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Lightweight Radioisotope Heater Unit (LWRHU) Production Qualification Impact Test

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by

M. A. H. Reimus and G. H. Rinehart

ABSTRACT

The lightweight radioisotope heater unit (LWRHU), a $^{238}PuO_2$-fueled heat source designed to provide one thermal watt in each of various locations on a spacecraft. Los Alamos National Laboratory designed, fabricated, and safety tested the LWRHU. The heat source consists of a hot-pressed $^{238}PuO_2$ fuel pellet, a Pt-30Rh vented capsule, a pyrolytic graphite insulator, and a fineweave-pierced fabric graphite aeroshell assembly. To compare the performance of the LWRHUs fabricated for the Cassini mission with the performance of those fabricated for the Galileo mission, a post-reentry impact test was performed on one of 180 flight-quality units produced for the Cassini mission. The results showed that deformation and fuel containment of the impacted Cassini LWRHU was similar to that of a previously tested Galileo LWRHU. Both units sustained minimal deformation of the aeroshell and fueled capsule; the fuel was entirely contained by the platinum capsule. The fuel fragmentation observed in the Cassini LWRHU, however, was superior to that of the Galileo unit. The fuel fragmentation distribution spread was much greater, and the weight fraction of ≤45-μm fines generated was an order of magnitude greater for the Galileo unit.

I. INTRODUCTION

The lightweight radioisotope heater unit (LWRHU) is a $^{238}PuO_2$-fueled heat source designed to provide one thermal watt in each of various locations on a spacecraft. Los Alamos National Laboratory designed, fabricated, and safety tested the LWRHU. The heat source consists of a hot-pressed $^{238}PuO_2$ fuel pellet, a Pt-30Rh vented capsule, a pyrolytic graphite insulator, and a fineweave-pierced fabric* (FWPF) graphite aeroshell assembly. A drawing of the heat source assembly is shown in Figure 1. Fabrication of the Cassini mission LWRHUs is described by Rinehart in Reference 1. Several tests were conducted in support of the Galileo mission to determine the response of the LWRHU to the thermal and mechanical environments postulated for spacecraft accidents on the launch pad and on reentry abort.[2] To compare the Cassini LWRHU's performance with the Galileo LWRHU test results, a post-reentry impact test was performed on a flight-quality Cassini LWRHU.

II. EXPERIMENTAL

A. Test Object

The heat source selected for the impact test was the last item fabricated for the Cassini mission: LRF-294. Details of LWRHU fabrication are given in a previous report.[1] A brief assembly history is given here.

All components of the capsule clad, except for the frit vent, were fabricated from Pt-30Rh alloy. The frit vent was a pressed and sintered disk of pure platinum powder. EG&G Mound Applied Technologies fabricated the components and electron-beam welded the frit vent and vent cap end into place before shipping the hardware to Los Alamos. Each piece of hardware was visually inspected at Los Alamos before it was

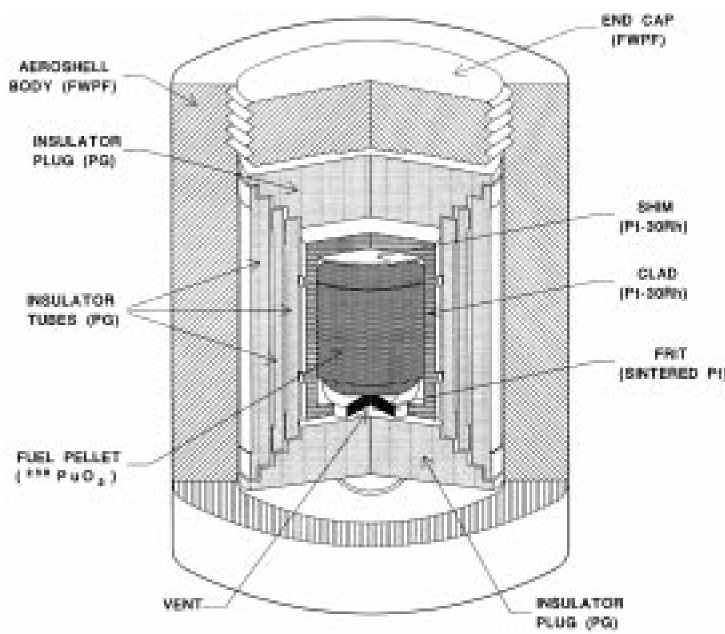


Figure 1. Light-weight radioisotope heat unit (LWRHU).

Fineweave-Pierced Fabric 3-D carbon/carbon composite, a product of AVCO Systems Division, 201 Lowell St., Wilmington, MA 01887.

released for production. After the fuel pellet was loaded into the clad, the blind end of the clad, opposite the vented end, was welded with a gas tungsten arc welding system in a helium atmosphere at Los Alamos.

After the end cap was welded, the capsule vent was activated with an end mill, the vent hole examined microscopically, and the entire capsule checked for loose alpha contamination. The capsule was then loaded, vent end down, into the graphite aeroshell and the graphite end cap glued into place. The aeroshell was then heat treated to cure the glue and checked for surface contamination.

This aeroshell assembly had a mass of 39.738 g and was 31.957 mm long and 25.943 mm in diameter. The aeroshell assembly contained fueled capsule CB873, which contained fuel pellet RU42-15. The graphite and clad components are identified in Table I. The cationic impurity levels for pellet lot RU42 are listed in Table II.

To simulate the thermal environment an LWRHU might be exposed to before impact after an accidental reentry into Earth's atmosphere, the LWRHU was placed in a vacuum furnace and exposed to a thermal pulse (AP2737) calculated at the Applied Physics Laboratory.[3] Both the calculated and actual pulses are shown in Figure 2.

B. Impact Testing and Postmortem Recovery

The LWRHU was placed into a cradle that supported it in the proper orientation for side-on impact. This cradle was machined directly into the inner projectile cylinder and loaded into the isotope fuels impact tester on an outer projectile cylinder that rides in the smooth bore of the launcher. Compressed gas drove this projectile assembly vertically to

Table I. LWRHU LRF-294 Components

Component	ID
Graphite Components	
Aeroshell body	LRF-294
Insulator cap	1398
Inner body	194
Middle body	213
Outer body	230
Insulator cap 2	399
Aeroshell cap	C294
Clad Components	
Body	CB873
Cap	869
Shim	934

Table II. Spectrochemical Data for Pellet Lot RU42	
Impurity	**$\mu g/g\ PuO_2$**
Al	55
B	<10
Ca	4
Cd	<10
Cr	120
Cu	<1
Fe	320
Mg	15
Mn	5
Mo	<20
Na	<50
Ni	27
Pb	<10
Si	495
Sn	<5
Zn	<5

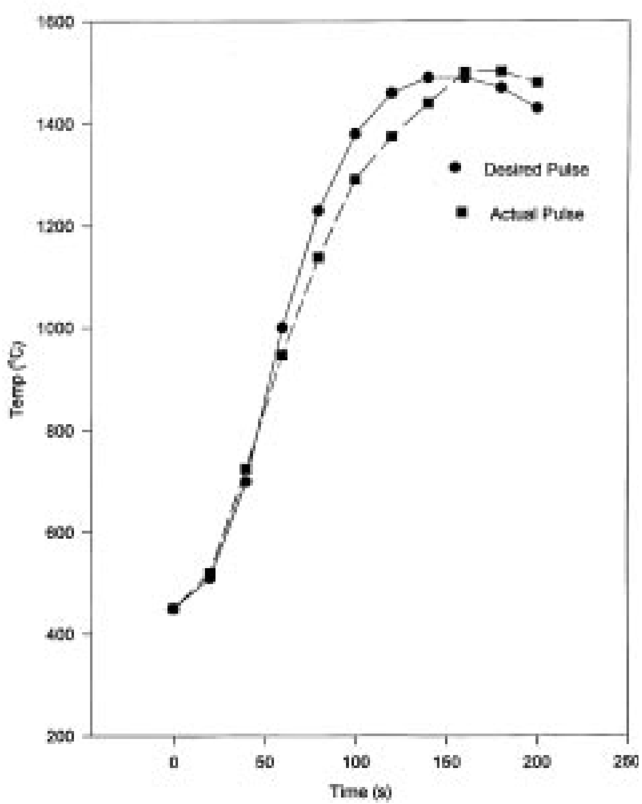


Figure 2. Temperature history of the LRF-294 reentry pulse.

the end of the barrel, where the outer and inner projectile cylinders were stopped by and sealed the tapered throats of the outer and inner catch tubes, respectively. The sample continued to fly to the end of the inner catch tube, where it impacted the hardened steel target.. The intended velocity was 54 m/s, and the impact was performed at LWRHU ambient temperature.

After the impact test, the sealed catch tube containing the heater unit was placed into a hood and the catch tube atmosphere monitored for radioactive activity though a side port. The test components were then removed from the catch tube. All test components were photographed and measured to determine postimpact dimensions, and the size and location of all cracks and surface anomalies were recorded.

The fueled capsule was removed from the aeroshell by removing the end cap. This was accomplished by cutting through the aeroshell approximately 5 mm from the end cap end with an isomet sectioning saw. The pyrolytic graphite components contained within the aeroshell were carefully removed, examined, and photographed. The fueled capsule was then removed from the graphite components, examined, its exterior dimensions measured, and photographed.

After documentation of its appearance, the capsule was opened and the fuel recovered and submitted for particle-size analysis. The welded portions of the clad material were then sectioned and submitted for metallographic examination.

III. RESULTS

On June 28, 1996, LWRHU LRF-294 was impacted at ambient temperature against a hardened 4340 steel target (6.98-cm thick) at 53.5 (±0.5) m/s. The test article orientation was side-on. The recovered aeroshell was intact, and survey smears of the test components had no detectable radioactivity, indicating the plutonia fuel was contained by the capsule. Observation revealed a small axial indentation on the impact face of the aeroshell and a small amount of graphite glue dislodged from the end cap. Small indents were observed on the edge of the end cap and on the edge of the blind end. Photographs of the recovered aeroshell are shown in Figure 3.

Approximately 5 mm of the aeroshell was removed from the end cap with an isomet wafering saw, and the pyrolytic graphite components were removed and examined. Figure 4 shows the appearance of the cut end of the aeroshell with a thin piece of the end cap remaining in place. No visible damage was observed on the interior of the FWPF aeroshell (see Figure 5).

Inside the FWPF aeroshell, an assembly of three nested concentric pyrolytic graphite cylinders with standoff rings insulates the fueled capsule from the aeroshell body. These cylinders are referred to as outer, middle, and inner insulating sleeves, according to their location in the cylinder assembly. A stepped pyrolytic graphite insulator tube plug is

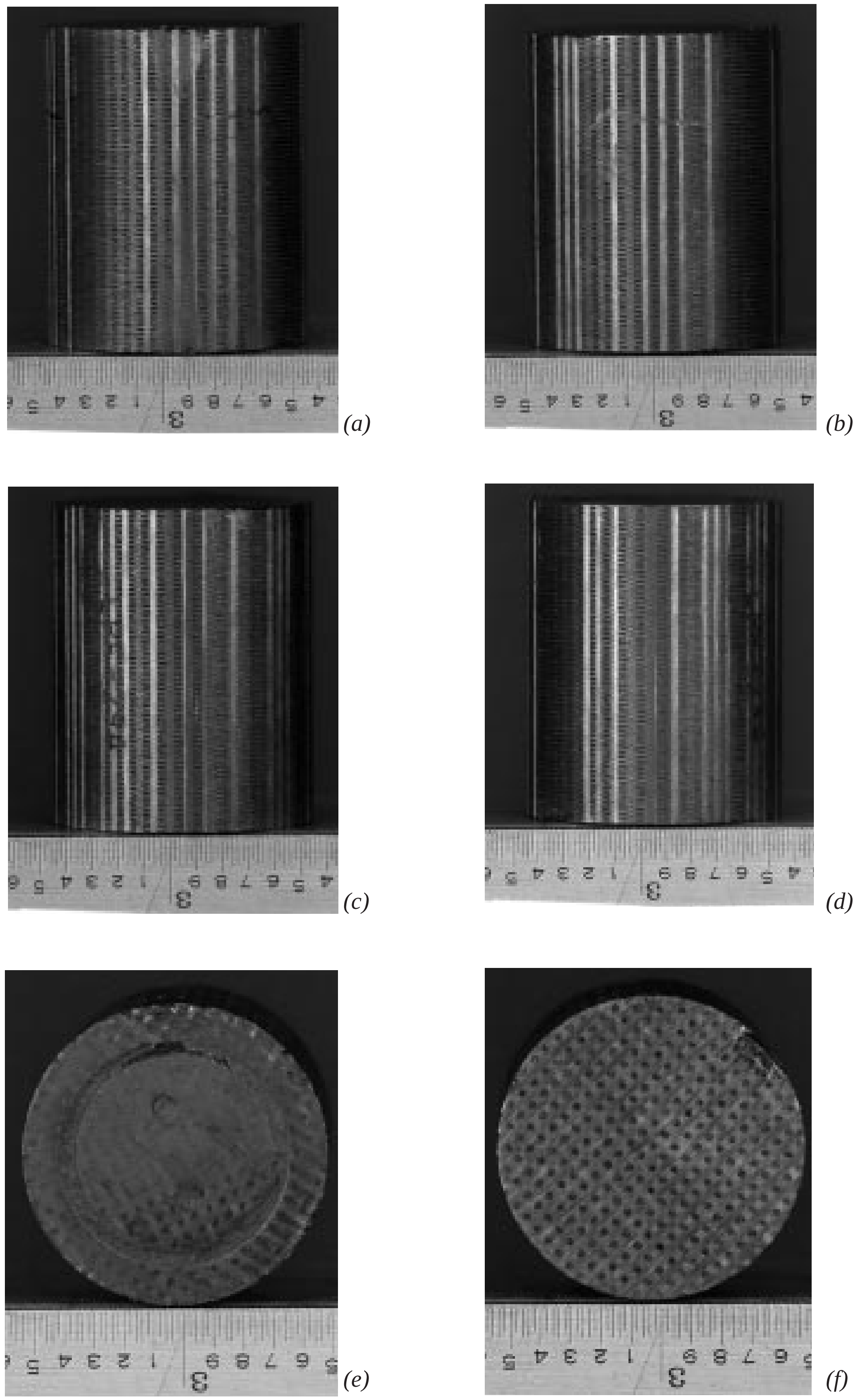


Figure 3. Impacted LRF-294 aeroshell: (a) impact face; (b) profile, 90 deg; (c) trailing face; (d) profile, 270 deg; (e) end cap; (f) blind end.

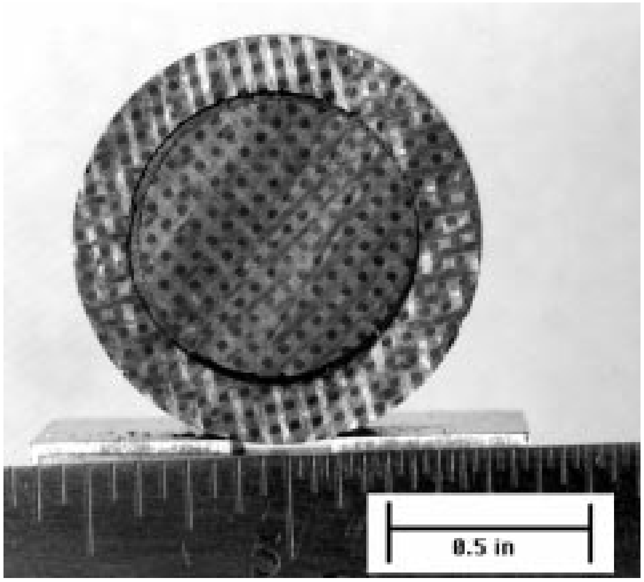


Figure 4. Sectioned end of the LRF-294 aeroshell before removal of the end cap.

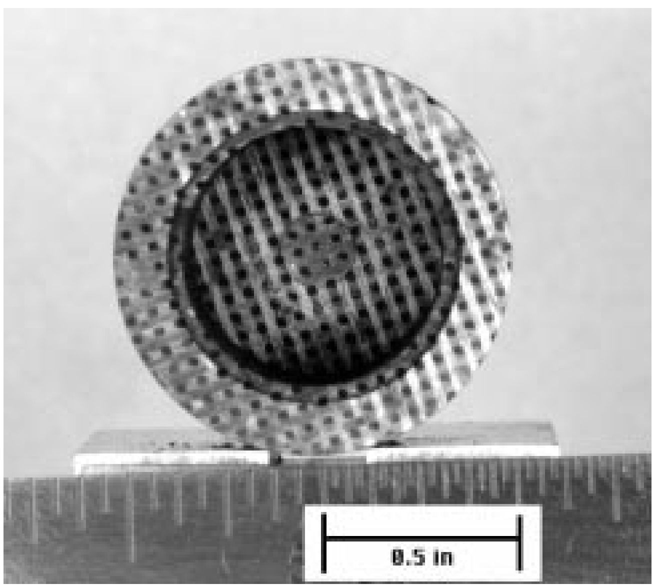
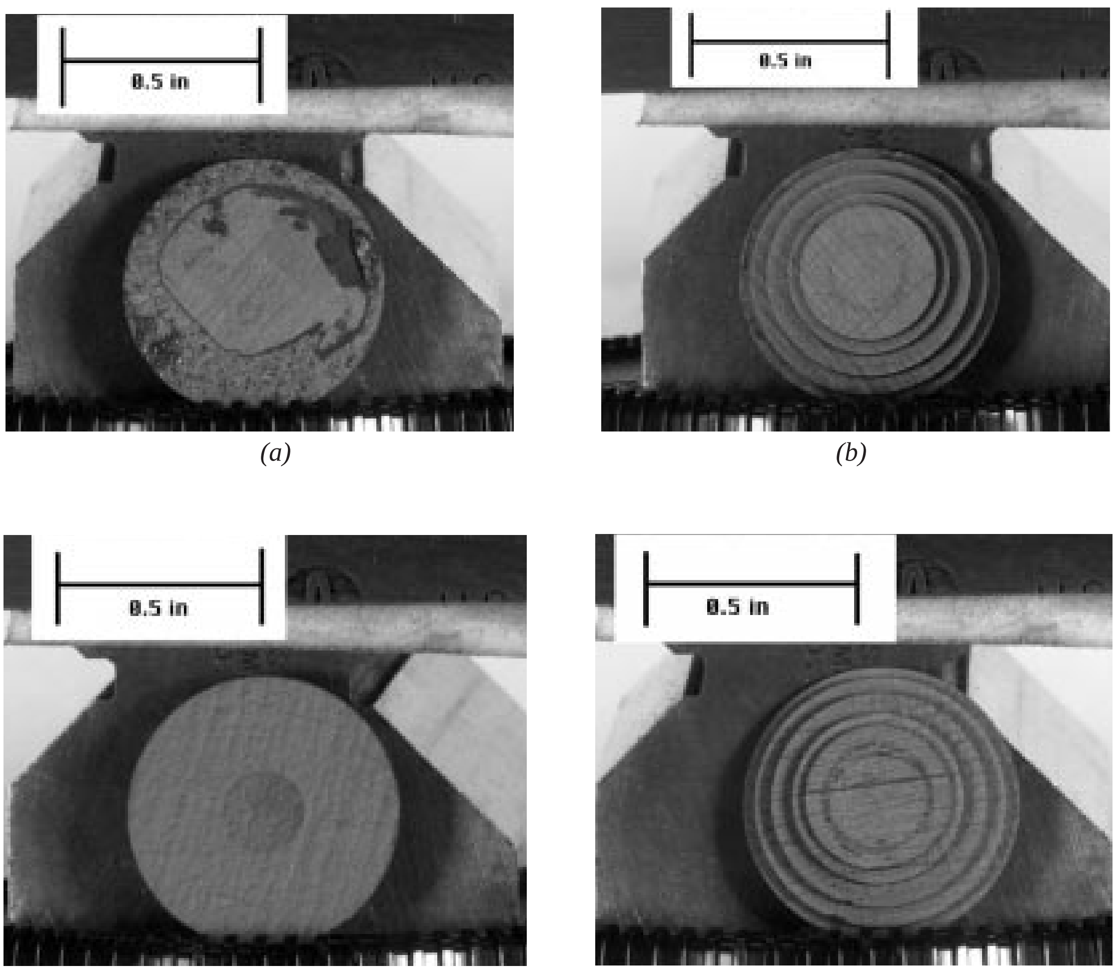


Figure 5. Interior of the LRF-294 aeroshell.

located at each end of the nested cylinders. Figure 6 shows the disassembled aeroshell, including the fueled capsule. When the aeroshell was opened, the open end insulator tube plug was found to be partially glued to the FWPF end cap. The interior surface of the pyrolytic end cap showed no visible damage, and the blind end insulator tube plug sustained no damage. Photographs of both insulator tube plugs appear in Figure 7.

An axial hairline crack, extending the entire length of the sleeve, was visible on the outer sleeve exterior. This crack penetrated the sleeve and was visible for approximately one-third of the sleeve length on the interior surface. This outer pyrolytic graphite insulating sleeve is pictured in Figure 8.

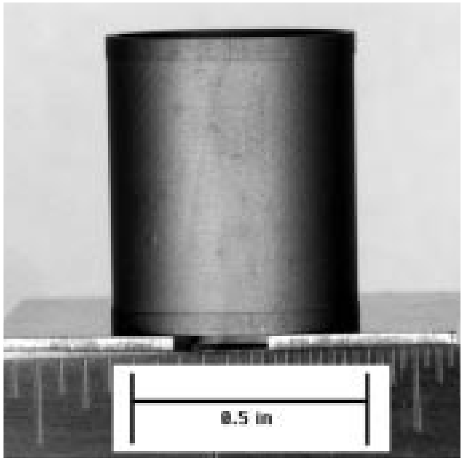
Figure 6. Disassembled LRF-294.



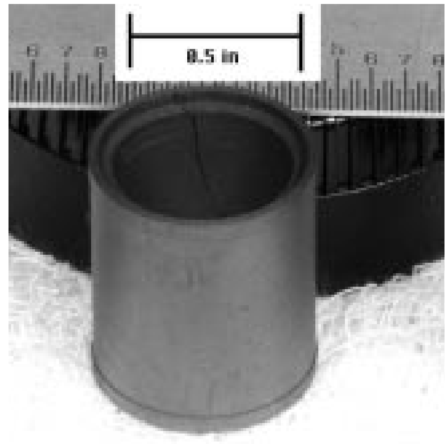
(a) *(b)*

(c) *(d)*

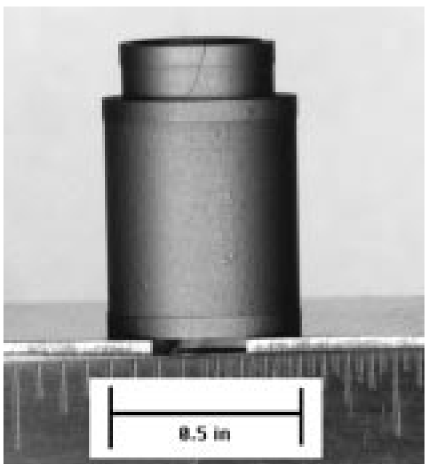
Figure 7. Pyrolytic graphite insulator tube plugs: (a) open end plug, exterior surface; (b) open end plug, interior surface; (c) blind end plug, exterior surface; (d) blind end plug, interior surface.



(a)



(b)



(c)

(d)

Figure 8. Outer pyrolytic graphite insulator sleeve: (a) profile, (b) oblique view, (c) end, (d) opposite end.

An axial hairline crack extending from one end and terminating at the stand-off ring on the opposite end was visible on the surface of the middle insulating sleeve. This crack penetrated the sleeve wall and was visible on the sleeve's interior surface. One other hairline crack was visible on the sleeve's interior surface. This middle pyrolytic graphite insulating sleeve is pictured in Figure 9; these photographs were taken during the disassembly process and show the inner insulating sleeve extending out one end of the middle sleeve. Figure 10 shows end views of the two cylinders before the inner cylinder position was perturbed.

Three hairline axial cracks were observed on the exterior surface of the inner insulator sleeve. A hairline transverse crack was also visible on the sleeve exterior and was bisected by one of the axial cracks. Two axial cracks and several transverse cracks were visible on the interior of the sleeve. Significant delamination of the inner sleeve

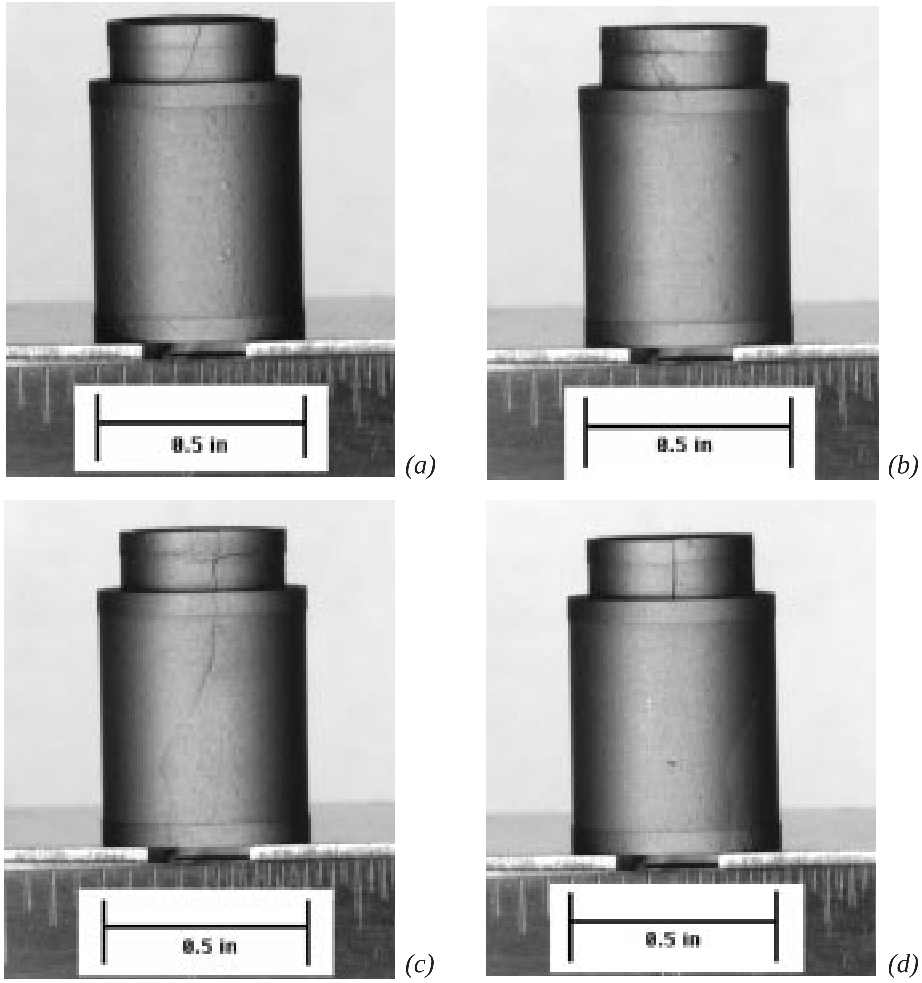


Figure 9. Middle pyrolytic graphite insulator sleeve with inner sleeve extending from one end: (a) profile, 0 deg; (b) 90 deg; (c) 180 deg; (d) 270 deg.

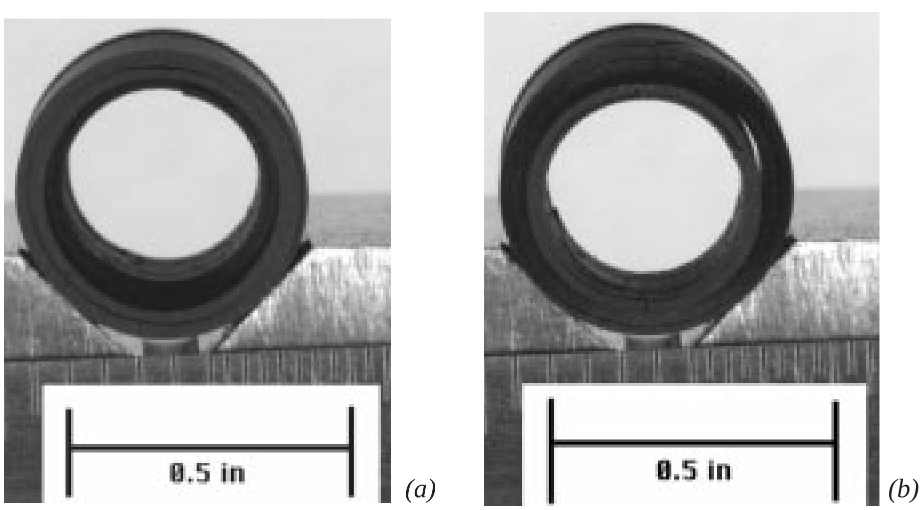


Figure 10. End views of concentric middle and inner pyrolytic graphite insulator sleeves: (a) end, (b) opposite end.

layers was visible on the end-on orientation of the sleeve and is visible in Figure 10. In spite of careful handling, several pieces fell off of the sleeve exterior during disassembly. The inner pyrolytic graphite insulator sleeve is pictured in Figure 11.

No visible damage to the fueled capsule was discovered. Profiles of the recovered capsule are pictured in Figure 12. The dimensions of the clad remained within the product specifications. The measured dimensions and comparison with the product specifications are listed in Table III.

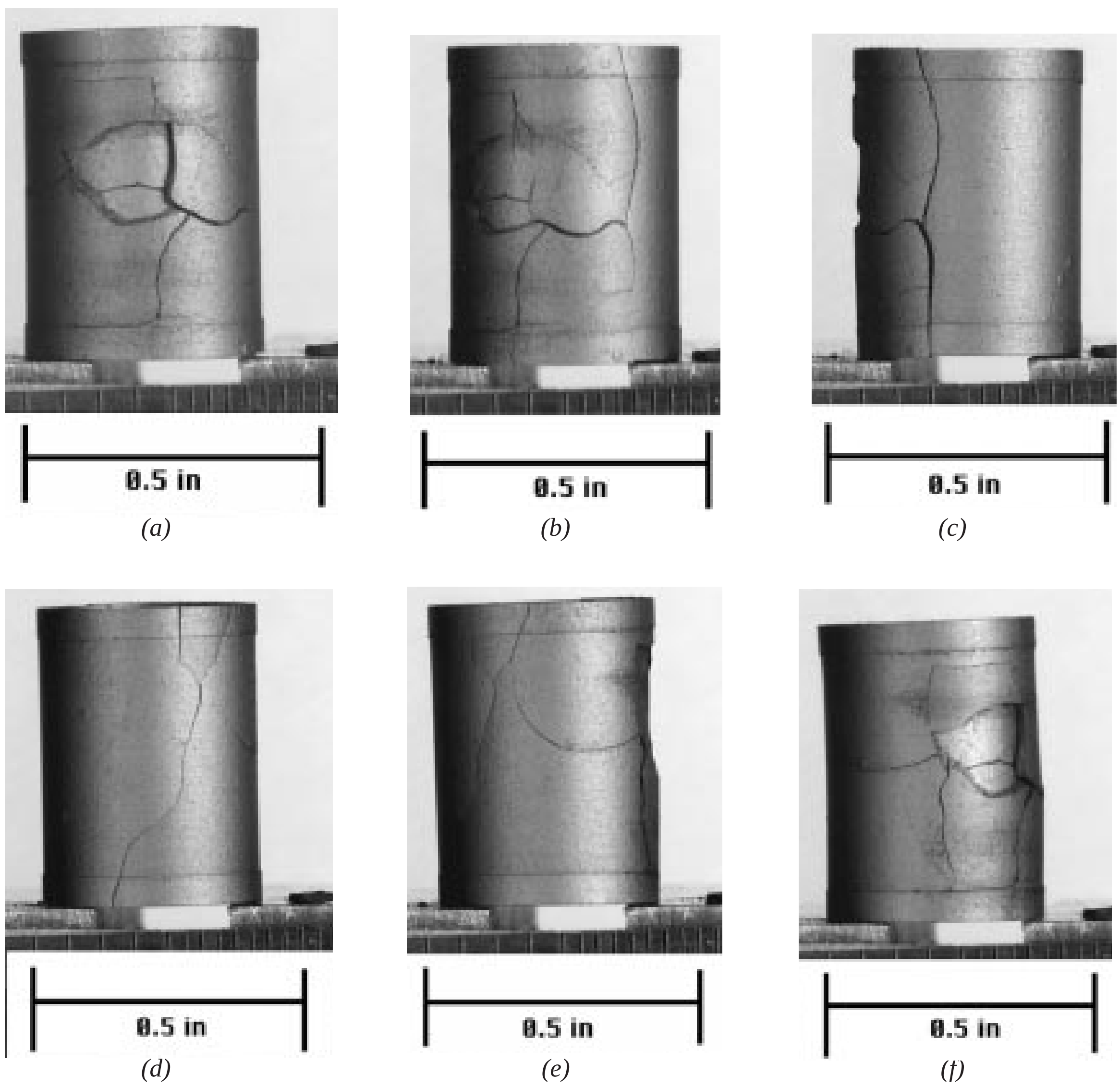


Figure 11. Inner pyrolytic graphite insulator sleeve: (a) profile, 0 deg; (b) 45 deg; (c) 90 deg; (d) 180 deg; (e) 270 deg; (f) 315 deg.

(a)

(b)

(c)

(d)

Figure 12. Fueled capsule CB873: (a) profile, 0 deg; (b) 90 deg.; (c) 180 deg; (d) 270 deg.

Table III. Postimpact Dimensions of Fueled Capsule CB873

Dimension	Postimpact (mm)	Product Specification (mm)
Maximum diameter*	8.603	≤8.65
Maximum length	12.746	≤12.85

**Measured at stand-offs.*

The fueled capsule was then defueled and the fuel submitted for particle-size analysis. The clad was sectioned and the welded ends of the capsule submitted for metallography. The results of the particle-size analysis are listed in Table IV.

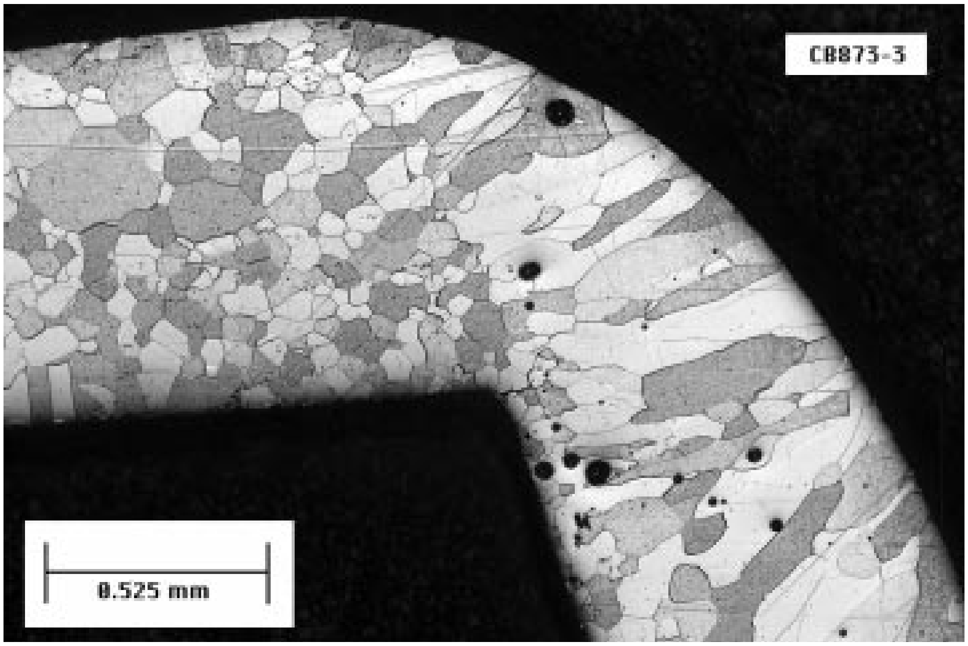
Examination of the welded areas of the capsule revealed typical microstructure. Micrographs of these structures are given in Figures 13 (end cap weld) and 14 (vent cap weld). The porosity of the end cap weld falls within the weld specification: any weld pore diameter or aggregate diameter of pores must be less than 0.25 mm. The weld is fully penetrating. The vent cap weld also falls within specification. The microstructure of this weld is much coarser than the end cap weld. The end cap weld's finer grain structure has the potential to increase the weld toughness and ductility.

IV. DISCUSSION

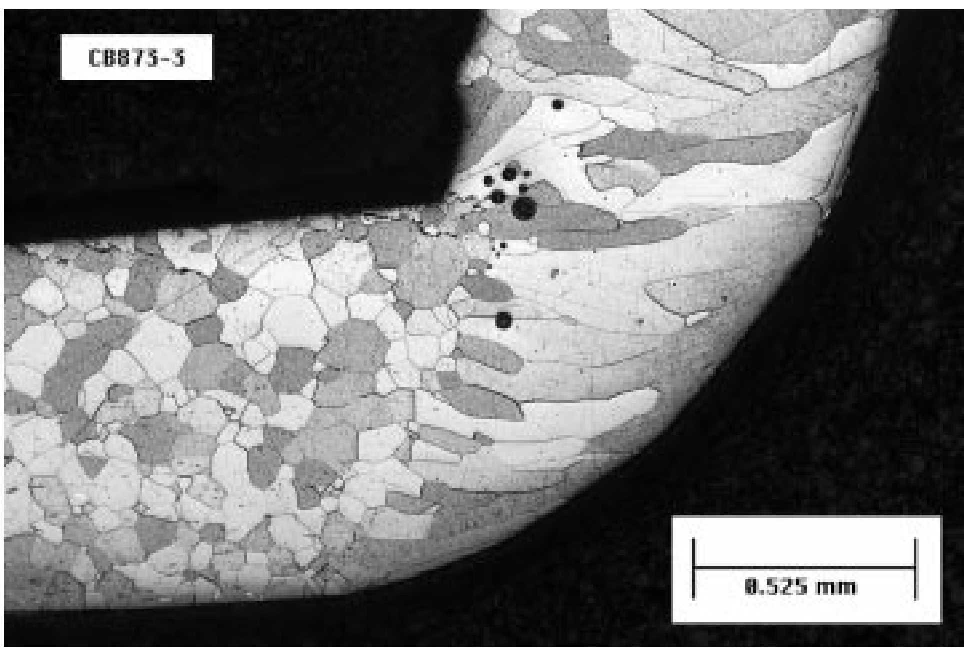
From LWRHU impact test data generated in support of the Galileo mission, the results of an impact test conducted under conditions similar to those used for the Cassini LWRHU tests were selected for comparison. The LWRHU LRF-021 was impacted at its ambient temperature against a hardened steel target at 49.3 m/s. The aeroshell and capsule experienced minimal deformation. The aeroshell experienced slightly more damage than the Cassini unit, LRF-294. This observation is based on a comparison of postimpact LRF-294 photographs with a postimpact LRF-021 photograph given in Reference 2. In both tests, the fueled capsule experienced minimal deformation and the fuel was entirely contained.

Table IV. Particle-Size Distribution of Fuel Recovered from Capsule CB873

Particle Size (μm)	Weight Fraction
+5600	0.6400
+2000 to 5600	0.2400
+850 to 2000	0.0655
+425 to 850	0.0145
+180 to 425	0.0182
+125 to 180	0.0073
+75 to 125	0.0073
+45 to 75	0.0036
<45	0.0036
Total	1.0000

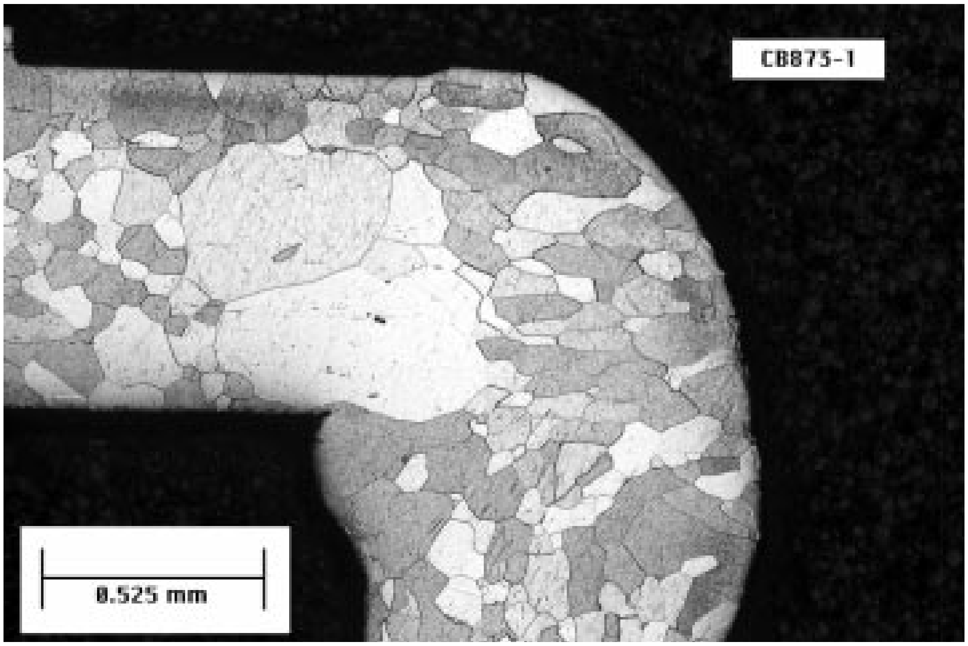


(a)



(b)

Figure 13. Microstructure of the capsule CB873 end cap weld: (a) weld corner, (b) opposite corner (NMT-9 micrographs CB873-3-17 and CB873-3-18, respectively).



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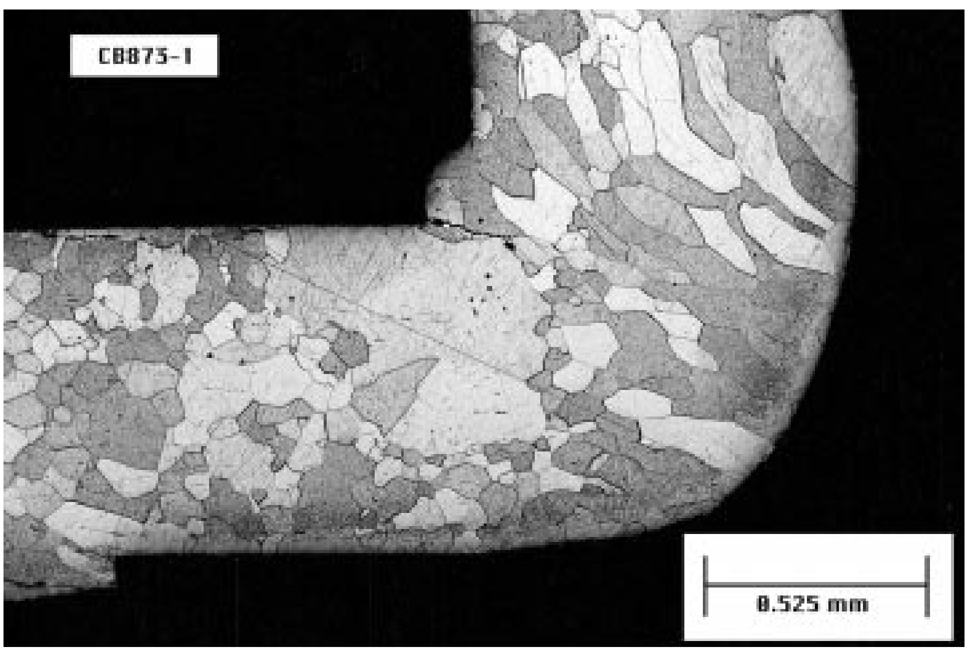

(b)

Figure 14. Microstructure of the capsule CB873 vent cap weld: (a) weld corner, (b) opposite corner (NMT-9 micrographs CB873-1-15 and CB873-1-16, respectively).

Table V compares the particle-size distributions of the fuel recovered from the two impacted LWRHUs. The fuel fragmentation response of these units is significantly different. The Cassini unit fuel was broken up much less than that of the Galileo unit. The Galileo fuel produced an order of magnitude greater weight fraction of fines <45 mm. Comparing these results indicates a superior response of the Cassini LWRHU to the impact test conditions.

Table V. Comparison of Particle-Size Distribution of Impacted LWRHUs

	Weight Fraction	
Particle Size (µm)	**LRF-294**	**LRF-021**
+2000	0.8800	0.1797
+850 to 2000	0.0655	0.3169
+425 to 850	0.0145	0.2388
+180 to 425	0.0182	0.1502
+125 to 180	0.0073	0.0273
+75 to 125	0.0073	0.0245
+45 to 75	0.0036	0.0160
<45	0.0036	0.0466
Total	1.0000	1.0000

V. CONCLUSIONS

The deformation and fuel containment of the impacted Cassini LWRHU LRF-294 was similar to that of an LWRHU produced for and tested in support of the Galileo mission, LRF-021. Minimal deformation occurred on the aeroshell and fueled capsule, and the fuel was entirely contained by the units. The fuel fragmentation response of the Cassini LWRHU, however, was superior to that of the Galileo unit. The fuel fragmentation distribution spread was much greater, and the weight fraction of <45-mm fines was an order of magnitude greater for the Galileo unit.

VI. ACKNOWLEDGMENTS

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