, and the heat shield. The fuel is Pu-238 in the form of plutonia molybdenum cermet (PMC).

The fuel capsule, shown in Figure B-4, consists of three metallic layers including 1) a liner of Ta-10W adjacent to the fuel and serving as the primary fuel compatibility member of the heat source, 2) a strength member of T-111 surrounding the liner and serving as the primary resistance to mechanical loads, and 3) the clad composed of Pt-20Rh protecting the strength member from air oxidation. The inner portion of the heat shield composed of Pyrolytic graphite is primarily a thermal barrier to the influx of heat during reentry. The outer shield, composed of POCO AXF-5Q graphite, acts as an aeroshell and abalator during reentry. An oxidation barrier of Inconel 718 surrounds the heat shield.

The converter part of the RTG consists primarily of the thermoelectric panels, their required supporting structure, and the heat source support structure. Twelve thermoelectric panels convert the decay heat of the fuel directly into electricity.

Figure B-1 Transit Triad Spacecraft Configuration

TABLE B-1

TRANSIT TRIAD 10-1X (RTG) DATA SUMMARY

1. Mission Transit Triad-01-1X
2. Launch Date 9/2/72
3. Orbital Parameters
 - o Period, minutes 100.6
 - o Inclination, degrees 90.1
 - o Apogee, km 838
 - o Perigee, km 742
 - o Orbital lifetime, years 150
4. System Description
 - o Type - RTG
 - o Fuel - PuO₂ molybdenum cermet (PMC) fuel.
Overall composition is approximately 82.5% PuO₂ and 17.5% Mo, and Pu composition is approximately 80% Pu-238, 16.5% Pu-239, and 3.5% other Pu isotopes. Fuel mass is 2640 g.
 - o Power - 850 thermal watts
 - o Activity - 24,000 Ci Pu-238
 - o Containment - The fuel capsule liner is Ta-10W enclosed within a T-111 strength member. This is then enclosed within an oxidation barrier consisting of Pt-20Rh clad.
 - o Aeroshell - Designed for intact reentry. Aeroshell consists of a thermal barrier composed of pyrolytic graphite and a heat shield composed of POCO AXF-5Q graphite. An oxidation barrier, consisting of an Inconel 718 can encloses the aeroshell.
 - o He Venting - He venting is allowed for using an Al₂O₃ porous disc and a capillary vent tube.

Figure B-3 Transit Triad RTG Heat Source Installed in Converter

Figure B-4 Transit Triad RTG Heat Source Design

The heat source support structure is designed to carry all mechanical loads from the heat source to the spacecraft structural system. The separate support structure for the heat source is required because the array of converter panels is significantly larger than the heat source envelope. The heat transfer mechanism from the heat source to the converter panels is radiation during space operation.

B.1.3 Fuel

The Transit baseline fuel form is PMC. The cermet consists of 82.5 weight percent of PuO_2 and 17.5 weight percent Mo. The fuel has a minimum power density of 3.2 watts/cm^3 and is pressed into discs with a nominal diameter of 5.44 cm and thickness of 0.538 cm. The discs have no overcoat of molybdenum.

A nominal fuel capsule loading of 850 thermal watts is employed. The fuel is in the form of 22 fuel discs, of which 13 have the dimensions given above and 9 are ground to smaller diameters to fit the hemispherical ends of the capsule. Approximately 2640 grams of PMC fuel form are used to achieve the nominal of 850 thermal watts at beginning of life. The operating power decreases slowly with time. More detailed information on PMC fuel is presented in Appendix H.

B.2 RADIOISOTOPIC INVENTORY VERSUS TIME

The radioisotopic inventory versus time for the Transit Triad RTG has been calculated using the methods described in Chapter 4 of the main text. The calculations assumed an initial radioisotopic mix characteristic of PMC fuel presented in Appendix H.

The results are summarized in Table B-2 and Figure B-5 that present the curie activity of the principal radioisotopes as a function of time.

In addition, the total production of helium and radon gas were calculated, and the results are presented in Figure B-6 as a function of time.

TABLE B-2

TRANSIT TRIAD (RTG) RADIOISOTOPIC
INVENTORY VERSUS TIME

Radioactivity Inventory (Curies) at Indicated Time (Sec)						
Radionuclide	Initial	10^7	10^8	10^9	10^{10}	10^{11}
Tl-207	-	-	-	5.54E-11	2.06E-08	1.96E-06
Pb-211	-	-	6.86E-14	5.54E-11	2.06E-08	1.97E-06
Pb-212	-	1.71E-04	9.79E-03	3.25E-02	2.09E-03	6.97E-11
Bi-211	-	-	6.86E-14	5.54E-11	2.06E-08	1.97E-06
Bi-212	-	1.71E-04	9.79E-03	3.25E-02	2.09E-03	6.97E-11
Po-211	-	-	-	1.66E-13	6.18E-11	5.91E-09
Po-212	-	1.10E-04	6.28E-03	2.08E-02	1.34E-03	4.46E-11
Po-215	-	-	6.86E-14	5.54E-11	2.06E-08	1.97E-06
Po-216	-	1.71E-04	9.79E-03	3.25E-02	2.09E-03	6.97E-11
Rn-219	-	-	6.86E-14	5.54E-11	2.06E-08	1.97E-06
Rn-220	-	1.71E-04	9.79E-03	3.25E-02	2.09E-03	6.97E-11
Ra-223	-	-	6.86E-14	5.54E-11	2.06E-08	1.97E-06
Ra-224	-	1.71E-04	9.79E-03	3.25E-02	2.09E-03	6.97E-11
Ac-227	-	-	6.86E-14	5.54E-11	2.06E-08	1.97E-06
Th-227	-	-	6.76E-14	5.46E-11	2.03E-08	1.98E-06
Th-228	-	1.71E-04	9.79E-03	3.25E-02	2.09E-03	6.97E-11
Pa-231	-	-	2.07E-12	2.07E-10	2.06E-08	1.97E-06
U-232	-	3.06E-03	2.18E-02	3.17E-02	2.03E-03	2.42E-15
U-233	-	9.69E-15	1.83E-11	1.32E-08	2.90E-06	1.18E-04
U-234	-	2.35E-02	2.33E-01	2.09	8.71	9.45
U-237	-	3.78E-02	3.30E-02	8.50E-03	1.12E-08	-
Pu-236	1.04	9.64E-01	4.75E-01	4.67E-04	-	-
Pu-238	2.64E+04	2.64E+04	2.58E+04	2.07E+04	2.24E+03	5.07E-07
Pu-239	1.98E+01	1.98E+01	1.98E+01	1.98E+01	1.96E+01	1.81E+01
Pu-240	1.08E+01	1.08E+01	1.08E+01	1.08E+01	1.05E+01	7.81
Pu-241	1.59E+03	1.57E+03	1.37E+03	3.54E+02	4.67E-04	-
Pu-242	7.63E-03	7.63E-03	7.63E-03	7.63E-03	7.63E-03	7.60E-03
Am-241	-	8.02E-01	7.50	4.04E+01	3.35E+01	3.48E-01
Subtotal	2.80E+04	2.80E+04	2.72E+04	2.11E+04	2.31E+03	3.57E+01
Actual Total	2.80E+04	2.80E+04	2.72E+04	2.11E+04	2.32E+03	3.70E+01

Figure B-5 Transit Triad (RTG) Radioisotopic Inventory Versus Time

Figure B-6 Transit Triad (RTG) Helium and Radon Gas Production Versus Time

B.3 EXTERNAL RADIATION FIELD VERSUS TIME

The external radiation field in the vicinity of the Transit Triad RTG has been calculated based on the methods described in Chapter 5 of the main text. Figure B-7 presents the gamma and neutron dose rates in the axial and radial directions at a distance of 1 m as a function of time. Figure B-8 presents the gamma and neutron dose rates in the axial and radial directions as a function of distance in a vacuum at a reference time of 10^8 sec (3.17 years) after fresh fuel loading.

Figure B-7

Transit Triad RTG External Dose
Rates Versus Time at 1m Distance

Figure B-8

Transit Triad RTG External Dose Rates
Versus Distance at Time $t=10^8$ Sec

B.4 AGING OF MATERIALS

B.4.1 Introduction

The categories of evaluation and general approach pursued in Section A.4 also will be applied in this assessment of the Transit Triad radioisotope thermoelectric generator. From the standpoint of materials degradation effects, orbital parameters are relatively similar to those of the Transit 4A and 4B satellite, except for a lower altitude, an essentially circumpolar orbit, and a considerably shorter lifetime. The radioisotope power source, however, is substantially different in design, fuel form, and planned reentry behavior (intact reentry versus burnup). Potential degradation mechanisms are evaluated in the subsections below.

B.4.2 Radioisotope Fuel: Containment Interactions

B.4.2.1 Compatibility Tests

Compatibility test data were reported in April 1971, covering the laboratory experiments in which plutonia-molybdenum cermet fuel (PMC) was in contact with tantalum-10 tungsten alloy at 900°C, for a period of 2,575 hours. The test capsule did not precisely represent the actual heat source configuration, nor the mass ratio of fuel to alloy. However, a reasonable degree of similitude was achieved.

The tantalum-10 tungsten alloy surface was dulled where it had been in contact with the PMC fuel; a micro-hardness check indicated a possibly significant 6% increase, and oxygen analysis showed a pickup of 85 parts per million, as compared with the control specimen. Photomicrographs revealed no apparent changes. No changes were noted in T-111 specimens similarly exposed.

The long-term compatibility tests performed by TRW, as described above, indicate little, if any, interaction between the PMC fuel and the Ta-10W liner at nominal operating temperature. This observation is further supported by data showing the

free energy changes in kilocalories per mole for the reactions of interest, at more elevated temperatures:

		<u>1000°C</u>	<u>1500°C</u>	<u>2000°C</u>
2Ta+10 PuO ₂	Ta ₂ O ₅ +5 Pu ₂ O ₃	+36	+27	-07
W+4 PuO ₂	WO ₂ +2 Pu ₂ O ₃	+69	+60	+36
Mo+4 PuO ₂	MoO ₂ +2 Pu ₂ O ₃	+77	+72	+55

At 850°C, the respective free energy change values are estimated as +39(Ta), +70(W), and +78(Mo), all suggestive of minimal reaction tendency at this relatively low temperature. In fact, work at the Battelle Laboratories indicates little reaction at even higher temperatures, in the range of 1400-1600°C.

There are lingering uncertainties, however, born of the fact that tantalum has been shown to react with oxygen at the relatively low temperaure of 250-450°C, in the presence of 7.6 cm equivalent oxygen pressure. Vacuum microbalance measurements yielded data conforming to the parabolic rate law, $W^2 = Kt + C$. The kinetics are such that two hours at temperatures, as shown, result in the indicated weight gain versus temperature:

Temperature, °C	250	300	350	400	450
Weight gain - Micrograms/cm ²	3	10	24	56	126

The oxidation of tungsten is known to proceed similarly.

An extrapolation to 900°C by means of an Arrhenius plot yielded, for the Transit TRIAD situation, a 2-hour oxidation effect of approximately 6,975 micrograms per cm², representing a potential oxygen pickup via the solid/solid or gas/solid reaction regime. One microgram per cm² weight gain is equivalent to about 4.45 micrograms per cm² of alloy loss. At this rate, the wall of the fuel capsule liner, about 0.048 cm thick, might be completely oxidized within 120 hours, providing that the oxide so developed presents no barrier to continuing oxygen penetration.

Presumably, a substantially longer period would be required to effect this degree of oxidation by solid state diffusion through the oxide layer.

The respective specific volumes (reciprocal of density) of Ta_2O_5 ($1/8.2 = 0.122 \text{ cm}^3$ per gram) and WO_3 ($1/7.16 = 0.140 \text{ cm}^3$ per gram) are each substantially greater than the corresponding values for their parent metals, Ta ($1/16.6 = 0.06 \text{ cm}^3$ per gram) and W (0.052 cm^3 per gram), thus indicating the porosity of the partially sintered oxide layer.

B.4.2.2 Corollary Test Data

Extensive studies on various Pioneer heat sources were performed by LASL, in coordination with MRC-Mound Laboratory. The permutations of the tests included time intervals ranging from 40 to 370 days; fuel/liner temperatures from 450°C to 955°C ; situations involving generator test operations or merely a heat-soak program; and designs incorporating a supplementary molybdenum - 46% rhenium inner liner in certain instances. Trends in the data show progressively increasing levels of oxygen in both the Ta-10W liner and the T-111 strength member; however, the oxidation effect on the strength member was only about 22 percent of that in the liner. The interposed inner Mo-Re liner appeared to reduce the overall degradation due to oxygen by a factor of 50 to 60. As anticipated, the liner oxidation was entirely due to oxygen from the fuel, whereas that in the strength member appeared to include a limited effect from adventitious atmospheric oxygen. The latter may be attributable to slightly contaminated assembly cell atmospheres, to incomplete outgassing of insulating materials, or to adsorbed oxygen on other heat source components. Minor quantities of carbon monoxide also may play a role in the oxygen transfer process.

The data trends derived from the Pioneer testing activities suggest catastrophic degradation of the Transit TRIAD capsule liner after extended operational lifetime, particularly after 150 years of contact, albeit at decreasing temperatures.

In laboratory tests designed by LASL to elicit the response of the T-111 strength member alloy (tantalum-8 tungsten, 2 hafnium) to an oxidizing environment simulating the reentry situation, samples were superficially oxidized respectively at 600-700°C, and 1650°C, followed by a 50-hour vacuum anneal at 1316°C to homogenize oxygen penetration through the plate. Thereafter, impact tests were performed, using a Magnaform machine to drive a hemispherically tipped punch into plates of unoxidized and oxidized alloy, respectively. These plates were resistively heated to 1316°C in an argon atmosphere, and punch velocity was approximately 10.4 meters per second. This represented the minimum energy to rupture unoxidized T-111 plates and was used throughout the tests. The application of fractographic analysis indicated that the oxygen content required for the change from ductile to brittle behavior at 1316°C was about 2000 parts per million (ppm). Deposition of HfO_2 precipitates at grain boundaries appears to contribute to grain boundary failure; in addition, increasing strain-rate influences the transition from ductile to brittle fracture.

Metallographic studies on specimens, treated to achieve oxygen contamination from 1000 to 6000 ppm at 1400°C and subsequently annealed to homogenize oxygen penetration, showed uniform microstructure only for the higher levels of oxygen content. Tensile specimens were prepared in like manner, to obtain various oxygen contamination levels from 0 to 6000 ppm. Property measurements, made at 1205°C, showed that ultimate tensile strength and yield strength are relatively unaffected by oxygen levels up to 6000 ppm. However, elongation declines significantly at levels above 2400 ppm. There is evidence that the hafnium content of the T-111 alloy exerts a gettering effect on oxygen, attaining a maximum at about 3600 ppm, and causing precipitation of a stable hafnium oxide in the grain boundaries.

Predictions of Pioneer capsule lifetimes by LASL staff established a rationale by which oxygen was required to diffuse through the Ta-10W liner, and, in certain instances, the Mo-Re barrier layer as well, in order to reach the T-111 strength member and to effect its oxidation to the degree noted in ground-test units of the Pioneer type of radioisotope heat sources.

In these tests, the T-111 alloy strength member showed evidence of a hardened skin after only 40 days exposure to generator environment. After 370 days, oxygen pickup amounted to 60 to 170 ppm, a level construed as no detectable degradation. Extrapolation of these data suggested a lifetime of as much as 800 days (19,200 hours or 6.9×10^7 seconds). However, both units referenced above contained the Mo-46 Re inner liner that effectively delayed oxidation of the strength member. Pioneer units under test, without benefit of this liner, showed an oxygen pickup of 400 to 1900 ppm, after 175 to 219 days, respectively, at nominal operating conditions; room-temperature testing showed brittleness and no bend capability. It is postulated therefore, that intact reentry capability will be seriously degraded as a consequence of continuing oxidation effects progressing from date of assembly through at least the first 63 years of operation, when capsule temperatures would have been in excess of about 570°C.

B.4.3 Phase Changes or Other Thermal Effects

Plutonium oxide, PuO_2 , as charged to the heat source assembly, is considered to be stoichiometric, with the fluorite cubic structure and a crystal density of 11.46 grams per cm^3 . Exposure to high temperatures and loss of oxygen by interaction with tantalum, for example, or by evaporation, tend to induce substoichiometry, leading toward a cubic sesquioxide, Pu_2O_3 , with a crystal density of 11.04 grams per cm^3 . As this change takes place, there may occur a proportionate amount of swelling due to the specific volume difference between the two oxides: PuO_2 ($1/11.46 = 0.0873 \text{ cm}^3$ per gram) and Pu_2O_3 ($1/11.04 = 0.0906 \text{ cm}^3$ per gram) or a 3.6 percent volume expansion. In addition, the thermal expansivity difference between PuO_2 (8.06×10^{-6} per °C)* and molybdenum (5.1×10^{-6} per °C)* generates stresses which lead to cracking and/or fragmentation. Radial cracking in PMC fuel has been noted in instances where disassembly after relatively short storage periods was necessary. In fact, a careful selection process has been necessary when rebuilding heat source assemblies, in order to assure reasonable integrity during mission lifetime.

As the plutonium oxide fuel suffers decay through alpha-emission, the uranium oxide content increases. The stoichiometry of this oxide probably will be con-

sistent with that of its plutonium oxide predecessor. Uranium oxide can exist in a number of compositions. The conventional UO_2 , cubic, with a density of 10.96 grams per cm^3 , or U_3O_8 , orthorhombic, with a density of 8.38 grams per cm^3 . In either case, the specific volumes are greater than their plutonium equivalents: UO_2 ($1/10.96 = 0.0912 \text{ cm}^3$ per gram), and U_3O_8 ($1/8.38 = 0.119 \text{ cm}^3$ per gram), with similar implications for expansion or swelling. Crystallographically, the Pu and U oxides are in solid solution with each other; their atomic radii differ only slightly: Pu^{4+} , 1.70 angstrom units; U^{4+} , 1.74 angstrom units. There appears to be little likelihood of formation of the U_4O_9 compound that contains excess oxygen.

B.4.4 Pressure Effects due to Gaseous Decay Products

The Transit TRIAD heat source capsule is provided with a pressure-relief device in the liner, permitting helium flow to the extent of $1 \times 10^{-4} \text{ cm}^3$ per second at a pressure differential of 1×10^{-2} atmosphere. The strength member is provided with two 0.05 to 0.10 mm holes drilled into the hemispherical end. The clad of a flight capsule has a 0.10 mm hole, again in the hemispherical end, in order to permit helium egress into the heat shield region. The porosity and spacing of the heat shield members permit a desired dissipation of the gas phase throughout the heat shield into the Inconel can, which, in turn is provided with a 0.10 mm capillary tube gas exit. "This tubing has sufficient resistance to helium flow to provide a helium backpressure of 0.1 atmosphere within the can for 100 percent helium released from the fuel."

Based on the curves presented in Figure B-6, the helium inventory levels out at 10^{11} seconds, or about 3,165 years, well beyond the nominal orbital life time of the TRIAD. Helium inventory at 150 years (4.73×10^9 seconds) is approximately 5 moles, with augmenting radon a negligible contribution at 4.5×10^{-12} moles. Temperature at the 150 year point has been estimated as 310°C , or 583°K . Assuming that the void volume of 23.8 cm^3 , derived from calculations of the

* Values for the 0- 100°C interval only; coefficients increase with temperature.

volume of the liner, less the volume (weight/density) of the fuel, is a reasonably accurate equivalent of the helium gas reservoir, a pressure level of 9823 atmospheres might result if the gas management system were closed off from the date of assembly. This pressure level, of course, would not be tolerable by a deteriorated liner, an embrittled strength member, nominal graphite shield elements, or a thin Inconel can. However, the seal plug in the pressure relief device in the liner is punctured before further assembly of the capsule, in accordance with design requirements, thus precluding pressure buildup of this magnitude, unless the PRD and gas management system are impeded by other means.

B.4.5 Interaction of Containment Materials

Dimensional interactions between the liner, strength member, clad, thermal barrier, and outer can of the heat source assembly have been adequately accommodated for nominal operating temperatures.

In the event of swelling of the molybdenum-bonded plutonium oxide fuel to an extent exceeding 1.5 percent, volumetrically, the Ta-10W liner would be susceptible to hoop stresses causing local contact between the liner and strength member. Solid state diffusion could occur slowly over time, to yield local bonding with the neighboring similar alloy. Data from the Pioneer heat source studies showed fuel swelling to the extent of 0.6% after 219 days of operation at nominal temperatures. A linear projection with time as the variable suggests that contact and bonding might begin after 400 or more days. Disbonding, as a consequence of shrinkage as operating temperature declines, might not occur until the nominal 150 year orbital lifetime had been completed.

Interactions between molybdenum and components of the capsule liner, and/or strength member, also are possible, since molybdenum and tantalum or tungsten are reported to form solid solutions, and intentional alloying of molybdenum with tungsten, titanium, zirconium, or hafnium has been accomplished. Thus, over time, solid-state diffusion between molybdenum and the Ta-10W alloy is anticipated, with the consequence of bonding in those areas of intimate contact. Self-diffusion between PMC liner also is expected. These effects have not been

quantified; however, it has been noted during disassembly of spare Viking generators, also employing this fuel form, that the fuel assembly was essentially monolithic. Brief exposure to a cell atmosphere of argon containing a minor amount of oxygen, however, led to rapid disintegration of the capsule liner and exposure of the PMC fuel assembly, which then could be separated more readily.

In the event that unanticipated swelling, contact, and solid state diffusion were to occur between the strength member and the platinum-20 rhodium cladding, relatively little effect would be noted. The substantial disparity in atomic radii (Ta, 3.30 Angstrom units and W, 3.16 Angstrom units, versus Pt, 3.92 Angstrom units and Rh, 3.80 Angstrom units) precludes more than limited mutual solid solubility.

B.4.6 Radiation Damage-Internal

The technique of line-broadening assessment, as related to the x-ray diffraction pattern of plutonium oxide, has been utilized by LASL in a study entitled, "The Effects of Self-Irradiation on the Lattice of $^{238}(80\%)\text{PuO}_2$." The mechanism of alteration appeared to be one of retained strain, in the amount of approximately 0.2 percent, during a 2-year period. Little crystalline size change was noted during that interval. However, the continued self-irradiation occurring during the remaining 148 years of the orbital lifetime of Transit TRIAD, to be specific, undoubtedly would develop not only a greater degree of strain, but also a significant level of particle and crystallite disintegration.

Micro-structural photographs of PMC fuel disks, maintained at the test temperature of 900°C show definite pockets where helium has gathered within the fuel particle. During the continuing process of helium evolution and release, local rupture of areas in the fuel particle will occur, leading to fragmentation and development of fines. This tendency is corroborated by the observation that during pretest heatup, and during each heatup subsequent to a test interruption, a typical PMC fuel "puck" showed a short period of high helium release rate, followed by a reduction to a low level, and then a gradual return to the normal helium generation rate. Detailed studies of the development of helium bubbles

within high-density fuel particles have shown that such bubbles characteristically gather in stringers along grain boundaries, thereby producing volume increases of about 10 percent with consequent deterioration of the mechanical properties of the oxide fuel at high temperatures. Damage in dense pellets becomes evident after about 6 months of aging and increases thereafter.

The 150-year orbital lifetime represents about 1.75 half-lives of the Pu-238 isotope fuel. The calculated 5 moles of helium produced in this period is essentially equivalent to 3.1×10^{24} alpha particles impinging upon the fuel and capsule surfaces in the vicinity of the total PMC heat source. At an estimated thickness of 0.05 mm, the molybdenum particle overcoat represents about 904 cm² of area for impingement of alpha particles. Correspondingly, the interior surface of the Ta-10W capsule liner provides about 234 cm² of surface area subject to radiation effects. Simplistically, the liner surface may be irradiated by alpha particles derived only from the exposed fuel particles at the surface of the radioisotope heat source, or approximately 17.5 percent of the total alpha fluence. The gross dose per unit of area amounts to $(3.1 \times 10^{24} \times 0.175 / 234 \text{ cm}^2)$, or approximately 2.3×10^{21} impacts per cm². The calculated dose to the thin film of molybdenum bonding the fuel particles would correspondingly approximate $(3.1 \times 10^{24} \times 0.825 / 904 \text{ cm}^2)$, or 2.8×10^{21} impacts per cm². Each of these fluence levels must be spread over the 4.73×10^9 seconds of lifetime, to yield an average dose of 0.5×10^{12} alphas per cm²-second to the liner, and 0.6×10^{12} alphas per cm²-second to the bonding molybdenum. The very limited damage that might be anticipated from this low dose rate is normally annealed out by the thermal agitation of the host lattice even at the slowly declining operating temperature.

The neutron emission of plutonium oxide fuel material includes that due to spontaneous fission, as well as that due to (α,n) reactions with oxygen -17 and -18, or other low atomic weight contaminants. To attain minimal external radiation dose levels for the heat source assembly, the fuel oxide is exchanged at 700-1000°C with oxygen-16, thereby reducing the total neutron emission rate to 3×10^4 neutrons per gram of Pu per second, over the 150 year orbital lifetime. The net amount of Pu-238 and associated Pu isotopes declines only slightly, from

2.80×10^4 to 2.45×10^4 curies. At a nominal specific power of 10 ± 1.0 curies per gram, approximately 24,500 grams represent the average radioisotope inventory, delivers a total neutron fluence of about 3.5×10^{18} . Distributed over the contiguous molybdenum bonding material and the tantalum alloy capsule liner, the prorated neutron dose rate could approach only 6.5×10^5 per cm^2 per second. At this level, no detectable damage would be expected, since concurrent annealing at operating temperatures would tend to remove substantially all defects introduced by the irradiation.

B.4.7 Space Irradiation

The effect of solar irradiation already has been recognized and accommodated in the design and operation of the thermoelectric converter. The in-orbit temperature profile shows temperatures of -13°C at the center of the upper cover assembly (representing a 5°C rise from the situation without earth or solar radiation), and 145°C at the center of a typical thermoelectric panel (representing a 9°C rise from the calculated no-radiation level). The effect on the radioisotope heat source, radiating its thermal energy to the thermoelectric elements, and progressively diminishing over time, is not expected to be significant.

At a nominal altitude of 800 kilometers, the particle density is estimated at 3×10^6 per cm^3 , of which about 2×10^5 are ions, including oxygen, nitrogen, and hydrogen, with the former predominating. The Transit TRIAD orbits near the inner Van Allen radiation belt surrounding the earth. During each orbiting period of 100.6 minutes, the satellite traverses approximately 45,000 kilometers. The heat source itself would not be subject to ambient irradiation during this trajectory, since it is protected by the mag-thorium cover structure assembly and by the thermoelectric panels provided with SiO_2 -coated radiative mirrors. The respective surface areas (cover, 2675 cm^2 and thermoelectric panel radiators, 6600 cm^2) could be contacted by up to 12×10^{12} and 30×10^{12} ions, etc., respectively. During its orbital lifetime, 785,000 orbits will have been accomplished. The total ion impingement over this extended interval would approximate 9.4×10^{21} and 2.4×10^{22} , respectively.

At a sputtering efficiency of less than 10^{-10} for atoms sputtered off by nitrogen or oxygen ions, the net material loss would only approximate 0.2 Angstrom unit, in either instance. This might slightly affect the silica coating on the radiative mirrors, but otherwise would be negligible.

B.4.8 Evaporation or Sublimation

In Section B.4.2, oxidation of the tantalum alloy capsule liner was discussed at length. Reference was made, as well, to the potential oxidation of the molybdenum bonding material at temperatures above 500°C , and the possible volatilization of its oxide, MoO_3 , at temperatures above 650°C . Temperature distribution within the TRIAD fuel capsule is such that molybdenum oxide, formed either during the preassembly stages of puck hot-pressing or machining, or during the operation of the generator, might be released from the fueled volume at a maximum temperature of approximately 950°C , to be transported in the vapor state to and through the pressure relief device, nominally at 750°C . Temperatures under 650°C would be typical of the graphitic thermal barrier, or gaps between the Pt-20 Rh cladding and the graphite barrier. Should the temperature of the PRD region be maintained at this level, the combined helium-radon- MoO_3 vapor stream would persist, since the vapor pressure of MoO_3 at 950°C approximates 100 torr, a significant driving force.

Should the PRD temperature drop below 650°C , however, plugging of the alumina filter by MoO_3 could readily occur, and eventually pressure buildup in the capsule would result. It has been estimated that such plugging could occur after an elapsed time of 40 years in orbit. Furthermore, an analysis by Fairchild Space and Electronics Co. indicates that the TRIAD capsule will rupture if the vent plugs completely at any time up to 5 years before reentry. This eventuality must be taken into consideration in any plan for retrieval of this satellite and/or its heat source.

Volatilization or sublimation of plutonium oxide species is a problem of substantially lesser magnitude. At fuel temperatures on the order of $900\text{--}950^{\circ}\text{C}$, the vapor pressure of the combined PuO_2/PuO oxides is approximately 10^{-16}

atmosphere. At this pressure, an orifice typical of those in the Transit TRIAD strength member and cladding would remain open for an estimated 4 million years. However, experience with numerous vent tests on Multi-Hundred Watt fueled sphere assemblies indicates that vent plugging is frequent, varying with the atmosphere in the test furnace. The temperature of the MHW fuel approximates 1325°C; at this temperature, the vapor pressure of the mixed plutonium oxide species attains 10^{-11} to 10^{-10} atmosphere. Material sufficient to plug a typical vent might be deposited in 3 to 5 years, according to typical calculations and trends. However, test profiles typically have shown vents closing and reopening, with time intervals of weeks or months in each state. Therefore, it becomes necessary to assume augmenting mechanisms of material transport, such as contribution of helium, oxygen, or other oxide vapor species from the fuel or capsule liner to the total vapor pressure. It becomes practical to assume that vent closure or filter plugging may not be permanent: temperature cycling or thickness buildup in the plugging deposit may produce strains to rupture the offending quasi-ceramic material; reduction in operating temperature with time may ultimately permit shrinking sufficient to generate a new path adequate to passage of helium, unimpeded from that time forward.

At an altitude of 800 kilometers, the ambient pressure is approximately 10^{-9} torr. It is instructive to evaluate the stability of various components of the heat source and converter assembly in vacuo, at their respective nominal operating temperatures. Tabulated below are the temperatures reported to be equivalent to a saturation vapor pressure of 10^{-8} torr; operating temperatures are contrasted:

<u>Component</u>	<u>Metal</u>	<u>Saturation Vapor Temperature, °C at 10⁻⁸ torr</u>	<u>Operating Temp. °C</u>
Converter Cases	Mg	189	-13
	Th	1347	
Foil Insulation	AP	677	399
Thermoelement	Pb	344	398-158
	Te	178	

Strap, Mirror	Ag	79	160
Hot Cap	Ni	912	399
Cold Cap	Fe	877	138
Cage Assembly	Ti	1057	449

From the tabulation above, it is evident that only in the case of the thermoelectric elements is there a significant probability of loss by vaporization. This effect had been anticipated in design documents and was verified by laboratory testing. A power output degradation of 23-25 percent was expected for a 5-year mission. The lead and tellurium volatilized from the thermoelements may be deposited in cooler portions of the converter, for example, in the aluminum foil insulation. No significant effect on heat source performance is anticipated.

Magnesium, the material appearing to be potentially susceptible to evaporation in space, is reported to lose less than 10^{-3} cm per year, unless its temperature reaches 444°K; this amount is tolerable for short-term missions, but may not be acceptable for assured integrity of the Transit TRIAD mission. The lowest temperature reported for vapor-pressure data on magnesium is 298°K; at this temperature the vapor-pressure is 2.5×10^{-20} torr. An approximate weight-loss rate calculated on this basis is 1.7×10^{-22} gm per cm^2 per second. For an assumed orbital lifetime of 4.74×10^9 seconds, this loss could amount to 7.9×10^{-13} gm per cm^2 , a negligible quantity from the operational or recovery standpoint.

B.4.9 Meteoroid Damage

The introductory discussion and meteoroid mass flux model introduced in Subsection A.4.8 may be re-applied in this subsection without further development. During the 150 years of orbital lifetime, the Transit TRIAD satellite will have accomplished approximately 785,000 passages through the nominal meteoroid flux, as previously stated:

<u>Mass of Meteoroid</u> (gram)	<u>Flux</u> (Particles per m ² per second)
1.0	3.89x10 ⁻¹⁵
10 ⁻⁶	8.17x10 ⁻⁸
4.46x10 ⁻⁹	2.36x10 ⁻⁶
5.0x10 ⁻¹¹	1.52x10 ⁻⁵

The radioisotope heat source will not have been exposed to direct impact, since the converter assembly acts as a shield and absorbs the impacts and their consequences. The prominently exposed converter area amounts to approximately 9275 cm²; for convenience, one can assume an area of 1 square meter. During the full orbital lifetime of 4.74x10⁹ seconds, the respective probable impacts are estimated, as shown below. The depth and radii of craters developed by the respective meteoroids are proportional to the cube root of the impact momentum; for these estimates, a velocity of 20 kilometers per second was assumed.

<u>Meteoroid Mass, g</u>	<u>Probable Impacts</u>	<u>Crater Depth and Radius</u>
1.0	1.8x10 ⁻⁵	2.7 cm
10 ⁻⁶	3.9x10 ²	2.7x10 ⁻² cm
4.46x10 ⁻⁹	1.4x10 ⁴	4.5x10 ⁻³ cm
4.0x10 ⁻⁴	7.2x10 ⁴	1.0x10 ⁻³ cm

Thus, apart from the low-probability impact of a 1-gram meteoroid, the nominal experience of the TRIAD assembly could be equivalent to a mild burnishing action, largely by particles in the range yielding craters 10 to 45 micrometers in diameter and depth. The impact significance of intermediate meteoroid masses has not been assessed, but should be anticipated. The impact significance of any meteoroid impact upon the heat source assembly would be mitigated by the spatial relationship of the heat source to the overall converter assembly, as well as by the energy loss during penetration of the adjacent components of the converter assembly. Such mechanisms may reduce the probability of significant impact in the heat source to approximately 2x10⁻⁷.

B.4.10 Cumulative Effects

The anticipated degradation mechanisms described above may be appraised conveniently by reference to the following table. Estimated milestones and their significance to various components of the TRIAD assembly are indicated.

<u>Milestone</u>	<u>Component</u>	<u>Effects</u>
120 Hours (4×10^5 seconds)	Ta-10W liner	(Very low probability) Gas phase oxidation: complete penetration
2575 Hours (9.3×10^6 seconds)	Ta-10W liner	Compatibility tests: surface dulled by contact with fuel; hardness increased 6%; oxygen pickup 85 ppm
200 days (1.7×10^7 seconds)	PMC Fuel	Swelling, cracking
	T-111	Embrittlement
400 days (3.4×10^7 seconds)	PMC Fuel	Self-bonding
500 days (4.3×10^7 seconds)	T-111 Strength Member	Significant embrittlement
2 years (6.3×10^7 seconds)	PuO ₂ in fuel	Crystallite strain 0.2%, fuel particle size reduction indicated, progressive with time
5 years (1.6×10^8 seconds)	Thermoelectric element	Based on TRW performance tests: 23 to 25% degradation expected
40 years (1.2×10^9 seconds)	Gas managment system	Plugging by MoO ₃ and other volatile oxides anticipated; periodic rupture and release also anticipated. • Catastrophic internal pressure development, if plug not ruptured prior to 40 years orbital life.
63 years (2×10^9 seconds)	Strength member	Degradation: excessive oxygen penetration
150 years (4.7×10^9 seconds)	Converter assembly	2×10^{-5} probability of penetration by 1-gram meteoroid, with possible limited damage to radioisotope heat source (2×10^{-7}).

Based on the estimates tabulated above, retrieval should be timed and engineered

to recognize the probability of a heat source condition significantly more pessimistic than those entertained as of the launch date or possibly during current mission performance.

B.5 REENTRY SOURCE TERMS

Reentry radioactive source terms have been calculated for Transit Triad for the following release scenarios:

- o High altitude burnup (vapor)
- o High altitude burnup (particulate release over land)
- o High altitude burnup (particulate release over ocean)
- o Land impact
- o Ocean impact.

The analysis assumes that reentry and associated release modes occur at the end of predicted orbit life (150 years). The release mode probability and associated source term (fraction of fuel released) were estimated based on the information on material aging effects developed in Chapter 4. The expected source terms were then calculated as the product of release mode probability and source term, all of which are summarized in Table B-3.

TABLE B-3

REENTRY RELEASE MODE PROBABILITIES AND SOURCE TERMS
FOR TRANSIT TRIAD (RTG)

<u>Release Mode</u>	<u>Release Probability</u>	<u>Source Term (% Inventory Released)</u>	<u>Source Term (Curies)</u>	<u>Expected Source Term (Curies)</u>
High Altitude Burnup (Vapor)	-	-	-	-
High Altitude Burnup (Particulate Release Over Land)	-	-	-	-
High Altitude Burnup (Particulate Release Over Ocean)	-	-	-	-
Land Impact	0.34	1%	7.80E+01	2.65E+01
Ocean Impact	0.66	100%	7.80E+03	<u>5.15E+03</u>
			Total	5.18E+03

B.6 REFERENCES

1. TRW Systems Group, Transit RTG Final Safety Analysis Report, TRW(A)-11464-0491 (March 1, 1971).
2. TRW Systems Group, Transit RTG Operations Manual, TRW(A)-11464-6017-T0-00 (April 1971).
3. TRW Systems Group, Transit RTG Final Safety Analysis Report, Addendum No. 3 (May 1971).
4. Weiner Associates, Inc., Transit Capsule Embrittlement, WAI-TM-71.19/C0019 (September 1971).
5. Los Alamos Scientific Laboratory, The Effects of Self-Irradiation on the Lattice of $^{238}\text{PuO}_2$, LA-4742 (October 1971).
6. Mulford, R.N.R., Degradation of Pioneer - Type Tantalum Alloy - PuO_2 Heat Sources, Los Alamos Scientific Laboratory, LA-5932 (July 1975).
7. Los Alamos Scientific Laboratory, Data Sheets for PMC Radioisotopic Fuel, LA-4976-MS.
8. See also References 8 to 14, Section A.6.

APPENDIX C

TRANSIT 5BN1/5BN2 (SNAP-9A)

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C.1 REFERENCE DESIGN INFORMATION

C.1.1 Mission

Transit 5BN1 and 5BN2 shown in Figure C-1 are each powered by a SNAP-9A plutonium-fueled RTG and were designed to provide all-weather navigational aids for ships and aircraft. The two satellites were launched from Vandenberg AFB on September 28, 1963 and December 5, 1963, respectively, by the 2-stage Thor-Ablestar Rocket Booster System and successfully placed in earth orbit. A summary of the orbital parameters and SNAP-9A system design features is presented in Table C-1 and discussed further below.

C.1.2 Nuclear Power System

The SNAP-9A RTG, shown in Figure C-2, is fueled with metallic plutonium containing 75% Pu-238 and had an initial power level of 525 thermal watts.

The main body of the generator is cylindrical, 22.86 cm in diameter and 21.27 cm in height. As shown in Figure C-2, six magnesium fins extend longitudinally from the surface of the outer magnesium housing. The fins are used to dissipate heat from the housing, which serves as a cold junction for the thermoelectric elements. A heat source, consisting of six fuel capsules mounted in a segmented graphite heat accumulator block, is centrally located in the generator. The heat block constitutes the hot junction for the 70 pairs of lead telluride thermoelectric elements. These elements convert the heat energy into usable electrical power. Molded Min-K insulation separates the heat accumulator block and outer magnesium housing, constraining heat to flow through the thermoelectrics, while also providing support for the graphite fuel block. In addition, discs of high density Min-K insulation are utilized at the top and bottom of the fuel block to minimize heat losses through these end cap areas and to provide a supporting structure for the fuel capsules. The peripheral molded Min-K is longitudinally segmented into two sections to assure removal during reentry. The entire RTG was designed for reentry burnup.

Figure C-1 Satellite 5BN (Typical), Exploded View

TABLE C-1

TRANSIT 5BN1/5BN2 (SNAP 9A) DATA SUMMARY

1.	<u>Missions</u>	Transit 5BN1	Transit 5BN2
2.	<u>Launch Dates</u>	9/28/63	12/5/63
3.	<u>Orbital Parameters</u>		
	o Period, minutes	107.3	107.0
	o Inclination, degrees	89.8	89.8
	o Apogee, km	1135	1119
	o Perigee, km	1072	1067
	o Orbital lifetime, years	1900	1800
4.	<u>System Description</u>		
	o Type	- SNAP 9A RTG	
	o Fuel	- Metallic Pu in delta phase (assumed to be 75% Pu-238 and 25% Pu-239). Fuel contained in six capsules with each capsule containing a half-cylinder fuel slug with a volume of 12.82 cm ³ and a void volume of 19.17 cm ³ . Fuel mass is 1284 g.	
	o Power	- 525 thermal watts	
	o Activity	- 17,000 Ci Pu-238 at launch	
	o Containment	- Each capsule consisted of a tantalum liner with an outer Haynes 25 strength member.	
	o Aeroshell	- None. Designed for reentry burnup. Fuel capsule contained within graphite fuel block and magnesium outer housing.	
	o He Venting	- No He venting. Each capsule designed to withstand He buildup within the void volume. Maximum internal He pressure estimated in SAR to be 14,400 psi 171 years after launch.

Figure C-2 **SNAP 9A Generator**

Each fuel capsule contains 214.1 grams of plutonium metal. The fuel is encapsulated in a 0.05 cm thick tantalum liner which, in turn, is housed in the Haynes-25 capsule shell as shown in Figure C-3. The tantalum liner prevents the plutonium fuel from alloying with, and penetrating, the capsule shell material. The Haynes-25 shell has a minimum wall thickness of 0.25 cm. The overall capsule length is 14.55 cm, and its outer diameter is 2.49 cm. The fuel, in the form of a half cylinder, occupies the entire length of the capsule and has a volume of approximately 12.78 cm³. This shape prevents longitudinal motion of the fuel within the capsule during the launch phase of missile operation, while providing in the capsule sufficient void volume (about 19.17 cm³) for the accumulation of helium gas.

C.1.3 Fuel

The SNAP-9A RTG is fueled with 1284 g of metallic plutonium in the delta phase, composed of approximately 75% Pu-238 and 25% Pu-239. More detailed information on the properties of the fuel are presented in Appendix H.

Figure C-3 SNAP 9A Fuel Capsule

C.2 RADIOISOTOPIC INVENTORY VERSUS TIME

The radioisotopic inventory versus time for the SNAP-9A RTG has been calculated using the methods described in Chapter 4 of the main text. The calculations assumed an initial radioisotopic fuel mix consisting of 75% Pu-238 and 25% Pu-239 in the metallic form and other fuel properties described in Appendix H.

The results are summarized in Table C-2 and Figure C-4 that present the curie activity of the principal parent and daughter radioisotopes as a function of time after fresh fuel loading.

In addition, the inventories of helium and radon gas were calculated and the results presented in Figure C-5 as a function of time.

TABLE C-2

TRANSIT 5BN1/5BN2 (SNAP 9A) RADIOISOTOPIC
INVENTORY VERSUS TIME (EACH SPACECRAFT)

Radioactivity Inventory (Curies) at Indicated Time (Sec)						
Radionuclide	Initial	10 ⁸	10 ⁹	10 ¹⁰	10 ¹¹	10 ¹²
Tl-207	-	6.80E-14	5.49E-11	2.04E-08	1.95E-06	1.24E-04
Pb-210	-	2.30E-11	1.85E-07	5.21E-04	6.81E-02	1.33
Pb-211	-	6.81E-14	5.51E-11	2.04E-08	1.95E-06	1.24E-04
Pb-214	-	9.03E-10	8.51E-07	5.21E-04	6.81E-02	1.33
Bi-210	-	2.30E-11	1.85E-07	5.21E-04	6.81E-02	1.33
Bi-211	-	6.81E-14	5.51E-11	2.04E-08	1.95E-06	1.24E-04
Bi-214	-	9.03E-10	8.51E-07	5.21E-04	6.81E-02	1.33
Po-210	-	1.29E-11	1.85E-07	5.21E-04	6.81E-02	1.33
Po-214	-	9.03E-10	8.51E-07	5.21E-04	6.81E-02	1.33
Po-215	-	6.81E-14	5.51E-11	2.04E-08	1.95E-06	1.24E-04
Po-218	-	9.03E-10	8.51E-07	5.21E-04	6.81E-02	1.33
Rn-219	-	6.81E-14	5.51E-11	2.04E-08	1.95E-06	1.24E-04
Rn-222	-	9.03E-10	8.51E-07	5.21E-04	6.81E-02	1.33
Ra-223	-	6.81E-14	5.51E-11	2.04E-08	1.95E-06	1.24E-04
Ra-226	-	9.03E-10	8.51E-07	5.21E-04	6.81E-02	1.33
Ac-227	-	6.81E-14	5.51E-11	2.04E-08	1.95E-06	1.24E-04
Th-227	-	6.72E-14	5.44E-11	2.02E-08	1.93E-06	1.23E-04
Th-230	-	1.96E-06	1.83E-04	1.01E-02	1.53E-01	1.33
Th-231	-	6.08E-08	6.08E-07	6.06E-06	5.83E-05	4.02E-04
Pa-231	-	2.06E-12	2.06E-10	2.04E-08	1.95E-06	1.24E-04
U-234	-	1.43E-01	1.28	5.36	5.80	5.37
U-235	-	6.08E-08	6.08E-07	6.06E-06	5.83E-05	4.02E-04
Pu-238	1.63E+04	1.59E+04	1.27E+04	1.37E+03	3.12E-07	-
Pu-239	1.96E+01	1.96E+01	1.96E+01	1.95E+01	1.80E+01	8.00
Pu-240	-	-	-	-	-	-
Pu-241	-	-	-	-	-	-
Pu-242	-	-	-	-	-	-
Am-241	-	-	-	-	-	-
Subtotal	1.63E+04	1.59E+04	1.27E+04	1.40E+03	2.45E+01	2.68E+01
Actual Total	1.63E+04	1.59E+04	1.27E+04	1.40E+03	2.45E+01	2.68E+01

Figure C-4

Transit 5BN1/5BN2 (SNAP 9A) Radioisotopic
Inventory Versus Time (per Spacecraft)

Figure C-5 Transir 5RN1/5BN2 (SNAP 9A) Helium and Radon Gas Production Versus Time

C.3 EXTERNAL RADIATION FIELD VERSUS TIME

The external radiation field in the vicinity of a SNAP-9A RTG has been calculated based on the methods described in Chapter 5 of the main text. The results are presented in Figures C-6 and C-7. Figure C-6 presents the gamma and neutron dose rates in the axial and radial directions at a distance of 1m as a function of time. Figure C-7 presents the gamma and neutron dose rates in the axial and radial directions as a function of distance in a vacuum at a reference time of 10^8 sec (3.17 years) after fresh fuel loading.

Figure C-6 Transit 5BN1/5BN2 (SNAP 9A) External Dose Rates Versus Time at 1m Distance

Figure C-7

Transit 5BN1/5BN2 (SNAP 9A) External Dose Rates
Versus Distance at Time $t=10^8$ Sec

C.4 AGING OF MATERIALS

C.4.1 Introduction

The Transit 5BN satellites share several prominent similarities with the Transit 4 units. Both series were launched as navigational aids, orbiting the earth at similar altitudes. The respective radioisotope thermoelectric generators were fueled with metallic plutonium; both designs incorporated tantalum liners and Haynes-25 strength members, anticipating complete containment of helium over respective lifetimes extending to 143 years (Transit 4A,B) and 171 years (Transit-lifetimes 5BN1,2).

Generator power output was increased essentially by a factor of 10 in the 5BN units. Centerline fuel temperature rose from 510°C to 634°C. Generator design practice reflected these differing thermal conditions. Orbital lifetime for the 5BN units originally was estimated at 900 years in contrast to the 1800 to 1900 years currently listed.

C.4.2 Radioisotope Fuel: Containment Interactions

The discussion presented in Subsection A.4.1 applies with even greater emphasis in relation to the kinetics of degradation of the tantalum liner, since fuel centerline temperatures are higher in this instance. The estimated penetration rate at 634°C is 2.3 micrometers per day; at this rate, the nominal lifetime of the liner is approximately 222 days, barely adequate for the pre-launch storage period.

Retrograde melting of the plutonium metal could occur subsequent to penetration of the tantalum liner. Interaction with the Haynes-25 strength member, to the extent of less than 0.1 percent iron or cobalt taken into solution in the plutonium, could result in new phases with temperatures in the range of 400 to 415°C. As absorption of Fe or Co continues, and as fuel temperature declines, the rate of degradation should diminish. It is estimated that a penetration of 25 percent of the strength member during the earlier years of the mission

lifetime could occur, with continuing degradation at a progressively slower rate thereafter.

C.4.3 Phase Changes or Other Thermal Effects

Degradation effects analogous to those described in Subsection A.4.3 are anticipated.

C.4.4 Pressure Effects Due to Gaseous Decay Products

As a credible forecasting approach, let us assume that the strength member is degraded in proportion to the decay of the plutonium-238 fuel. Over its service lifetime, this component will essentially undergo a stress-rupture test, rendered unique by the conditions of declining temperature, due to isotope decay and increasing stress, due to helium pressure, occurring concomitantly.

Conventionally, stress-rupture data reported for Haynes-25 show the following values for a test at 815°C: stress to rupture at 10 hours was 30,000 psi; at 100 hours, 22,000 psi; and at 1000 hours, 18,000 psi. At 815°C, the modulus of elasticity is approximately 24×10^6 psi; for the temperature range of interest in the assessment of the strength member the modulus is estimated at 28×10^6 psi.

At 10^7 seconds (0.3 years or 2,778 hours) and 643°C, pressure is negligible. At 10^8 seconds (3.17 years or 27,782 hours), temperature is 632°C and pressure is less than 1,000 psi. However, at 10^9 seconds (31.7 years or 277,825 hours), temperature has declined to 499°C, but pressure has risen to 7,500 psi. Assuming that the effective modulus of elasticity of Haynes-25 declines from 28×10^6 psi to 22.8×10^6 psi as a consequence of exposure to Pu-238 metal decaying from a level of 1.6×10^4 curies to 1.3×10^4 curies, and further to 2.3×10^6 psi as a consequence of Pu-238 decay to 1.3×10^3 curies, during the advancement in age from 10^7 seconds to 10^9 seconds, one can postulate a critical weakness to internal pressure development. A linear trend of stress-to-rupture versus time in decade intervals suggests a value of 15,600 psi at 10^8 seconds, and 9,935 psi at 10^9 seconds, declining further to 770 psi at 10^{10} seconds. However, pressure

has already built up to 7,500 psi at 10^9 seconds; the declining trend in stress-to-rupture and the rising trend in pressure will cross at about 1.4×10^9 seconds (44.4 years or 289,000 hours), and failure would occur. The graphite heat transfer blocks and the thermal insulation surrounding the heat source afford little support or buttressing action against the rupture forces within. As a result, helium would leak into the heat transfer assembly, as well as into the insulation; both effects would tend toward a temperature rise in the converter. Chemical interactions could proceed as structural gaps open and access of the Pu-Ta-Co metal phases to the graphite components. At the current low temperatures, however, little further degradation would be expected.

C.4.5 Interactions of Containment Materials

Compatibility of the tantalum liner with the Haynes-25 strength member is irrelevant unless and until fuel volume changes or helium pressure buildup force these components with contact. Fuel incursion into the strength member and its possible effects have been postulated above. Heat transfer at points of contact would be more effective than in areas where an annulus remained, with the consequences of accelerated solid state diffusion at such points, possibly in the midsection of each half-cylindrical fuel capsule. At these contact points, development of porosity, thinned sections, and undetermined metal phases would tend to localize weaknesses and to promote selective rupture when pressures reach a critical value.

C.4.6 Radiation Damage - Internal

In general conformity with the discussion presented in Subsection A.4.6, radiation damage is expected to be insignificant, on a net effect basis.

C.4.7 Space Irradiation

Material degradation and loss are considered to be negligible, based on the assessment of space irradiation effects at similar altitudes, discussed in Subsection A.4.7.

C.4.8 Evaporation or Sublimation

The magnesium housing for the 5BN heat source assembly is the only structural component potentially susceptible to weight loss in space. However, its initial nominal skin temperature of 430°K is sufficiently low to preclude significant sublimation in space during mission duration and for many years thereafter. At 440°K, as stated in Subsection B.4.7, reported thickness loss is less than 10⁻³ cm per year. At the progressively declining temperatures to be relevant after the mission is completed, the rate and extent of evaporation of magnesium would be negligible.

C.4.9 Meteoroid Damage

Since altitude and inclination may be the prime determinants of potential meteoroid damage, one may anticipate that effects on the 5BN satellite should be similar to those described for the Transit 4A/B and Transit TRIAD systems.

C.4.10 Cumulative Effects

The anticipated degradation mechanisms described above may be evaluated by reference to the following table. Estimated milestones and their significance to various components of the Transit 5BN1 and 5BN2 RTGs are indicated.

<u>Milestone</u>	<u>Component</u>	<u>Effects</u>
222 days	Ta-Liner	Integranular attack by plutonium metal and complete intergranular penetration
222 + days	Haynes-25 Strength Member	25+% penetration of strength member by plutonium metal during early years with decreasing penetration afterwards
171 years	Fuel capsule	Capsule rupture due to helium pressure buildup

1,800 years
(Transit 5BN2)

RTG

Reentry burnup

1,900 years
(Transit 5BN1)

RTG

Reentry burnup

Radiation damage due to alpha particles and a modest neutron fluence is expected to have little net degradation effect. Effects of sputtering or other forms of space radiation also are expected to be negligible. Evaporation effects decline with age of the satellites, corresponding to declining temperature. Meteoroid effects are limited to the most exterior surfaces, and they, too, are considered to be negligible.

C.5 REENTRY SOURCE TERMS

Reentry radioactive source terms have been calculated for Transit 5BN1 and 5BN2 for the following release scenarios:

- o High altitude burnup (vapor)
- o High altitude burnup (particulate release over land)
- o High altitude burnup (particulate release over ocean)
- o Land impact
- o Ocean impact.

The analysis assumes that reentry and associated release modes occur at the end of predicted orbit life (1900 and 1800 years for Transit 5BN1 and 5BN2, respectively). The release mode probability and associated source term (fraction of fuel released) were estimated based on the information on material aging effects developed in Chapter 4. The expected source terms were then calculated as the product of release mode probability and source term, all of which are summarized in Tables C-3 and C-4 for Transit 5BN1 and 5BN2, respectively.

TABLE C-3

POSTULATED REENTRY RELEASE MODE PROBABILITIES AND SOURCE TERMS
FOR TRANSIT 5BN1 (SNAP-9A)

<u>Release Mode</u>	<u>Release Probability</u>	<u>Source Term (% Inventory Released)</u>	<u>Source Term (Curies)</u>	<u>Expected Source Term (Curies)</u>
High Altitude Burnup (Vapor)	1.0	100%	2.50E+01	2.50E+01
High Altitude Burnup (Particulate Release Over Land)	-	-	-	-
High Altitude Burnup (Particulate Release Over Ocean)	-	-	-	-
Land Impact	-	-	-	-
Ocean Impact	-	-	-	-
			Total	2.50E+01

TABLE C-4

POSTULATED REENTRY RELEASE MODE PROBABILITIES AND SOURCE TERMS
FOR TRANSIT 5BN2 (SNAP-9A)

<u>Release Mode</u>	<u>Release Probability</u>	<u>Source Term (% Inventory Released)</u>	<u>Source Term (Curies)</u>	<u>Expected Source Term (Curies)</u>
High Altitude Burnup (Vapor)	1.0	100%	2.48E+01	2.48E+01
High Altitude Burnup (Particulate Release Over Land)	-	-	-	-
High Altitude Burnup (Particulate Release Over Ocean)	-	-	-	-
Land Impact	-	-	-	-
Ocean Impact	-	-	-	-
			Total	2.48E+01

C.6 REFERENCES

1. Martin Marietta Nuclear Division, SNAP-9A Radioisotope-Fuel Generator, Final Safety Analysis for Transit Mission, MND-P-2775-2 (March 1963).
2. Sandia Laboratories, Material Interactions of the Operational SNAP-9A Generator, SC-RR-64-605.
3. Martin Marietta Nuclear Division, SNAP-9A Pu-238 Fueled Thermoelectric Power Supply for Auxiliary Space Power, Final Report, MND-P-3098-2.
4. See also References 8 to 14, Section A.6.

APPENDIX D

SNAPSHOT (SNAP-10A)

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D.1 REFERENCE DESIGN INFORMATION

D.1.1 Mission

The Snapshot spacecraft was designed as an experimental testing platform for the SNAP-10A reactor power system. Snapshot was launched on April 3, 1965 by an SLV-3 rocket with an S-01A upper stage. The S-01A with the SNAP-10A mounted forward, the combination comprising the spacecraft as shown in Figure D-1, was then separated from the SLV-3 and successfully placed in a circular polar orbit, and the SNAP-10A turned on. Although the SNAP-10A was designed to operate for a period of approximately three years in orbit, it prematurely shutdown after 43 days due to a malfunctioning control circuit. A summary of the orbital parameters and the SNAP-10A system design features is presented in Table D-1 and discussed further below.

D.1.2 Nuclear Power System

The SNAP-10A Power Unit shown in Figure D-2 consists of two principal components: (1) a compact ZrH-U^{235} fueled reactor core, reflected by beryllium metal, which serves as the heat source, and (2) a conical-shaped network of thermoelectric modules which produces the electrical output. The reactor is cooled by a sodium-potassium liquid-metal eutectic (NaK) which transfers the thermal energy produced as a result of the fissioning process to the thermoelectric power conversion system. The reactor power level is controlled through the use of movable sections of the beryllium neutron reflector which is placed concentrically around the reactor vessel. NaK coolant flow is provided by a thermoelectric pump mounted at the top of the reactor. A lithium hydride neutron shield is placed below the reactor within the power conversion array to reduce the radiation levels in the space utilized for electronic components. Diagnostic instrumentation is provided to permit ground evaluation of the performance of the power unit through the vehicle telemetry system. With a normal reactor power level of 34 thermal kilowatts, the electrical output is rated at a minimum of 500 watts for a design period of one year. The overall weight of the system is 440 kg and the overall

Figure D-1

S-01A/SNAP-10A Satellite Vehicle

TABLE D-1

SNAPSHOT (SNAP 10A) DATA SUMMARY

1.	<u>Mission</u>	Snapshot
2.	<u>Launch Date</u>	4/3/65
3.	<u>Orbital Parameters</u>	
	o Period, minutes	111.6
	o Inclination, degrees	90.0
	o Apogee, km	1313
	o Perigee, km	1282
	o Orbital lifetime, years	3000-4000
4.	<u>System Description</u>	
	o Type	- Fission reactor with NaK heat transfer loop to a thermo-electric conversion network
	o Fuel	- ZrH-U ²³⁵ fuel reflected by beryllium metal. Fuel contains 10.5% U enriched to 93% U-235 and 7% U-238. Fuel mass is 61 kg.
	o Power	- 34,000 thermal watts
	o Activity	- Initial fuel loading is 4.93 kg of highly enriched U
	o Containment	- Fuel is contained within 37 Hastelloy-N clad fuel elements. The core pressure vessel containing the fuel elements and NaK is composed of 316 SS.
	o Aeroshell	- None. Designed for reentry burnup.

Figure D-2 **SNAP-10A Reactor Power System**

dimensions are 1.32 m in diameter at the base, 0.41 m in diameter at the top, and approximately 3.43 m in length.

The SNAP-10A was designed to burn up on reentry into the earth's atmosphere following orbital decay.

D.1.3 Fuel

The SNAP-10A fuel is composed of uranium zirconium hydride (10% uranium) with the uranium being 93% enriched U-235. More detailed information on fuel properties are presented in Appendix H.

D.2 RADIOISOTOPIC INVENTORY VERSUS TIME

The radioisotopic inventory versus time for SNAP-10A has been evaluated using the methods described in Chapter 4 of the main text. The calculations assume initial fuel mix characteristics of ZrUH fuel summarized in Appendix H. Furthermore, the fact that SNAP-10A operated for only 43 days prior to shutdown has been accounted for.

The results for the fission products resulting from SNAP-10A operation are summarized in Table D-2 and Figure D-3 that present the curie activity of the principal fission radioisotopes as a function of time. Similar information is presented in Table D-3 and Figure D-3 for the actinide inventory.

TABLE D-2

SNAPSHOT (SNAP-10A) RADIOISOTOPIC INVENTORY VERSUS TIME
(FISSION PRODUCTS)

Radioactivity Inventory (Curies) at Indicated Time After Shutdown (Sec)						
Radionuclide	Initial	10^7	10^8	10^9	10^{10}	10^{11}
Kr-85	4.75	4.64	3.88	6.14E-01	6.29E-03	-
Sr-90	3.65E+01	3.62E+01	3.37E+01	1.67E+01	1.47E-02	-
Y-90	3.65E+01	3.62E+01	3.37E+01	1.67E+01	1.47E-02	-
Y-91	1.57E+03	4.02E+02	1.77E-03	-	-	-
Zr-93	1.21E-03	1.21E-03	1.21E-03	1.21E-03	1.21E-03	1.21E-03
Zr-95	1.78E+03	5.24E+02	8.55E-03	-	-	-
Nb-95	1.73E+03	9.11E+02	1.84E-02	-	-	-
Te-99	5.01E-03	5.07E-03	5.07E-03	5.07E-03	5.07E-03	5.01E-03
Ru-106	7.95E+01	6.40E+01	9.06	2.91E-08	-	-
Rh-106	7.95E+01	6.40E+01	9.06	2.91E-03	-	-
Cd-113M	7.02E-03	6.91E-03	6.03E-03	1.56E093	2.01E-09	-
Sn-119M	8.72E-02	6.28E-02	3.31E-03	5.52E-16	-	-
Sn-123	5.66	3.03	1.10E-02	-	-	-
Sb-125	4.70	4.39	2.12	1.53E-03	-	-
Te-125M	9.88E-01	5.18E-01	3.74E-04	-	-	-
Te-127	8.69E+01	6.11	8.12E-03	-	-	-
Te-127M	1.25E+01	6.23	8.29E-03	-	-	-
I-129	1.19E-05	1.23E-05	1.24E-05	1.24E-05	1.24E-05	1.24E-05
Cs-134	1.10E-01	9.93E-02	3.79E-02	2.58E-06	-	-
Cs-135	5.12E-04	5.15E-04	5.15E-04	5.15E-04	5.15E-04	5.15E-04
Cs-137	3.82E+01	3.79E+01	3.54E+01	1.84E+-1	2.59E-02	-
Ba-137M	3.62E+01	3.59E+01	3.37E+01	1.74E+01	2.45E-02	-
Ce-144	8.60E+02	6.48E+02	5.15E+01	4.81E-10	-	-
Pr-144	8.60E+02	6.48E+02	5.15E+01	4.98E-10	-	-
Pr-144M	1.03E+01	7.78	6.17E-01	5.97E12	-	-
Pm-147	1.44E+02	1.40E+02	6.57E+01	3.51E-02	-	-
Sm-151	8.83E-01	8.86E-01	8.66E-01	6.99E-01	8.32E-02	4.73E-11
Eu-155	2.13	2.03	1.35	2.16E-02	2.47E-20	-
Subtotal	7.38E+03	3.58E+03	3.32E+02	7.05E+01	1.70E-01	6.75E-03
Actual Total	1.67E+05	4.27E+03	3.34E+02	7.05E+01	1.72E-01	8.66E-03

TABLE D-3

SNAPSHOT (SNAP-10A) RADIOISOTOPIC INVENTORY VERSUS TIME
(ACTINIDES)

Radioactivity Inventory (Curies) at Indicated Time After Shutdown (Sec)						
Radionuclide	Initial	10^7	10^8	10^9	10^{10}	10^{11}
Tl-207	1.89E-09	2.79E-09	3.45E-08	1.64E-06	4.16E-05	4.05E-04
Pb-211	1.89E-09	2.80E-09	3.45E-08	1.64E-06	4.19E-05	4.05E-04
Bi-211	1.89E-09	2.80E-09	3.45E-08	1.64E-06	4.19E-05	4.05E-04
Bi-212	5.07E-09	9.82E-09	3.48E-08	3.91E-08	2.50E-09	3.42E-11
Po-211	5.69E-12	3.41E-12	1.04E-10	4.92E-0	1.26E-07	1.21E-06
Po-212	3.25E-09	6.28E-09	2.23E-08	2.49E-08	1.60E-09	2.19E-11
Po-215	1.89E-09	2.80E-09	3.45E-08	1.64E-06	4.1E-05	4.05E-04
Po-216	5.07E-09	3.82E-09	3.48E-08	3.90E-08	2.50E-09	3.42E-11
Rn-219	1.89E-09	2.80E-09	3.45E-08	1.64E-06	4.19E-05	4.05E-04
Rn-220	5.07E-09	9.82E-09	3.48E-08	3.90E-08	2.50E-09	3.42E-11
Ra-223	1.89E-09	3.28E-09	3.45E-08	1.64E-06	4.19E-05	4.05E-04
Ra-224	5.07E-09	9.82E-09	3.48E-08	3.91E-08	2.50E-09	3.42E-11
Ac-227	1.89E-09	3.37E-09	3.45E-08	1.64E-06	4.19E-05	4.05E-04
Th-227	1.87E-09	2.97E-09	3.40E-08	1.62E-06	4.13E-05	3.99E-04
Pa-231	1.25E-07	1.68E-07	5.46E-07	4.30E-06	4.19E-05	4.05E-04
U-233	2.01E-07	2.01E-07	2.01E-07	2.01E-07	2.04E-07	2.31E-07
U-234	4.19E-05	4.19E-05	4.19E-05	4.19E-05	4.22E-05	4.24E-05
U-235	6.20E-03	6.20E-03	6.20E-03	6.20E-03	6.20E-03	6.20E-03
U-237	1.32E+01	9.14E-05	6.14E-11	1.58E-11	2.09E-17	7.61E-29
U-238	9.79E-05	9.79E005	9.79E-05	9.79E-05	9.79E-05	9.79E-05
U-239	4.19E+02	-	-	-	-	-
Np-239	4.19E+02	6.28E-13	1.93E-16	1.93E-16	1.88E-16	1.45E-16
Pu0-236	7.19E-08	6.74E-08	3.37E-08	3.25E-11	-	-
Pu-238	3.42E-05	3.48E-05	3.40E-05	2.73E-05	2.97E-06	6.68E-16
Pu-239	1.12E-02	1.12E-02	1.12E-02	1.12E-02	1.12E-02	1.03E-02
Pu-240	2.20E-05	2.20E-05	2.19E-05	2.19E-05	2.13E-05	1.58E-05
Pu-241	2.97E-06	2.91E-06	2.55E-06	6.59E-07	8.69E-13	3.17E-29
Am-241	1.15E-09	2.64E-09	1.51E-08	7.64E-08	6.31E-08	6.57E-12
Subtotal	8.49E+02	1.77E-02	1.76E-02	1.76E-02	1.79E-02	2.03E-03
Actual Total	8.49E+02	2.44E-02	2.43E-02	2.43E-02	2.45E-02	2.69E-02

D.3 EXTERNAL RADIATION FIELD VERSUS TIME

The external radiation field in the vicinity of SNAP-10A has been calculated based on the methods described in Chapter 5 of the main text. Figure D-4 presents the gamma dose rates in the axial and radial direction at a distance of 1m as a function of time after shutdown. Figure D-5 presents the gamma dose rates in the axial and radial directions as a function of distance in a vacuum at a reference time of 10^8 sec (3.17 years) after shutdown.

Figure D-4. Snapshot (SNAP 10A) External Dose Rates Versus Time After Shutdown at 1m Distance

Figure D-5.
Snapshot (SNAP 10) External Dose Rates
Versus Distance at Time $t = 10^8$ Sec

D.4 AGING OF MATERIALS

D.4.1 Introduction

Details of the safety analysis originally developed for the SNAP-10A reactor power system are contained in classified reports and, hence, are beyond the scope of this discussion. However, many of the operating parameters have been published; selected values of interest are indicated below:

SNAP-10A Reactor System Parameters

Core Volume (m^3)	8.5×10^{-3}
Power Density (w/cm^3)	3.5
Fuel-Moderator	UZrH _x
Hydrogen atoms per cm^3	6.5×10^{22}
Maximum Temperature	566°C
Heat Flux ($\text{Btu}/\text{hr}\text{-ft}^2$)	10,200
Neutron Flux ($\text{n}/\text{cm}^2\text{-sec}$)	1.8×10^{11}
Reactor Coolant	NaK-78
Temperature out/in	532/474°C
Radiator Temperature	357°C
Radiator Area (m^2)	5.81

D.4.2 Cumulative Effects

To maintain brevity, discussions under topics in Subsections D.4.1 through D.4.6 are consolidated under the above heading.

In view of the fact that the SNAP-10A reactor system operated for only 43 days (1032 hours or 3.7×10^6 sec), very limited thermochemical effects would be noted between the UZr Hydride fuel and the cladding.

Since the density of zirconium diminishes by about 15 percent as the hydride, ZrH_{1.92}, is formed, release of some hydrogen from the fuel matrix would tend to

reverse this trend, initiating an increase in density and a corresponding minor volume shrinkage.

Creep and stress-rupture phenomena would be incipient only. At the nominal operating temperature of 566°C, the ultimate tensile strength of the Hastelloy-N tubing is approximately 500 times the fuel dissociation pressure. The corresponding 1000-hour stress rupture value is about 300 times the projected fuel dissociation pressure. Correspondingly, the liquid metal cooling system would show negligible evidence of attack, since the 316 austenitic stainless steel shows good resistance to alkali metals at temperatures up to 800°C.

Interaction of containment materials and internal radiation damage would be expected to be negligible at the temperatures and neutron fluence deliverable during the short operating lifetime of the reactor.

Space irradiation at a nominal 1300 kilometer altitude will be somewhat less significant than that for the Transit series of space craft, since the population of ions and particles is further diminished.

Solar energy absorption, of course, will raise the temperature of certain components of the system slightly above ambient temperature.

Evaporation of components of the operational reactor would have been negligible during the brief period the system was at design temperature. Thereafter, such effects would be further reduced.

Meteoroid damage assessments would read much like those for the Transit systems, with two major exceptions: the probability of impact is increased by the availability of substantially greater surface area, as well as by the extended orbital lifetime, projected to be 3000 to 4000 years. Burnishing and cratering should be anticipated. The probability of craters 2 to 3 cm deep somewhere over the surface area of approximately 100,000 cm², is approximately 2.8×10^{-4} . In addition, lesser effects should be expected from smaller meteoroids.

Reentry would dispose of the majority of a system probably rather heavily damaged exteriorly. Retrieval, if contemplated, should be planned to occur at a point in orbital lifetime for the SNAP-10A when component integrity is still adequate for handling-tool impact, and when source term levels do not pose a hazard to the retrieval system operators.

D.5 REENTRY SOURCE TERMS

Reentry radioactive source terms have been calculated for Snapshot (SNAP-10A) for the following release scenarios:

- o High altitude burnup (vapor)
- o High altitude burnup (particulate release over land)
- o High altitude burnup (particulate release over ocean)
- o Land impact
- o Ocean impact.

The analysis assumes that reentry and associated release modes occur at the end of predicted orbit life (3000 years). The release mode probability and associated source term (fraction of fuel released) were estimated based on the information on material aging effects developed in Chapter 4. The expected source terms were then calculated as the product of release mode probability and source term, all of which are summarized in Table D-4.

TABLE D-4

POSTULATED REENTRY RELEASE MODE PROBABILITIES AND SOURCE TERMS
FOR SNAPSHOT (SNAP-10A)

<u>Release Mode</u>	<u>Release Probability</u>	<u>Source Term (% Inventory Released)</u>	<u>Source Term (Curies)</u>	<u>Expected Source Term (Curies)</u>
High Altitude Burnup (Vapor)	1.0	100%	2.65E-02	2.65E-02
High Altitude Burnup (Particulate Release Over Land)	-	-	-	-
High Altitude Burnup (Particulate Release Over Ocean)	-	-	-	-
Land Impact	-	-	-	-
Ocean Impact	-	-	-	-
			Total	2.65E-02

D.6 REFERENCES

1. Rockwell Atomics International, Design and Integration of Zirconium Hydride Reactor Power Systems, AI-AEC-13072 (June 30, 1973).
2. Rockwell Atomics International, Aerospace Safety Program Summary Report, AI-AEC-13100 (July 30, 1973).
3. Atomics International, Progress Report, SNAP-10A Nuclear Auxiliary Power Unit Development, April-June 1961, NAA-SR-6693 (November 15, 1961).
4. Atomics International, Final SNAPSHOT Safeguards Report, NAA-SR-10022.
5. Glasstone and Sesonske, Nuclear Reactor Engineering, Van Nostrand Reinhold, New York, N.Y. (1967).
6. Corliss, Nuclear Reactors for Space Power, USAEC (1971).
7. Watsons, J.D., and J.R. Watch, SNAP High Temperature Materials Problems, in Materials and Fuels for High-Temperature Nuclear Energy Applications (Proceedings of the National Topical Meeting, ANS, San Diego, CA edited by M.T. Simnad and L.R. Zumwalt, M.I.T. Press, Cambridge, MA (1962).
8. See also Reference 8 to 14, Section A.6.

APPENDIX E

NIMBUS III (SNAP 19)

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E.1 REFERENCE DESIGN INFORMATION

E.1.1 Mission

Nimbus III, shown in Figure E-1, is a meteorological observational satellite and was launched from Vandenberg AFB on April 14, 1969 and placed into earth orbit. Power is provided by two SNAP-19 RTGs. A summary of the orbital parameters and system design features of the SNAP-19 RTG is presented in Table E-1 and discussed further below.

E.1.2 Nuclear Power System

The heat source for SNAP-19, designed for intact reentry, is shown in Figure E-2. The heat source is a right circular cylinder 7.62 cm in diameter and 16.51 cm long. The fuel consists of plasma-fired plutonium-238 dioxide microspheres with a nominal thermal capacity of 628 watts.

The fuel capsule consists of two Haynes-25 cups welded together with a filter/gas-vent combination installed in one end to allow for helium venting.

To provide a barrier during reentry to prevent possible reaction between Haynes-25 and a POCO AXM-5Q graphite heat shield, two protective measures are provided. A tantalum canister, coated on its inside surface with Zirconia, is used as a barrier around the capsule. In addition, a multi-layer coating was applied to the inside surface of the graphite heat shield adjacent to the outside surface of the canister to provide further protection.

Compliance members consisting of tantalum felt provide mechanical support of the canistered fuel capsule within the heat shield and allow for thermal expansion of the capsule with respect to the surrounding graphite.

Figure E-1 Nimbus III Spacecraft

TABLE E-1

NIMBUS III (SNAP 19) DATA SUMMARY

1. Mission Nimbus III
2. Launch Date 4/14/69
3. Orbital Parameters
 - o Period, minutes 107.3
 - o Inclination, degrees 99.7
 - o Apogee, km 1135
 - o Perigee, km 1074
 - o Orbital lifetime, years 3600
4. System Description
 - o Type - SNAP 19 RTG
 - o Fuel - Fuel in the form of plasma-fired PuO₂ microspheres. Pu composition approximately 80% Pu-238 and 20% Pu-239. Fuel mass is 1573 g.
 - o Power - 628 thermal watts per RTG
 - o Activity - 37,000 Ci Pu-238 at launch (total for two RTGs)
 - o Containment - Haynes 25 capsule
 - o Aeroshell - Designed for intact reentry. POCO AXM-5Q graphite outer shell, and zirconia coated tantalum canister enclosed capsule. The tantalum, a refractory metal, prevents reaction between the Haynes 25 and graphite during reentry since the Haynes 25 and fuel will probably become molten during reentry.
 - o He Venting - He venting is allowed using a zirconia frit filter pressed into one end of the capsule. (NOTE: Entire SNAP 19 RTG is sealed to prevent outgassing of thermoelectric materials. The effect of this sealoff on helium pressure buildup has not been evaluated yet.)

Figure E-2 SNAP-19 RTG Heat Source

E.1.3 Fuel

The fuel consists of approximately 1573g of Pu-238 dioxide in the form of plasma-fired microspheres. More detailed information on microsphere fuel is presented in Appendix H.

E.2 RADIOISOTOPIC INVENTORY VERSUS TIME

The radioisotopic inventory versus time for Nimbus III SNAP-19 RTGs has been calculated using the methods described in Chapter 4 of the main text. The calculations on initial radioisotopic fuel mix characteristic of PuO₂ microsphere fuel is presented in Appendix H.

The results are summarized in Table E-2 and Figure E-3 that present the curie activity of the principal radioisotopes as a function of time for both SNAP-19 RTGs combined aboard Nimbus III.

In addiiton, the total production of helium and radon gas were calculated and the results are presented in Figure E-4 as a function of time.

TABLE E-2

NIMBUS III (SNAP 19) RADIOISOTOPIC
INVENTORY VERSUS TIME

Radioactivity Inventory (Curies) at Indicated Time (Sec)						
Radionuclide	Initial	10^8	10^9	10^{10}	10^{11}	10^{12}
Tl-207	-	2.29E+02	9.21E+01	1.74E-01	1.55E-01	8.45E-02
Pb-211	-	2.30E+02	9.23E+01	1.75E-01	1.55E-01	8.47E-02
Pb-212	-	1.51E-02	4.97E-02	3.19E-03	3.81E-07	3.86E-07
Bi-211	-	2.30E-02	9.23E+01	1.75E-01	1.55E-01	8.47E-02
Bi-212	-	1.51E-02	4.97E-02	3.20E-03	3.81E-07	3.86E-07
Po-211	-	6.90E-11	2.67E-01	5.24E-04	4.66E-04	2.55E-04
Po-212	-	9.64E-03	3.19E-02	2.05E-03	2.45E-07	2.48E-07
Po-215	-	2.30E+02	9.23E+01	1.73E-01	1.55E-01	8.47E-02
Po-216	-	1.51E-02	4.97E-02	3.19E-03	3.81E-07	3.86E-07
Rn-219	-	2.30E+02	9.23E+01	1.75E-01	1.55E-01	8.47E-02
Rn-220	-	1.51E-02	4.97E-02	3.19E-03	3.81E-07	3.86E-07
Ra-223	-	2.30E+02	9.23E+01	1.75E-01	1.55E-01	8.47E-02
Ra-224	-	1.51E-02	4.97E-02	3.19E-03	3.81E-07	3.86E-07
Ac-227	2.55E+02	2.30E+02	9.21E+01	1.75E-01	1.55E-01	8.47E-02
Th-227	-	2.27E+02	9.09E+01	1.73E-01	1.53E-01	8.35E-02
Th-228	-	1.51E-02	4.97E-02	3.19E-03	3.81E-07	3.86E-07
Pa-231	1.66E-01	1.66E-01	1.66E-01	1.64E-01	1.55E-01	8.47E-02
U-232	-	3.33E-02	4.86E-02	3.12E-03	1.56E-14	-
U-233	3.31E-02	3.31E-02	3.31E-02	3.31E-02	3.28E-02	3.05E-02
U-234	2.50E-02	3.26E-01	2.71	1.13E+01	1.22E+01	1.13E+01
U-237	-	3.40E-02	8.76E-03	1.15E-08	-	-
Pu-236	1.60	7.40E-01	7.19E-04	-	-	-
Pu-238	3.40E+04	3.31E+04	2.67E+04	2.88E+03	6.50E-07	-
Pu-239	2.45E+01	2.57E+01	2.45E+01	2.43E-01	2.24E+01	9.97
Pu-240	1.67E+01	1.67E+01	1.67E+01	1.62E+01	1.21E+01	6.47E-01
Pu-241	1.64E+03	1.41E+03	3.67E+02	4.81E-04	-	-
Pu-242	1.29E-02	1.29E-02	1.29E-02	1.29E-02	1.29E-02	1.22E-02
Am-241	3.26E-01	8.04	4.21E+01	3.45E+01	3.59E-01	-
Subtotal	3.59E+04	3.62E+04	2.78E+04	2.98E+03	4.83E+01	2.26E+01
Actual Total	3.59E+04	3.66E+04	2.78E+04	2.98E+03	4.83E+01	4.93E+01

Figure E-3 Nimbus III (SNAP 19) Radiological Inventory Versus Time (2 RTGs)

Figure E-4 Nimbus III (SNAP 19) Helium and Radon Production Versus Time

E.3 EXTERNAL RADIATION FIELD VERSUS TIME

The external radiation field in the vicinity of the two combined SNAP-19 RTGs aboard Nimbus III has been calculated based on the methods described in Chapter 5 of the main text. Figure E-5 presents the gamma and neutron dose rates in the axial and radial directions at a distance of 1m as a function of time. Figure E-6 presents the gamma and neutron dose rates in the axial and radial directions as a function of distance in a vacuum at a reference time of 10^8 sec (3.17 years) after fresh fuel loading.

Figure E-5 Nimbus III (SNAP 19) External Dose Rates Versus Time at 1m Distance

Figure E-6

Nimbus III (SNAP 19) External Dose Rates
Versus Distance at Time $t=10^8$ Sec

E.4 AGING OF MATERIALS

E.4.1 Introduction

Several innovations in design and selection of materials are embodied in the Nimbus III heat sources; these include the use of plutonium oxide microspheres as fuel, Haynes-25 as fuel capsule, and a zirconia-sprayed tantalum barrier between the capsule and the graphite heat shield. The potential benefits to extended orbital lifetime are addressed in the summary section which follows.

E.4.2 Cumulative Effects

The use of plasma-fired Pu-238 oxide microspheres provides a short-term improvement in potential source term, since the denser fuel form represents an aggregate with fewer initial fines and substantially decreased surface area available for solid state reactions or for vapor loss mechanisms. Ease of loading and uniformity of heat transfer within the capsule are additional advantages. However, in the longer term, these microspheres also are subject to helium pressure disaggregation, with the resulting fragments probably providing a somewhat lower percentage of small particles contributing to environmental dispersion.

The Haynes-25 liner is rated as resistant to oxidation at temperatures in the 1093 to 1204°C range. Nominal operating temperature of the capsule is approximately 760°C. In this heat source, the Haynes-25 alloy is free from the potential damage to be sustained by contact with metallic plutonium. In addition, it provides substantial resistance to rupture stresses at elevated temperatures, a necessary attribute should the gas venting devices become plugged prematurely.

The optimum, implicit in the statements above, must be tempered by the lack of proportionate long-term compatibility testing and by the uncertainty surrounding the contribution of alpha-particle and neutron irradiation effects upon the chemistry of oxidation of metallic materials in the heat source assembly. To this must be added the potential contribution of helium and other gas species to the vapor transport mechanism(s) partially responsible for vent plugging.

Calculations by Fairchild staff indicate that the Nimbus capsule would not rupture if such plugging does not occur until 100 years after launch. This statement, is predicated upon retention of the original metal section and properties.

Internal radiation damage is expected to be annealed out almost completely. Space irradiation effects should be qualitatively similar to those typical of the Transit 4A/4B missions. Meteoroid damage, other than burnishing effects, has a probability of producing significant craters of approximately 3×10^{-4} .

E.5 REENTRY SOURCE TERMS

Reentry radioactive source terms have been calculated for Nimbus III (SNAP-9A) for the following release scenarios:

- o High altitude burnup (vapor)
- o High altitude burnup (particulate release over land)
- o High altitude burnup (particulate release over ocean)
- o Land impact
- o Ocean impact.

The analysis assumes that reentry and associated release modes occur at the end of predicted orbit life (3600 years). The release mode probability and associated source term (fraction of fuel released) were estimated based on the information on material aging effects developed in Chapter 4. The expected source terms were then calculated as the product of release mode probability and source term, all of which are summarized in Table E-3.

TABLE E-3

POSTULATED REENTRY RELEASE MODE PROBABILITIES AND SOURCE TERMS
FOR NIMBUS III (SNAP-19)

<u>Release Mode</u>	<u>Release Probability</u>	<u>Source Term (% Inventory Released)</u>	<u>Source Term (Curies)</u>	<u>Expected Source Term (Curies)</u>
High Altitude Burnup (Vapor)	-	-	-	-
High Altitude Burnup (Particulate Release Over Land)	-	-	-	-
High Altitude Burnup (Particulate Release Over Ocean)	-	-	-	-
Land Impact	0.34	1%	4.80E-01	1.63E-01
Ocean Impact	0.66	100%	4.80E+01	<u>3.17E+01</u>
			Total	3.19E+01

E.6 REFERENCES

1. Mound Laboratory, Summary Report on SNAP-19B (IRHS) Program, MLM-16 (June 27, 1969).
2. Martin Marietta Nuclear Division, Design Safety Philosophy and Criteria for the SNAP-19 Nimbus, MND-3169-8.
3. See also References 8 to 14 of Section A.6.

APPENDIX F

LES 8/9 (MHW/RTG)

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F.1 REFERENCE DESIGN INFORMATION

F.1.1 Mission

The Multi-Hundred Watt Radioisotope Thermoelectric Generator (MHW-RTG) is utilized to provide electric power for the Lincoln Laboratory Experimental Satellite Numbers 8 and 9 (LES 8/9). The LES 8/9 satellites were launched into a synchronous earth orbit by a Titan IIIC launch vehicle from the Eastern Test Range (ETR) on March 14, 1976. Figure F-1 depicts the launch configuration for the LES 8/9 mission. The SOLRADS were two other satellites on the mission, but they did not employ the MHW-RTG. The Titan IIIC vehicle consisted of a three-stage, liquid hypergolic propellant core vehicle supplemented by two solid rocket motor strap-ons.

At the end of Stage II operation, the launch vehicle placed the Transtage (Stage III) and payload into an elliptical parking orbit having a perigee of 152 km. Transtage first burn occurred between the second and third equatorial crossing, placing it and the payload into a transfer orbit. The second burn simultaneously circularized the orbit and obtained the proper orbital inclination at the synchronous altitude. After the second burn was completed, the LES satellites, with the MHW-RTG's aboard, were released. Figure F-2 is an artist's concept of the LES-9/RTG configuration in orbit. A summary of the orbital parameters and system design features is presented in Table F-1 and discussed further below.

F.1.2 Nuclear Power System

The MHW-RTG is a radioisotope fueled, thermoelectric generator comprised of two major components: the Isotope Heat Source (IHS) and the Converter. A conceptual drawing of the RTG is presented in Figure F-3, which shows a cut-away portion of the Converter to illustrate its internal construction and the position of the IHS.

Figure F-1 Titan IIIC Launch Vehicle

Figure F-2 LES 8/9 RTG Configuration

Figure F-2 LES 8/9 RTG Configuration

TABLE F-1

LES 8/9 (MHW RTG) DATA SUMMARY

1. Mission LES-8/LES-9
2. Launch Date 3/14/76
3. Orbital Parameters
 - o Period, minutes 1440
 - o Inclination, degrees 25
 - o Apogee, km 35,900
 - o Perigee, km 35,900
 - o Orbital lifetime, years 10^6
4. System Description
 - o Type - 2 MHW-RTGs per spacecraft
 - o Fuel - Pressed and sintered PuO_2 (PPO) fuel. Overall composition is approximately 87.2% Pu, 11.2% O_2 and 1% impurities, and Pu composition is 80.3% Pu-238, 15.9% Pu-239 and 3.8% other Pu isotopes. Fuel mass is 12.1 kg.
 - o Power - 2400 thermal watts for each of two RTG on each spacecraft or 4800 thermal watts per spacecraft
 - o Activity - 74,500 Ci Pu-238 in each RTG at launch or 149,000 Ci Pu-238 in each spacecraft
 - o Containment - Each RTG contains 24 fuel sphere assemblies, each consisting of an iridium fuel clad within resin-impregnated Thornel-50 pyrolyzed graphite impact shells.
 - o Aeroshell - Designed for intact reentry. The aeroshell is composed of POCO-AXF-5Q1 graphite surrounded by a Pyrocarb-406 graphite ablation sleeve.
 - o He Venting - He venting is provided for with each iridium post-impact containment shell having an iridium powder frit filter and the RTG beryllium outer shell having a pressure relief device.

Figure F-3

MHW Radioisotope Thermoelectric Generator

The IHS shown in Figure F-4 is in the shape of a right circular cylinder and consists of 24 fuel containers having individual impact protection, the aeroshell, the outer can and vent tube, and the emissivity sleeve exterior to the outer can. The isotopic fuel is plutonium-238 in the form of the oxide, PuO_2 . The fuel containers, or Fuel Sphere Assemblies (FSA), consist of the fuel sphere, a metallic (iridium) shell which serves to contain the fuel, and a graphite impact shell which provides the primary resistance to mechanical impact loads. The aeroshell is also of graphite and serves as an ablator during reentry as well as an attenuator of reentry heating to the IHS interior. Oxidation protection, secondary containment, increased reentry capability, and providing handling and Converter mounting interfaces are the functions of the outer clad, which is also iridium. The graphite emissivity sleeve enhances radiant heat transfer to the Converter as well as providing additional strength and protection for the IHS during reentry. Hence, the IHS is comprised of only three basic materials: PuO_2 , fuel, iridium, and graphite.

The Converter consists of the outer case, which is the main support structure for the thermoelements as well as the IHS; the end closure structures that physically hold the Heat Source; the thermoelectric elements; the multifoil insulation packet and interval frame; and the gas management system. 312 thermoelectric couples convert decay heat from the fuel directly into electrical energy. They are supported in cantilever fashion from the beryllium outer case; the couples support the insulation packet. The end closure structures provide preload to the IHS to enable the RTG to withstand the launch and ascent dynamic environment. The gas management system maintains an argon environment to allow partial power operation on the launch pad; full power operation in space is effected by venting on signal from the Transtage, or redundantly, through the pressure relief device (PRD) activated by space vacuum (i.e., drop in atmospheric pressure during ascent).

F.1.3 Fuel

The radioisotope fuel material is an isotopic mixture of plutonium in the dioxide form, PuO_2 , containing 80.2% Pu-238 and is called pressed plutonium dioxide (PPO)

Figure F-4 **MHW Heat Source**

fuel. The physical form of the fuel is in multiple, sphere shaped, solid ceramic compacts having a diameter of 3.72 cm.

Each fuel sphere contains an initial thermal inventory of 100 ± 2 watts. A total of 24 spheres provides a nominal thermal power of 2400 watts for the IHS at beginning-of-life. This IHS power requires 6.05 kg of PuO_2 . The total activity based on 12.1 Ci/g is 7.32×10^4 Curies per Heat Source.

More detailed information on the characteristics of PPO fuel is presented in Appendix H.

F.2 RADIOISOTOPIC INVENTORY VERSUS TIME

The radioisotopic inventory versus time for the two MHW-RTGs on both LES 8 AND LES 9 have been calculated using the methods described in Chapter 4 of the main text. The calculations assumed an initial radioisotopic mix characteristics of PPO fuel presented in Appendix H.

The results are summarized in Table F-2 and Figure F-5 that present the curie activity of the principal radioisotopes as a function of time.

In addition, the total production of helium and radon gas were calculated and the results are presented in Figure F-6 as a function of time.

TABLE F-2

LES 8/LES 9 (MHW-RTG) RADIOISOTOPIC
INVENTORY VERSUS TIME (PER SPACECRAFT)

Radioactivity Inventory (Curies) at Indicated Time (Sec)							
Radionuclide	Initial	10^8	10^9	10^{10}	10^{11}	10^{12}	10^{13}
Tl-207	-	9.64E+02	3.87E+02	7.33E-01	6.51E-01	3.55E-01	4.36E-03
Pb-211	-	9.68E+02	3.88E+02	7.34E-01	6.53E-01	3.56E-01	4.37E-03
Pb-212	-	6.33E-02	2.09E-01	1.34E-02	1.60E-06	1.62E-06	1.91E-06
Bi-211	-	9.68E-02	3.88E+02	7.34E-01	6.53E-01	3.56E-01	4.37E-03
Bi-212	-	6.33E-02	2.09E-01	1.34E-02	1.60E-06	1.62E-06	1.58E-07
Po-211	-	2.90E-10	1.12	2.20E-03	1.96E-03	1.07E-03	1.31E-05
Po-212	-	4.05E-02	1.34E-01	8.63E-03	1.03E-06	1.04E-06	1.22E-06
Po-215	-	9.68E+02	3.88E+02	7.28E-01	6.53E-01	3.56E-01	4.37E-03
Po-216	-	6.33E-02	2.09E-01	1.34E-02	1.60E-06	1.62E-06	1.92E-06
Rn-219	-	9.68E+02	3.88E+02	7.34E-01	6.53E-01	3.56E-01	4.37E-03
Rn-220	-	6.33E-02	2.09E-01	1.34E-02	1.60E-06	1.62E-06	1.91E-06
Ra-223	-	9.68E+02	3.88E+02	7.34E-01	6.53E-01	3.56E-01	4.37E-03
Ra-224	-	6.33E-02	2.09E-01	1.34E-02	1.60E-06	1.62E-06	1.91E-06
Ac-227	1.07E+03	9.66E+02	3.87E+02	7.34E-01	6.53E-01	3.56E-01	4.37E-03
Th-227	-	9.55E+02	3.82E+02	7.25E-01	6.44E-01	3.51E-01	4.31E-03
Th-228	-	6.33E-02	2.09E-01	1.34E-02	1.60E-06	1.62E-06	1.91E-06
Pa-231	6.98E-01	6.98E-01	6.98E-01	6.90E-01	6.52E-01	3.56E-01	4.37E-03
U-232	-	1.40E-01	2.04E-01	1.31E-02	1.56E-14	-	-
U-233	1.39E-01	1.39E-01	1.39E-01	1.39E-01	1.38E-01	1.28E-01	7.67E-02
U-234	1.05E-01	1.37	1.14E+01	4.73E+01	5.12E+01	4.73E+01	2.12E+01
U-237	-	1.43E-01	3.68E-02	4.85E-08	-	-	-
Pu-236	6.73	3.11	3.02E-03	-	-	-	-
Pu-238	1.43E+05	1.39E+05	1.12E+05	1.21E+04	2.73E-06	-	-
Pu-239	1.03E+02	1.03E+02	1.03E+02	1.02E+02	9.40E+01	4.19E+01	1.27E-02
Pu-240	7.03E+01	7.03E+01	7.01E+01	6.80E+01	5.08E+01	2.72	5.44E-13
Pu-241	6.90E+01	5.93E+03	1.54E+03	2.02E-03	-	-	-
Pu-242	5.43E-02	5.43E-02	5.43E-02	5.43E-02	5.40E-02	5.13E-02	3.04E-02
Am-241	1.37	3.38E+01	1.77E+02	1.45E+02	1.51	-	-
Subtotal	1.51E+05	1.52E+05	1.17E+05	1.25E+04	2.11E+02	2.07E+02	2.87E+02
Actual Total	1.51E+05	1.54E+05	1.17E+05	1.25E+04	2.11E+02	2.07E+02	2.87E+02

Figure F-5 LES 8/LES 9 (MHW-RTG) Radioisotopic Inventory Versus Time (per Spacecraft)

Figure F-6 LES 8/9 (MHW-RTG) Helium and Radon Gas Production Versus Time (per Spacecraft)

F.3 EXTERNAL RADIATION FIELD VERSUS TIME

The external radiation field in the vicinity of the MHW-RTGs has been calculated based on the methods described in Chapter 5. The results are presented in Figures F-7 and F-8. Figure F-7 presents the gamma and neutron dose rates in the axial and radial directions at a distance of 1 m as a function of time. Figure F-8 presents the gamma and neutron dose rates in the axial and radial directions as a function of distance in a vacuum at a reference time of 10^8 sec (3.17 years) after fresh fuel loading.

The gamma dose rates appear to be quite sensitive to impurities, especially Ac-227, reported in the literature to occur in MHW fuel but not precisely quantified. The calculations assumed both zero and approximately a 0.12 w/o Ac-227 impurity. The gamma dose rates calculated on this basis were dominated almost entirely by Ac-227 and its short-lived daughters during a time period of approximately 1 to 30 years after loading of fresh fuel, with a rapid buildup of dose rates during the first year. Discussions with LASL and MRC personnel indicated the Ac-227 impurity level in these fuels is extremely small and this was not considered to be a problem.

Figure F-7 LES R/LES 9 (MHW-RTG) External Dose Rates
Versus Time at 1m Distance

Figure F-8

LES 8/LES 9 (MHW-RTG) External Dose Rates
Versus Distance at Time $t=10^8$ Sec

F.4 AGING OF MATERIALS

F.4.1 Introduction

The Multi-Hundred Watt units powering the Lincoln Experimental Satellites represent substantially different engineering and technology in their design and construction, as well as orbital location and lifetimes in strong contrast with the navigational and meteorological satellites discussed earlier. Anticipated aging effects reflecting these differences are discussed in the summary subsection below.

F.4.2 Cumulative Effects

The fueled sphere assembly, comprising a 100-watt pressed plutonium-238 oxide sphere, its iridium containment capsule, and a woven graphite-fiber impact shell, is designed for intact, safe reentry after fulfillment of mission requirements. Minor variability of the fuel sphere -- in dimensions, in radial density profile, in thermomechanical properties, and in microtexture -- must be expected. Similar minor variability in the metallurgy, chemistry, and response to impact testing has been recognized for the capsule. Corollary statements could be made for the graphite components of the system. All components conformed to specifications drawn as tightly as space engineering requirements could be consistently met by developmental technology.

The interacting probabilities of success for each respective component in the path defined by a reentry trajectory will be affected by the then current condition of each component. Experience has shown that although it is one of the noblest metals, very resistant to chemical attack, iridium is susceptible to oxidation at temperatures above 600°C. This presence of residual Ir oxides is avoided in heat source assembly procedures by prior outgassing of the cleaved hemishells. Oxidation is expected to be mitigated by the integral woven graphite-fiber impact shell upon reentry into an oxidizing atmosphere, or upon burial in soil at the earth's surface.

These tests also indicated the sporadic and impermanent nature of the vent-plugging mechanism, allowing helium release in bursts after interim accumulation within the capsule. Occasional observations of local iridium depletion and redeposit, primarily associated with the weld-band, add impetus to the thesis of iridium movement via the vapor phase chemistry route. In its total history, the MHW fuel capsule has seen maximum temperatures at the fuel center and at the fuel equator, where the capsule welding operation took place, shielded by the thin weld-band. The materials transport reactions could have been initiated during welding and could continue at progressively declining rates as the nominal temperature of operation drops from 1325°C to 971°C after 40 years, and to 682°C after 80 years of orbital lifetime, respectively. Calculations by Fairchild staff indicate no capsule rupture even if vents were plugged at those points in time; this calculation, however, is predicated upon the survival of the original section and physical properties of the iridium.

The matter of radiation damage by alpha particles has been reviewed and indications are that little damage would be sustained. Evaporation of iridium appears to proceed only via the oxidation route. Space irradiation would need to penetrate the beryllium housing, the graphite aeroshell, and the fibrous graphite impact shell in order to reach the fuel capsule; this effect is considered to be negligible. The fact that the LES 8/9 units are orbiting at an altitude of 35,900 kilometers ($L=5.6$) indicates that both the flux and the energy of low-energy protons would be lower than at lesser altitudes. High-energy protons are essentially non-existent, and electrons at energies greater than 0.25 MeV exist at a flux of approximately 10^6 per cm^2 second.

Meteoroid damage could become significant. There exists a 1 percent probability of impact by a 1-gram meteoroid traveling at 20 km per second, resulting in a probable puncture of the beryllium outer case and possibly penetration of the graphite aeroshell. Such an impact also might deviate the satellite from its intended orbit.

Retrieval of these heat sources from their orbital altitude appears as a substantially greater challenge than retrieval of Transit units. Reentry of the

LES 8/9 units with earth impact may anticipate a source term greater than 1 percent, in view of the patent uncertainty of predicting aging mechanisms and their effect after a million years of space exposure.

F.5 REENTRY SOURCE TERMS

Reentry radioactive source terms have been calculated for LES 8/9 using for the following release scenarios:

- o High altitude burnup (vapor)
- o High altitude burnup (particulate release over land)
- o High altitude burnup (particulate release over ocean)
- o Land impact
- o Ocean impact.

The analysis assumes that reentry and associated release modes occur at the end of predicted orbit life (10^6 years). The release mode probability and associated source term (fraction of fuel released) were estimated based on the information on material aging effects developed in Chapter 4. The expected source terms were then calculated as the product of release mode probability and source term, all of which are summarized in Table F-3.

TABLE F-3

POSTULATED REENTRY RELEASE MODE PROBABILITIES AND SOURCE TERMS
FOR LES 3/9 (MHW-RTG)

<u>Release Mode</u>	<u>Release Probability</u>	<u>Source Term (% Inventory Released)</u>	<u>Source Term (Curies)</u>	<u>Expected Source Term (Curies)</u>
High Altitude Burnup (Vapor)	-	-	-	-
High Altitude Burnup (Particulate Release Over Land)	-	-	-	-
High Altitude Burnup (Particulate Release Over Ocean)	-	-	-	-
Land Impact	0.27	1%	-	1.20
Ocean Impact	0.73	100%	4.44E+02	<u>3.24E+02</u>
			Total	3.25E+02

F.7 REFERENCES

1. General Electric, Multi-Hundred Watt Radioisotope Thermoelectric Generator Program, Final Safety Analysis Report for LES 8/9, GEMS-419 (March 1975).
2. Los Alamos Scientific Laboratory, Performance of Multi-Hundred Watt Fueled-Sphere Assemblies in the Safety Sequential Test Program, LA-5916 (July 1975).
3. Los Alamos Scientific Laboratory, Performance of Multi-Hundred Watt Fueled-Sphere Assemblies in the Safety Verification Test, LA-6082 (January 1976).
4. Los Alamos Scientific Laboratory, Thermodynamic Analysis of MHW Space Electric Power Generator, LA-5202-MS (March 1973).

APPENDIX G

GALILEO/ISPM (GPHS-RTG)

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G.1 REFERENCE DESIGN INFORMATION

G.1.1 Mission

The Galileo Mission and the International Solar Polar Missions (ISPM) are interplanetary missions to be launched by the Space Shuttle.

The Galileo Mission is designed to explore Jupiter and consists of two spacecraft, the Galileo Orbiter and the Galileo Probe, shown in Figures G-1, which will be launched together by the Space Shuttle, shown in Figures G-2 through G-4 from the Kennedy Spacecraft Center (KSC). The Galileo Orbiter, designed to orbit Jupiter, will be powered by two plutonium-fueled General Purpose Heat Source (GPHS)-RTGs. The Galileo Probe is designed for a parachute descent into the Jovian atmosphere. Additionally, each spacecraft will have a number of plutonium-fueled Light Weight Radioisotope Heater Units (LWRHU). The two spacecrafts will be attached to an Inertial Upper Stage (IUS) within the Space Shuttle bay. Following launch and earth orbit injection, the spacecraft and the IUS will be separated from the Space Shuttle. The spacecraft will then be placed in a trajectory towards Jupiter following Centaur burn and separation. The presently planned launch date for the Galileo Mission is May 1985.

ISPM was originally designed to explore the sun with two spacecraft from high solar latitude viewing angles near each pole. This was to be a joint NASA and European Space Agency (ESA) mission with each agency providing one spacecraft, shown in Figure G-5. The spacecraft were to be launched combined in a single Space Shuttle. Following earth orbit injection and Space Shuttle separation, the Initial Upper Stage (IUS) was to place each spacecraft into a gravitational-assist trajectory towards Jupiter. Jupiter would then be used as a gravitational sling to take each spacecraft out of the ecliptic planes and back toward the sun. The two spacecraft were then to go around the sun near the solar north and south poles, respectively. Each spacecraft was to have used one GPHS-RTG. Since the conception of the original missions, changes have resulted in the deletion of the NASA spacecraft. The present launch date is March/April 1986.

Figure G-1 Galileo Spacecraft

Figure G-3 Space Shuttle Layout

Figure G-4 General Space Shuttle Mission Profile

G-6

Figure G-5 **International Solar Polar Mission Spacecraft**

The rest of this Appendix is based on a single GPHS-RTG in order to combine the features common to both Galileo and ISPM. A summary of the GPHS-RTG design features are presented in Table G-1.

G.1.2 Nuclear Power System

The GPHS-RTG, shown in Figure G-6, is a radioisotopic fueled, thermoelectric generator consisting of two major elements: the converter and the heat source. The power system is designed to provide 290 electrical watts under initial space operational conditions for a thermal fuel loading of 4410 watts.

The GPHS is a stacked column of 18 individual modules. Each module, shown in Figure G-7, primarily consists of an aeroshell, two Graphite Impact Shells (GIS), and four Fueled Clads (FC). Each FC consists of a fuel pellet of plutonium-238 in the form of the oxide PuO_2 encased in an iridium shell which serves to contain the fuel. Two of these FC's, separated by a graphite floating membrane, are then encased in a GIS which provides the primary resistance to mechanical impact loads. Both the GIS and the floating members are constructed of FWPF-3D graphite. A FWPF-3D graphite aeroshell, which serves as the module's primary structural element and ablator, provides protection for two graphite impact shells. Each GIS is separated from the aeroshell by a CBCF graphite insulator.

The converter consists of the outer case, which is actively cooled and is the main support structure for the thermoelectric elements as well as the GPHS; the axial and mid span heat source supports; the thermoelectric elements; multifoil insulation packet and internal frame; and the gas management system. Five hundred seventy-six thermoelectric couples convert decay heat from the fuel directly into electrical energy. These couples are supported in a cantilever fashion from the aluminum outer case; the couples support the insulation packet. The heat source

TABLE G-1

Galileo/ISPM (GPHS-RTG) DATA SUMMARY

1. <u>Missions</u>	Galileo	ISPM
2. <u>Launch Dates</u>	April-May 1985	April-May 1986
3. <u>Orbital Parameters</u>	<u>Assumptions</u>	
o Period, minutes	--	
o Inclination, degrees	28°	
o Apogee, km	--	
o Perigee, km	--	
o Orbital lifetime, years	Prompt Reentry	
4. <u>System Description</u>		
o Type	- RTG	
o Fuel	- Pressed and sintered PuO ₂ consisting of coarse grains in a fine grain porous matrix (GROG fuel). Overall composition of 87.2% Pu, 11.8% O ₂ , and 1% impurities, and a Pu composition of 83.6% Pu-238, 13.85% Pu-239, and 2.55% other Pu isotopes. Fuel mass is 10.7 kg.	
o Power	- 4410 thermal watts per RTG	
o Activity	- 135,000 Ci Pu-238 per RTG	
o Containment	- Each RTG contains 72 fuel pellets, each encapsulated within an iridium post impact containment shell. Two such capsules are contained within a FWPF-3D graphite impact shell (GIS).	
o Aeroshell	- Two GISs are contained within each of 18 FWPF-3D graphite aeroshell that in turn are assembled in a stack configuration. Each GIS is separated from the aeroshell by a CBCF graphite insulator. The RTG has an aluminum outer casing designed to burn off during GPHS reentry, releasing the 18 aeroshell modules individually that are to survive reentry and protect each fuel capsule upon earth impact.	
o He Venting	- He venting is provided for with each of the 72 capsules having an He vent. The entire sealed RTG has a pressure relief device that is command punctured.	

G-10

Figure G-6 General Purpose Heat Source - RTG

support system provides preload to the GPHS to enable the RTG to withstand the launch and ascent dynamic environments and to prevent separation of the GPHS modules. The gas management system consists of a pressure relief device (PRD) and a gas management valve (GMV) which in configuration with the pressure tight converter case are used to maintain the desired internal environment of the generator. This system maintains an inert gas environment to allow partial power operation on the launch pad. Full power operation in space is achieved after venting the inert gas through the PRD. The GMV is a manually actuated valve required for pressure maintenance of the generator during ground storage.

G.1.3 Fuel

The radioisotope fuel material is an isotopic mixture of plutonium in the form of the dioxide, PuO_2 , containing 83.5 percent $^{238}\text{PuO}_2$. The physical form of the fuel is in multiple, basically cylindrical shaped, solid ceramic pellets. The pellets have an average diameter of 2.75 cm and are 2.76 cm long. Geometric density of the fuel is 9.60 g-cm^{-3} , and with a specific thermal power of 0.42 W-g^{-1} , the corresponding power density is 3.99 W-cm^{-3} .

Each fuel pellet contains an initial thermal inventory of 62.5 wats. A total of 72 pellets provides a nominal thermal power of 4410 watts for the GPHS at the beginning-of-life. This GPHS power requires 10.73 kg of PuO_2 . The $^{238}\text{PuO}_2$ activity based on 12.6 Ci-g^{-1} is 1.35×10^5 curies per heat source.

More detailed information on the fuel properties are presented in Appendix H.

G.2 RADIOISOTOPIC INVENTORY VERSUS TIME

The radioisotopic inventory versus time for the GPHS-RTG have been calculated using the methods described in Chapter 4 of the main text. The calculations assumed an initial radioisotopic mix characteristics of the fuel as presented in Appendix H.

The results are summarized in Table G-2 and Figure G-8 that present the curie activity of the principal radioisotopes as a function of time.

In addition, the total production of helium and radon gas were calculated and the results are presented in Figure G-9 as a function of time.

TABLE G-2

GALILEO/ISPM (GPHS-RTG) RADIOISOTOPIC
INVENTORY VERSUS TIME (PER SPACECRAFT)

Radioactivity Inventory (Curies) at Indicated Time (Sec)								
Radionuclide	Initial	<u>10⁸</u>	<u>10⁹</u>	<u>10¹⁰</u>	<u>10¹¹</u>	<u>10¹²</u>	<u>10¹³</u>	<u>10¹⁴</u>
Tl-207	-	8.55E+02	3.43E+02	6.50E-01	5.77E-01	3.14E-01	3.47E-03	2.75E-03
Pb-211	-	8.58E+02	3.44E+02	6.51E-01	5.79E-01	3.15E-01	3.48E-03	2.75E-03
Pb-212	-	4.68E-02	1.55E-01	9.96E-03	1.42E-06	1.44E-06	1.61E-06	3.23E-06
Bi-211	-	8.58E+02	3.44E+02	6.51E-01	5.79E-01	3.15E-01	3.48E-03	2.75E-03
Bi-212	-	4.68E-02	1.55E-01	9.96E-03	1.42E-06	1.44E-06	1.61E-06	3.23E-06
Po-211	-	2.58	1.03	1.95E-03	1.74E-03	9.47E-04	1.04E-05	8.25E-06
Po-212	-	2.99E-02	9.91E-02	6.37E-03	9.10E-07	9.18E-07	1.03E-06	2.07E-06
Po-215	-	8.58E+02	3.44E+02	6.51E-01	5.79E-01	3.15E-01	3.48E-03	2.75E-03
Po-216	-	4.68E-02	1.55E-01	9.96E-03	1.42E-06	1.44E-06	1.61E-06	3.23E-06
Rn-219	-	8.58E+02	3.44E+02	6.51E-01	5.79E-01	3.15E-01	3.48E-03	2.75E-03
Rn-220	-	4.68E-02	1.55E-01	9.96E-03	1.42E-06	1.44E-06	1.61E-06	3.23E-06
Ra-223	-	8.58E+02	3.44E+02	6.51E-01	5.79E-01	3.15E-01	3.48E-03	2.75E-03
Ra-224	-	4.68E-02	1.55E-01	9.96E-03	1.42E-06	1.44E-06	1.61E-06	3.23E-06
Ac-227	9.47E+02	8.56E+02	3.43E+02	6.51E-01	5.79E-01	3.15E-01	3.48E-03	2.75E-03
Th-227	-	8.47E+02	3.39E+02	6.43E-01	5.71E-01	3.11E-01	3.42E-03	2.71E-03
Th-228	-	4.68E-02	1.55E-01	9.96E-03	1.42E-06	1.44E-06	1.61E-06	3.23E-06
Pa-231	6.19E-01	6.19E-01	6.19E-01	6.15E-01	5.78E-01	3.15E-01	3.48E-03	2.75E-03
U-232	-	1.04E-01	1.51E-01	9.69E-03	1.16E-14	-	-	-
U-233	1.23E-01	1.23E-01	1.23E-01	1.23E-01	1.22E-01	1.13E-01	5.92E-02	1.42E-02
U-234	9.29E-02	1.26	1.05E+01	4.37E+01	4.73E+01	4.37E+01	1.96E+01	6.56E-03
U-237	-	8.85E-02	2.29E-02	3.00E-08	-	-	-	-
Pu-236	4.97	2.30	2.23E-03	-	-	-	-	-
Pu-238	1.32E+05	1.29E+05	1.03E+05	1.12E+04	2.52E-06	-	-	-
Pu-239	7.95E+01	7.95E+01	7.94E+01	7.88E+01	7.26E+01	3.23E+01	9.79E-03	-
Pu-240	4.02E+01	4.02E+01	4.01E+01	3.89E+01	2.91E+01	1.56	-	-
Pu-241	4.28E+03	3.68E+03	5.51E+02	1.26E-03	-	-	-	-
Pu-242	5.11E-02	5.11E+01	5.11E-02	5.11E-02	5.04E-02	4.82E-02	2.86E-02	1.56E-04
Am-241	1.21E-03	2.14E+01	1.09E+02	9.07E+01	9.43E-01	-	-	-
Subtotal	1.37E+05	1.36E+05	1.07E+05	1.14E+04	1.56E+02	8.05E+01	1.97E+01	4.56E-02
Actual Total	1.37E+05	1.39E+05	1.07E+05	1.15E+04	1.62E+02	1.91E+02	2.65E+02	3.02E-01

Figure G-8 Galileo/ISPM (GPHS-RTG) Radiological Inventory Versus Time (per RTG)

Figure G-9

Galileo/ISPM (GPHS-RTG) Helium and Radon
Gas Production Versus Time (No Venting Assumed)

G.3 EXTERNAL RADIATION FIELD VERSUS TIME

The external radiation field in the vicinity of the GPHS-RTG has been calculated based on the methods described in Chapter 5 of the main text. The results are presented in Figures G-10 and G-11. Figure G-10 presents the gamma and neutron dose rates in the axial and radial directions at a distance of 1m as a function of time. Figure G-11 presents the gamma and neutron dose rates in the axial and radial direction as a function of distance in a vacuum at a reference time of 10^8 sec (3.17 years) after fresh fuel loading.

The gamma dose rates appear to quite sensitive to impurities, essentially Ac-227, reported in the literature to occur in GPHS fuel but not precisely quantified. The calculations assumed both zero and approximately 0.12 w/o Ac-227 impurity. The gamma dose rates calculated on this basis were dominated almost entirely by Ac-227 and its short-lived daughters during a time period of approximately 1 to 30 years after loading of fresh fuel, with a rapid buildup of dose rates during the first year. Discussions with LASL and MRC personnel indicated the Ac-227 impurity level in these fuels is extremely small and was not considered to be a problem.

G-10 Galileo/ISPM (MHW-RTG) External Dose Rates
Versus Time at 1m Distance (per RTG)

Figure G-1
Galileo/ISPM (GPHS-RTG) External Dose Rates
Versus Distance at Time $t=10^8$ Sec

G.4 AGING OF MATERIALS

The Galileo/International Solar Polar Mission satellites, currently planned to be powered by the General Purpose Heat Source, remain to be finalized, assembled, and launched. In prospect, the heat sources represent the ultimate in engineering and technology applicable to the mission requirements. Generic similarities to the Multi-Hundred Watt heat sources discussed in Section F.4 suggest that many of the mechanisms of aging also will be similar. Since orbital parameters have not been established, the probable effects of space conditions remain to be evaluated and the prospective orbital lifetime has not been stated.

G.5 REENTRY SOURCE TERMS

Reentry radioactive source terms have been calculated for Galileo/ISPM using the following release scenarios:

- o High altitude burnup (vapor)
- o High altitude burnup (particulate release over land)
- o High altitude burnup (particulate release over ocean)
- o Land impact
- o Ocean impact.

The analysis assumes that reentry and associated release modes occur at the end of predicted orbit life (prompt reentry assumed). The release mode probability and associated source term (fraction of fuel released) were estimated based on the information on material aging effects developed in Chapter 4. The expected source terms were then calculated as the product of release mode probability and source term, all of which are summarized in Table G-3. The results are presented on a per GPHS-RTG basis.

TABLE G-3

POSTULATED REENTRY RELEASE MODE PROBABILITIES AND SOURCE TERMS AND
FOR GALILEO/ISPM (GPHS-RTG)

<u>Release Mode</u>	<u>Release Probability</u>	<u>Source Term (% Inventory Released)</u>	<u>Source Term (Curies)</u>	<u>Expected Source Term (Curies)</u>
High Altitude Burnup (Vapor)	-	-	-	-
High Altitude Burnup (Particulate Release Over Land)	-	-	-	-
High Altitude Burnup (Particulate Release Over Ocean)	-	-	-	-
Land Impact	0.27	1%	1.37E+03	3.70E+02
Ocean Impact	0.73	100%	1.37E+05	<u>1.00E+05</u>
			Total	1.00E+05

G.6 REFERENCES

1. General Electric, Silicon Germanium Radioisotope Thermoelectric Generator Program, Preliminary Safety Analysis Report for the International Solar Polar Mission, GEMS-80SD54228 (March 1980).
2. General Electric, General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG) Final Design Review (October 28-30, 1980).
3. Teledyne Energy Systems, Selenide Isotope Generator for the Galileo Mission, TES-33009-42 (June 1979).

APPENDIX H

FUEL PROPERTIES

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H.1 INTRODUCTION

Backup information on fuel properties is presented in this appendix, supporting the evaluations presented in the main text and Appendices A through G. The following fuel types are covered:

- o Metallic plutonium fuel (SNAP-3, SNAP-9A)
- o PuO_2 microsphere fuel (SNAP-19)
- o Plutonium molybdenum cermet (PMC) fuel (Transit Triad RTG)
- o Pressed PuO_2 (PPO) fuel (MHW-RTG)
- o Grog PuO_2 fuel (GPHS-RTG)
- o ZrHU (SNAP 10A).

The following information is presented for each fuel type:

- o Composition
- o Mass and power densities, specific activity
- o Melting point
- o Crystalline phases
- o Thermal conductivity
- o Material compatibility and reaction summary

H.2 METALLIC PLUTONIUM FUEL

H.2.1 Fuel Description

Metallic plutonium fuel in a melt cast form is used in Transit 4A/4B (SNAP 3) and Transit 5BN1/5BN2 (SNAP 9A).⁽¹⁾ This fuel form and associated RTGs were designed for reentry burnup.

H.2.2 Fuel Composition

The composition of metallic plutonium fuel has been assumed to be 75% Pu-238 and 25% Pu-239.

H.2.3 Physical Characteristics

Density	19.82 g/cm ³ @ 20°C
	16.70 g/cm ³ @ 480°C
Melting Point	640°C
Specific power	16.8 Ci/g
	0.545 w/g

H.3 PuO₂ MICROSPHERE FUEL

H.3.1 Fuel Description

Pu-238 in the form of plasma-fired PuO₂ microspheres was used in the SNAP 19 RTG onboard Nimbus III.

H.3.2 Fuel Composition

No information was available on the isotopic composition of PuO₂ microsphere fuel. Therefore, the same isotopic composition used for PPO fuel, presented in Section H.5, was assumed in this case.

H.3.3 Physical Characteristics

Density	
Particle	9.8-10.4 g/cm ³
Bulk	6.7 g/cm ³
Melting Point	2150-2355 °C
Specific Power	0.37-0.42 W/g
	11.2-12.7 Ci/g
Power Density	2.5-2.8 W/Cc

H.4 PLUTONIUM MOLYBDENUM CERMET FUEL

H.4.1 Fuel Description

Plutonium molybdenum cermet (PMC) fuel is made by coating PuO_2 particles with molybdenum by chemical deposition and then hot pressing the coated particles into discs. ^(2,3) PMC fuel has been used in the Transit Triad RTG.

H.4.2 Fuel Composition

- (1) PuO_2 81-84% (84% assumed)
- (2) Mo 16-19% (16% assumed)
- (3) Composition of PuO_2
 - Pu 88.15-88.36% (88.36% assumed)
 - O 11.64-11.85% (11.64% assumed)

(4) Composition of Pu

<u>Isotope</u>	<u>wt %</u>
Pu-236	10^{-4}
Pu-238	80
Pu-239	16.5
Pu-240	2.5
Pu-241	0.8
Pu-242	0.1

H.4.3 Physical Characteristics

Density 10.4 g/cm³

Melting Point

PuO_2 Phase	2300 °C
Mo Phase	2620 °C

Specific Power	0.30	w/g
Power Density	3.2	w/cm ³ (minimum)

H.5 PURE PuO₂ FUEL

H.5.1 Fuel Description

PPO fuel is a hot pressed and sintered form of PuO₂ used in the MHW-RTG for LES 8/9. (5.6)

H.5.2 Fuel Composition

- (1) Oxygen 11.8 wt%
- (2) Plutonium 87.2 wt%

<u>Isotope</u>	<u>wt %</u>
Pu-236	0.00012
Pu-238	80.3
Pu-239	15.9
Pu-240	3.022
Pu-241	0.643
Pu-242	0.132

- (3) Impurities 1 wt%

<u>Isotope</u>	<u>wt %</u>	
Am-241	0.0033	
Np-237	0.130	
U-2434	0.14	
Pu-231	0.1211	
Th-232	0.1211	
U-233	0.1211	Assumed percentages
U-235	0.1211	
U-236	0.1211	
Ac-227	0.1211	

H.5.3 Physical Characteristics

Density

Theoretical	11.46	g/cm^3
Actual	9.05	g/cm^3
Melting Point	2400	$^{\circ}\text{C}$
Boiling Point	3870	$^{\circ}\text{C}$
Specific power	0.40	W/g
	12.1	Ci/g
Power density	4.58	W/cm^3 (initial)

H.6 GROG PuO₂ FUEL

H.6.1 Fuel Description

Grog fuel is a hot pressed and sintered form of PuO₂ that will be used in the GPHS-RTG on the Galileo Mission and International Solar Polar Mission.⁽⁷⁾ It differs from PPO fuel in that the Pu-238 has been increased from 80.2 to 83.5% of the plutonium. Furthermore, the structure is more heterogenous, consisting of larger size fuel pieces in a fine fuel matrix. The structure is designed to improve the impact response of the fuel.

H.6.2 Fuel Composition

- (1) Oxygen 11.8 wt%
- (2) Plutonium 87.2 wt%

<u>Isotope</u>	<u>wt %</u>
Pu-236	0.0001
Pu-238	83.6
Pu-239	13.85
Pu-240	1.95
Pu-241	0.45
Pu-242	0.14

- (3) Impurities 1 wt%

<u>Isotope</u>	<u>wt %</u>	
Am-241	0.0033	
Np-237	0.130	
U-2434	0.140	
Pu-231	0.1211	
Th-232	0.1211	
U-233	0.1211	Assumed percentages

U-235	0.1211	Assumed percentages
U-236	0.1211	
Ac-227	0.1211	

H.6.3 Physical Characteristics

Density		
Theoretical	11.46	g/cm ³
Actual	9.46	g/cm ³
Melting Point	2400	°C
Boiling Point	3870	°C
Specific power	0.42	W/g
	12.6	Ci/g
Power density	4.78	W/cm ³ (initial)

H.7 ZrHU FUEL

The fuel used in the SNAP-10A reactor is ZrHU, consisting of approximately 90% Zr and 10% U.⁽⁸⁾ The uranium is enriched to 93.15% U-235. No additional information was considered necessary to support the evaluations presented in the main text and Appendix D.

H.8 REFERENCES

1. Martin Marietta Nuclear Division, SNAP 9A Radioisotope-Fueled Generator, Final Safety Analysis for Transit Mission, MND-P-2775-2 (March 1963).
2. Mound Laboratory, Summary Report on SNAP-19B (IRHS) Program, MLM-1600 (June 27, 1969).
3. TRW Systems Group, Transit RTG Final Safety Analysis Report, TRW(A)-11464-0491 (March 1, 1971).
4. Keenan, T. K., R. A. Kent, and R. N. Mulford, Data Sheets for PMC Radioisotopic Fuel, Los Alamos Scientific Laboratory, LA-4976-MS (June 1972).
5. General Electric, Multi-Hundred Watt Radioisotope thermoelectric Generator Program, Final Safety Analysis Report for LES 8/9, GEMS-419 (March 1975).
6. Keenan, T. K., R. A. Kent, R. N. Mulford, and M. W. Shupe, Data Sheets for PPO Radioisotope Fuel, Los Alamos Scientific Laboratory, LA-5160-MS (December 1973).
7. General Electric, Preliminary Safety Analysis Report for the International Solar Polar Mission, GEMS-80SD54228 (March 1980).
8. Atomics International, Final Snapshot Safeguards Report, NAA-SR-10022.