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Title: LIGHT-WEIGHT RADIOISOTOPE HEATER IMPACT TESTS

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LIGHT-WEIGHT RADIOISOTOPE HEATER IMPACT TESTS

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Abstract

The light-weight 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 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, and to determine a failure threshold, two types of impact tests were conducted. A post-reentry impact test was performed on one of 180 flight-quality units produced for the Cassini mission and a series of sequential impact tests using simulant-fueled LWRHU capsules were conducted respectively. 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. Sequential impacting, in both end-on and side-on orientations, resulted in increased damage with each subsequent impact. Sequential impacting of the LWRHU appears to result in slightly greater damage than a single impact at the final impact velocity of 50 m/s.

INTRODUCTION

The light-weight 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, a 3-D carbon/carbon composite; a product of TEXTRON Specialty Materials) 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 1996. 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 (Tate and Land 1985). 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. A series of impact tests on simulant-fueled LWRHUs were also performed to provide information on the failure thresholds of various LWRHU components. This report summarizes the results of these tests. The reader is referred to previous reports for further detail (Reimus and Rinehart 1997a and Reimus and Rinehart 1997b).

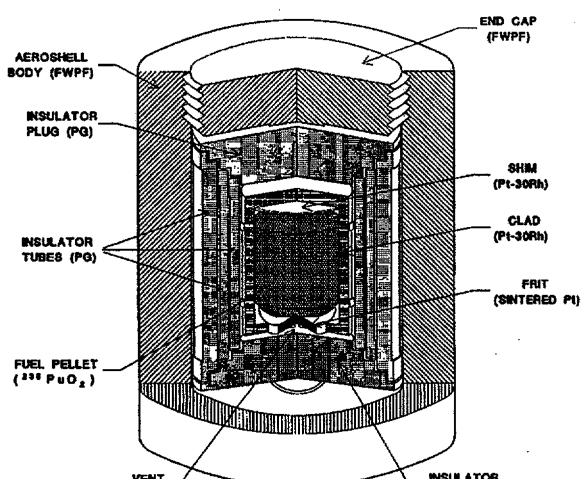


Figure 1. Light-Weight Radioisotope Heater Unit (LWRHU)

EXPERIMENTAL

Production Qualification and Sequential Impact Test Series LWRHUs

The heat source selected for the Cassini production qualification impact test was the last item fabricated for the Cassini mission: LRF-294 (containing fueled capsule CB873). To simulate the thermal environment an LWRHU might be exposed to before impact after an accidental reentry into Earth's atmosphere, the LRF-294 was placed in a vacuum furnace and exposed to a thermal pulse (AP2737) calculated at the Applied Physics Laboratory (Tate 1980).

The two LWRHU capsules (identification numbers 624 and 625) were fabricated with simulant-fuel pellets (depleted urania) specifically for vibration testing prior to being selected for sequential impact testing. The capsules were radiographically examined to verify weld penetration and to determine fuel pellet integrity. The capsules were then loaded into graphite aeroshells at LANL. The entire assemblies were then shipped to EG&G MAT where they were subjected to random and sinusoidal vibration testing. The capsules were then removed from the graphite components and inspected. No apparent degradation was sustained by the graphite components and capsule cladding (Johnson 1997). These capsules were then shipped back to LANL where they were radiographically examined. Comparison of the radiographic examinations of the capsules before and after vibration testing revealed that a slight amount of damage was sustained by the pellets. The pellet loaded into capsule 625 was integral, however, one corner at the vented end of the capsule appeared to have been abraded by vibration of the pellet inside the capsule. The pellet loaded into capsule 624 had a transverse crack separating it into two pieces. Examination of the pellet after the vibration testing revealed rounding of the edges of both pieces that appeared to have been caused by abrasion.

The capsules 624 and 625 were loaded into new sets of graphite components; aeroshells LRF-090 and LRF-370, respectively. The end caps were glued into place, and the aeroshells heat treated to cure the glue.

Impact Testing and Postmortem Recovery of LWRHUs

The Cassini production qualification LWRHU, LRF-294, 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. The LWRHU was impacted against a 6.98-cm-thick hardened 4340 steel target. The intended velocity was 54 m/s, and the impact was performed at LWRHU ambient temperature.

Prior to impact testing, each sequential impact test series LWRHU was loaded into an aluminum enclosure can fabricated from Al-6061-T6 (Figure 2). The aeroshells were loaded into the cans with the glued end cap oriented opposite the can screw cap. An aluminum load plate was placed on top of the aeroshell, two Belleville washers placed on the load plate, and the cap screwed into place.

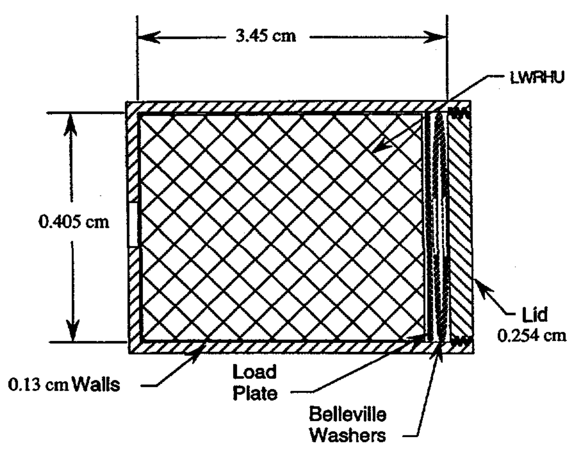


Figure 2. Aluminum Enclosure Can

The initial test velocity was specified as 20 m/s. Each subsequent test was conducted at a velocity 10 m/s higher than the previous one. The LWRHUs were sequentially impacted at the incrementally increased velocity until the aeroshells were sufficiently distorted such that they could not be inserted into new aluminum cans. At each test velocity, the LWRHUs were loaded next to each other into recessed areas that supported the test objects in the proper orientation for side-on and end-on impact. They were positioned at a sufficient distance from each other so that they would not interact with each other before, during, or after impact. The recessed areas were machined directly into the inner projectile cylinder.

After the impact test, the sealed catch tube containing the heater unit(s) was opened. The test components were then removed and photographed and the size and location of all cracks and surface anomalies recorded. Postimpact dimensions of the production qualification LWRHU were measured during test recovery and the postimpact dimensions of the sequentially impacted LWRHUs were measured at the conclusion of the test series.

The fueled capsules were removed from the aeroshells 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 aeroshells, an assembly of three nested concentric pyrolytic graphite cylinders with stepped pyrolytic graphite insulator tube plugs located at each end, were carefully removed, examined, and photographed. The fueled capsules were then removed from the graphite components, examined, their exterior dimensions measured, and photographed. After documentation of its appearance, the production qualification 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. The sequentially impacted capsules were not opened.

PRODUCTION QUALIFICATION LWRHU IMPACT TEST RESULTS

On June 28, 1996, LWRHU LRF-294 was impacted at ambient temperature against a hardened steel target 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 indentations were observed on the edge of the end cap and on the edge of the blind end. A photograph of the disassembled aeroshell is shown in Figure 3.

No visible damage was observed on the interior of the FWPF aeroshell. The interior surface of the pyrolytic end cap showed no visible damage, and the blind end pyrolytic cap sustained no damage. Hairline axial cracks were observed in each of the three pyrolytic graphite sleeves. No visible damage to the fueled capsule was discovered. Profiles of the recovered capsule are pictured in Figure 4. The dimensions of the clad remained within the product specifications.

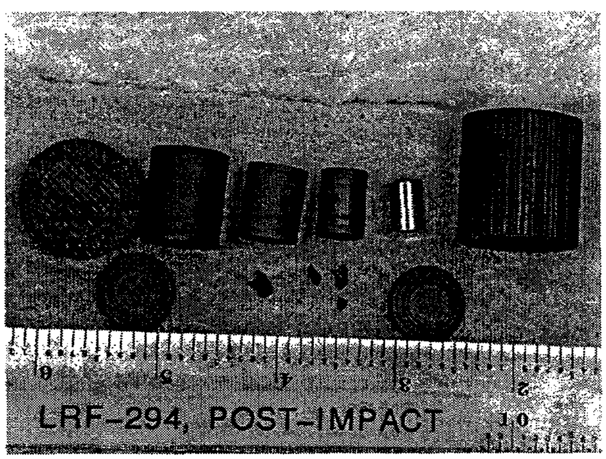


Figure 3. Disassembled LRF-294

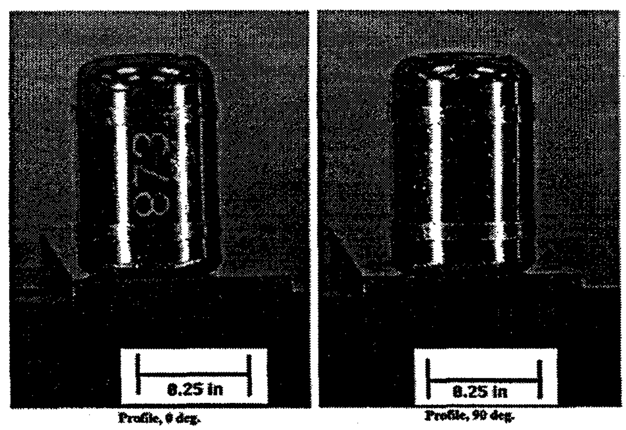


Figure 4. Fueled Capsule CB873

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. Examination of the welded areas of the capsule revealed typical microstructure, and full penetration of the welds. The results of the particle-size analysis are discussed later in this report.

SEQUENTIALLY IMPACTED LWRHUs RESULTS

Impact at 20 m/s

On July 31, 1996, simulant-fueled LWRHUs LRF-090 and LRF-370 were impacted at ambient temperature against a hardened steel target at 21.21 ± 0.06 m/s. The aluminum enclosures containing the aeroshells were intact, and survey smears of the test components had no detectable radioactivity, indicating the depleted urania fuel was contained by the capsules.

The deformation of the impact face of the side-on impacted enclosure containing LRF-090 was typical of that observed in these types of tests. A flattened area was visible oriented axially on the impact face. The aeroshell was minimally affected by the impact. The aeroshell was successfully loaded into a new aluminum enclosure.

The enclosure containing LRF-370 was impacted end-on. The small dent on the end opposite the impact face of this enclosure appears to have been caused by postimpact rebounding of the can against the inner catch tube. There was no visible evidence of damage to the aeroshell exterior, and it was successfully loaded into a new aluminum enclosure.

Impact at 30 m/s

On August 8, 1996, simulant-fueled LWRHUs LRF-090 and LRF-370 were impacted at ambient temperature against a hardened steel target at approximately 30 m/s. Unfortunately, velocity data was not captured because of instrumentation error. The aluminum enclosures containing the aeroshells were intact, and survey smears of the test components had no detectable radioactivity, indicating the depleted urania fuel was contained by the capsules.

Aeroshell LRF-090, impacted side-on, sustained more deformation than the end-on impacted aeroshell. There was a dent with delamination of graphite fibers corresponding to the impact face on the blind end (opposite end cap) of the aeroshell. A small amount of the graphite glue on the end cap had also been dislodged. There was no evidence of contamination on the aeroshell exterior. This aeroshell was successfully loaded into a new aluminum can.

Small pieces of graphite were dislodged from the edges of the aeroshell on the blind end of LRF-370. No other visible exterior damage or deformation was observed. There was no evidence of contamination on the aeroshell exterior. This aeroshell was successfully loaded into a new aluminum can.

Impact at 40 m/s

On August 14, 1996, simulant-fueled LWRHUs LRF-090 and LRF-370 were impacted at ambient temperature against a hardened steel target at 38.12 ± 0.04 m/s. The aluminum enclosures containing the aeroshells were intact, and survey smears of the test components had no detectable radioactivity, indicating the depleted urania fuel was contained by the capsules.

The side-on impact of LRF-090 resulted in a flattened impact area (approximately 1.3 cm wide) of the aluminum enclosure housing. Both ends of the aeroshell had graphite fiber delamination along the impacted edge. Small pieces of graphite were dislodged from the blind end of the aeroshell. A small amount of the end cap graphite glue was dislodged. There was no evidence of contamination of the aeroshell exterior. The aeroshell was successfully loaded into a new aluminum can.

Aeroshell LRF-370 was supposed to be impacted end-on. Instead, this aeroshell was impacted on its side, with its axial plane oriented approximately 10 degrees from the base. The aeroshell impacted on the end cap terminus. It appears that the projectile fixture did not release the aluminum can evenly, causing the can to rotate and impact at the angle observed. Delamination of graphite fibers was observed in the areas impacted. Graphite glue was dislodged from approximately one third of the glue gap radius. There was no evidence of contamination on the aeroshell exterior. This aeroshell was successfully loaded into a new aluminum enclosure.

Impact at 50 m/s

Simulant-fueled LWRHUs LRF-090 and LRF-370 were impacted at ambient temperature against a hardened steel target at 51.20 ± 0.03 m/s on August 26, 1996. The aluminum enclosures containing the aeroshells were intact, and survey smears of the test components had no detectable radioactivity, indicating the depleted urania fuel was contained by the capsules.

A flattened area measuring approximately 1.5 cm wide was observed on the impact face of side-on impacted LRF-090. There was delamination of the graphite in the end cap along the edge of the impact face. Graphite glue was dislodged from approximately 70% of the glue gap radius. An axial crack was observed on the impact face of the aeroshell, extending from the blind end. This hairline crack measured approximately 0.85 cm long. There was no evidence of contamination of the aeroshell exterior. Figure 5 shows photographs of the aeroshell. Postimpact dimensions of the aeroshell are given in Table I. Table II lists the aeroshell graphite weight loss. The aeroshell could not be loaded into a new aluminum can. Impact testing of this unit concluded with this test.

The end-on impact plane of LRF-370 was approximately five degrees off the desired impact orientation plane. The can was distorted slightly outward directly behind the impact face. Small pieces of graphite were dislodged from the end cap along the edge radius and the aeroshell cylindrical surface. Graphite glue was dislodged from approximately 50% of the glue gap circumference of the end cap. Graphite fibers were dislodged and projecting from the surface. Approximately 0.66 cm beneath the end cap, a transverse crack extending from approximately 180 to 0 degrees was noted. The center of the crack was approximately 180 degrees from the edge of the end cap at the point of greatest impact. There was no evidence of contamination on the aeroshell exterior. Figure 6 shows photographs of the removed aeroshell. Postimpact dimensions of the aeroshell are shown in Table I. Table II lists the aeroshell graphite weight loss. The aeroshell could not be loaded into a new aluminum can. Impact testing of this unit concluded with this test.

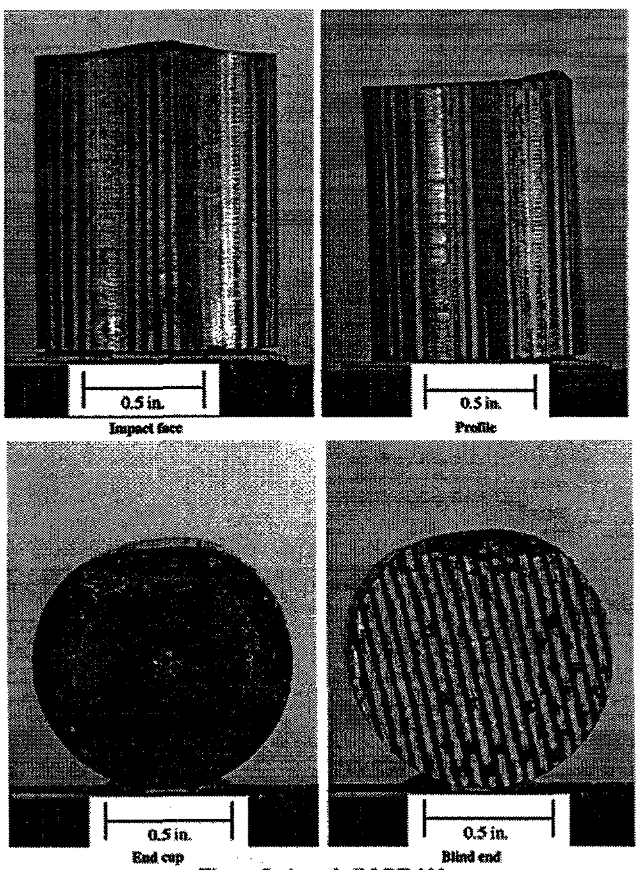


Figure 5. Aeroshell LRF-090

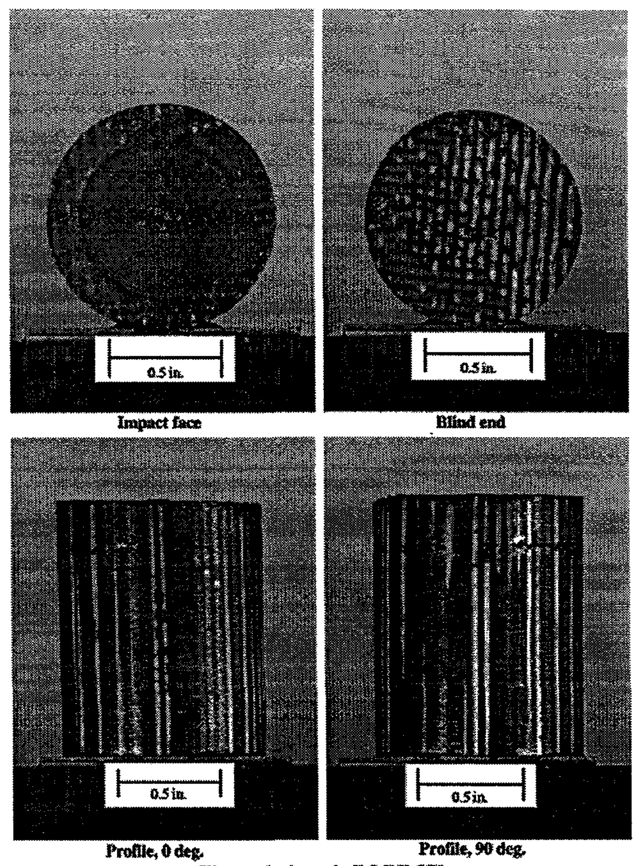


Figure 6. Aeroshell LRF-370

TABLE I. Dimensional Changes of LRF-090 and LRF-370

Dimension	LRF-090 (Side-on)	LRF-370 (End-on)
Diameter, mm		
Maximum, Postimpact	26.477	26.155
Minimum, Postimpact	25.273	25.936
As-fabricated	25.970	25.944
Length, mm		
Maximum, Postimpact	33.553	32.232
Minimum, Postimpact	32.085	31.668
As-fabricated	31.976	31.955

TABLE II. Weight Loss of LRF-090 and LRF-370

	LRF-090	LRF-370
As-Fabricated Weight (g)	39.950	39.048
Postimpact Weight (g)	39.901	38.932
Weight loss (g)	0.049	0.116

Disassembly of LRF-090 and LRF-370

Upon removing the end cap of LRF-090, the pyrolytic end cap was observed to be cracked but intact. Tapping on the end of the aeroshell dislodged this end cap, revealing the ends of the pyrolytic graphite cylinders. These were severely cracked and could not be removed from the aeroshell without further damage to them. Figure 7 shows photographs of the opened aeroshell showing the condition of the inner pyrolytic graphite cylinders. The LWRHU capsule, 624, was removed by further tapping of the aeroshell. The capsule deformation was that expected of a side-on impacted test object (Figure 8). The capsule was somewhat flattened on the impact face. Close examination of the capsule revealed no cracks or breaches of the clad metal. All smears of the graphite components and capsule exterior revealed no detectable contamination, confirming containment of the simulant fuel. Postimpact dimensions of capsule 624 are listed in Table III.

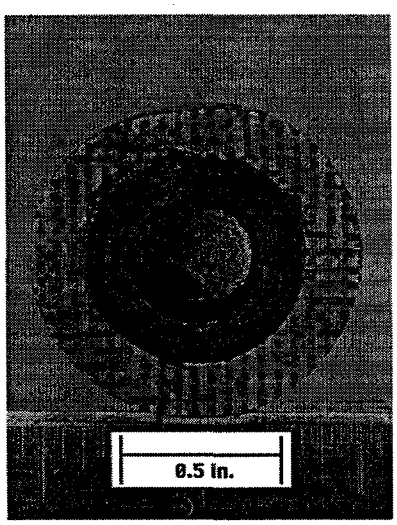
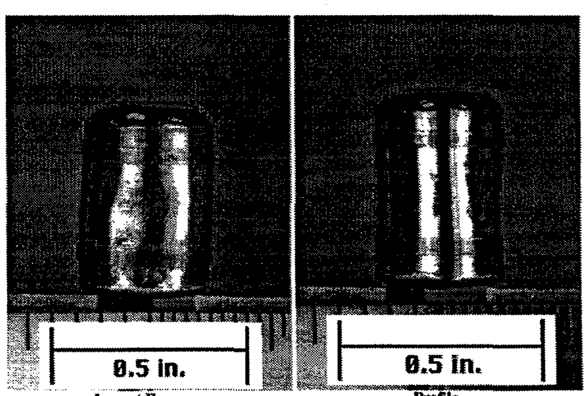


Figure 7. Sectioned LRF-090



Impact Face Profile

Figure 8. Fueled Capsule 624

TABLE III. Postimpact Dimensions of Capsules 624 and 625		
Dimension (mm)*	Capsule 624	Capsule 625
Diameter, Vent end		
Maximum	8.849	8.583
Minimum	8.116	8.523
Diameter, Blind end		
Maximum	8.800	8.787
Minimum	8.334	8.730
Length	12.828	12.240
Specification Diameter:	<8.65	
Specification Length:	<12.85	

*Measured at stand-offs.

Upon removal of the end cap of LRF-370, the pyrolytic end cap was observed to be cracked but intact. The pyrolytic graphite cylinders were severely cracked, although they did not appear to be as severely damaged as those of LRF-090 (Figure 9). As with LRF-090, the cylinders could not be removed without further damaging them. The LWRHU capsule, 625, was removed and appeared to be minimally deformed as shown in Figure 10. The weld bead at the impacted end, opposite the vent, appeared to be somewhat flattened. There was no evidence of clad metal cracks or breaches. All smears of the graphite components and capsule exterior revealed no detectable contamination, confirming simulant-fuel containment. Postimpact dimensions of capsule 625 are listed in Table III.

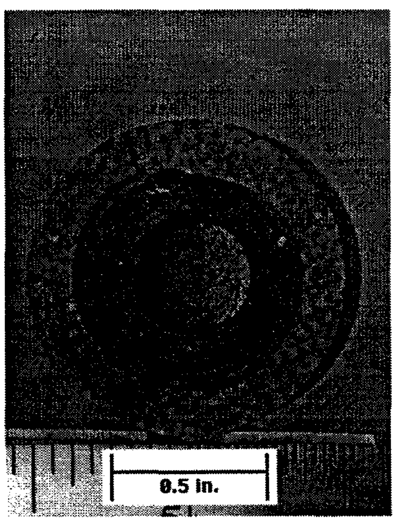
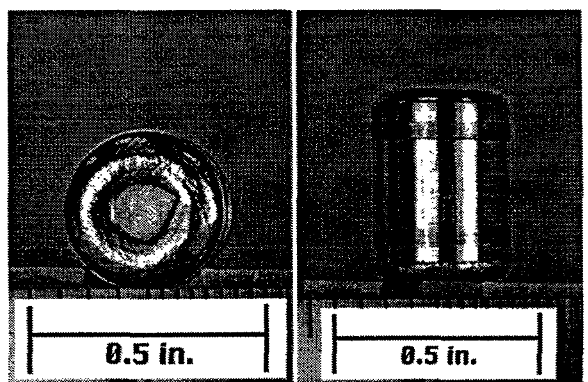


Figure 9. Sectioned LRF-370



Impact face Profile

Figure 10. Fueled Capsule 625

DISCUSSION

Production Qualification Impact Test

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. Specifically, historical data of an impact test conducted in the side-on orientation containing unaged fuel is used here 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 Tate and Land 1985. In both tests, the fueled capsule experienced minimal deformation and the fuel was entirely contained.

Table IV 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 μm. Comparing these results indicates a superior response of the Cassini LWRHU to the impact test conditions.

Sequential Impact Test Series

The dimensional changes of LRF-090 and LRF-370 are listed in Table I and the weight measurement differences are summarized in Table II. Both aeroshells lost weight. This can be attributed to the loss of small pieces of graphite and graphite glue dislodged during impact testing. Aeroshell LRF-370, impacted in end-on orientation, lost roughly twice as much graphite (0.116 g) as LRF-090, impacted in side-on orientation (0.049 g).

Table I summarizes the overall amount of deformation the aeroshells experienced as a result of the sequential impacts. The deformation of the fueled capsules is summarized in Table III. The data reveals that LRF-090, impacted in side-on orientation, underwent a slightly greater amount of deformation than LRF-370. This agrees with previous experience with deformation of test objects subjected to side-on and end-on orientations; the side-on impact orientation results in greater deformation, this being the more vulnerable orientation (Tate 1982). The capsules performed similarly, with the amount of deformation being greater in the side-on impacted capsule, 624. However, it was noted that each capsule's dimensions were distorted to the point of being out of dimensional specification.

TABLE IV. 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

A comparison of the impact responses of the sequentially impacted LWRHUs to the Cassini production LWRHUs follows. The production LWRHU, LRF-294, was impacted in side-on orientation at ambient temperature, and therefore, its impact response will be compared to that of LRF-090. Both aeroshells were minimally deformed, and the fuel in the capsule was totally contained. The LRF-090 aeroshell and capsule 624 were slightly more deformed than the LRF-295 aeroshell and capsule CB873, respectively. Capsule CB873 was not sufficiently deformed to bring it out of dimensional specification, whereas capsule 624 was.

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 these tests, LRF-021 was selected for comparison. This aeroshell experienced slightly more damage than the side-on impacted LRF-090. This observation is based on a comparison of postimpact LRF-090 photographs taken at the end of the sequential test series with a postimpact LRF-021 photograph given in Tate and Land 1985. Dimensional data were not immediately available and were not used in a direct comparison. The fueled capsule recovered from LRF-021 experienced minimal deformation, and the fuel was entirely contained. Fueled capsule 624, recovered from LRF-090, sustained more deformation, however, the fuel was entirely contained. The results of the two tests are comparable based on the end result, total fuel containment.

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-μm fines was an order of magnitude greater for the Galileo unit.

Sequential impacting, in both end-on and side-on orientations, resulted in increased damage with each subsequent impact. Although the tests were conducted until the aeroshells were distorted and out of dimensional specification, the simulant-fueled capsules were not severely deformed, cracked, or breached. The simulant-fuel was entirely contained.

Sequential impacting of the LWRHU appears to result in slightly greater damage than single impact at the final impact velocity of 50 m/s. The deformation and fuel containment of the sequentially impacted LWRHUs were, however, comparable to those of LWRHUs produced for and tested in support of the Galileo and Cassini missions: LRF-021 and LRF-294, respectively. Minimal deformation occurred on the aeroshell and the fuel was entirely contained by the units. The sequentially impacted capsules were slightly more deformed and were shown to be outside of dimensional specification.

Acknowledgments

We thank Walter Bast for fabrication of the impact launcher projectile hardware.

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