Title:

COMPARISON OF GENERAL PURPOSE HEAT
SOURCE TESTING WITH THE ANSI N43.6-
1997 (R 1989) SEALED SOURCE STANDARD

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Comparison of General Purpose Heat Source Testing with the ANSI N43.6-1977 (R1989) Sealed Source Standard

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March 26, 1998

Executive Summary

DOE Standard 1027 provides guidance for facility managers in complying with the requirements of DOE Order 5480.23. Attachment 1 to the DOE Standard allows for exclusion from the facility's radioactive inventory of material contained in sealed sources engineered to meet the requirements of ANSI N43.6. This paper provides a comparison of the testing of Radioisotope Thermoelectric Generators (RTGs) and RTG components with the testing requirements of ANSI N43.6-1977 (R1989) "Sealed Radioactive Sources, Categorization". Extensive testing of RTGs and RTG components has been performed to demonstrate the ability of RTGs to survive accidents related to Space Shuttle launches. The purpose of this comparison is to demonstrate that the RTGs meet or exceed the requirements of the ANSI standard for accidents in the Chemistry and Metallurgy Research (CMR) building at the Los Alamos National Laboratory, thus allowing the RTGs or RTG components to be excluded from the radioactive inventory in the CMR.

The following test specifications were chosen based on the accident analysis performed for the CMR Basis for Interim Operations:

Test		Specification for Class X
Temperature		> 600°C
Thermal Shock		No Test
External Pressure	Static	No Test
	Dynamic	100 psi
Impact		> 100 J
Vibration		No Test
Puncture		>350 J/cm ²

In all cases, the RTG or RTG component (specifically, the Fueled Clad) testing exceeds these specifications. Per the ANSI standard, Fueled Clad should be considered to be an ANSI sealed source with the designation ANSI 77EXXX1X.

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Introduction

This analysis provides a comparison of the testing of Radioisotope Thermoelectric Generators (RTGs) and RTG components with the testing requirements of ANSI N43.6-1977 (R1989) "Sealed Radioactive Sources, Categorization". The purpose of this comparison is to demonstrate that the RTGs meet or exceed the requirements of the ANSI standard, and thus can be excluded from the radioactive inventory of the Chemistry and Metallurgy Research (CMR) building in Los Alamos per Attachment 1 of DOE STD 1027-92.

The approach used in this analysis is as follows:

- describe the ANSI sealed source classification methodology,
- develop sealed source performance requirements for the RTG and/or RTG components based on criteria from the accident analysis for CMR,
- compare the existing RTG or RTG component test data to the CMR requirements, and
- determine the appropriate ANSI classification for the RTG and/or RTG components based on CMR performance requirements.

The CMR requirements for treating RTGs as sealed sources are derived from the radiotoxicity of the isotope (^{238}Pu) and amount (13 kg) of radioactive material contained in the RTG. The accident analysis for the CMR BIO identifies the bounding accidents as wing-wide fire, explosion and earthquake. These accident scenarios set the requirements for RTGs or RTG components stored within the CMR.

Background

Radioisotope Thermoelectric Generators utilizing the General Purpose Heat Source (GPHS) modular design have been used for space power applications on the Galileo, Ulysses and Cassini Missions. Figure 1 shows a schematic drawing of an assembled RTG. Figure 2 shows a schematic drawing of the GPHS assembly. For each mission, an independent Final Safety Analysis Report

Figure 1. Schematic Drawing of a General Purpose Heat Source RTG

Figure 2. Schematic Drawing of a General Purpose Heat Source (GPHS) showing two Fueled Clads (FCs) encapsulated a Graphite Impact Shell (GIS) and two GISs inserted into the GPHS.

(FSAR) has been prepared to document the hazard analysis and to describe the mitigations for the various accident scenarios associated with the space craft launch and re-entry (General Electric, 1988; General Electric, 1989; Lockheed-Martin, 1996). The accident scenarios for space applications include pre-launch fires and explosions, launch accidents (especially explosions) and spacecraft crashes. Extensive testing of RTGs and RTG components has been performed in support of the accident analyses. Because release of radioactive material from an RTG most likely results from failure of the Fueled Clad (FC) component, and since the bounding accidents involve fires, explosions, and crashes, most of the RTG and RTG component testing for space applications has focused on FC performance under conditions of dynamic stress.

As shown in Figures 1 and 2, the RTG consists of a stack of General Purpose Heat Sources (GPHSs) each of which contains four sintered $^{238}\text{PuO}_2$ fuel pellets. These fuel pellets are encapsulated in a vented iridium alloy shell (the iridium encapsulated fuel is called a Fueled Clad (FC)); two FCs are loaded into a Graphite Impact Shell (GIS); and two GISs are assembled into the GPHS. The FCs are currently fabricated at the plutonium facility, TA-55, at the Los Alamos National Laboratory before being sent to the Mound Plant in Ohio for final assembly and testing of the RTGs. A proposal has been submitted to the DOE to transfer the final assembly and testing of the RTGs to the CMR building in Los Alamos.

The CMR building is a hazard category 2 nuclear facility operated by the Nuclear Materials Technology Division (NMT) of the Los Alamos National Laboratory. NMT Division is currently developing a Basis for Interim Operations (BIO) for CMR as a step towards a Facility Safety Analysis Report (FSAR) that meets the requirements of DOE Order 5480.23. In anticipation of moving the final assembly and testing of RTGs to CMR, the BIO includes process descriptions and accident analysis for the proposed RTG final assembly and testing program.

The accident analyses of the BIO evaluate the potential for off-site release of radioactive materials due to a variety of accident scenarios. These analyses are used to determine the maximum amount of Material at Risk (MAR) allowed in any wing of the CMR. Because of its high specific activity, ^{238}Pu contained in a RTG would contribute significantly to the MAR inventory. However, DOE guidance for preparing an FSAR (DOE STD 1027, Attachment 1) states that "sealed radioactive sources that are engineered to pass the special form testing specified by the Department of Transportation (DOT) in 49 CFR 173.469 or testing specified by ANSI N43.6 'Sealed Radioactive Sources, Categorization,' may be excluded from summation of a facility's radioactive inventory." If the FCs can be shown to meet the requirements of either of these standards, the encapsulated ^{238}Pu is not counted as MAR in the Safety Basis of the facility.

Proposed LANL RTG Program

NMT division has proposed to bring the full process of assembling RTGs to LANL. This proposal involves extending the current work at TA-55 (producing iridium alloy encapsulated FCs) to assembling full GPHS units at TA-55. These GPHS units would then be welded into Module

Reduction and Monitoring Facility (MRMF) cans for shipment to CMR. At CMR, the MRMF cans would be opened as needed for assembly of the RTG. At a minimum, the units in CMR will consist of triply encapsulated material: the iridium encapsulated FC, the GIS encapsulation, and the GPHS (aeroshell) body. As mentioned above, most of the performance testing of RTGs has revolved around the FC, primarily because the iridium encapsulation is the most important and most competent of the layers preventing the release of radioactive material. In the present analysis, we will focus on the FC because that is where the bulk of the testing data exists. However, we should always remember that the GIS, the GPHS aeroshell and the RTG assembly all provide additional protection and encapsulation for the FC.

ANSI N43.6-1977 (R1989) Sealed Source Testing and Classification

The ANSI N43.6-1977 (R1989) standard, *Sealed Radioactive Sources, Classification*, provides methods for testing and classifying the performance of sealed sources depending on application. This standard specifies a series of increasingly severe tests of sealed source performance with respect to the following variables: temperature, external pressure, impact, vibration, and puncture. The classification of sealed sources is given in Table I (from the ANSI N43.6 standard). Depending on the environment to be encountered in normal usage, the radiotoxicity of the isotope in the sealed source, and the amount of material in the source, the required performance classification can be established following the ANSI standard. This evaluation for Fueled Clads is presented in Appendix A.

In addition to providing a scheme for classifying sealed sources, the ANSI standard specifies minimum acceptable procedures for performing the tests and for post-test integrity testing of the source(s). Alternative test procedures that are demonstrated to meet these minimum requirements are also acceptable for determining the performance classification numbers.

Required Performance Classification for Fueled Clads

The present analysis is focused on the assembly, testing and storage of RTGs within the CMR. Thus, the performance classification(s) of the FCs, GPHSs, and RTGs are determined by the major accident scenarios postulated in the BIO: wing-wide fire, explosion, and earthquake. The radiotoxicity of ^{238}Pu and the amount of material contained in a Fueled Clad and/or a full RTG suggest that the performance classification should be robust with respect to these major accident scenarios as summarized in Table II.

Temperature. The temperature requirements from Table I contain both temperature and thermal shock components. These components are separated in Table II for clarity. A FC/GPHS/RTG is designed to operate at temperatures well above the test requirements for temperature from Table I. However, the temperatures of fires can locally exceed the temperatures listed in Table I. Temperature testing requirements for FCs should demonstrate maintenance of

Table I - Classification of Sealed Source Performance Tests [from ANSI N43.6-1977 (R1989)]							
TEST	CLASS						
	1	2	3	4	5	6	X
Temperature	No Test	-40°C (20 min) +80°C (1 hr)	-40°C (20 min) +180°C (1 hr)	-40°C (20 min) +400°C (1 hr) and thermal shock 400°C to 20°C	-40°C (20 min) +600°C (1 hr) and thermal shock 600°C to 20°C	-40°C (20 min) +800°C (1 hr) and thermal shock 800°C to 20°C	Special Test
External Pressure	No Test	25 kN/m ² abs. (3.6 lb/in ²) to atmosphere	25 kN/m ² abs. to 2 MN/m ² (290 lb/in ²) abs.	25 kN/m ² abs. to 7 MN/m ² (1,015 lb/in ²) abs.	25 kN/m ² abs. to 70 MN/m ² (10,153 lb/in ²) abs.	25 kN/m ² abs. to 170 MN/m ² (24,656 lb/in ²) abs.	Special Test
Impact	No Test	50 g from 1 m and free drop ten times to a steel surface from 1.5 m	200 g from 1 m	2 kg from 1 m	5 kg from 1 m	20 kg from 1 m	Special Test
Vibration	No Test	30 min 25 to 500 Hz @ 5 g peak amp.	30 min 25 to 50 Hz @ 5 g peak amp. and 50 to 90 Hz @ 0.635 mm amp. peak-to-peak and 90 to 500 Hz @ 10 g	90 min 25 to 80 Hz @ 1.5 mm amp. Peak-to- peak and 80 to 2000 Hz @ 20 g	Not Used	Not Used	Special Test
Puncture	No Test	1 g from 1 m	10 g from 1 m	50 g from 1 m	300 g from 1 m	1 kg from 1 m	Special Test

integrity at temperatures approaching the temperatures of fires. For the CMR accident analysis, the maximum hot layer temperature is less than 600°C (CMR BIO Appendix E and Appendix F).

Thermal Shock. Operation of the fire suppression system or spraying a FC with water during firefighting could cause thermal shocks that might breach the iridium encapsulation. As discussed above, the minimum configuration of these units in CMR includes both the GIS and the GPHS aeroshell which provide a barrier between the FC and water released by the fire suppression system or firefighters. In addition, the proposal evaluation team has indicated that the RTG or components must be protected from exposure to water. We are currently investigating methods for providing this protection (probably via construction of an Inert Atmosphere Assembly Chamber (IAAC)). The GIS, GPHS aeroshell, RTG shell (when present), and IAAC will provide protection from direct exposure of the FC to water, thus mitigating the possibility of thermal shock to the FC.

External Pressure. The external pressure test from the ANSI standard is a static loading test. Because the FC/GPHS/RTG components will be stored at atmospheric pressure conditions, static loading is not an important issue. However, in an explosion, the response to a dynamic pressure or shock is an important consideration related to external pressure. For this reason, the external pressure requirements from Table I are separated into static and dynamic categories in Table II. For the final assembly, testing and storage of RTGs in CMR, static pressure categorization should meet Class 2. The dynamic pressure categorization should be consistent with overpressures expected in

Table II. Cross-walk Between ANSI N43.6 Environment Tests and the Major Accident Scenarios from the CMR BIO.

TEST	MAJOR ACCIDENT SCENARIOS		
	Wing-Wide Fire	Explosion (no fire)	Earthquake (no fire)
Temperature	X		
Thermal Shock	X		
External Pressure (Static)			
External Pressure (Dynamic)		X	
Impact		X	X
Vibration			
Puncture		X	X

an explosion. The CMR BIO evaluated the case of a methane explosion in a laboratory. Based on the energy release from 3.6 lb TNT equivalent, the peak overpressure from the explosion would be 8.4 psi and the peak temperature would be 238°C (Table 3.15, CMR BIO).

Impacts. Blunt impacts from flying debris (explosion) or from falling objects (earthquake) could rupture the iridium shell leading to a release of material. Impact categorization should be consistent with the likely velocity of debris or falling objects. An object falling from a height of 10 m (33 ft) would attain a velocity of 14 m/s.

Vibration. Failures of FCs resulting from vibration during fires, explosions or earthquakes are extremely unlikely, and vibration testing is not deemed necessary for the assembly, testing and storage of RTGs in the CMR.

Puncture. Punctures of FCs could result from flying debris (explosions) or falling objects (earthquake) in a manner similar to the impacts discussed above. The major difference between impacts and punctures is the contact area between the flying or falling object and the FC. Puncture categorization should be consistent with the size and velocity of debris or falling objects. As described above, an object falling from a height of 10 m would attain a velocity of 14 m/s. Another possible contributor to puncture would be a bullet fired from a gun. A table of projectile weights, calibres and muzzle velocities is presented in Appendix B.

RTG Testing

Testing of RTGs, GPHSs, GISs and FCs has largely been performed using simulated FCs made of depleted uranium oxide encapsulated in an iridium shell. These tests were performed with the simulated FCs heated to the normal operating temperature for FCs within RTGs ($\sim 1090^{\circ}\text{C}$); a bare FC in air has a temperature of approximately 300°C . In the discussion below, the term FC refers to a simulated FC heated to $\sim 1090^{\circ}\text{C}$ before the test.

Temperature Testing. Pavone and Seabourn (1983) reported the results of tests of a bare FC and of a GIS containing two FCs in direct contact with a solid rocket propellant fire. In these tests, the FC and GIS were initially heated to 1090°C . The fire lasted for approximately 10 minutes. None of the three FCs were breached in the fire.

Thermal Shock Testing. I have not found any reference to thermal shock testing of FCs.

External Pressure (Dynamic)/Shock Tube Testing. Bare FC modules and other configurations (initially at 1090°C) were tested in shock tubes using 13 to 300 pounds of C-4 explosives. Overpressures ranged from 200 psi to 2200 psi. For overpressures up to 1750 psi, no FCs were breached. These tests are summarized in Lockheed-Martin (1996) which refers to the original data sources. A copy of this summary is attached as Appendix H.

Impact Testing. An impressive series of tests of impacts with a variety of objects and surfaces is summarized in Lockheed-Martin (1996) (see appendix H) which refers to the original data sources. Impacts of bare FCs (starting temperatures of 1091°C) with concrete surfaces at velocities of 45-86 m/s showed no release of fuel. Gas gun tests of bare FCs at velocities of 100-120 m/s showed significant distortion but no breaches of the containment. Three large fragment tests were conducted by propelling a simulated solid rocket booster casing fragment (1.4 m square) with a rocket sled to impact a simulated section of an RTG. Fragment velocities ranged from 95 to 212 m/s. In the 115 m/s test, none of the eight FCs was breached. In the 212 m/s test, two of the eight FCs were breached. The post-test analysis indicated that these were breached from secondary impacts. In the 95 m/s test, two of the eight FCs were breached. In the RTG End-on Impact Test, full RTGs were accelerated by rocket sled at velocities of 57.6 and 77.1 m/s. The rocket sled was stopped abruptly approximately four feet in front of the concrete target wall. The RTGs left the sled when it stopped and crashed into the target wall. None of the 20 FCs from the 57.6 m/s test were breached; three of 24 FCs from the 77 m/s test were breached. The RTG shells in both tests were severely damaged.

Vibration Testing. Part of the RTG testing process includes vibration testing of the full RTG assembly. These tests are described briefly by Amos and Goebel, (1989). There is no requirement for vibration testing of the RTG or its components to meet the ANSI N43.6 standard for sealed sources.

Puncture Testing. George, et. al. (1985) reported a series of tests conducted with 18 g, 50-caliber, aluminum alloy bullets fired at velocities from 320 to 550 m/s at GPHS half modules. In two of the five tests, there was no breach of the FCs; in two other tests, the weld failed; in the fifth test, there was a large hole in the FC. George (1986) also reported a second series of tests conducted with 3.25 g, 30-caliber, titanium alloy bullets fired into bare FCs at velocities of 420 to 684 m/s. In two of the three tests (bullet velocities of 423 and 446 m/s), small breaching cracks were observed in the FC. In the third test (bullet velocity of 684 m/s), the FC was breached.

Analysis

Temperature. The normal operating temperature of a fueled clad is approximately 1090°C, and the testing described above for FCs exposed to a solid rocket fuel fire indicate that the FCs are robust at very high temperatures. No data has been found to indicate that the RTG or RTG components has been tested for thermal shock. However, the additional protection afforded by the GIS, the GPHS, and the RTG shell mitigates failures of the iridium shell due to thermal shock. The RTG testing far exceeds the ANSI N43.6 temperature testing requirements for sealed sources. The appropriate temperature classification for FCs (GPHSs and RTGs) is "X".

External Pressure (Static). No static pressure test has been identified, and none is required.

External Pressure (Dynamic). The RTG testing demonstrated that the FCs are not breached at overpressures of up to 1750 psi. The overpressure from an explosion in the CMR is calculated to be 8.4 psi. The RTG clearly exceeds this expected overpressure rating. The appropriate external pressure classification for FCs (GPHSs and RTGs) is "X".

Impact. Impact test requirements from Table I and test data for FCs were analyzed to provide a means of comparison between the tests and the ANSI criteria. The results of this analysis are summarized in Table 3. The final velocity for a free fall from 1 m was calculated to be 4.41 m/s ($d = v_0 t + \frac{1}{2}gt^2$). This velocity was used to calculate the momentum and energy of impact from the masses from the ANSI test. The class "X" calculation assumes a 1000 kg slab of 1 m diameter falling onto a FC from a height of 10 m. This object is equivalent to a 55 cm (22 in.) thick slab of concrete or a 16 cm (6.4 in.) thick slab of steel having a diameter of 1 m. This calculation further assumes that the impact absorbed by the FC is distributed among other objects having an equal stiffness as an FC. The FC test is a calculation of the impact of a 200 g FC moving at 45 m/s (the minimum reported velocity described in the RTG testing section) with a large stationary object.

As can be seen from Table 3, the actual test of the FCs exceeds the criteria for class 6 as well as the calculated impact from a falling slab. However, most of the impact testing of FCs occurs at velocities well above the 45 m/s chosen here. The RTG impact testing exceeds the maximum requirements of ANSI N43.6 for impacts. The appropriate impact classification for FCs (GPHSs and RTGs) is "X".

Table 3. Comparison of FC impact testing with ANSI N43.6 standard							
	ANSI N43.6 Class						FC test
	2	3	4	5	6	X	
mass (kg)	0.05	0.2	2	5	20	1000	0.2
velocity at impact (m/s)	4.41	4.41	4.41	4.41	4.41	14	45
energy of impact (J)	0.486	1.94	19.4	48.6	194	88.2†	203
† The energy of impact on the FC was reduced by the ratio of the area of the FC (7.07 cm ²) to the assumed area of the falling object (7584 cm ²).							

Vibration. Although extensive vibration testing of the RTGs is performed for performance and acceptance testing, there is no specific vibration testing performed on FCs. As stated above, no vibration testing is required for the CMR accident analysis. The appropriate vibration testing classification for FCs (GPHSs and RTGs) is "1", no test.

Puncture. Puncture test requirements from Table I and test data for FCs were analyzed to provide a means of comparison between the tests and the ANSI criteria. The final velocity for a free fall from 1 m was calculated to be 4.41 m/s ($d = v_0 t + \frac{1}{2}gt^2$), and the specified pin diameter is 3 mm. The velocity was used to calculate the energy of impact for the masses from the ANSI test, and the pin area was used to convert this energy of impact to an energy of impact per square centimeter. The Class "X" criteria are based on the .38 special hand weapon carried by the security police in CMR. The mass, velocity and impact area of a .38 calibre bullet were taken from Appendix B. The masses, velocities and impact areas for the aluminum and titanium bullets were taken from George, et al. (1985) and George (1986). The results of these analyses are summarized in Table 4. As can be seen from this table, the minimum test of the FCs far exceeds the criteria for class 6. The velocities used in the FC tests far exceed the velocities that might be expected from falling debris due to an earthquake and is within the velocity range used in evaluating the effects of debris from an explosion. The RTG impact testing exceeds the maximum requirements of ANSI N43.6 for impacts. The appropriate impact classification for FCs (GPHSs and RTGs) is "X".

Table 4. Comparison of FC puncture testing with ANSI N43.6 standard

	ANSI N43.6 Class						Al bullet	Ti bullet
	2	3	4	5	6	X		
mass (kg)	0.001	0.01	0.05	0.3	1	.0102	0.018	0.00325
velocity at impact (m/s)	4.41	4.41	4.41	4.41	4.41	259	320	420
energy of impact (J)	0.0097	0.0972	0.486	2.92	9.72	344	922	287
area of impact (cm ²)	0.071	0.071	0.071	0.071	0.071	0.73	1.27	0.454
energy per unit area (J/cm ²)	0.138	1.38	6.88	41.3	138	356	728	632

Conclusions

Extensive testing of RTGs and RTG components meets the requirements of ANSI N43.6-1977 (R1989) for classifying the FC as a sealed source in the application of assembly, testing and storage of RTGs within CMR. The performance criteria developed in this analysis are summarized as follows:

Table 5. Performance Specifications for Class "X" for RTGs and RTG components in the CMR building.

Test		Specification for Class X
Temperature		> 600°C
Thermal Shock		No Test
External Pressure	Static	No Test
	Dynamic	100 psi
Impact		> 100 J
Vibration		No Test
Puncture		>350 J/cm ²

Per the ANSI standard, the appropriate marking for the FC for this application is:

ANSI 77EXXX1X

References

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APPENDIX A
**ANSI N43.6-1977 (R1989) Procedure to Establish Classification
and Performance Requirements for a Fueled Clad as a Sealed Source**

1. Establish radiotoxicity group from Table 2¹.

From Table 2, the ²³⁸Pu is in Group A, High Toxicity.

2. Determine amount of activity allowable from Table 3¹.

From Table 3, the maximum activity allowable for a Group A isotope is 0.3 Ci leachable or reactive material and 3 Ci non-leachable or non-reactive material.

3. If the desired quantity does not exceed the allowable quantity of Table 3¹, an evaluation of fire, explosion, and corrosion probabilities shall be made. If no significant probability with respect to fire, explosion, and corrosion exists, the required classification for the source (performance requirements) may be taken directly from Table 4¹. If a significant probability does exist, the factors listed in 4.2¹ shall be evaluated with particular attention to the temperature and impact requirements.

Because the desired quantity of ²³⁸Pu in a Fueled Clad exceeds the Table 3 activity level, this section is not applicable.

4. If the desired quantity exceeds the allowable quantity of Table 3¹, an evaluation of fire, explosion or corrosion probability and a separate evaluation of the specific source usage and source design shall be made.

The RTG is designed to power space vehicles. The FCs (GPHSs and RTGs) are tested to ensure that the FC can contain the ²³⁸Pu fuel in the event of fire, explosion, and vibration that might be encountered in a launch and/or re-entry. Extensive testing of the FCs in explosions - including overpressure from shock, large fragment impact tests and small fragment impact tests - has been performed. Some testing of FCs and GPHSs in fires has also been performed. This testing is summarized in Appendix H of the Final Safety Analysis Report, Volume II, Book 2 of 2 for the GPHS-RTGs in support of the Cassini Mission.

For the purposes of this evaluation, the RTG needs to be able to withstand conditions appropriate for storage within the CMR, specifically, the bounding accidents evaluated in the accident analysis - wing-wide fire and earthquake. For these conditions, it is necessary that the FCs remain intact at high temperatures and that the FCs survive impacts from large, heavy objects.

¹Of ANSI N43.6-1977 (R1989)

5. After the required classification of the source for the particular application or usage has been established, the performance test conditions can be obtained directly from Table 1¹.

The application or usage for the fueled clad is assembly, testing and storage of RTGs in the CMR. Performance test conditions are established in the text.

6. Alternatively, the source may be tested, the source Class determined from Table 1¹, and some suitable application selected from Table 4¹. Sources of an established classification may be used in any application having less severe specific performance requirements (classification numbers).

Appendix B

Ballistics Information

Ballistic-Resistant Door Selection Chart

This chart, for comparative purposes, provides a compilation of the weapons and bullets against which Overly has

been required to test its products. In addition to UL, performance requirements were also established by NIJ (Standard 0108.01), the Naval Civil Engineering Laboratory (SAMIT), the U.S. Department of State (SD-STD-

01.01 and SD-STD-01.02), the U.S. Department of Defense (DOD Threat Levels 1 through 6) and other agencies. These requirements have been published but may either be classified or not generally available.

Overly Model	Weapon	Classification				Bullet(1) WT/grains	Muzzle (2) Velocity FPS	Energy At Impact Ft/Lbs.	No. of (3) Rounds	Impact Area(3)
		UL	Federal Agencies	NIJ	DOD					

Commercial Protection Levels

ULDF-1 SDM (6)	22LRHV			Type I	Threat Level 1	40 Lead	1050	98	5	12" circle
	.38 Special			Type I		158 RNL	850	253	5	12" circle
	.38 Special Automatic	MPSA				130 MCL	1280	475	3	4" circle
	12 Gauge Shotgun		SG	Type 1		#4 shot	1375	NA	3	on sample
	.357 Magnum			Type IIA		158 JSP	1250	548	5	12" circle
	.357 Magnum			Type II		158 JSP	1395	682	5	12" circle
ULDF-2 SDH (6)	.357 Magnum	HPSA			Threat Level 1	158 SPL	1450	740	3	4" circle
	9 mm			Type IIA		124 FMJ	1090	327	5	12" circle
	9mm			Type II		124 FMJ	1175	380	5	12" circle
ULDF-3 SDS(6)	.44 Magnum	SPSA			Threat Level 2	240 SPL	1470	1150	3	4" circle
ULDF-4 ULDF-4F(4) SDR(6)	30-06 Rifle	HPR			Threat Level 3	220 SPL	2410	2830	3	4" circle

Military Protection Levels

ARUT(5) ARSD-TPF ARSD-PPF ARSD-EPF	7.62 mm Rifle .308 Winchester (single round)			Type III	Threat Level 4	150 FMJ	2863	2727	5	12" circle
AR-5 (if specified)	7.62 mm Rifle .308 Winchester (five round)			Type III	Threat Level 5	150 FMJ	2863	2727	5	12" circle
	NATO 7.62 Rifle (one round)		SHPR			147 M80	2860	2223	3	4" circle
	NATO 7.62 Rifle (25 rounds)		SAMIT		Threat Level 6	147	2860	2725	25	8" circle
	7.62 Rifle Armor Piercing		SAMITAP	Type IV		150 M61AP	2860	2998	25	8" circle
	5.56 mm Automatic		SHPA			150 M193	3180	3850	3	8" circle
	9 mm Sub Machine Gun		SMG			115	1450	537	3	8" triangle

Notes:

- Abbreviations used in this chart: AP—Armor Piercing; FMJ—Full Metal Jacket; HPR—High Power Rifle; HPSA—High Power Small Arms; JSP—Jacketed Soft Point; LRHV—Long Rifle High Velocity; MCL—Metal Cased Lead; MPSA—Medium Power Small Arms; RNL—Round Nose Lead; SAMIT—Small Arms Multiple Impact Threat; SAMITAP—Small Arms Multiple Impact Threat Armor Piercing;

- Optimum muzzle velocity. UL permits deviation of +5% -10% of listed velocity. NIJ permits either +40 fps or +- 50 fps depending on armor type.

- Number of rounds and impact area shown is for opaque material. Additional tests are required for transparent materials.
- ULDF-4F is a fire-rated 3 hr. "A" label door unit.
- All models prefixed AR are attack-resistant and designed for varying applications.
- First listed door in each category is swinging model; SD series doors are sliding models.

Appendix H

Safety Test Results

APPENDIX H

RTG SAFETY TESTS

H.1 INTRODUCTION

This Appendix provides a summary of safety tests conducted to support safety analyses of the GPHS-RTG. Tests are identified as follows.

- a) Pre-1986 Tests
 - Shock Tube Tests
 - Fragment/Projectile Tests
 - Solid Propellant Fire Test
 - Bare Clad Impact Tests (BCI)
 - Module Impact Tests (DIT and SVT)
- b) Post-1986 Tests
 - Bare Clad Impact (BCI)
 - SRB Fragment Tests in Gas Gun (FGT)
 - Large Fragment Impact (LFT)
 - Fragment/Fuselage Tests (FFT)
- c) Cassini Tests
 - End-on Converter Test
 - Aluminum Fragment Test
 - Cold-Process Verification (CPV)

Results from these tests are summarized in the following paragraphs. A more detailed discussion of the safety tests conducted prior to the Galileo and Ulysses missions can be found in Appendix G of "Final Safety Status Report for the Ulysses Mission," Reference H-1.

H.2 PRE-1986 TESTS

H.2.1 Shock Tube Tests

Shock Tube Tests included both Bare Module Tests (BMT) and Converter Segment Tests (CST), as described in References H-2 through H-8. This test series evaluated the effects of a shock wave hitting the RTG as the result of an explosion. In the bare module tests, the test module was oriented with one of the side surfaces normal to the direction of shockwave propagation. On either side of the test module dummy graphite blocks were placed to simulate a stack of three modules. The test modules were heated to 1090°C, the temperature of the iridium clad at launch, before being subjected to static overpressure.

The first tests conducted in the Converter Segment Test series were conducted using a flat plate representation of a quarter section of the converter housing and thermopile. In

subsequent tests, beginning with CST-5, a cylindrical section of the converter, 14 inches long, was used as a simulation.

Test conditions for all of the shock tube tests are summarized in Table H-1 and test results are summarized in Table H-2. These shock tube tests use a C-4 high explosive to generate the shock wave. It should be noted that the test articles were impacted by the explosion products from the C-4 in addition to the shock wave. This would cause more damage than just the shock wave. In cases where the graphite was stripped away, its response is listed as "Free Flight Fuel Clads". For the bare module tests, post-test examination showed all of the fuel clads to be crack-free. Test results for the CST series of tests are summarized in Tables H-3 and H-4. For these tests, uranium fuel particle distributions are listed, both the coarse distribution and the distribution of fines below 10 microns in size.

Table H-1. Test Conditions for Shock Tube Tests

Test Designation	Overpressure (psi)	Impulse (psi-s)	Tube Length (ft)	HE Charge (lb C-4)
BMT-1	200 ± 10	1.22 ± 0.2	66	13
BMT-2	735 ± 30	3.2 ± 0.4	66	60
BMT-3	1070 ± 50	3.75 ± 0.5	66	110
CST-1	736 ± 70	3.2 ± 0.4	58	60
CST-2	1028 ± 100	3.75 ± 0.5	61	106
CST-3	1684 ± 300	4.2 ± 0.8	68	178.5
CST-4	1750 ± 175	4.0 ± 0.8	62	256.5
CST-5/RTG-1	1815 ± 180	4.0 ± 0.8	62	256.5
CST-6/RTG-2	1962 ± 190	3.36 ± 0.7	49	300
CST-7/RTG-3	1873 ± 360	3.4 ± 0.4	48	277
CST-8/RTG-4	429 ± 40	2.1 ± 0.4	64	27.5
CST-9/RTG-5	2212 ± 220	2.4 ± 0.5	48	205

Table H-2. Shock Tube Test Results

Test Designation	Overpressure (psi)	Response	Distortion Range(1)
BMT-1	200	No Graphite Damage	1.001 - 1.003
BMT-2	735	Minor Graphite Damage	1.002 - 1.029
BMT-3	1035	Free Flight Fuel Clads	1.003 - 1.020
CST-1	736	Free Flight Fuel Clads	1.022 - 1.069
CST-2	1028	Free Flight Fuel Clads	1.018 - 1.059
CST-3	1684	Free Flight Fuel Clads	1.052 - 1.113
CST-4	1750	Free Flight Fuel Clads	1.009 - 1.094
CST-5/RTG-1	1815	Free Flight Fuel Clads	1.082 - 1.104(2)
CST-6/RTG-2	1962	(5)	
CST-7/RTG-3	1873	Free Flight Fuel Clads	1.038(3)
CST-8/RTG-4	429	Retained in Graphite	1.004 - 1.055
CST-9/RTG-5	2212	Free Flight Fuel Clads	1.066(4)

- (1) Ratio of Major Diameter to Minor Diameter Post Test
- (2) 1 Clad Breached, Post Test (Not Measured for Ovality)
- (3) Three Clads Recovered Integral
- (4) One Clad Recovered Integral
- (5) Aborted Test

H.2.2 Fragment/Projectile Tests

These tests as described in References H-9 and H-10 were conducted to determine the effects of small fragments and projectiles impinging on the GPHS as a result of a launch vehicle explosion. Tests were initially conducted with FWPF plates to determine the velocity attenuation provided as a function of velocity, followed by tests of half-module targets using aluminum bullets, and tests of bare fuel clads using titanium bullets. The final test in this series was of an aluminum plate fragment impacting a GPHS module edge-on at a velocity of 3000 fps.

Table H-3. Coarse Particle Size Distribution from Converter Segment Tests

Urania Particle Size (Microns)		CST-1 (Clad 1)	CST-2 (IRG-128)	CST-3 (L-12)	CST-4 (L-10)	CST-5 (L-24)	CST-7 (M-35)	CST-8 (IRG-133)	CST-9 (M-46)	CST-9 (M-40)
		Weight Fraction								
	+6000	0.6774	0.9263	0.3567	0.8104	0.8407	0.8765	0.9009	0.1276	0.3726
-6000	+2000	0.1836	0.0437	0.1905	0.0580	0.0701	0.0818	0.0556	0.3027	0.2450
-2000	+ 841	0.0850	0.0179	0.2794	0.0572	0.0481	0.0242	0.0274	0.2912	0.2076
- 841	+ 420	0.0308	0.0058	0.1094	0.0394	0.0212	0.0075	0.0067	0.1374	0.0968
- 420	+ 177	0.0141	0.0033	0.0379	0.0228	0.0121	0.0045	0.0044	0.0825	0.0500
- 177	+ 125	0.0024	0.0007	0.0140	0.0037	0.0023	0.0011	0.0011	0.0177	0.0081
- 125	+ 74	0.0024	0.0009	0.0054	0.0037	0.0023	0.0011	0.0013	0.0179	0.0069
- 74	+ 44	0.0012	0.0004	0.0022	0.0018	0.0009	0.0007	0.0008	0.0080	0.0033
- 44	+ 30	0.0009	0.0003	0.0015	0.0010	0.0008	0.0005	0.0006	0.0052	0.0029
- 30	+ 20	0.0004	0.0001	0.0007	0.0005	0.0002	0.0004	0.0003	0.0019	0.0013
- 20	+ 10	0.0005	0.0002	0.0007	0.0006	0.0003	0.0006	0.0003	0.0026	0.0017
- 10		0.0013	0.0004	0.0017	0.0010	0.0008	0.0010	0.0006	0.0053	0.0039

NOTE: Distributions are corrected for impurities.

Table H-4. Urania Fine Particle Size Distribution from Converter Segment Test

Urania Particle Maximum Size In the Range (Microns)	(Weight Fraction)								
	CST-1 (Clad 1)	CST-2 (IRG-128)	CST-3 (L-12)	CST-4 (L-10)	CST-5 (L-24)	CST-7 (M-35)	CST-8 (IRG-133)	CST-9 (M-46)	CST-9 (M-40)
1.00	0.000169	0.000023	0.000218	0.000141	0.000108	0.000076	0.000030	0.000140	0.000235
2.00	0.000152	0.000038	0.000327	0.000318	0.000126	0.000056	0.000091	0.000273	0.000578
3.00	0.000199	0.000052	0.000293	0.000149	0.000133	0.000084	0.000117	0.000896	0.000737
4.00	0.000263	0.000046	0.000066	0.000173	0.000085	0.000134	0.000101	0.001021	0.000536
5.00	0.000128	0.000059	0.000100	0.000095	0.000066	0.000146	0.000054	0.001056	0.000390
6.00	0.000101	0.000035	0.000123	0.000018	0.000069	0.000078	0.000044	0.000668	0.000248
7.00	0.000032	0.000035	0.000039	0.000000	0.000055	0.000069	0.000026	0.000327	0.000113
8.00	0.000096	0.000030	0.000234	0.000043	0.000027	0.000021	0.000052	0.000487	0.000337
9.00	0.000068	0.000011	0.000083	0.000000	0.000077	0.000088	0.000019	0.000174	0.000359
10.00	0.000093	0.000030	0.000228	0.000085	0.000053	0.000282	0.000076	0.000238	0.000329

NOTE: Distributions are corrected for impurities.

H.2.2.1 FWPF Plate Tests

In these tests, 18 gram, 50 caliber aluminum alloy bullets were fired into FWPF graphite plates at velocities of 320, 633 and 900 m/s. The thickness of the plate used in each test (0.191 inches) corresponded to the minimum wall thickness of the GPHS aeroshell on the small face. The results of these tests are summarized in Table H-5.

Table H-5. Attenuation of Aluminum Bullet Velocity in FWPF Graphite Plate

Bullet Velocity (m/s)		Velocity Decrement	
Initial	Exit	(m/s)	(%)
320	288	32	10.0
633	580	53	8.4
900	832	68	7.5

H.2.2.2 Aluminum Bullet Tests

A series of tests were conducted in which 18 gram, 50 caliber, blunt-nose aluminum alloy bullets were fired into GPHS half-module targets containing fueled clads with depleted uranium fuel simulant. The iridium clads were pre-heated to their launch temperature of 1090°C. The test conditions and post-test strains of the target clads are listed in Table H-6.

Table H-6. Summary of Aluminum Bullet Tests Using Half-Modules

Test No.	Temperature (°C)	Velocity (m/s)	Clad ID	Bullet Contact Area (mm) ²	Remarks
1	1091	319	IRG-113	93	No breach
2	1030	415	IRG-119	288	Weld unzipped over 330° Crack 2.5 mm wide Small area of Ir/Al reaction
3	1080	458	IRG-130	342	Large hole (10 x 3.5 mm) Brittle Ir/Al Intermetallic
4	1060	460	IRG-111	266	No breach, small area of Ir/Al reaction
5	1120	550	IRG-112	169	Hairline crack (6.0 mm long) and along weld center line (4.0 mm long) No Ir/Al reaction

H.2.2.3 Titanium Bullet Tests

These tests were conducted using a 3.25 g (0.007 lb), 30-caliber, blunt-nose titanium alloy bullet, fired into bare fuel clads with depleted urania fuel simulant. The clads were also pre-heated to the nominal launch temperature of 1090°C. Test conditions and test results are summarized in Table H-7.

Table H-7. Summary of Titanium Bullet Tests Using Fueled Clads

Test	Target Clad	Temperature (°C)	Bullet Velocity (m/s)	Remarks
TIB-Eng	Virgin EUO*	1095	446	Several, small breaching cracks (total area 25.25 mm ²)
TIB-1	CST-6**	1085	423	Several, small breaching cracks (total area 1.3 mm ²)
TIB-2	CST-6**	1110	684	Breach, total crack area 215 mm ² 86.5% of fuel simulant remained in the clad

*EUO clad fabricated from two blind cups with 1/16 in. vent hole in one cup.

**The two clads recovered from CST-6 test.

H.2.2.4 Aluminum Fragment Test

This test was conducted at the Sandia rocket sled test facility. An aluminum plate fragment, 8 x 8 x 0.125 inches, was propelled at a velocity of 3000 fps and impacted edge-on into a GPHS module. This fragment was defined as being representative of the upper range of velocity and corresponding size that could be generated in an upper range explosion of the Shuttle launch vehicle in an accident such as LOX tank overpressurization.

In the test, the plate fragment did not release as planned from the rocket sled, and the module was hit by the fragment while it was still attached to the sled fixture. The test resulted in the fragment completely slicing through all four fueled clads. Because of the uncertainty in the test conditions, results are inconclusive.

H.2.3 Solid Propellant Fire Test

A test was conducted, as reported in Reference H-11, in which GPHS components were exposed to a 10.5 minute fire from a 3 foot cube of UTP-3001 solid propellant, considered essentially the same as the Shuttle SRB and Titan IV SRMU propellant. A bare GPHS fueled clad with urania fueled simulant was pre-heated to 1091°C, representing the launch temperature, and dropped next to one vertical face of the propellant cube immediately before it was ignited. Also, an assembly consisting of two fueled clads with urania simulant

in a GIS was pre-heated to 1091°C and exposed in the same manner to the propellant cube as was the bare fueled clad.

A glassy deposit that formed on the exterior of the iridium clad of the bare fueled clad resulted in erosion of approximately 15% of the shell thickness, but the shell was not breached nor otherwise affected, and there was no damage to the interior. The test of the impact assembly resulted also in roughly a 20% reduction in the thickness of the graphite shell wall nearest the burning solid propellant, but there was no apparent damage to either iridium clad. Thus, exposure of either intact fueled clads or GIS with fueled clads to a long duration, single proximity, solid-propellant fire would not be expected to result in a breach of the clad and release of the plutonia to the environment. While there was no self-heating produced as in the plutonia fueled flight capsules, this would not be expected to raise the resulting temperature by an appreciable amount over the duration of the fire.

H.2.4 Bare Clad Impact Tests

The Bare Clad Impact (BCI) tests, reported in References H-12 through H-17, were conducted to determine the response of the GPHS bare fueled clads as a result of their striking different surface media. These tests were conducted to reflect conditions that could potentially occur as the result of a launch pad or early ascent explosion. If the graphite members of the GPHS module were stripped off by an explosion, the bare clads would then impact on the surfaces in the vicinity of the launch pad over a wide range of velocities.

The first four tests (BCI-1 through BCI-4) were conducted to determine the response of the FCs against concrete as a function of velocity. This surface is the highest probability hard surface around the launch pad (sand is the most probable of all surfaces). The maximum velocity tested in these four tests was 90 m/s which is the upper limit for the contained impact facility in which plutonia fuel can be tested. The fifth test (BCI-5) was conducted on steel as a comparison with the concrete tests. Also BCI-5 provided a comparison with the SVT full module impacts, the majority of which have been conducted at the 54 m/sec, (10% above module terminal velocity against steel).

The results of the first five bare clad tests are summarized in Table H-8. Based on these results, the threshold for incipient failure of the bare FC on concrete is around 65 m/s, while that for steel is seen to be around 54 m/s. Notice from Table H-8 that the first test, BCI-1, performed at 76 m/s, deviates significantly from the trend of failure magnitude and fuel release quantity from the other three tests. In the post-test examination of the BCI-1 clad, it was discovered that a reaction had occurred apparently between the iridium clad and the tantalum thin walled can used to encapsulate the FC for the test. This reaction probably occurred during the pre-heat operation used to raise the temperature of the clad to that representative of the launch temperature. The material reaction could have possibly affected the iridium grain boundary chemistry so that its mechanical strength would be altered.

Tests BCI-7 through BCI-10 were conducted to investigate the effects of a test artifact observed in BCI-6, the reaction of iridium with vermiculite used in the catch box for converter segment tests. Tests did demonstrate that the microcracks observed in non-impact areas on BCI-6 were most likely caused by clad degradation from exposure to thermal decomposition products of vermiculite. Tests BCI-7 through BCI-10 showed significantly lower releases than BCI-6. Test results for this series are summarized in Table H-9, and the results of particle size analyses are listed in Table H-10.

H.2.5 GPHS Module Impact Tests

Two series of GPHS Module Impact Tests were performed. The first of these included impact tests conducted during the GPHS design verification program (Table H-11). These are the tests in the Design Iteration Test (DIT) series which begin with DIT-2, as reported in References H-18 through H-22.

Table H-8. Bare Fuel Clad Impact Tests (Pre 1986 Test Program)

Test No.	FC ID	NDE Value	Velocity (m/s)	Temperature (°C)	Target	% Strain***			Fuel Release (g)	Release <10 microns (g)
						Dia.	Length	Height		
BCI-1*	209	2.0	76.24	1091	concrete	31.7	27.0	-23.2	14.2076	0.2215
BCI-2	164	1.4	53.7	1091	concrete	9.6	-11.2	-10.2	0	0
BCI-3	351	2.1	64.77	1091	concrete	12.3	-15.2	-10.3	0.0008	0.0001
BCI-4	353	2.6	90.45	1091	concrete	24.4	23.6	-19.9	12.9**	0.1553
BCI-5	346	7.5	53.19	1091	steel	14.5	14.2	-14.2	0.0064	0.0023

* BCI 1 data are considered to be atypical. LANL's test report concluded that the results of this test should not be considered typical of the fueled clad response. Ta, Cl, O, Fe, and Cu were found to have reacted with the clad in several areas where the large failure occurred. This part of the clad was in contact with Ta foil (with possible mill scale) at temperature prior to the impact event. Such reaction areas were not observed on later BCI tests.

** Includes an estimated amount of less than 1.0 g tungsten foil.

*** % dimensional change.

Table H-9. Bare Fuel Clad Impact Tests (Pre 1986 Test Program)

Test No.	FC ID	Fuel or Simulant	Velocity (m/s)	Temperature (°C)	Target	% Strain***			Fuel Release (g)	Release <10 microns (g)
						Dia.	Length	Height		
BCI-6*	L-9	S	54.34	1091	steel	9.1	19.4	-14.4	11.233	0.246
BCI-7	L-6	S	53.64	1091	steel	6.7	14.0	-9.6	0.204	NA
BCI-8	L-5	S	54.50	1091	steel	8.4**	12.7	-9.6	0	0
BCI-9	M-3	S	54.48	1091	steel	10.2	14.8	-14.9	0.0090	0.0078
BCI-10	M-4	S	54.19	1091	steel	10.3	11.3	-13.4	0	0

* This fueled clad was recovered from the CST-4 1750 psi shock tube overpressure test. The iridium clad had reacted with vermiculite in the catch tube. The vermiculite was grit-blasted off the iridium surface prior to the bare clad impact test.

** 11.4% at the edge of pellet push-through.

*** % dimensional change.

Table H-10. Particle Size Analyses Bare Clad Impact Tests

WEIGHT FRACTIONS OF TOTAL PELLETS							
Test	BCI-6	BCI-8#	BCI-9	BCI-10#		BCI-2#	BCI-1 ^Δ
PARTICLE SIZE -Microns	URANIA SIMULANTS					PLUTONIA FUEL	
	L-9*	L-5*	M-3	M-4*	Avg.**	FC-164	FC-209
+6000	0.6094	0.5500	0.8228	0.5068	0.6223	0.7749	n.d.
-6000 +2000	0.1487	0.2259	0.0482	0.2197	0.1606	0.1260	n.d.
-2000 +841	0.1168	0.1334	0.0640	0.1621	0.1191	0.0319	0.4898
-841 +420	0.0589	0.0422	0.0342	0.0623	0.0494	0.0114	0.0987
-420 +177	0.0338	0.0255	0.0199	0.0295	0.0272	0.0178	0.0754
-177 +125	0.0083	0.0051	0.0027	0.0058	0.0055	0.0097	0.0263
-125 +74	0.0078	0.0056	0.0034	0.0043	0.0053	0.0106	0.0360
-74 +44	0.0042	0.0032	0.0015	0.0024	0.0028	0.0077	0.0670
-44 +30	0.0032	0.0023	0.0009	0.0017	0.0020	0.0045	0.0822
-30 +20	0.0013	0.0010	0.0005	0.0008	0.0009	0.0038	0.0811
-20 +10	0.0026	0.0018	0.0006	0.0011	0.0015	0.0000	0.0278
-10	0.0052	0.0040	0.0014	0.0033	0.0035	0.0017	0.0156

* Not Corrected for Impurities.

** Average of BCI-6, -8, -9, -10.

Unbreached Clads - Size Analysis Is for Material Contained.

Δ Released Material Only - Not for Total Pellet

Table H-11. Summary of Design Verification Impact Tests

Test No.	Velocity (m/s)	Impact Angle	Temperature (K)	Capsule No.	% Strain*		Fuel Release
					Length	Height	
DIT-2	58	0°	925	IRG-105	-	3.5	no
				IRG-106	-	3.4	no
				IRG-107	-	5.4	yes
				IRG-110	-	6.7	yes
DIT-3	58	30°	930	SRP-127	3.2	-	no
				SRP-140	4.29	-	no
				SRP-251	4.45	-	no
				SRP-317	1.22	-	no
DIT-4	58	0°	930	SRP-394	5.0	-	no
				SRP-398	4.0	-	no

* % dimensional change.

The second test series, the Safety Verification Test (SVT), as reported in References H-23 through H-25, included impact of GPHS modules simulating conditions that would occur as the result of an unplanned reentry followed by Earth impact. The original plan for this series was to address the types of reentries that would span the temperature range expected at impact. An orbital decay type of reentry was chosen to represent the most probable with corresponding impact temperatures in the upper range. For the lower range of impact temperatures, the minimum-gamma super orbital reentry was chosen, a low probability of occurrence. The lower range of impact temperatures is of interest because of the iridium material approaching the limited ductility temperature range. Because of the low probability event represented by the $\gamma_{\min}$ type of reentry, only two of the module tests in the SVT series have addressed these conditions, SVT-1 and SVT-2. Results of the SVT series are summarized in Table H-12, and the results of analysis of the released fuel are summarized in Table H-13. Particle size distributions from fueled clads that were not breached are listed in Table H-14.

Table H-12. Summary of Safety Verification Impact Tests

Test No.	Velocity (m/s)	Impact Angle	Temperature (K)	Capsule No.	% Strain*		Fuel Release
					Length	Height	
SVT-1	54.4	0°	919	FC-232	5.8	-11.1	no
				FC-238	3.8	-7.3	no
				FC-261	5.6	-11.1	yes
				FC-410	1.4	-9.6	yes
SVT-2	55.0	0°	917	FC-355	4.1	-10.4	no
				FC-369	4.1	-9.3	no
				FC-449	4.4	-10.5	yes
				FC-273	5.6	-10.3	no
SVT-3	54.4	0°	975	FC-343	5.7	-9.0	no
				FC-350	2.6	-8.5	no
				FC-454	2.9	-6.4	no
				FC-457	5.6	-7.2	yes
SVT-4	54.0	0°	975	FC-348	6.4	-11.3	yes
				FC-354	4.0	-8.2	no
				FC-139	5.1	-8.5	no
				FC-162	3.4	-9.3	no
SVT-5	54.0	90°	975	FC-267	5.5	-9.1	no
				FC-260	4.1	-13.7	no
				FC-415	1.2	-4.5	no
				FC-426	0	-6.9	no
SVT-6	54.6	90°	975	FC-361	8.8	-17.6	no
				FC-373	6.2	-14.9	yes
				FC-225	3.7	-8.8	no
				FC-189	2.9	-7.2	no
SVT-7	53.5	15°	975	FC-364	5.3	-13.5	yes
				FC-368	5.4	-9.9	no
				FC-165	5.7	-10.0	yes
				FC-112	4.0	-9.5	yes

* % dimensional change.

Table H-12. Summary of Safety Verification Impact Tests (Cont'd)

Test No.	Velocity (m/s)	Impact Angle	Temperature (K)	Capsule No.	% Strain*		Fuel Release
					Length	Height	
SVT-8	54.3	15°	975	FC-437	5.4	-7.9	no
				FC-436	3.6	-5.2	no
				FC-391	6.5	-10.0	yes
				FC-441	5.3	-8.1	no
SVT-9	54.6	30°	975	FC-591	3.7	-8.9	no
				FC-592	2.4	-6.1	no
				FC-473	2.0	-5.1	no
				FC-501	4.3	-5.7	no
SVT-10	54.3	30°	975	FC-589	2.5	-3.5	no
				FC-590	5.0	-6.6	no
				FC-152	3.6	-7.3	no
				FC-185	3.7	-6.8	no
SVT-11	54.4	0°	975	FC-372	2.9	-7.1	no
				FC-345	3.2	-7.9	no
				FC-365	1.7	-8.9	no
				FC-341	2.7	-8.2	no
SVT-12	75.5	0°	975	FC-628	4.5	-5.1	yes
				FC-629	6.0	-9.1	no
				FC-226	6.2	-11.5	yes
				FC-277	5.6	-9.8	no
SVT-13	53.4	0°	975	FC-605	5.0	-7.8	no
				FC-604	5.6	-6.9	yes
				FC-546	1.9	-6.0	no
				FC-526	2.9	-6.0	no

• % dimensional change.

Table H-13. Breached Clad Fuel Release Analysis from SVT Tests

Test No.	Fuel Release	
	Total (g)	<10 Microns (g)
SVT-1	0.1100	0.0128
SVT-2	0.0280	0.0041
SVT-3	0.0177	0.0051
SVT-4	0.0257	0.0076
SVT-6	0.0147	0.0091
SVT-7	0.2227	0.1390
SVT-8	0.0860	0.0687
SVT-12	0.0458	0.0377
SVT-13	0.0183	0.0144

H.3 POST-1986 TESTS

The safety test programs conducted after 1986 that supported analyses for the Galileo and Ulysses FSARs included additional Bare Fueled Clad Impact tests as well as several new series:

- SRB Fragment in Gas Gun
- Large SRB Fragment Impact Tests
- SRB Fragment/Orbiter Fuselage Tests
- GIS Impact Tests

Each of these test series are discussed in the following paragraphs.

H.3.1 Bare Clad Impact Tests

Additional BCI tests conducted for the Ulysses FSAR, reported in References H-12 through H-17, were directed toward higher velocities, in the 73 to 74 m/s range. These tests also provided additional data for comparison between plutonia fuel and urania fuel simulant and data on differences in fueled clad response to impact on various media.

Table H-14. SVT Impact Fuel Size Distribution for Unbreached Clads

SVT	1	3	6	8	4	5	9	10	10	11	12	13
FC	232	343	361	437	139	260	473	590	152	345	629	605
SIZE, μm	WEIGHT FRACTION											
+6000	0.1209	0.1027	0.0464	0.1585	0.1631	0.1949	0.5025	0.2509	0.1447	0.1607	0.2483	0.2112
+2000 to 6000	0.2263	0.2228	0.1901	0.4663	0.3637	0.2072	0.3370	0.5288	0.5869	0.3774	0.2357	0.3058
+841 to 2000	0.3309	0.3532	0.3146	0.2224	0.2620	0.3020	0.1096	0.1433	0.1805	0.2477	0.2413	0.2907
+420 to 841	0.1568	0.1546	0.2193	0.0807	0.0957	0.1472	0.0278	0.0423	0.0482	0.1140	0.1259	0.0978
+177 to 420	0.0957	0.0917	0.1296	0.0408	0.0573	0.0795	0.0122	0.0199	0.0228	0.0600	0.0741	0.0529
+125 to 177	0.0149	0.0142	0.0212	0.0065	0.0102	0.0127	0.0018	0.0030	0.0037	0.0093	0.0142	0.0093
+74 to 125	0.0171	0.0176	0.0242	0.0064	0.0119	0.0150	0.0019	0.0030	0.0035	0.0092	0.0170	0.0093
+44 to 74	0.0084	0.0115	0.0174	0.0047	0.0098	0.0110	0.0016	0.0023	0.0028	0.0063	0.0136	0.0064
+30 to 44	0.0078	0.0085	0.0104	0.0034	0.0077	0.0087	0.0013	0.0016	0.0019	0.0040	0.0095	0.0043
+20 to 30	0.0062	0.0074	0.0122	0.0047	0.0063	0.0079	0.0019	0.0022	0.0025	0.0050	0.0102	0.0052
+10 to 20	0.0070	0.0089	0.0048	0.0027	0.0070	0.0092	0.0070	0.0008	0.0010	0.0031	0.0058	0.0036
-10	0.00808	0.00691	0.00978	0.00277	0.00551	0.00475	0.00107	0.00183	0.0019	0.0033	0.0044	0.0035
10	0.001531	0.002523	0.003001	0.00096	0.001995	0.001834	0.00015	0.00053	0.00047	0.0008	0.0008	0.0017
9	0.001116	0.001430	0.001094	0.00018	0.000534	0.000594	0.00006	0.00027	0.00019	0.0002	0.0003	0.0005
8	0.000784	0.000861	0.000769	0.00019	0.000375	0.000417	0.00012	0.00015	0.00027	0.0005	0.0008	0.0003
7	0.000263	0.000192	0.000172	0.00025	0.000419	0.000140	0.00016	0.00013	0.00018	0.0004	0.0004	0.0002
6	0.000992	0.000242	0.000972	0.00023	0.000422	0.000308	0.00008	0.00023	0.00010	0.0001	0.0004	0.0002
5	0.000383	0.000315	0.001000	0.00014	0.000428	0.000299	0.00010	0.00009	0.00007	0.0003	0.0004	0.0001
4	0.000441	0.000341	0.000800	0.00025	0.000344	0.000313	0.00007	0.00012	0.00006	0.0002	0.0004	0.0001
3	0.000579	0.000235	0.000635	0.00016	0.000336	0.000253	0.00008	0.00007	0.00008	0.0002	0.0003	0.0001
2	0.000398	0.000260	0.000492	0.00014	0.000387	0.000243	0.00009	0.00008	0.00007	0.0003	0.0003	0.0001
1	0.001593	0.000511	0.000846	0.00027	0.000309	0.000417	0.00016	0.00016	0.00010	0.0003	0.0003	0.0002

In Section H.2.4, Tables H-8 and H-9 summarized BCI test results for tests conducted prior to 1986, BCI-1 through BCI-10. The results for BCI tests conducted to support the Ulysses FSAR are summarized in Table H-15. Note that tests BCI-12 through BCI-14 were sequential tests, in that the clads used had previously been subjected to shock waves representative of the environment of an explosion of the Centaur as part of the Converter Segment Test series. The last five tests, BCI-28 through BCI-32 were also conducted as sequential impact tests. In these latter tests, the fueled clads were first subjected to an SRB fragment impact in the simulated GPHS-RTG configuration, as part of the SRB Fragment Gun Test series. Then the bare fueled clads were impacted against KSC concrete as a secondary impact, the impact being on the previously damaged face of the fueled clad.

H.3.2 SRB Fragment Tests in Gas Gun

The conditions and results for the five fragment gas gun tests, as reported in References H-26 through H-28, are given in Table H-16. There were no clad failures in any of the tests even at the relatively large distortions seen on the leading clads in the fueled tests, FGT-2, FGT-4 and FGT-5. Also, from these tests, the simulant clads can be seen to distort much less than the fueled clads. On an average, the deformation of the leading clads in the tests with fuel are approximately three times that of the tests with simulant; the trailing clad deformations are higher by a factor slightly larger than two.

H.3.3 Large SRB Fragment Impact Tests

In this series of tests, reported in References H-29 through H-30, a large fragment (1.42m square) from an SRB casing was propelled by a rocket sled to impact with a simulated section of an RTG. A simulated heat source was located inside the converter, heated prior to installation such that its temperature would be 1090°C at the time of impact.

The simulated heat source consisted of a stack of eight modules, with flight type modules containing simulant located in the second and fifth positions from the bottom. The six remaining positions were occupied by modules made from bulk graphite and containing solid molybdenum slugs representing fueled clads.

A summary of the test conditions is provided in Table H-17.

Table H-15. Bare Fuel Clad Impact Tests (Ulysses)

Test No.	FC ID	Fuel or Simulant	Velocity (m/s)	Temperature (°C)	Target	% Strain*			Fuel Release (g)	Release <10 microns (g)
						Dia.	Length	Height		
BCI-11	M-5	S	160	1091	concrete	NA	NA	NA	135	NA
BCI-12	M-11	S	206	1091	sand	5.9	-2.4	-4.6	0	0
BCI-13	D	S	250	1091	sand	3.3	0.3	-3.5	0	0
BCI-14	M-48	S	116.6	1091	concrete	6.3	9.6	-3.0	0.0145	0.0075
BCI-15	214	F	53.34	1091	steel	14.3	19.1	-23.9	0.0114	0.0072
BCI-16	L-11	S	51.34	1091	steel	10.8	14.2	-7.0	0.0020	0.0002
BCI-17	M-25	S	75.1	1091	concrete	7.1	11.0	-4.5	NA	NA
BCI-18	M-6	S	56.89	1091	steel	7.5	10.8	-5.7	0.0116	0.0030
BCI-19	M-16	S	55.04	1091	steel	8.2	14.8	-12.7	0.0025	0.0012
BCI-20	M-45	S	66.28	1091	steel	11.1	16.4	-10.6	0.0056	0.0008
BCI-21	M-49	S	75.89	1091	steel	16.2	21.0	-18.8	0.0129	0.0017
BCI-22	M-43	S	85.59	1091	steel	22.0	25.3	-22.1	43.74	0.689
BCI-23	Q-4	S	55.48	1091	steel	8.1	10.9	-8.9	0	0
BCI-24	Q-5	S	65.08	1091	steel	6.3	3.2	-22.2	0.0004	NA
BCI-25	536	F	65.66	1091	steel	18.4	23.8	-24.2	<0.1	NA
BCI-26	212	F	74.86	1091	steel	19.4	27.7	-13.8	<0.2	NA
BCI-27	297	F	85.74	1091	steel	20.8	27.4	-21.9	0	0
BCI-28	Q-8	S	45.05	1091	concrete	7.7	13.9	-12.4	0	0
BCI-29	761	F	45.75	1091	concrete	13.5	36.4	-16.8	0	0
BCI-30	769	F	46.1	1091	concrete	13.8	19.7	-17.1	0	0
BCI-31	247	F	60.55	1091	concrete	15.2	19.5	-21.0	0	0
BCI-32	270	F	45.01	1091	concrete	13.8	13.7	-17.5	0	0

* % dimensional change.

Table H-16. SRB Fragment Gas Gun Test Results

Test ID	Fueled Clad ID	Fuel or Sim.	Location		Position		Vel. (m/s)	% Distortion	
			Lead	Trail	Closed End	Open End		Shield Cup	Vent Cup
FGT-1	Q-13	S	√			√	100	8.1	6.7
	Q-12	S	√		√		100	7.7	12.4
	M-32	S		√		√	100	7.1	7.9
	Q-14	S		√	√		100	3.0	3.4
FGT-2	489	F	√			√	100	27.3	33.9
	490	F	√		√		100	17.9	29.1
	349	F		√		√	100	13.1	12.4
	326	F		√	√		100	9.2	11.7
FGT-3	Q-9	S	√			√	120	6.3	15.0
	Q-8	S	√		√		120	10.8	7.4
	Q-11	S		√		√	120	5.2	4.8
	Q-10	S		√	√		120	5.7	4.4
FGT-4	767	F	√			√	120	22.9	29.5
	769	F	√		√		120	26.4	26.3
	761	F		√		√	120	13.7	13.2
	758	F		√	√		120	8.5	9.9
FGT-5	247	F	√			√	120	26.0	23.6
	327	F	√		√		120	26.1	29.0
	270	F		√		√	120	14.2	13.7
	757	F		√	√		120	9.5	11.2

Note: The fueled clads did not breach in any of these tests.

Table H-17. Summary of Test Conditions for Large SRB Fragment Impact Tests

Test Designation	Test Module Positions in Stack	Dummy Module Positions	Temperature (°C)	Fragment Velocity (m/s)	Fragment Orientation
LFT-1	2, 5	1, 3, 4, 6, 7, 8	1090	115	Face on
LFT-2	2, 5	1, 3, 4, 6, 7, 8	1091	212	Face on
LFT-3	2, 5	1, 3, 4, 6, 7, 8	1090	95.4	Vertical Edge-On

In the first test (LFT-1), the converter half-section was damaged such that approximately a quarter section of the housing was completely severed over the length of the shell. The remainder of the converter was severely flattened; the majority of the multifoil insulation assembly remained inside the shell.

The RTG test assembly was propelled into a 4.5 m-long corrugated steel catch tube filled to 4.0 m with vermiculite. The catch tube slid on the sled track rails for about 180 m, leaving the test articles behind and located between and along the rails. The converter section dropped out of the catch tube and came to rest about 30 m down the track from the impact point. Both test modules were released from the converter section as were the dummy modules. The test module in the fifth position was essentially intact and was found beside the converter housing. Both GISs from the module in the second position were released from the aeroshell, but the fueled clads remained in the GISs. The aeroshell from this module had a penetrating corner deformation, resulting from what was deduced to be an impact on one of the tie-down brackets for the rocket sled rails. This impact caused the GISs to be released.

The results of the test are shown in Table H-18. There were no breaches in any of the clads. The deformations from this test are seen to be relatively small, especially when distortions of 1.7 to 4.3% are possible just by closing up the clearance between the clad and fuel in one direction based on the manufacturing tolerances.

In the second large fragment test (LFT-2), the RTG section was severely damaged and fragmented as shown on Figure H-1. The catch tube for this test was a corrugated steel culvert tube filled to 1.2 m with sawdust followed by 1.8 m of vermiculite at the open or catch

Table H-18. Post-Test Dimensions of LFT-1 Urania Fueled Clads

Fueled Clad ID	Location		Position		Fueled Clad Half	% Strain*			% Distortion
	Lead	Trail	Closed End	Open End		Dia.	Hgt.	Lgt.	
2nd Position Module (076)									
Q-17	✓			✓	Vent Cup	+0.9	-2.9	+1.0	3.9
					Shield Cup	+0.9	-2.1		3.1
Q-15	✓		✓		Vent Cup	+0.2	-2.6	+0.6	2.9
					Shield Cup	+0.9	-2.3		3.1
Q-18		✓		✓	Vent Cup	+2.9	-1.5	+2.1	4.5
					Shield Cup	+2.6	-5.7		8.8
Q-16		✓	✓		Vent Cup	+0.3	-0.6	+1.3	0.9
					Shield Cup	+0.2	-1.3		1.5
5th Position Module (077)									
Q-23	✓			✓	Vent Cup	+2.9	-2.8	+2.0	5.9
					Shield Cup	+3.1	-2.8		6.1
Q-19	✓		✓		Vent Cup	+2.8	-4.9	+1.8	8.1
					Shield Cup	+2.2	-2.1		4.4
Q-22		✓		✓	Vent Cup	+0.6	-1.0	+0.9	1.6
					Shield Cup	+0.8	-2.6		3.5
Q-20		✓	✓		Vent Cup	+0.4	-0.6	-0.7	1.0
					Shield Cup	+0.3	-0.9		1.2

* % dimensional change.

Figure H-1. RTG Case after LFT-2

end of the track. In addition, the catch tube was front loaded with about 227 kg of lead to assist in decelerating the SRB fragment. The catch tube was severely damaged and separated into two pieces when it was propelled by the fragment onto the concrete pad to one side of the track. The smaller portion of the catch tube was found about 40 m from its original position; the larger portion traveled 40 m further down the track, also on the east side.

Except for clad Q-27, the graphite was completely stripped from the fueled clads in both modules. Q-27, from the C or trailing GIS, blind-end location of the GPHS module in the fifth stack position, was recovered in a GIS remnant. The fueled clads (except for Q-27) were recovered in or near the major section of the catch tube. One clad, Q-25, from the module in the fifth stack position was breached, and about 0.023 g of fuel was released. Another clad, Q-33, from the module in the second stack position was also breached, and about 1.73 g of fuel was released. Both of these clads had sharp discontinuities which were shown to be caused by secondary impacts with pieces of the SRB fragment that had been arrested in the catch tube. In addition, clad Q-34 from this same module had a large indentation, apparently from a secondary impact.

The post-test dimensions of the simulant fueled clads from LFT-2 are shown in Table H-19. The deformations shown are well below any deformation that would be expected to result in breaching, especially in the full-up RTG configuration as used in the test. Thus, these results support the supposition that the breaches that occurred were a result of secondary impacts and not by the initial fragment impact.

For the third test (LFT-3), the fragment edge at impact was oriented so that the entire module stack would be struck along the transverse centerline of one of the leading fueled clads. There was no catch tube used for this test. Instead, two very large mounds of dirt were piled up on either side of the sled track to act as a catch medium. The dirt mounds had been covered with plastic sheets to enhance the recovery of the clads by indicating their entry points into the mound.

All eight of the iridium capsules were recovered from the left dirt mound. Two of the capsules were breached, one was recovered bare, two were recovered in an intact GIS, and three were recovered in partial GISs. Sixteen of the 24 molybdenum slugs were also recovered. Three of those showed evidence of being hit by the SRB fragment.

Table H-19. Post-Test Dimensions of LFT-2 Urania Fueled Clads

Fueled Clad ID	Location		Position		Fueled Clad Half	% Strain*			% Distortion
	Lead	Trail	Closed End	Open End		Dia.	Hgt.	Lgt.	
2nd Position Module (PAL -0078)									
Q-34	√			√	Vent Cup	+1.3	-10.8		13.6
					Shield Cup	+1.3	-11.2.	+10.3	14.0
Q-33	√		√		Vent Cup	+0.6	-5.1		6.0
					Shield Cup	Not measured**			+8.1
Q-32		√		√	Vent Cup	+0.1	-1.8		1.9
					Shield Cup	-0.1	-2.4	-1.1	2.4
Q-31		√	√		Vent Cup	+0.9	-2.6		3.6
					Shield Cup	+0.6	-3.2	+0.2	3.9
5th Position Module (PAL 0080)									
Q-26	√			√	Vent Cup	+0.3	-8.5		9.6
					Shield Cup	+0.9	-3.4	+4.8	4.4
Q-25	√		√		Vent Cup	+2.4	-4.3		8.1
					Shield Cup	+0.3	-4.3	+8.4	4.4
Q-28		√		√	Vent Cup	+0.7	-2.6		3.4
					Shield Cup	+1.0	-3.1	+0.0	4.2
Q-27		√	√		Vent Cup	+0.5	-2.3		2.9
					Shield Cup	+0.9	-3.3	-0.9	4.3

* % dimensional change.

**Secondary impact modified as-impacted dimensions.

The post-test dimensions of the simulant fueled clads are shown in Table H-20. Except for the clads that were impacted directly by the SRB fragment, the deformations are seen to be very small, as might be expected.

Table H-20. Post-Test Dimensions of LFT-3 Urania Fueled Clads

Fueled Clad ID	Location		Position		Fueled Clad Half	% Strain*			% Distortion
	Lead	Trail	Closed End	Open End		Dia.	Hgt.	Lgt.	
<u>2nd Position Module</u>									
Q-46	✓			✓	Vent Cup	Indeterminate (1)			
					Shield Cup	0.0	-1.0		
Q-49	✓		✓		Vent Cup	-0.6	-0.8		0.2
					Shield Cup	+0.0	-1.0	-0.4	1.0
Q-30		✓		✓	Vent Cup	-0.8	-0.7		-0.1
					Shield Cup	-0.9	-0.8	+8.4	-0.1
Q-29		✓	✓		Vent Cup	+0.8	-2.2		3.1
					Shield Cup	+1.1	-2.0	+0.9	3.2
<u>5th Position Module</u>									
Q-50	✓			✓	Vent Cup	+2.9	-3.5		6.6
					Shield Cup	(2) +25.9/+11.7 +9.4 -17.0			31.8
Q-51	✓		✓		Vent Cup	-0.5	-0.8		0.3
					Shield Cup	-0.6	-0.8	-0.4	0.2
Q-41		✓		✓	Vent Cup	+0.3	-0.3		0.6
					Shield Cup	+0.0	-0.7	-0.6	0.7
Q-43		✓	✓		Vent Cup	+0.3	-2.8		3.2
					Shield Cup	+1.2	-2.0	+0.1	3.3

(1) Fueled clad separated in half at weld joint. Secondary impact deformations precluded accurate measurements.

(2) Includes breach width/excludes breach width.

* % dimensional change.

H.3.4 Fragment/Fuselage Tests

These tests, reported in Reference H-31, were directly related to the attenuation provided to fragments of intervening structure of the Shuttle wing and fuselage structures. Since the tests were specific to that launch vehicle and have little applicability to the Cassini launch configuration, the results will not be discussed in this report. Details of this series of test can be found in Reference H-1.

H.4 CASSINI SAFETY TESTS

A review of the safety analyses performed for the Galileo and Ulysses RTG missions concluded that there were several events for which new or modified RTG response models would improve risk assessment evaluation. It was concluded that additional safety testing, beyond that performed for the aforementioned missions, would facilitate construction of improved models for the following two events: a) RTG terminal velocity impact; and b) edge-on collisions of plate fragments with an RTG.

The first event is a potential consequence of an early malfunction of the launch vehicle whereby an RTG is struck in-flight and breaks away from the spacecraft. Previous terminal impact testing was restricted to modules, GIS assemblies or fueled clad assemblies.

The second event results from a study of the accident environments for the Titan IV/Centaur vehicle. The studies indicate that thin plate fragments from the spacecraft and Centaur structural members can provide a threat to the GPHS fuel containment system as a result of explosions originating at propellant interfaces. Previous tests to evaluate thin plate fragment penetration have been limited to GPHS modules and fueled clad assemblies. Testing to evaluate the attenuating properties of the RTG housing, multifoil insulation, and internal hardware was, therefore, needed.

A safety test program was implemented to evaluate RTG terminal velocity impact and thin plate fragment impact with an RTG. A description of each test and the test results are presented herein.

H.4.1 RTG End-On Impact Test

H.4.1.1 Background

Analysis of RTG trajectories following near-pad release from an in-flight vehicle indicate that concrete targets can be impacted at speeds approaching terminal velocity. Quantitative data was not available to deduce rotational motion of the RTG during its flight to impact. However, qualitative arguments suggested that an RTG would undergo random tumbling and thus have a probability (though a low one) of impacting at an approximately end-on attitude. In this event, the maximum impact speed is the terminal velocity of the RTG in tumbling flight which is approximately 56 m/s.

The purpose of the RTG impact tests was to produce test data on fueled clad distortion versus GPHS module stack position in the RTG and the variability in distortion at each position. A secondary objective was to obtain data on fractional fuel-simulant release in the event of a breach in the fueled clad.

H.4.1.2 Test Description

Testing was conducted at the Sandia National Laboratory (SNL) Rocket Sled Test Track (Area III) and was coordinated by Los Alamos National Laboratory (LANL), as described in Reference H-32. The test schematic is shown in Figure H-2. A stack of nine simulated GPHS modules was heated in a furnace with an argon atmosphere. The furnace was mounted on a test stand and positioned over a simulated RTG which was mounted to a rocket test sled (reference Figure H-3).

Hydrocode analyses were conducted (Reference H-33) which included detailed modeling of the first four modules in the stack and a distributed mass for the trailing fuel stack. The distortions of the fuel clads in the first four modules were generally only one to two percent larger for an 18 module stack than for a 9 module stack at both the 57 m/s and 77 m/s impact velocities. Module 5 and higher had total distortions of 2 percent or less for an impact at 77 m/s. Therefore, it was concluded that the use of a half generator in the impact tests would yield valid data for the modules of interest.

The heat source stack was heated to approximately 1210°C and remotely lowered from the furnace into the simulated RTG. The simulated RTG was remotely rotated 90°, after the heat source was latched in place, to orient it for impact at the outboard end, as shown in Figure H-4. A more detailed description of the sled design can be found in Reference H-32. After allowing the heat source to cool to approximately 1090°C (the estimated impact temperature) the sled rocket was fired, propelling the simulated RTG into a concrete target. The sled was designed to compress as it impacted a steel aperture plate, located approximately four feet in front of the concrete target (reference Figure H-5). The aperture plate was designed to stop the sled while allowing the simulated RTG to pass through its opening and impact the concrete target.

Test instrumentation consisted of furnace thermocouples, video of the heated stack as it was lowered and latched into the simulated RTG, break wire and laser tracking for velocity determination, and high speed cameras to record the impact event.

The concrete target used for the test was obtained from the Cape Canaveral Air Station and was typical of the concrete used for installations in the vicinity of the launch pads. The concrete target dimensions were 36 inches x 48 inches x 18 inches thick.

Two impact tests were conducted. The first test (RTG-1) was conducted at a velocity of 57.6 m/s. The test hardware for this test was designated as Test Article 1 (TA-1). A second test (RTG-2) was conducted at a higher velocity (77.1 m/s) in order to establish a threshold for obtaining a breach in the fuel clad. The hardware used for this test was designated as Test Article 2 (TA-2).

Figure H-2. RTG End-On Impact Test Schematic

Figure H-3. RTG End-On Impact Test Stand and Test Setup

HEAT SOURCE LOADING POSITION

IMPACT POSITION

Figure H-4. Simulated RTG Mounted on Test Sled

Figure H-5. Setup of Steel Aperture Plate and Concrete Impact Target

H.4.1.3 Test Hardware

The simulated RTG test article consisted of approximately one half of a full length RTG converter shell. (Two full length Al 2219 converter shells were machined in half and the outboard half of each shell was used for the two tests). The outboard end of the converter, which was impacted against the concrete target, was prototypical of the RTG design. It included an Al 2219 pressure dome and outboard heat source support system which was comprised of the outboard multifoil insulation end cap, titanium preload frame (spider), FWPF pressure plate, etc. Four spring loaded latches, located on the inboard end of the converter housing, secured the heat source stack in the converter. A blanket insulation (Cerafelt) was used inside the converter to maintain heat source temperature and a purge line was provided to maintain an inert cover gas to minimize oxidation. Two trunnions were provided to permit 90° rotation of the simulated RTG on the rocket test sled, after heat source loading, to orient it for the impact event. The simulated RTG test article is shown in Figure H-6.

Side View

Top View

Figure H-6. Simulated RTG Test Article – End-On Impact Test

The heat source stack is shown in Figure H-7. The heat source stack consisted of eight modules with FWPF aeroshells and a ninth module having a POCO™ AXF-5Q graphite aeroshell. The module stack positions were numbered 1 through 9 with the number 1 module located at the outboard end of the converter (first position module at impact end). The modules were stacked using FWPF lock members and the modules were held in place with FWPF tie rods as shown in Figure H-7.

Figure H-7. Heat Source Stack Configuration for RTG End-on Impact Tests

A lifting lug and latching plate, fabricated from POCO™ AXF-5Q, were used to lower and latch the heat source stack into the simulated RTG. The GIS and fuel simulants used in the heat source stack varied according to their location in the stack (reference Table H-21).

Table H-21. Heat Source Stack Design for RTG End-On Impact Tests

Test	Stack Position *	Heat Source Materials		
		Aeroshell	GIS	Fuel Clad Simulant
RTG-1	1, 2, 3	FWPF	FWPF	Urania Simulant/Flight Ir Clad
	4, 5	FWPF	POCO™	Urania Simulant/Engineering Ir Clad
	6, 7, 8	FWPF	POCO™	Molybdenum Mass
	9	POCO™	Not Used	Molybdenum Mass
RTG-2	1, 2, 3, 4	FWPF	FWPF	Urania Simulant/Flight Ir Clad
	5, 6	FWPF	POCO™	Urania Simulant/Engineering Clad
	7, 8	FWPF	POCO™	Molybdenum Mass
	9	POCO™	Not Used	Molybdenum Mass

* Position 1 is the lead module in the impact event

For the RTG-1 test, modules one through three contained FWPF GISs and welded, flight quality, iridium clads containing urania fuel simulant. Modules four and five contained POCO™ AXF-5Q GISs and welded, engineering quality, iridium clads with urania fuel simulant. Modules six, seven and eight contained POCO™ AXF-5Q GISs and molybdenum mass simulants. The ninth module consisted of a POCO™ aeroshell containing four molybdenum mass simulants (no GISs). The heat source for the RTG-2 test differed slightly, as shown in Table H-21. The weight and dimensions of all urania fuel simulant pellets were determined prior to encapsulation and the girth weld of all fueled clads were ultrasonically tested prior to test. Further description of all the heat source hardware may be found in Reference H-32.

H.4.1.4 Test Results

The test results presented herein were obtained from Reference H-32.

H.4.1.4.1 RTG-1 Test (Impact Velocity: 57.6 m/s)

The RTG-1 test was conducted at an impact velocity of 57.6 m/s representing the terminal velocity of an RTG in tumbling flight. Iridium fuel clad temperature, at time of impact, was $1071 \pm 5^\circ\text{C}$.

The simulated RTG rebounded after impacting the concrete target (Figure H-8) with a modest twisting of the inboard (trailing) end of the housing. The inboard end struck the cushioned rear side of the aperture plate through which it traveled after being released from the sled. Deformation to the RTG outer shell, shown in Figure H-9, was primarily at the outboard end, above the circumferential stiffening ring which is located 2.95 inches from the outboard flange. The outboard pressure dome remained intact but was compacted such that the imprint of the titanium support frame (part of the outboard heat source support system) was apparent (reference Figure H-8 [top figure]). The condition of the titanium support frame (spider) after impact is shown in Figure H-10. Its deformation from the impact is believed to have contributed to the deformation of the GISs in modules #1 and #2. There was considerable breakup of the heat source stack inside the converter. A piece of the stack tie rod and lifting lug, along with one intact module (#9), were ejected from the back (inboard end) of the converter housing. Modules #6, #7, and #8 also remained intact but fell free from the RTG housing after the test.

Field observations noted that one fueled clad had been ejected from its module and GIS, but remained in the RTG (reference Figure H-11). This was observed after removal of modules #6, #7, #8, and #9. Upon disassembly of the converter in the laboratory, additional fueled clads were observed to have been ejected from their module and GIS. Two ejected fueled clads were determined to have been from the A GIS in module #2 and two fueled clads were also ejected from modules #4 and #5. The two GISs in each aeroshell were designated as A and C for point of reference. The A GIS was inserted into the A cavity in the aeroshell which was identified by a small dimple on the face of the aeroshell that has the flight control bevel machined on the edges. Module #3 split in half, along a line roughly parallel to the GIS cavities. One of the GISs was intact, while the other was missing a portion of its wall. The fueled clads were completely contained within the two GISs in module #3.

The module #1 and #2 aeroshells and GISs were shattered into several pieces. Fueled clad deformations are listed in Table H-22. The largest deformations were experienced by the fueled clads in module #1, as expected. No visible cracks or breaches were observed in any of the fueled clads. Fueled clad SC0076 was located in the blind (non-threaded) end of the A GIS in module #1. It exhibited the greatest deformation, as indicated by distortion calculations, of all the fueled clads impacted in this test (reference Figure H-12). Despite its

Figure H-8. Simulated RTG after 57 m/s Impact

relatively large deformation, neither SC0076 nor any other fueled clad had breached. The impact face of this fueled clad was centered at approximately 270° from the weld start. Because it was the most highly deformed, it was selected for metallographic examination. It was defueled (simulant removed) and the fuel simulant submitted for particle size analysis. The results of the particle analysis are shown in Table H-23.

RTG-1 – 180°

Figure H-9. RTG Outer Shell Damage after 57 m/s Impact

Figure H-10. Titanium Preload Frame ("Spider") with Inconel Studs after 57 m/s Impact

Figure H-11. Simulated RTG Inboard End (Opposite Impact) Showing Ejected Fueled Clad

Table H-22. Fueled Clad Distortion after 57 m/s Impact Test (RTG-1)

Module	Fueled Clad ID	Distortion, % (1)				
		Axial	Vent Cup, Diametral		Shield Cup, Diametral	
			Max.	Min.	Max.	Min.
1	SC0077	8.30	12.60	-15.08	10.71	-4.28
1	SC0076	19.48	20.57	-17.14	15.94	-11.31
1	SC0079	5.84	9.34	-2.06	6.26	-3.77
1	SC0078	5.93	11.65	-8.65	10.37	-5.14
2	SC0081	2.12	6.34	-6.51	4.03	-1.03
2	SC0080	8.72	13.28	-7.80	8.40	-5.91
2	SC0083	4.91	4.88	-3.94	4.88	-3.34
2	SC0082	2.88	6.94	-7.88	4.71	-1.20
3	SC0085	2.29	1.63	-4.37	1.29	-0.51
3	SC0084	1.78	3.34	-3.94	2.49	-1.80
3	SC0088	1.35	1.37	-4.11	0.94	-1.80
3	SC0087	1.02	0.86	-2.40	0.94	-1.63
4	SC0065	1.61	0.51	-1.97	0.77	-1.80
4	SC0064	2.03	1.46	-4.97	1.29	-3.86
4	SC0067	1.02	0.77	-3.00	1.97	-2.40
4	SC0066	2.29	2.14	-3.08	1.89	-3.60
5	SC0069	0.00	-0.26	-0.17	0.26	0.17
5	SC0068	-0.08	-0.34	0.00	0.26	0.26
5	SC0071	-0.85	-0.34	-0.26	0.34	0.17
5	SC0070	-0.08	-0.34	-0.17	0.34	0.17

(1) Distortion calculations based on nominal dimensions (length = 1.181 in. and cup diameter = 1.167 in.).

Six metallographic sections were removed from fueled clad SC0076. Examination of the vent revealed typical microstructure. The microstructure of the single-pass weld and weld overlap areas was typical of the microstructure usually observed in these areas. The grain size in the single-pass weld area averaged 10.7 grains/weld width (78.1 $\mu\text{m}/\text{grain}$), and the grain size in the weld overlap area averaged 9.5 grains/weld width (84.7 $\mu\text{m}/\text{grain}$). The microstructures of the vent and shield cup walls were also typical. The grain sizes in these areas are shown in Table H-24.

a) Impact Face

b) Profile

c) Trailing Face

d) Opposite Profile

Figure H-12. Fueled Clad SC0076 after 57 m/s Impact Test

e) Vent End

f) Blind End

Figure H-12. Fueled Clad SC0076 after 57 m/s Impact Test (Cont'd)

Table H-23. Particle Size Analysis of Retained Urania after 57 m/s Impact Test (RTG-1)

Particle Size Range (μm)	Fueled Clad SC0076 (1)
+5600	0.4929
+2000 to 5600	0.3074
+850 to 2000	0.1256
+425 to 850	0.0408
+180 to 425	0.0196
+125 to 180	0.0036
+75 to 125	0.0037
+45 to 75	0.0023
+30 to 45	0.0007
+20 to 30	0.0010
+10 to 20	0.0016
+9 to 10	0.0001
+8 to 9	0.0001
+7 to 8	0.0001
+6 to 7	0.0001
+5 to 6	0.0001
+4 to 5	0.0001
+3 to 4	0.0002
+2 to 3	0.0000
+1 to 2	0.0000
<1	0.0000
Total	1.0000
Weight Fraction < 10 μm	0.0008

(1) No fuel released

Table H-24. Vent and Shield Cup Microstructure, Fueled Clad SC0076

Area/Orientation	Grain Size, Grains/Width *	Grain Size, $\mu\text{m}/\text{Grain}$
Shield Cup/Axial	25.0	26.1
Shield Cup/Transverse	25.5	25.6
Vent Cup/Axial	28.5	22.8
Vent Cup/Transverse	28.9	22.6

* Grains/nominal wall thickness of 0.65 mm.

H.4.1.4.2 RTG-2 Test (Impact Velocity: 77 m/s)

The RTG-2 test was conducted at an impact velocity of 77.1 m/s, exceeding the terminal velocity of a RTG in tumbling flight by more than one-third. Iridium fuel clad temperature, at time of impact, was $1090 \pm 5^\circ\text{C}$.

Deformation of the RTG outer shell was significant, as shown in Figure H-13. The RTG outer shell was compacted, as a result of the impact, by approximately 6 inches. The pressure dome sheared off and was found lying beside the RTG. Several of the pressure dome attachment bolts were imbedded in the concrete target. Four fueled clads were ejected from the outboard end of the RTG. They were from modules #1, #2, and #4. Four modules (#6, #7, #8, and #9) were ejected from the back (inboard end) of the RTG. Module #6 was cracked in half and contained one intact GIS. The other GIS was cracked and its fueled clads released. The other three modules were intact. A summary of the fueled clad deformations is shown in Table H-25.

Three of the four fueled clads ejected from the outboard (leading) end of the RTG were breached (fueled clads SC0092, SC0096 and SC0107). A large section of iridium was missing from the vent cup of fueled clad SC0092, located in the open (threaded) end of the C GIS in module #1 (Figure H-14). The impact face of the fueled clad was centered at approximately 0 degrees at the weld start. The area of this breach was measured to be 485 mm². Breached fueled clad SC0096 was located in the open end of the C GIS in module #2, (Figure H-15). A transverse breaching crack was located in the vent cup in the impact face (0° from weld start). This crack measured approximately 10.81 mm long and had a width of approximately 1.48 mm. The widest area of the crack appears to have been pushed open by fragmentation of the simulant fuel pellet beneath the clad wall. The crack appears to have been caused by impact with a relatively sharp edge of an external component upon impact, such as the titanium "spider" located at the outboard end of the RTG.

Figure H-13. Simulated RTG after 77 m/s Impact Test

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Table H-25. Fueled Clad Distortion after 77 m/s Impact Test (RTG-2)

Module	Fueled Clad ID	Distortion, % (1)				
		Axial	Vent Cup, Diametral		Shield Cup, Diametral	
			Max.	Min.	Max.	Min.
1	SC0090	4.10	7.28	-7.03	6.77	-3.34
1	SC0089	10.65	12.51	-14.48	10.11	-8.83
1	SC0092	14.98	NM (2)	NM (2)	10.03	-4.28
1	SC0091	5.87	10.45	-12.00	5.48	-5.31
2	SC0094	2.47	4.71	-5.91	2.57	-2.31
2	SC0093	1.95	3.43	-2.48	2.48	-2.31
2	SC0096	21.48	10.37	-17.40	9.43	-11.48
2	SC0095	5.18	7.71	-11.31	6.68	-7.03
3	SC0103	2.04	2.83	-4.63	2.48	-1.37
3	SC0097	2.47	3.94	-4.20	4.03	-2.31
3	SC0105	3.90	3.00	-7.63	3.26	-5.06
3	SC0104	4.24	4.28	-6.43	4.54	-7.71
4	SC0108	1.78	0.94	-1.71	2.06	-3.00
4	SC0106	1.45	1.97	-4.46	1.54	-1.80
4	SC0107	4.16	-3.86	6.34	4.80	-6.51
4	SC0086	1.36	3.17	-4.46	3.08	-2.66
5	SC0069	0.76	1.28	-2.23	1.28	-2.06
5	SC0068	3.54	3.08	-4.54	4.28	-7.46
5	SC0071	3.15	4.46	-7.54	3.94	-5.83
5	SC0070	3.99	4.03	-3.68	2.66	-2.74
6	SC0101	0.85	0.51	-0.60	0.26	-0.17
6	SC0100	0.51	0.09	-1.28	-0.09	-0.69
6	SC0109	0.43	2.14	-3.68	1.03	-2.66
6	SC0102	2.38	1.20	-5.74	1.80	-3.60

(1) Distortion calculations based on nominal dimensions (length = 1.181 in. and cup diameter = 1.167 in.).

(2) Not measurable, parts of the cup missing.

Figure H-14. Fueled Clad SC0092 (Module #1) after 77 m/s Impact Test

e) Vent End

f) Blind End

Figure H-14. Fueled Clad SC0092 (Module #1) after 77 m/s Impact Test (Cont'd)

Figure H-15. Fueled Clad SC0096 (Module #2) after 77 m/s Impact Test

e) Vent End

f) Blind End

Figure H-15. Fueled Clad SC0096 (Module #2) after 77 m/s Impact Test (Cont'd)

Five metallographic sections were removed from fueled clad SC0096. Examination of the vent revealed typical microstructure. The microstructure of the breached area revealed intergranular failure. The microstructure along the crack edge showed thinning of the clad wall and grain elongation. The width of the crack, in the area examined, measured 1.06 mm. The microstructure of the single-pass weld and weld overlap areas was typical of microstructures usually observed in these areas. The grain size in the single-pass weld area averaged 10.7 grains/wall thickness (80.6 $\mu\text{m}/\text{grain}$), and the grain size in the weld overlap area averaged 9.3 grains/wall thickness (70.0 $\mu\text{m}/\text{grain}$). The microstructures of the vent and shield cup walls were also typical. The average grain sizes of the shield and vent cup walls are shown in Table H-26.

Table H-26. Vent and Shield Cup Microstructure, Fueled Clads SC0096 and SC0107

Fuel Clad ID	Area/Orientation	Grain Size, Grains/Width *	Grain Size, $\mu\text{m}/\text{Grain}$
SC0096	Shield Cup/Axial	27.4	23.7
	Vent Cup/Axial	22.7	28.8
SC0107	Shield Cup/Axial	25.3	25.8
	Vent Cup/Axial	27.2	24.0

* Grains/nominal wall thickness of 0.65 mm.

Breached fueled clad SC0107 was located in the open end of the C GIS in module #4 (Figure H-16). The impact face was centered at approximately 200 degrees from the weld start. A weld centerline crack was centered at approximately 90 degrees from the weld start, spanning from approximately 45 to 135 degrees. This crack measured approximately 16.58 mm long and had a width of approximately 1.05 mm. The weld shield was also breached and the uranium was visible through the crack. The crack was centered between two flattened areas of the clad and appears to have been caused by compression of the clad.

Four metallographic sections were removed from SC0107. Examination of the vent revealed typical microstructure. The microstructure of the breached area revealed a clean intergranular fracture with little, if any, wall thinning and grain elongation. Fusion of the weld shield to the weld was also observed in this location. The microstructure along the crack edge showed cleavage between the grains, typical of iridium ductile failure. The width of the crack, in the area examined, measured 1.26 mm. Another crack was observed underneath the weld shield, outside of the weld, in another area of the clad. This crack initiated in the interior of the clad and had approximately 29% penetration.

a) Impact Face

b) Profile

c) Trailing Face

d) Opposite Profile

Figure H-16. Fueled Clad SC0170 (Module #4) after 77 m/s Impact Test

e) Vent End

f) Blind End

Figure H-16. Fueled Clad SC0170 (Module #4) after 77 m/s Impact Test (Cont'd)

The microstructure of the single-pass weld and weld overlap areas was typical of the microstructures usually observed in these areas. The grain size in the single-pass weld area averaged 10.7 grains/wall thickness (71.9 $\mu\text{m}/\text{grain}$), and the grain size in the weld overlap area averaged 9.8 grains/wall thickness (82.0 $\mu\text{m}/\text{grain}$). The microstructure of the vent and shield cup walls was also typical. The average grain sizes of the vent and shield cup walls are shown in Table H-26.

The fuel simulant recovered from the three breached clads was analyzed to determine particle size distribution. The particle size distribution is shown in Table H-27. The quantity of fuel simulant estimated to have been released is as follows:

- FC SC0092-Module 1: 12.164 grams
- FC SC0096-Module 2: 0.229 grams
- FC SC0107-Module 4: 0.026 grams

Table H-27. Particle Size Analysis of Retained Urania From Breached Fueled Clads in RTG-2 Test (Impact Velocity 77 m/s)

Particle Size Range (μm)	Weight Fraction of Retained Fuel		
	SC0092	SC0096	SC0107
+5600	0.5953	0.5296	0.8111
+2000 to 5600	0.2623	0.3215	0.1435
+850 to 2000	0.0852	0.1033	0.0318
+425 to 850	0.0273	0.0257	0.0077
+180 to 425	0.0133	0.0122	0.0033
+125 to 180	0.0027	0.0027	0.0004
+75 to 125	0.0025	0.0016	0.0004
+45 to 75	0.0027	0.0012	0.0008
+30 to 45	0.0012	0.0006	0.0002
+20 to 30	0.0020	0.0004	0.0002
+10 to 20	0.0035	0.0005	0.0003
+9 to 10	0.0002	0.0000	0.0000
+8 to 9	0.0002	0.0000	0.0000
+7 to 8	0.0002	0.0000	0.0000
+6 to 7	0.0002	0.0000	0.0000
+5 to 6	0.0002	0.0001	0.0000
+4 to 5	0.0003	0.0001	0.0001
+3 to 4	0.0005	0.0003	0.0002
+2 to 3	0.0001	0.0001	0.0000
+1 to 2	0.0001	0.0001	0.0000
<1	0.0000	0.0000	0.0000
Total	1.0000	1.0000	1.0000
Weight Fraction < 10 μm	0.0020	0.0007	0.0003

H.4.1.5 Discussion of Results

H.4.1.5.1 Impact Response and Fuel Release

There were no fueled clad failures in the RTG-1 test (57 m/s impact), although four fueled clads experienced dimensional strains greater than 10%. These were located in modules #1 and #2 which were located at the end of the RTG which was impacted.

Three of the fueled clads in the RTG-2 test (77 m/s impact) had breached. Two of the fueled clads, SC0092 and SC0096, appeared to fail due to contact with the titanium heat source support frame. Fueled clad SC0092 had a large breach area (485 mm²) that resulted in a release of approximately 12 g of simulant fuel. Fueled clad SC0096 had a much smaller breach that resulted in a release of approximately 0.2 g of simulant fuel. Fueled clad SC0107 experienced a weld failure. This intergranular failure occurred between columnar grains located in the weld centerline. Fusion of the weld with the weld shield was also evident in this location. This failure appeared to be the result of fragment push-through and resulted in a release of approximately 0.026 g.

H.4.1.5.2 Pellet Fragmentation

Based on the data shown in Tables H-23 and H-27, there was a slight difference between the particle size profiles of urania recovered from the fueled clads after the two tests. The most significant difference was in the $\leq 10 \mu\text{m}$ range size. The fraction of urania recovered from fueled clad SC0092 (RTG-2) was approximately twice the amount recovered from fueled clad SC0076 (RTG-1) and fueled clad SC0096 (RTG-2).

There was a significant difference between the fragmentation of fueled clad SC0107, recovered from the RTG-2 test, and the other fueled clads recovered from the RTG-1 test. The fraction of urania recovered from SC0107 in the +5600 μm range is almost twice that recovered from SC0076, SC0092, and SC0096. Fueled clad SC0107 did not undergo the same magnitude of deformation as the others. Because it was not deformed as severely as the other fueled clads, the fuel pellet would not be expected to be as fragmented as the other fuel pellets.

Table H-28 compares the particle size distribution of the urania recovered from the RTG-1 and RTG-2 tests to the distribution of urania recovered from a clad impacted in a full module CPV impact test (SC0074). The particle size distribution of SC0074 was very similar to the other distributions and there was no apparent difference between them.

Table H-28. Comparison of Fuel Simulant Fragmentation for RTG-1, RTG-2 and CPV Impact Tests

Particle Size Range, μm	Weight Fraction Retained Fuel				
	RTG-1 SC0076	RTG-2 SC0092	RTG-2 SC0096	RTG-2 SC0107	CPV SC0074 *
+180	0.9863	0.9834	0.9923	0.9974	0.9946
+125 to 180	0.0036	0.0027	0.0027	0.0004	0.0018
+75 to 125	0.0037	0.0025	0.0016	0.0004	0.0015
+45 to 75	0.0023	0.0027	0.0012	0.0008	0.0011
+30 to 45	0.0007	0.0012	0.0006	0.0002	0.0001
+20 to 30	0.0010	0.0020	0.0004	0.0002	0.0002
+10 to 20	0.0016	0.0035	0.0005	0.0003	0.0003
≤ 10	0.0008	0.0020	0.0007	0.0003	0.0004
Total	1.0000	1.0000	1.0000	1.0000	1.0000

* Clad recovered from a full module impact against a steel target, 54 m/s. (Reference H-36.)

H.4.2 Edge-On Fragment Test

H.4.2.1 Background

Analyses performed to estimate accident environments for inclusion in the Environmental Impact Statement for the Cassini mission suggested that plate fragments formed from breakup of the propulsion module subsystem (PMS) and the Centaur propellant tank/structure may constitute a potential threat to the RTGs among explosion-related environments. Fragmentation can be produced by an explosion initiated by the flight termination system (FTS) or from tipover of the vehicle and impact on the launch pad apron resulting from one SRMU failing to fire.

Analyses performed by Eck and Jaffe (Reference H-34) on the breakup of the PMS resulting from a Command Shutdown and Destruct System (CSDS) event recommended the following fragment definition for the edge-on fragment test.

Material: Al 7075 T6
Thickness: 0.16 cm
Velocity: 304.8 m/s (1000 fps)

The fragment material is representative of the PMS skin and the velocity was considered to be an over-estimate of the upper range for those fragments that can hit the RTG. The fragment test was designed to provide data on the penetrability of the RTG by plate fragments at edge-on incidence.

H.4.2.2 Test Description

Testing was conducted at the Sandia National Laboratory (SNL) Rocket Sled Test Track (Area III) and was coordinated by Los Alamos National Laboratory (LANL) as described in Reference H-35. The test setup is shown in Figure H-17. A stack of three simulated GPHS modules was heated in a furnace with an argon atmosphere which was positioned over a simulated section of an RTG. The simulated RTG section was held in place by four rods hanging from a platform which supported the heating furnace and which allowed the rocket sled to pass underneath during the test. A motorized mechanism transferred the heat source stack into the simulated RTG. A 140 second delay allowed the heat source stack temperature to decrease from 1225°C to approximately 1090°C at the time of impact. A continuous flow of argon gas was maintained as a protective atmosphere in the furnace and in the simulated RTG.

The 7075-T6 aluminum plate fragment, 0.16 cm thick by 20.32 cm deep with an unsupported span of 58.42 cm, was mounted in the support arms of the utility sled (reference Figure H-18). Static pretest alignment involved placing the plate centerline 4.92 cm below the intended impact point. This arrangement compensated for the expected upward displacement of the plate due to plate upward bowing and sled twist as determined in the impact point trials. The rocket sled was propelled by 15 High Velocity Aerial Rockets (HVARs). The test was designed to have the fragment hit the converter housing edge-on and at a location directly in line with the long axis of the GIS in the center GPHS module (reference Figure H-19).

Figure H-17. Edge-On Fragment Test Setup

Figure H-18. Aluminum Fragment Test Configuration

Test instrumentation consisted of furnace thermocouples, video of the heated stack as it was transferred into the RTG, high speed cameras and break wire velocity determination on the track just before impact. The high speed cameras included an onboard black and white film camera, operating at approximately 960 frames per second, which viewed the plate during the launch to impact trajectory. The cameras provided a 400 frames per second side view of the impact, a view from the east side at approximately 10,000 frames per second, a view through a mirror showing the bottom of the RTG at approximately 10,000 frames per second and a front quarter view at approximately 10,000 frames per second showing the impact from the northeast direction. Banks of flash bulbs provided illumination during a period of 60 ms timed to coincide with the impact. An image motion camera stationed four feet after impact allowed determination of sled velocity just after impact. Three break wires, located just before impact, provided time interval measurements used for backup velocity determination.

Figure H-19. Heat Source/Fragment Impact Orientation

H.4.2.3 Test Hardware

The simulated RTG test article (RTG-3), shown in Figure H-20, was prototypical of the RTG design at the point of impact with the aluminum fragment. It consisted of a section of the Al 2219 outer shell, sized to contain three GPHS modules. It contained multifoil insulation around the inner diameter and silicon germanium unicouples were installed in the vicinity of the impact. A graphite heat source support plate was located in the base of the RTG to ensure proper heat source alignment. A purge line was provided at the base of the simulated RTG to provide an inert cover gas (argon) after heat source loading to minimize oxidation. The simulated RTG test article was open at the top end after the heat source stack was installed; the bottom end was closed using an end plate as shown in Figure H-20.

The design of the heat source stack is shown in Figure H-21. The heat source test hardware was fabricated by Los Alamos National Laboratory (LANL). The heat source stack consisted of a GPHS module with flight quality graphite components and four flight quality iridium clads containing urania fuel simulant. A simulated module (POCO™ graphite aeroshell with molybdenum mass simulants) was located above and below the GPHS module to provide the correct mass simulation. The three modules were stacked using FWPF lock numbers and the modules held in place with POCO™ tie rods, as shown in Figure H-21. A POCO™ end plate, located at the base of the stack, was used to locate the heat source in the RTG.

Figure H-20. Simulated RTG Test Article (RTG-3) - Edge-On Fragment Impact Test

Figure H-21. Heat Source Configuration for Edge-On Fragment Impact Test

H.4.2.4 Test Results

The test results presented herein were obtained from Reference H-35. The edge-on fragment test was conducted on March 26, 1996. The measured impact velocity was 306 ± 1.5 m/s as measured from the image motion camera. The heat source impact temperature was estimated to be $1090^{\circ}\text{C} \pm 10^{\circ}\text{C}$ based on previous engineering cool-down tests.

High-speed photography of the impact indicated that the fragment leading edge impacted the converter approximately 0.63 cm above its midpoint. The fragment penetrated the converter shell to the depth of the fuel modules. The converter was cut and torn over approximately 80% of its circumference (Figure H-22). The width of the gap was approximately 2 cm. The cut was clean at its upper edge but the lower edge was folded over, toward the inside of the shell. Radiological surveys of the converter outer surface and the impact vicinity, conducted immediately following the impact, indicated that no uranium was released outside of the converter.

Figure H-22. Simulated RTG after Fragment Impact Test

The top of the converter housing showed indications that materials within the housing were ejected through the top opening. One of the POCO™ graphite modules was ejected out of the top of the converter and was found lying a few feet from the converter. Lying directly next to the ejected module was a molybdenum mass simulant that was expelled from the ejected module. The other molybdenum simulant was also ejected and located within a couple of feet of the module. The POCO™ module was intact, but chipped. Preliminary field observations revealed no cracks. Other pieces of graphite were also observed in the impact area and appeared to have originated from the top part of the graphite stack. A few pieces of FWPF graphite were also found.

A relatively large area of the fragment was torn off from the sled. This area, roughly trapezoidal in shape, measured approximately 23 cm at the leading edge and 39 cm at the trailing edge. This area was not recovered in one piece, but represented the sum of several relatively small fragments. Most of these fragments were scattered outside of the converter housing, but a few fragments were seen inside the converter during preliminary investigation.

Post mortem examination of the test components began at Los Alamos on April 4, 1996. All graphite and aluminum fragment pieces that were recovered at the test site outside of the converter were gathered together and photographed. Graphite recovered outside the converter consisted primarily of graphite components located at the top of the graphite stack including the stack lifting lug and the top POCO™ module. Graphite recovered from inside the converter consisted of the bottom POCO™ module, bottom support pieces and the FWPF module. One molybdenum mass simulant was totally dislodged from the bottom module; the other was partially dislodged. The aluminum plate fragments recovered outside the converter were severely deformed as were the fragments recovered from the converter interior. Approximately 3/4 of the fragments recovered from the converter interior had locally melted and resolidified.

Post-test disassembly of the converter revealed that the fragment penetrated into the A GIS cavity of the FWPF module. One corner of the module, at the GIS cavity, was sheared off. The graphite module cap of this cavity was dislodged and had a gash that was apparently caused by penetration of the aluminum fragment. The A GIS was ejected from the module. One half of the GIS end cap had been severed from the GIS; the other half remained in place. A relatively large piece of the GIS at the impact area (approximately one quarter of the top end) had been sheared off. Neither clad had been dislodged from the GIS. The open end clad (SC0126) was breached on its shield cup (Figure H-23). Further disassembly revealed no other breaches in the remaining clad (SC0125) in the A GIS (Figure H-24). The C GIS was unbreached and totally intact. The two fueled clads in the C GIS, SC0127 (Vent Cup 3130) and SC0128 (vent cup 3132) were also unaffected, as shown in Figure H-25.

Figure H-23. Fueled Clad SC0126 (A GIS) after Fragment Impact Test

Figure H-23. Fueled Clad SC0126 (A GIS) after Fragment Impact Test (Cont'd)

Figure H-24. Fueled Clad SC0125 (A GIS) after Fragment Impact Test

Figure H-25. Fueled Clads SC0127, Vent Cup 3130 and SC0128, Vent Cup 3132 (C GIS) after Fragment Impact Test

The post test dimensional inspection data for the four fueled clads are shown in Table H-29.

Table H-29. Fueled Clad Distortion after Edge-On Fragment Test

Fueled Clad ID	Axial	Distortion %			
		Vent Cup, Diametral		Shield Cup, Diametral	
		Max.	Min.	Max.	Min.
SC0125	0.5539	0.5044	-1.1432	0.7734	-1.1769
SC0126	3.8102	0.7066	-1.2113	1.3786	-1.1769
SC0127	0.5682	-0.5027	-0.9383	-0.1345	-0.2017
SC0128	0.7019	-0.2690	-1.0424	-0.3693	-0.8392

Fueled clad SC0126, which was located at the open end of the A GIS, had a small transverse breach (1.84 mm long, 0.40 mm wide) that was apparently caused by impact with the plate fragment (Figure H-23). This breach was located approximately between 200 to 220 degrees on the shield cup radius. Material which appeared to be an Al/Ir reaction product surrounded the breach. This material was also observed on the clad in several locations. Upon further investigation, this single breach actually consisted of two separate breaches. One was a circle-shaped breach that measured approximately 2.1 mm in diameter (3.41 mm² breach area). The other breach measured approximately 3.68 mm long and 0.56 mm at its widest point (approximately 2.06 mm² breach area). Two other transverse hairline cracks were observed on the shield cup. One crack measured approximately 7.92 mm long and was located below the weld at approximately 115 degrees from the weld start. The other crack was located at approximately 350 degrees, on the cup radius, and measured approximately 3.58 mm. An atypical discoloration of the clad material was observed approximately 130 degrees from the weld start. The estimated amount of fuel released was 0.0890 g, based on the weight of the recovered fuel retained in the fueled clad.

Because SC0126 was the most severely deformed, it was selected for metallographic analysis. It was defueled and the fuel submitted for particle size analysis. The fuel particle size analysis is provided in Table H-30. Twelve sections were cut from SC0126 and submitted for metallographic examination. The microstructure of the single-pass weld region was typical of the microstructure usually observed in this area. The microstructure of the weld overlap region was somewhat atypical with some thinning of the weld center-line cross section. It exhibited a relatively wide heat-affected zone and a very coarse

microstructure. The grain size in the single-pass weld area averaged 12.0 grains/wall thickness and the grain size in the weld overlap area averaged 8.5 grains/wall thickness. The microstructures of the vent and shield cup walls were typical. The grain sizes in these areas are shown in Table H-31.

Table H-30. Particle Size Analysis of Fuel Retained In Fueled Clad SC0126 after Edge-On Fragment Test

Particle Size Range (μm)	Weight Fraction of Retained Fuel *
+5600	0.8533
+2000 to 5600	0.0983
+850 to 2000	0.0354
+425 to 850	0.0072
+180 to 425	0.0031
+125 to 180	0.0010
+75 to 125	0.0006
+45 to 75	0.0005
+30 to 45	0.0000
+20 to 30	0.0001
+10 to 20	0.0002
+9 to 10	0.0000
+8 to 9	0.0000
+7 to 8	0.0000
+6 to 7	0.0000
+5 to 6	0.0000
+4 to 5	0.0001
+3 to 4	0.0002
+2 to 3	0.0000
+1 to 2	0.0000
<1	0.0000
Total	1.0000

* Approximately 0.0890 g fuel released.

Table H-31. Vent Shield Cup Microstructure, SC0126

Area/Orientation	Grain Size, grains/wall thickness ⁽¹⁾	Grain Size, μm /grain
Shield Cup/Axial	26.1	24.9
Shield Cup/Transverse	25.0	26.0
Vent Cup/Axial	27.4	23.7
Vent Cup/Transverse	25.9	25.1

(1) Grains/nominal wall thickness of 0.65 mm.

Metallographic examinations of the observed Al/Ir reaction product showed the reaction to be clearly defined and it appeared to be homogeneous. The intermetallic compound had several fractures indicating that it was a fairly brittle material. One of the intermetallic metallographic sections was submitted for SEM/EDS examination. The examination confirmed the presence of an Al/Ir reaction product having an Al:Ir atomic ratio of 7:3.

Examination of the two transverse shield cup breaches revealed intergranular failure. The fracture ends also exhibited wall thinning and grain alignment. There was a minute deposit of the Al/Ir intermetallic product in both fracture sites. Metallographic examination of the discolored area of the clad revealed no unusual microstructure.

H.4.2.5 Discussion Of Results

Impact Response and Fuel Release

The aluminum fragment penetrated the converter housing, resulting in significant damage. The fragment breached the FWPF module, the leading-edge GIS and a fueled clad in the open end of the leading GIS. This fueled clad, SC0126, was the only one of the four that breached. The breaches appeared to be the direct result of contact with the thin aluminum fragment. There did not appear to be any breaches resulting from the typical failure scenario of fuel fragment pushing through the cladding. The strain values of the clads were relatively low, and based on recent impact test results, would not be expected to result in clad failures (Reference H-32 and H-36).

Although a brittle Al/Ir intermetallic deposit was formed by reaction of the aluminum fragment with the hot iridium clad metal, it did not appear to significantly affect the failure mechanism of the clad. It may, however, have prevented a more significant release of fuel