LA-UR- 97-3285

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CONF-980103--

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Submitted to: INSTITUTE FOR SPACE AND NUCLEAR POWER STUDIES
SPACE TECHNOLOGY & APPLICATIONS INTERNATIONAL FORUM (STAIF-98)
JANUARY 25-29, 1998
ALBUQUERQUE, NM

Los Alamos
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RADIOISOTOPE THERMOELECTRIC GENERATOR/THIN FRAGMENT IMPACT TEST

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Abstract

The General-Purpose Heat Source (GPHS) provides power for space missions by transmitting the heat of ^{238}Pu decay to an array of thermoelectric elements in a radioisotope thermoelectric generator (RTG). Because the potential for a launch abort or return from orbit exists for any space mission, the heat source response to credible accident scenarios is being evaluated. This test was designed to provide information on the response of a loaded RTG to impact by a fragment similar to the type of fragment produced by breakup of the spacecraft propulsion module system (PMS). The results of this test indicated that impact of the RTG by a thin aluminum fragment traveling at 306 m/s may result in significant damage to the converter housing, failure of one fueled clad, and release of a small quantity of fuel.

INTRODUCTION

The General-Purpose Heat Source (GPHS) is a modular component of the radioisotope thermoelectric generators (RTGs) that will provide power for the National Aeronautics and Space Administration's (NASA's) Cassini mission to Saturn. An RTG generates electric power by using the heat of ^{238}Pu α-decay to create a temperature differential across a thermoelectric array. Each RTG is loaded with 18 GPHS modules, and each GPHS module (Figure 1) contains four $^{238}PuO_2$ fuel pellets that provide a total thermal output of approximately 250 W. Each fuel pellet is encapsulated in a vented, DOP-26 iridium alloy shell. Two capsules are held in a Fineweave-Pierced Fabric (FWPF, a 3-D carbon/carbon composite; a product of TEXTRON Specialty Materials) graphite impact shell (GIS), and two GISs are contained within a FWPF aeroshell.

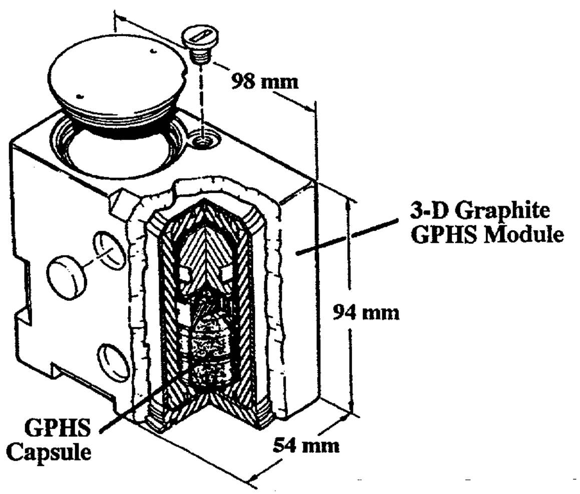


Figure 1. GPHS Module

The modular GPHS design was developed to address both survivability during launch abort and return from orbit. Previous testing conducted in support of the Galileo and Ulysses missions documented the response of the GPHS heat source to a variety of fragment-impact, aging, atmospheric reentry, and Earth impact conditions (Schonfeld 1984, Schonfeld and George 1984a, Schonfeld and George 1984b, George and Schonfeld 1984a, George and Schonfeld 1984b, Pavone et al. 1985, George and Pavone 1985, and George and Pavone 1986). Tests that required field testing of heat source and RTG components (such as solid-propellent fire, explosive overpressure, large fragment interaction, etc.) were performed using GPHS capsules fueled with $^{238}UO_2$ (^{235}U-depleted) (George et al. 1985, George 1986, Cull et at. 1986, Cull and Pavone 1986, and George 1987).

This report describes test RTG-3. This test, an edge-on fragment impact test, was third in a series of RTG impact tests. The first two tests, RTG-1 and RTG-2, were designed to provide information on the response of a loaded RTG to end-on impact against a concrete target (Reimus et al. 1996). The RTG impact tests were designed to evaluate the response of GPHSs, GPHS modules and loaded radioisotope thermoelectric generators (RTGs) to conditions that may be experienced as a result of potential on- and near-pad accidents involving failures of the Cassini spacecraft and/or launch vehicle (Bradshaw 1993). Specifically, the edge-on collision impact test was designed to provide information on the response of a loaded RTG to impact by the type of fragment that may be generated by breakup of the spacecraft propulsion module system (PMS). This test series utilized GPHS capsules fueled with $^{238}UO_2$. This report summarizes the results of this test. The reader is referred to a previous report for more detail (Reimus and Hinckley 1996).

BACKGROUND

The urania pellets used in this study were fabricated from urania powder produced by Oak Ridge National Laboratory (urania lot # NF-30-4225). All of the pellets used were fabricated by cold pressing followed by sintering

The graphite components used in the tests series were obtained from EG&G Mound Applied Technologies (EG&G MAT). The converter section was loaded with a stack made up of one FWPF graphite module, the target module, and two POCO graphite (polycrystalline graphite) modules. The POCO modules were located at both ends of the stack, with the FWPF graphite module in the middle. These modules were included to provide inertial constraint during the impact. The POCO modules each contained two molybdenum cylindrical slugs; each slug having a mass equivalent to a loaded GIS. The target module contained FWPF graphite GISs loaded with urania-fueled GPHSs with flight-quality iridium cladding.

The RTG converter shell used in this test was provided by Lockheed Martin Missiles and Space (LMMS). It consisted of a representative section of a converter housing and included multifoil insulation surrounding the graphite modules and thermoelectric elements (unicouples) installed in the converter housing. The aluminum plate fragment used in this test was fabricated from a sheet of 7075 aluminum with a T6 temper.

EXPERIMENTAL PROCEDURES

Engineering Testing

Several engineering tests, designed to determine the effects of various experimental parameters, were conducted at the Sandia National Laboratory (SNL) Rocket Sled Test Track area within Area III. An initial test was performed to verify that the desired test velocity, 305 m/s, could be achieved. The fragment deflected due to the extreme aerodynamic forces and blew out of the attachment clamps at approximately 200 m/sec. In the second test, the same fragment mount bracket was used, however, the fragment was held rigidly. The target for this test was a steel cylinder that was supported by four strings to simulate an free restraint. As predicted by a LANL hydrocode, the cylinder cut a path through the fragment before momentum was transferred to it. This test verified that the fragment restraint scheme was essentially irrelevant to due to the high energy levels of the impact.

An alternative approach in which the converter would be accelerated and the fragment stationary would theoretically produce a collision with the same energy exchange without extreme aerodynamic forces placed on the fragment. In the third test, a mock converter housing was mounted to an attachment on the SNL utility sled and impacting it into a fragment that was minimally supported by small wooden dowels. Both the fragment and the mock converter failed.

Test four reversed the roles of the two components in test three. The fragment was restrained as in the second test, and the converter was supported against a steel ring that was supported in a semi-rigid manner; with little resistance to deflection. The results were very similar to that of the third test. The fragment failed almost identically. At this point, the test scheme was specified to be acceleration of a rigidly held fragment into a stationary simulant converter housing assembly supported in a semi-rigid mounting scheme.

A fifth test was conduccted to measure the amount of fragment deflection and the data used in later tests to align the fragment for the desired impact point on the converter housing assembly. The sixth and final engineering test confirmed the operation of the furnace, stack lowering apparatus, converter housing assembly supports, sled fragment support bracket, and the pre-test alignment of the fragment.

Field Testing

The test hardware consisted of the furnace and its support stand and the rocket sled. The furnace, designed to heat its contents in an argon atmosphere, had Canthol elements that were conditioned to reach 1200-1250°C. The furnace had a bottom door that could be remotely operated so that the graphite stack could be lowered from the furnace into the converter housing. The support stand was a steel structure that supported the furnace, the graphite stack lowering apparatus and the converter housing assembly. The converter assembly was held in place by four rods and a steel ring plate attached to the bottom of the platform of the support stand. The aluminum fragment (7075-T6) that impacted the converter housing edge-on was mounted on the rocket sled (Figure 2). The aluminum fragment measured 0.16 cm thick by 20.32 cm deep and had an unsupported span (impact edge) of 58.42 cm. The fragment support was aligned such that the plate centerline was placed 4.92 cm below the center of the converter housing (Figure 3) to compensate for the upward displacement of the fragment plate.

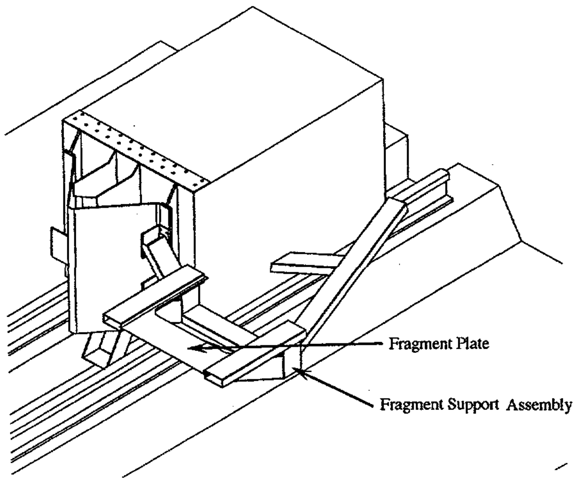


Figure 2. Aluminum fragment mounted on a support bracket on the side of the sled.

The graphite module stacks were heated to approximately 1225°C. The rockets were readied and the test sequence began with the remote opening of the furnace door. The stack was then remotely lowered from the furnace into the RTG housing. The fueled clads in the heated stack cooled to approximately 1090°C in the time required for the stack to be lowered into the converter housing and was impacted by the fragment. This sequence was carefully timed and and the rocket sled launched after 140 seconds had passed from stack placement initiation. The stack cooling characterisistics were measured prior to testing at LANL and at the test site at SNL.

RESULTS

The representative section of a GPHS RTG was impacted by a aluminum plate on March 26, 1996. The measured impact velocity was 306 ± 1.5 m/s and the RTG graphite module stack temperature was 1090 ± 10°C.

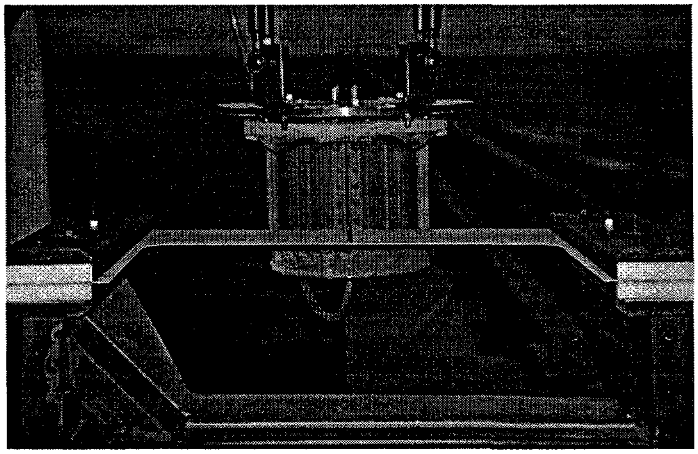


Figure 3. Alignment of the fragment with converter housing

High-speed photography of the impact indicated that the plate leading edge impacted the converter approximately 0.63 cm above its midpoint. The fragment penetrated the converter shell, microfoil insulation, thermoelements, GPHS graphitics, and contacted a fueled clad. The converter was cut and torn over approximately 80% of its circumference (Figure 4). The width of the gap was approximately 2 cm. Radiological surveys of the converter outer surface and the impact vicinity conducted immediately following the impact indicated that no urania was released outside of the converter.

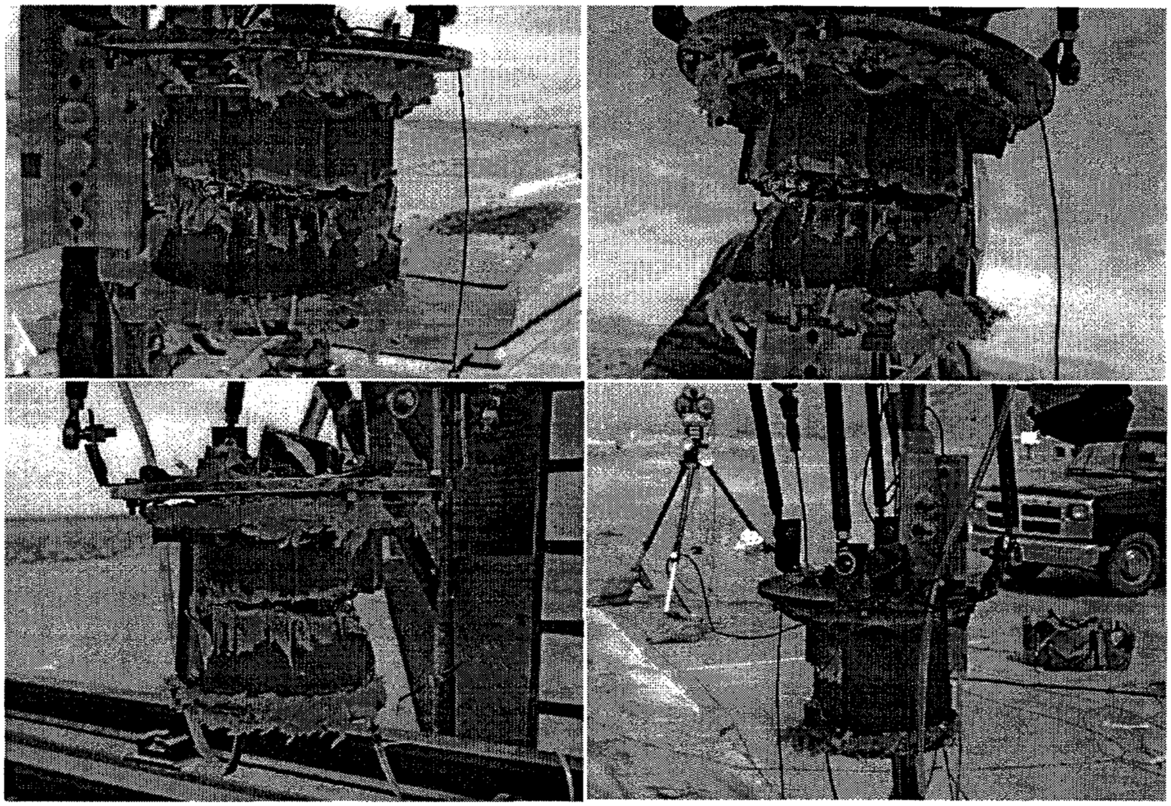


Figure 4. Impacted Converter Housing

The top of the converter housing showed indications that materials within the housing were ejected though 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. The 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 relatively large area of the fragment was torn off from the sled (Figure 5). 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-test disassembly of the converter revealed that the leading edge of the fragment, that was oriented roughly parallel to the long axis of the leading edge GIS, penetrated into the GIS cavity of the target GPHS module (Figure 6). 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 plate. The GIS was ejected from the module. 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 was breached on its shield cup (SC0126). Further disassembly revealed no other breaches in the remaining clads. The other GIS was unbreached and totally intact. Capsule deformations are listed in Table I.

TABLE I. Capsule Strains

		STRAIN, %			
		Vent Cup, Diametral		*Shield Cup, Diametral*	
GPHS	Axial	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

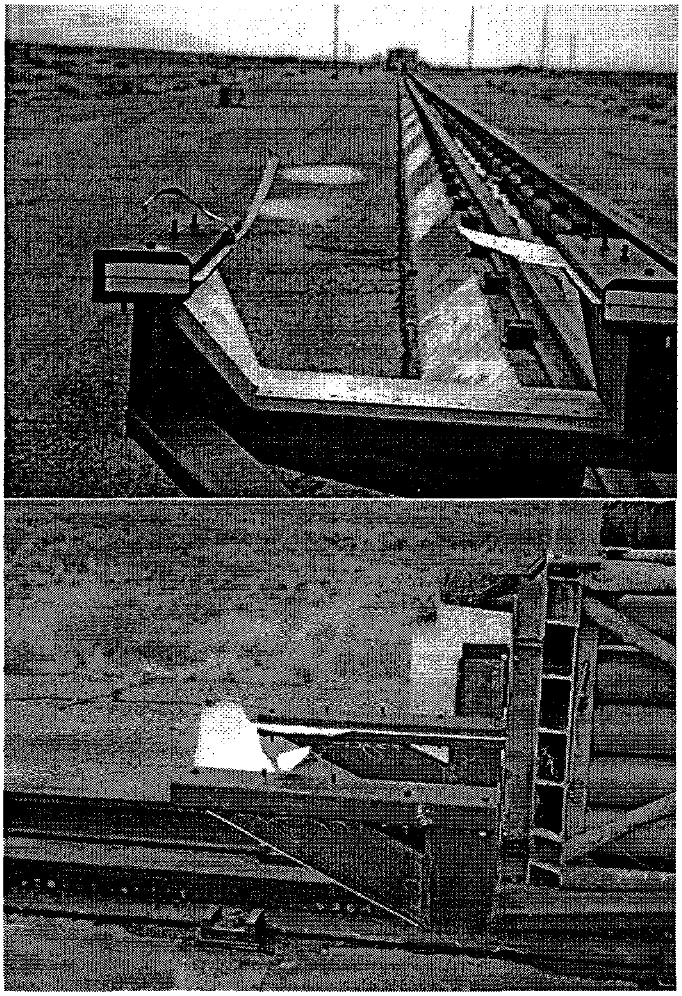


Figure 5. Fragment Remaining on Sled

Capsule SC0126, which was located at the open end of the leading edge 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 7). This breach was located between approximately 200 to 220 deg on the shield cup knuckle. Melted aluminum and material which appeared to be an Al/Ir reaction product surrounded the breach. This material was also observed on the capsule in several locations. Upon futher investigation, this single breach actually consisted of two separate failures. During examination, fragments of the aluminum fragment that partially covered these clad failures, began to flake off. Subsequent meaurement revealed that this material had covered breaches that were larger than the initial measurement taken. One was a circle-shaped breach that measured approximately 2.1 mm in diameter (3.41 mm^2 breach area). The other breach measured approximately 3.68 mm long and 0.56 mm at its widest point (approximately 2.06 mm^2 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 deg from the weld start carets. The other crack was located at approximately 350 deg, on the cup knuckle, and measured approximately 3.58 mm. An atypical discoloration of the clad material was observed approximately 130 deg from the weld carats. The estimated amount of fuel released from the capsule is 0.0890 g (based on weight of recovered fuel retained by the capsule).

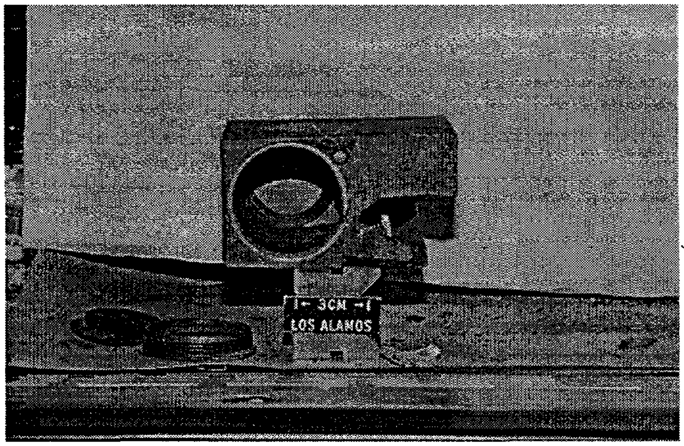
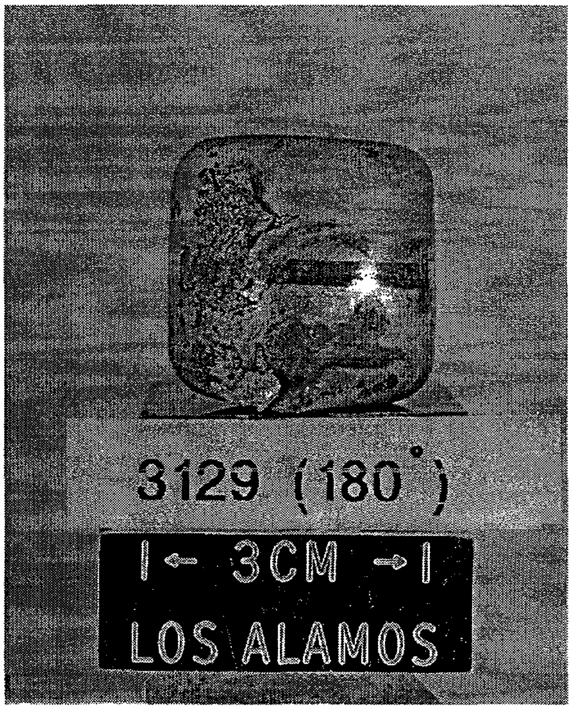


Figure 6. End View of Impacted Target Module

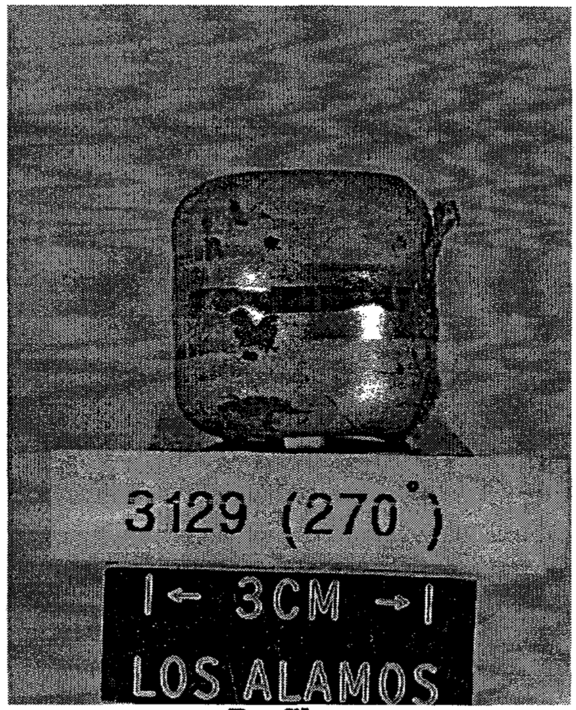
Because SC0126 was the most severly affected capsule, it was selected for metallographic analysis, and defueled and the fuel submitted for particle size analysis. The microstructure of the single-pass weld region was typical. The microstructure of the weld overlap region was somewhat atypical with modest thinning of the weld center-line cross section, and a relatively wide heat-affected zone. The microstructures of the vent and shield cup walls were typical.

Metallographic examination of the Al/Ir reaction product revealed that it was clearly defined and homogeneous.

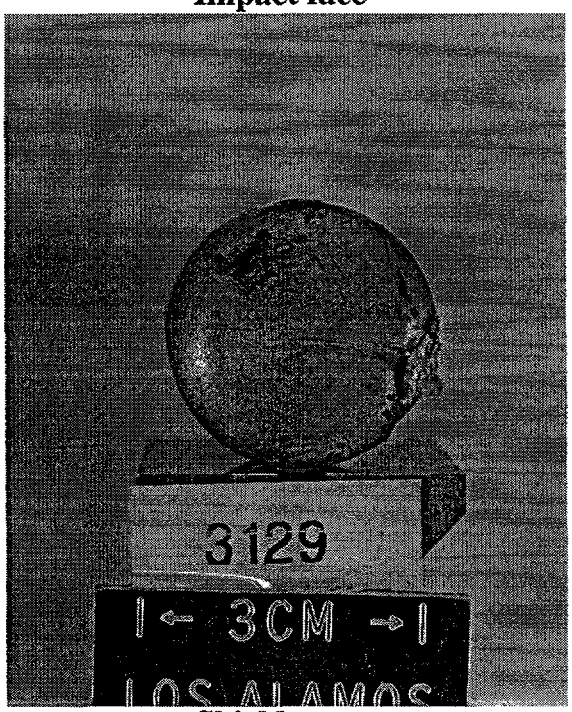
The Al/Ir intermetallic compound contained several fractures. Scanning electron microscope (SEM) examination confirmed the presence of an Al/Ir reaction product having an Al:Ir atomic ratio of approximately 7:3.



Impact face



Profile



Shield cup

Figure 7. Capsule SC0126

Examination of the two transverse shield cup breaches revealed intergranular failures with moderate grain elongation prior to failure. There was a minute deposit of the Al/Ir intermetallic product in both fracture sites, but there were no indications that the formation of the intermetallic had contributed to the failures. Metallographic examination of the discolored area of the clad revealed no unusual microstructure.

DISCUSSION

Impact Response and Fuel Release

The aluminum plate penetrated the converter housing resulting in significant damage to the shell. The plate penetrated the target GPHS module, the leading-edge GIS and the capsule at the open end of the GIS. This capsule, SC0126, was the only one of the four loaded that breached. The clad failures appeared to be direct result of impact of the aluminum plate along a small area of the GPHS clad.

There did not appear to be any failures resulting from fuel fragment push-through. The strain values of the clads were relatively low, and based on recent impact test results, would not have expected to result in clad failures (Reimus et al. 1996 and Reimus and George 1996).

Although a brittle Al/Ir intermetallic deposit was formed by reaction of the aluminum plate with the hot iridium clad metal, it did not appear to have significantly affected the clad impact response. It may, however, have prevented a more significant release of fuel from the capsule. The reaction product surrounded the breaches, and effectively reduced their size.

Pellet Fragmentation

Table II compares the particle size distribution of the urania recovered from other RTG impact tests. The distribution of SC0126 compares most closely to that of SC0107, recovered from RTG-2. The relative amount of SC0126 fuel in the < 100 μm range is significantly less than in the other capsules. Capsule SC0107 was the least severly deformed of the breached capsules recovered from RTG-2. Capsule SC0126 was even less deformed than SC0107. However, it does appear that there may be a correlation between overall capsule deformation and fines generation, particularly for the < 10 μm weight fraction.

CONCLUSIONS

The side-on impact of a simulant RTG converter assembly with a thin aluminum fragment traveling at 306 m/s resulted in significant damage to the converter and a small breach in one GPHS capsule with minumal fuel fragmentation. Failure of the single GPHS capsule failure appeared to have been caused by penetration of the iridium clad by the thin aluminum plate. The Al/Ir intermetallic produced by the reaction of the aluminum plate with the hot iridim cladding did not appear to adversely affect the clad impact response, and may have prevented a more significant release of fuel from the capsule.

TABLE II. Pellet Fragmentation of Simulant-Fueled Clads in RTG Tests

	WEIGHT FRACTION				
Retained Fuel Particle Size Range, μm	RTG-1 SC0076	RTG-2 SC0092	RTG-2 SC0096	RTG-2 SC0107	SC0126
+180	0.9863	0.9834	0.9923	0.9974	0.9973
+125 to 180	0.0036	0.0027	0.0027	0.0004	0.0010
+75 to 125	0.0037	0.0025	0.0016	0.0004	0.0006
+45 to 75	0.0023	0.0027	0.0012	0.0008	0.0005
+30 to 45	0.0007	0.0012	0.0006	0.0002	0.0000
+20 to 30	0.0010	0.0020	0.0004	0.0002	0.0000
+10 to 20	0.0016	0.0035	0.0005	0.0003	0.0002
<10	0.0008	0.0020	0.0007	0.0003	0.0003
TOTAL	1.0000	1.0000	1.0000	1.0000	1.0000

Acknowlegments

We thank A. Herrera, M. Barney, and D. Montoya for designing and conducting the field tests, and E. Burciaga, C. Lynch and P. Moniz for performing metallography, sample preparation, and particle size analyses. We would like to give special thanks to B. Kampfe and F. Mathews of Sandia National Laboratory for design of the sleds and coordination of tests at the Sandia sled test facility.

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