WEINER ASSOCIATES, INC.

PROF. ENGINEERS
STATE OF MD.

3914 HICKORY AVENUE • BALTIMORE, MD. 21211

TELEPHONE: 301-889-3327

MASTER

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A REVIEW AND EVALUATION OF TRW SAFETY
ANALYSIS REPORT, VOLUMES I AND II FOR
THE PIONEER RADIOISOTOPE HEATER UNIT

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I. INTRODUCTION

In order to maintain a proper temperature balance on the Pioneer F and G spacecraft, a one-watt PuO_2 Radioisotope Heater Unit (RHU) is being designed and fabricated by TRW Systems and Mound Laboratory, Monsanto Research Corporation. A complete aerospace nuclear safety study was performed by TRW with the assistance of the Sandia Corporation and NASA Ames Research Center. The purpose of this report is to review the TRW Safety Analysis Report, Volumes I and II, in depth, to determine if all potential accident situations are adequately satisfied and to comment on the radiological consequences of all potential environments. As such, this represents the judgment of Weiner Associates, Inc. on the aerospace nuclear safety position of the RHU.

Each Pioneer RHU consists of one thermal watt of PuO_2 which is contained within a sealed, metallic capsule and graphite re-entry protection materials. The design and safety analyses of the RHU assumed that solid solution cermet fuel (SSC) would be used, although plutonia molybdenum cermet (PMC) may be used. From a safety standpoint, the PMC fuel and SSC fuel are reasonably similar. In some cases, such as fines production, the PMC should be better than SSC. Nominally, a total of eleven RHU's, representing a fuel inventory of 334 curies are required for each of the Pioneer F and G spacecraft. Nine RHU's are used in the Thruster Cluster Assemblies (TCA's) of the spacecraft propulsion subsystem, and one each is used in the Sun Sensor Assembly and Magnetometer. Additionally, two RHU's may be required on the Propellant Tank, thus raising the total to thirteen RHU's per spacecraft.

The design of the RHU is shown in Figure 1-1, reproduced here. The RHU is a cylinder which is 0.87 inch in diameter and 1.85 inches long and operates at temperatures of less than 200°F . The total weight of each RHU is 0.12 pound. The capsule is sealed, and the helium which is generated by the radioactive decay process is contained within the capsule.

II. SUMMARY OF PROGRAM CONCLUSIONS

TRW states that all prelaunch accidents, such as handling and shipping, can be eliminated from consideration since their environments are less severe than ascent and launch environments (although air transport was not considered for Transit). Therefore, they were not analyzed. Based on the experience of the Transit RTG, this assumption is reasonable (See Section III).

The key safety problems are associated with the launch pad and ascent aborts. A summary (WAI's review) of launch pad and ascent environments and how they were analyzed by TRW is presented in Table 1.

It is stated in Volume I that under certain unlikely conditions, fuel may be released from the RHU's as a result of (1) a launch pad abort

Figure 1.1. One Watt Radioisotope Heater Unit

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TABLE 1
PROBLEMS ASSOCIATED WITH PRELAUNCH, LAUNCH, AND ASCENT ABORT OF PIONEER RHU'S
AND COMPARISON OF COVERAGE IN TRW SAR

Phase	Environment	Environment Magnitude	How Analyzed in SAR	Comments
Launch Pad	(1) Mechanical			
	(a) Overpressure	808 psia from a TE364-4 explosion, based on a 10% TNT equivalence.	RHU in a simulated TCA assembly was exposed to TNT blast; peak pressure 915 psia.	Based on the theoretical blast overpressure, calculations (which have conservative assumptions), the RHU will survive the booster explosion.
	(b) Shrapnel	Worst case was calculated to be piece of shrapnel (6Al4V Titanium) at 1850 ft./sec., using Gurney's equations.	Pieces of 6Al4V Ti were fired into bare capsule at 1850 ft./sec.; capsule was not breeched.	Calculation of shrapnel velocities is very tenuous, based on the analytical methods available. However, it is felt that the value of 1830 ft./sec. is probably conservative.
	(c) Impact	Terminal velocity is 130 ft./sec. at sea level.	Impact tested at 125% terminal velocity into hard target (0°, 45°, 90°).	No breach of capsule seems probable for launch pad impact, which will be less than terminal velocity.
	(2) Thermal/Chemical			
	(a) Liquid Propellant Fire	Heat flux vs. time for fireball as given in Figure 2-24; no discussion of chemical effects.	Thermal model analysis plus oxygen-acetylene plus oxygen-propane torch tests.	Neither the thermal analysis or the torch experiment can simulate the actual fireball chemistry and its corrosive effects. Torch tests must be considered inadequate. Resultant hazards analysis is summarized in Table 4-2. However, the conclusion that the capsule remains intact in the fire appears reasonable.

Table 1 - (continued)

Phase	Environment	Environment Magnitude	How Analyzed in SAR	Comments
Ascent	(b) Solid Propellant Fire	Contact with piece of solid propellant 11 inches thick.	Thermal model analysis and solid contact fire tests with TE 364-4 propellant.	Bare capsule could be breeched if this improbable event occurs. As indicated in Table 4-2, this results in the maximum isopleth area.
	(c) Residual Fire	Heat flux of 13 BTU/ft. ² -sec. for up to 1 hour.	Oxygen-propane torch tests.	
	(1) Mechanical			
	(a) Impact	Terminal velocity is 130 ft./sec. at sea level; TE364-4 motor could cause impact up to 400 ft./sec.	Impact tested at 125% terminal velocity into hard target (0°, 45°, 90°).	Breach of capsule alone, if impacted into hard rock formation does not appear likely. However, if the capsule (RHU) impacts attached to the spacecraft and 4th stage motor, a breach could result if it impacted concrete or granite. Most likely impact medium at ETR launch site is sand or water at this I.I.P.
	(2) Thermal			
	(a) Re-entry	Various heating and thermal stress environments are possible depending on conditions (velocity and angle) of abort.	Thermal model analysis, thermal-stress analysis, hyperthermal arc tunnel testing; AC plasma torch testing.	Both AC plasma torch and DC hyperthermal arc, while capable of achieving very high heating rates, cannot produce accurate ablation data of POCO graphite. This is especially true as higher re-entry velocities and heating rates are achieved. Consequently ablation analyses are only estimates at best. However they are considered safe.

which involves burning of the third-stage propellant, (2) an ascent abort which leads to a grazing re-entry 25 months or more after fuel encapsulation, or (3) a random orbital decay 20 years or more after fuel encapsulation. WAI feels that re-entry from a many skip re-entry could cause excessive ablation of the graphite heat shield, especially with the uncertainty of high velocity ablation data. However, all re-entry releases do not produce a hazard greater than 1 MPB, and whether additional releases can occur should not detract from the overall safety evaluation of the RHU's.

A comparison of TRW's conclusions and WAI's conclusions on the various safety events is given in Table 2.

III. PRELAUNCH ACCIDENT EVALUATION

One potential hazard not considered or referenced by TRW was air transport of the RHU's in the Pioneer spacecraft enroute from NASA-Ames to the ETR facility. The Transit RTG program considers all transportation accidents except air transport. The type of environment that could be encountered as a result of an aircraft crash would be:

- A. Impact--velocities could be on the order of supersonic speeds or higher for a power down attitude of a subsonic jet transport craft. Power down impact would be the worst case, although the probability of occurrence is very low. Impact tests have been performed up to 400 ft./sec. for the RHU's. The anticipated power down impact velocity could be 1,000-1,500 ft./sec. based on available air crash data. However, much of the impact energy would be absorbed by the aircraft. Additional impact protection would be supplied by the Pioneer spacecraft. The potential source term for an air crash could be calculated from Figure 4-1 of Volume II, reproduced here. This does not account for the energy absorbed by the aircraft. It is possible, however, for the impact source term to be 4-5 times larger than the impact at 400 ft./sec. analyzed to .667 curies. As indicated in Table 4-2, the isopleth area for lung retention for impact at 400 ft./sec. is lower than for a solid propellant fire. However, for completeness, TRW should calculate the isopleth areas for ground release, meteorological conditions 1 and 2, for a source term of $5 \times .67 = 3.35$ curies.
- B. Fire--It is unlikely that the thermal environment of an aircraft fire would be more severe than the Atlas-Centaur prompt and residual fire. The RHU capsule survived the simulated prompt fire and a one-hour residual fire of approximately 1,850°F. The one-hour fire of 1,850°F is more severe than the maximum fire environment that could result from an airplane crash.

- SSCS FUEL PUCKS IMPACTED INDIVIDUALLY (REF. 4-2)
- △ SSC FUEL PUCKS IMPACTED INDIVIDUALLY (REF. 4-1, 4-3)
- SSCS MULTIPLE NUMBERS OF FUEL PUCKS IMPACTED TOGETHER (REF. 4-4)
- — ESTIMATED RHU CURVE FOR SSC MULTIPLE NUMBERS OF FUEL PUCKS IMPACTED TOGETHER

Figure 4-1. Percentage of Fuel Fines Generated by Impact

TABLE 2

COMPARISON OF WAI CONCLUSIONS WITH TRW CONCLUSIONS
FOR VARIOUS ABORT ENVIRONMENTS

Safety Event	Importance	TRW Conclusion	WAI Conclusion
Transportation	Medium	All are less severe than launch and ascent environments.	Release of fuel from air crash during transportation is possible. Probability is low. It is suggested TRW redo fallout analysis with larger source term.
Shock Overpressure	High	RHU will survive launch vehicle explosion.	WAI concurs based on tests performed.
Shrapnel Impact	High	RHU strength member and inner liner will survive shrapnel impact.	WAI feels that this is probably the case, although no accurate method of calculating shrapnel velocity is available.
Liquid Propellant Fire	High	RHU capsule will not fail in liquid fire.	WAI concurs.
Solid Propellant Fire	High	RHU capsule could release fuel if exposed directly to large piece of solid propellant.	WAI concurs based on tests performed and the possibility of creep failure of strength member.
Impact	High	Breech of capsule could occur if impacts attached to Pioneer spacecraft. Terminal velocity impact will not breach capsule.	WAI concurs.
Re-entry	Medium	RHU will survive all possible re-entry environments.	WAI has some reservations on calculation of aerodynamic heat rates and ablation. However, no appreciable fallout hazard occurs.

IV. REVIEW OF VOLUME II--SAFETY ANALYSES AND TESTSA. Explosive Overpressure Environment

It is concluded that the Atlas-Centaur stage will have a 20 percent TNT equivalence and the solid propellant (TE 364-4) a 10 percent TNT equivalence, based on the literature reviewed. It is mentioned on page 2-3 that higher yields have been obtained from the Project PYRO data. To be conservative, a higher yield for the Atlas-Centaur stages should be used. However, Table 2-1, reproduced here, indicates that the maximum overpressure results from the solid propellant blast, and the use of a 20 percent yield instead of a higher yield is a reasonable approximation based on this table.

Table 2-1. Peak Static Overpressures

<u>Stage</u>	<u>TNT Equivalent Yield (percent)</u>	<u>Peak Static Overpressure (psia)</u>
Atlas	20 (spherical charge)	203
Centaur	20 (spherical charge)	280
TE 364-4	10 (hemispherical charge)	808

The peak static overpressure of 808 psia, which the RHU could experience as a result of a TE 364-4 ground blast, was selected for the overpressure test performed at Sandia. Based on the test performed on overpressure, it seems unlikely that the RHU capsule could be breached by a launch pad abort.

B. Shrapnel Penetration

One of the most difficult areas in a launch pad abort is the shrapnel velocity, produced by the blast. To date no accurate mathematical analysis technique is available to calculate shrapnel velocities for complex geometries and when blockage (of the spacecraft) is considered. The analytical methods available consider either spherical or slab geometries as discussed in the SAR on page 2-18. It is felt that the shrapnel velocity obtained by using the equation on page 2-18 is conservative since it assumed that all of the blast energy is imparted to the casing mass. However, it is also assumed that the shrapnel size distribution is uniform.

A more meaningful value might be the calculation and testing to find the threshold kinetic energy (mass, velocity) required to penetrate the RHU capsule. This could then be compared with maximum credible shrapnel energies. As is, the margin of safety, based on the calculated impact velocity of 1,850 ft./sec. is not known.

This information (margin of safety) could be more meaningfully used to assess shrapnel survival capability.

Hence all that can be said here is that the capsule survival shrapnel energies which were anticipated through very approximate computations and any safety factor on the capsule is unknown.

However, the ultimate hazard from a shrapnel breach of a RHU has been shown to be quite low and hence uncertainties here can be tolerated.

C. Liquid Propellant Fire

A study of simulating liquid propellant fireballs in a test chamber was made in Reference 1, and it was concluded that the upper limit temperature and heat flux environment can be predicted by the PYRO tests and the TRW model (Reference 2). Some variances between PYRO and theoretical analyses exist, as well would be expected, but the theoretical calculations are generally higher and thus conservative. Figure 1 is a comparison of heat flux vs. time for the TRW model and PYRO data extrapolations for a Saturn V abort. The upper limit curve compares to Figure 2-24 on the Pioneer SAR with the difference being that Figure 2-24 is for a total propellant of 299,000 lb. for the Atlas-Centaur.

One area that was found to be very vague was a knowledge of the transient chemical environment in the fireball and its effect on materials. In general, many of the combustion products in the fire are still reacting for some time after ignition. The equilibrium species for a Saturn V fireball are given in Table 3, based on the TRW (reference 2) model, as a function of time. It can be seen that the equilibrium chemistry varies considerably with time. The failure of the oxygen-acetylene and oxygen-propane tanks to duplicate this chemical environment is one limiting feature of this type of testing. Also, the average heat flux (200 BTU/ft.² for 9 seconds) technique equal to the integrated area of Figure 2-24 for 9 seconds is not sufficient in simulating the proper thermal response. As can be seen in Figure 2-25 of the SAR, the temperature response is very rapid in the first few seconds of exposure to the fire. Thus, in order to get a good thermal response, the curve as shown in Figure 2-24 must be followed. It would be a good idea to rerun the thermal analyses as shown in Figure 2-25 (reproduced here) for the torch test heat flux profile and see the temperature variations of the thermal model.

1. Conclusions of Liquid Propellant Model

- a. The thermal flux for an Atlas-Centaur abort can be predicted with reasonable confidence.

TABLE 3
TRW THERMAL EQUILIBRIUM CHEMICAL SPECIES
IN THE SATURN V FIREBALL - (Ref. 2)

Time (sec.)	Species Concentrations (Mole. Fraction)*								
	H ₂ O	CO	H ₂	H	CO ₂	OH	N ₂	O ₂	O
0	.36	.25	.21	.07	.06	.04	-	-	.008
10	.41	.17	.12	.009	.09	.006	.18	-	-
22	.36	.03	.013	-	.16	-	.447	-	-
32	.29	-	-	-	.143	-	.53	.03	-

*Only species with concentrations greater than .005 (Mole. Fraction) are shown.

Figure 1. SATURN V FIREBALL HEAT FLUX vs. TIME

RADIANT HEAT FLUX ~Btu./Ft. - Sec.

Time ~ Sec.

Figure 2-25. Temperatures Due to Launch Pad Abort Fireball

- b. The chemical species concentration and its corrosive effect on the RHU materials is not known.
- c. The chemical environment of a liquid propellant fire is not duplicated in the torch experiments.
- d. The technique of using a lower heat flux for a longer time is not entirely appropriate in predicting the temperature response of the RHU, both with the re-entry heat shield and the bare capsule. However, the overall conclusion that the capsule survives the liquid fire, even without the graphite removal, appears valid.

D. Solid Propellant Fire

A review of the thermal analysis and the solid propellant fire tests performed at Sandia indicates the possibility that a breach of the capsule will occur if the graphite heat shield is removed by the blast overpressure and/or shrapnel when rupture is considered. If the heat shield stays on, a breach is not credible. The key safety question is: "Can a bare heat source land on top of a large piece of burning solid propellant?" This can only be assessed qualitatively, i.e. the probability of a bare capsule landing on a large piece of burning propellant is very, very unlikely.

Unfortunately, from an overall review standpoint, the maximum radiological hazard occurs from a solid propellant fire breach as illustrated in Table 4-2 of the SAR.

The suggestion is that, due to the very low probability of the above mentioned accident occurring (no quantitative probability can accurately be generated), the possibility of breach of the capsule from a solid propellant fire should not prevent obtaining launch approval since downrange fallout seems to be within acceptable limits.

The problem could be partially resolved by thickening the T-III strength member to .080 inches, the same thickness as the Transit capsule which survived the solid propellant fire test in good shape. However, this solution would require slight enlargement of the RHU storage tubes in the TCU and Sun Sensor assemblies. NASA cooperation would be required.

E. Re-entry Environment

A significant amount of work was done to define the abort conditions of the launch vehicle, defining the initial re-entry conditions, calculating the breakup altitude of the Pioneer spacecraft, analyzing thermal response of the RHU's when released, analyzing ablation for various releases and testing the RHU's in DC-hyperthermal arc tunnel and in an RF plasma torch.

The matrix of initial re-entry conditions, based on the Pioneer spacecraft, is indicated in Figure 3-10, reproduced here. It can be seen that prompt re-entry, skip re-entry or earth escape can occur. It does not appear that the altitude of breakup of the Pioneer spacecraft can greatly affect the total aerodynamic heating to the RHU, and analyzing the re-entry of the RHU alone is a good approximation (usually conservative).

1. Ablation of RHU heat shield

Based on Table 3-9 of Volume II, there is sufficient graphite thickness to survive the re-entry environments selected for analysis. However, no analysis of total ablation vs. the number of skips before final re-entry was made, similar to the SNAP-27 multi-skip re-entry. A maximum number of skips up to 17 was considered. However, if more skips occur, the total amount of ablation could exceed the POCO graphite thickness.

A specific statement by TRW as to the accuracy limits of its trajectory analysis relative to skip re-entry should be supplied.

2. Plasma Testing Program

Both the NASA-Ames hyperthermal arc tunnel and an RF plasma torch were used to simulate the re-entry thermal environment. Much higher heating rates were achieved with the RF torch (at lower gas flow rates). Heating rates up to 3,190 BTU/ft.²-sec. were achieved with the Tafa RF torch. This corresponds to a high speed, steep angle re-entry. The main objective of this type of setting is to simulate the thermal shock environment of superorbital re-entry to determine if cracking of the graphite heat shield occurs.

The hyperthermal arc tunnel simulates the flow environment to some extent, but the pressure is substantially lower than the real re-entry pressure. Thus, the amount of ablation is not comparable to actual re-entries (although some scaling of the ablation results to real re-entry can usually be made).

3. Conclusions of Re-entry Analysis

In addition to the mentioned failure case of grazing re-entry after 25 months or orbital decay re-entry after 20 years, a multiple skip re-entry after a large number of skips could erode the graphite away. The number of skips required has not been determined.

However, as shown in Section 4 of Volume II, no significant radiological hazard seems to result from a re-entry abort because of the small inventory of all the RHU's on the Pioneer spacecraft.

Figure 3-10. Reentry Conditions Resulting from Ascent Malfunctions

F. Impact and Post-Impact

Based on the impact tests performed, it does not appear that a breach of the capsule can occur if the RHU re-enters alone. The only case where a breach could result is if the RHU remains attached to the spacecraft for an early ascent abort. Impact velocities up to 400 ft./sec. were considered possible.

For the RHU impacting alone, the T-111 will contain the fuel for a long period of time. Burial and fuel meltdown does not appear to be a problem. Much of the Transit RTG oxidation data, although at a higher temperature, is applicable.

The low terminal velocities (130 ft./sec.) of the heat source are very beneficial in that they not only do not breach the strength member but assure survival of the outer clad as well. This fact, coupled to the low operating temperatures of the capsule, assure no releases from post-impact oxidation. This is a serious problem in other heat source designs at higher temperatures and with larger inventories.

G. Hazards Analysis

The hazards analysis was concerned with defining, for cases where a release can occur, the quantity and characteristics of released PuO_2 fuel, tracing the released material to the point at which it interacts with man, and defining the nature, extent, and probability of interaction. Such interaction may be in the form of (1) inhalation or ingestion of nuclear material which will cause radiation to internal organs and/or (2) external radiation to the body or parts of the body due to nuclear material which is deposited on the body or adjacent surfaces. In general, the most severe hazard occurs as a result of inhaling particles less than 4 microns in size, where the residence time in the lungs can be very long due to deep impregnation in the air sacs.

As discussed in the previous section of Re-entry Environment, another potential failure mode is multi-grazing re-entry; however, this is not considered of great importance since the maximum fallout concentration, even with very conservative assumptions, is quite low for all re-entry cases.

The calculation of source term for impact at 400 ft./sec. is reasonable based on the available information generated for the Transit RTG program for SSCS. If PMC is to be used instead of SSC, the source term should still be appropriate. PMC, in theory, should generate less fines than SSC for the same V^2 term.

A summary of meteorological conditions chosen was given in Table 4-1 and the hazards analysis summary in Table 4-2 of Volume II. Both are presented here for reference.

Table 4-1. Meteorological Data

Potential Accident Phase	Release Mechanism	Particle Size (Microns)	Meteorological Condition					
			(1) Average Condition			(2) Worst Case Condition		
			Release Height (Meters)	Stability	Wind Speed (Meters/sec)	Release Height (Meters)	Stability	Wind Speed (Meters/sec)
Launch	Liquid Fireball	<4.6	100	D	5	100	F	2.5
			200	D	5	100	F	2.5
Pad Abort	Solid Propellant Fire	Vapor	25	D	5	25	F	2.5
	Impact	<4.6	0	D	5	0	F	2.5
Reentry	Melt	<4.6	45 Km Altitude Release, Atmospheric Dispersion confined to one Hemisphere					
	Impact	Same as Launch Pad Abort						

Table 4-2. Hazards Analysis Summary

Potential Accident Phase	Release Mechanism	Particle Size (Microns)	Source Term (Curies)	Release Height (Meters)	Meteorological Condition	LUNG RETENTION (v C1)									
						Maximum Value				0.016			0.000533		
						Value	Isopleth Area (km ²) Max. Val./2	Downwind Touchdown Distance (km)	Downwind Length (km)	Isopleth Area (km ²)	Downwind Touchdown Distance (km)	Downwind Length (km)	Isopleth Area (km ²)	Downwind Touchdown Distance (km)	Downwind Length (km)
Launch Pad Abort	Liquid Fireball	<4.6	1.07	100	1	1.93 x 10 ⁻⁴	3.4	1.47	6.8	0	-	0	0	-	0
				100	2	1.12 x 10 ⁻⁴	138.7	5.2	86.3	0	-	0	0	-	0
				200	1	3.36 x 10 ⁻⁵	34.9	4.0	24.5	0	-	0	0	-	0
				200	2	1.01 x 10 ⁻⁵	>196.2	29.1	>70.9	0	-	0	0	-	0
	Solid Propellant Fire	Vapor	6.91	25	1	0.0305	-	0.5	-	0.062	0.264	0.80	9.35	0.110	11.6
				25	2	0.0438	-	1.5	-	0.659	0.559	4.27	260	0.317	116.0
	Impact	<4.6	0.67	0	1	(Maximum at point of impact)				0.010	0	0.325	0.50	0	2.4
				0	2					0.061	0	1.27	5.74	0	13.7
Reentry	Melt	<4.6	334	45,000	Long Settling Time	4.1 x 10 ⁻⁸	Hemisphere	-	-	0	0	0	0	0	0
	Impact									Less than launch pad abort.			Less than launch pad abort.		

1. Solid Propellant Fire

The details of the mass transport theoretical calculations to generate Figure 4-2 are not given. Past analyses of this type (Reference 3) have generally made some rather sweeping assumptions in order to get quantitative vaporization values. This is particularly true where the chemical environment is unknown, as is the case around the burning solid propellant.

It was also stated that "based on observations of the solid propellant fire test, it is estimated that the cloud rise is approximately 25 meters." It is unlikely that the solid propellant fire would occur without a liquid propellant fire. This added thermal effect (of the liquid fire) would significantly increase the release height to 100 meters or more and reduce the ground level concentration.

Thus the lung burden isopleths shown in Figures 4-4 to 4-6 for a solid fire release are quite conservative.

V. REFERENCES

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3. Williams, D. C., "Vaporization of PuO_2 in a Launch Pad Abort Fireball," Sandia Report SC-RR-68-441, August, 1968.