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**Cryogenic Explosion Environment
Modeling and Testing of Space
Shuttle and Light-Weight
Radioisotope Heater Unit
Interactions**

Ernest W. Johnson

October 1985

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Miamisburg, Ohio 45342

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Abstract

In order to assess the risk to the world's populace in the event of a Space Shuttle accident when radioisotope-containing heat sources are on board, testing of that system must be performed to determine release point, environments required, and the size distribution of the released fuel. To evaluate the performance of the Light-Weight Radioisotope Heater Unit (LWRHU) (101 of these 1-W items are placed on the Galileo spacecraft which will be launched from the Space Shuttle), some high-velocity impact and flyer plate testing was carried out. The results showed that a bare uranium-fueled LWRHU clad (approximately 1-mm thick platinum-30 wt % rhodium alloy) will withstand 1100 m/s flyer plate (3.5-mm thick aluminum) impacts and 330 m/s impacts upon the Space Shuttle floor (approximately 12-mm thick aluminum) without rupture or fuel release. Velocities in the order of 600 m/s on a steel surface will cause clad failure with fuel release. The fuel breakup patterns were characterized as to quantity in a specific size range. These data were employed in the formal Safety Analysis Report for the LWRHU to support the planned 1986 Galileo launch.

1. Introduction

The Galileo spacecraft, scheduled for launch in May 1986, requires 100 W of thermal energy spread over various locations in order to function properly. The Department of Energy has authorized the design and construction of a 1-W system containing plutonium-238 (named the Light-Weight Radioisotopic Heater Unit or LWRHU) to fulfill this NASA requirement. The Space Transportation System (STS or Shuttle) and spacecraft could encounter failures throughout the mission that would result in subjecting the LWRHUs to high-velocity flyer plates (principally aluminum) and, because of the high-static impulse associated with certain cryogenic propellant explosions, impart to the LWRHUs sufficient energy to produce velocities that could approach 750 m/s. Methods and results of tests performed to simulate these high-speed events using conventional off-the-shelf explosive components and existing

explosion test facilities at Mound and UDRI are discussed.

The Light-Weight Radioisotope Heater Unit (LWRHU) (design overview shown in Figure 1) is planned for use on the NASA Galileo Mission (GLL) to provide thermal energy to various systems on the orbiter and probe that are adversely affected by the low temperature a spacecraft encounters during an interplanetary mission such as the GLL to Jupiter. The use of these plutonium-fueled sources in 1-W increments permits employment of a single design and provides the spacecraft user the option of how many and where they are positioned to satisfy the proper thermal environment to components requiring such consideration. The locations of these items on the GLL spacecraft are shown in Figure 2. The use of the radioisotope plutonium-238 in these devices necessitates the assessment of postulated radiological risks

FIGURE 1 - The principal features of the Light-Weight Radioisotope Heater Unit are portrayed above.

which might be experienced in case of accidents or malfunctions of the shuttle (space transportation system or STS) or GLL spacecraft during phases of the mission in the vicinity of the earth. Mound was charged by DOE to perform this assessment.

To perform this work, Mound was directed to employ the accident variables provided in JSC 08116 [1], previously performed safety testing performed by Los Alamos National Laboratory (LANL) [2], and Failure Abort Sequence Trees from the General Electric Company [3]. Some of the environmental conditions were defined after the original test program was completed by LANL, so certain test data were missing which were required to

complete the assessment. In the following sections, descriptions of requirements, tests, and conclusions will be given to identify how these data deficiencies were filled.

2. Space Transportation System(STS)

The Galileo launch configuration within the STS is shown in Figure 3. The major materials that would provide hazardous environments to the LWRHUs during the various near-earth phases of the GLL Mission are the liquid propellant inventories:

- A. The forward part of the external tank (ET) contains 552 m³ (630 Mg) of liquid oxygen;

FIGURE 2 - The cruise configuration of the GLL spacecraft showing the location of the 101 LWRHUs.

FIGURE 3 - The general spatial relationships between the Galileo spacecraft and the shuttle are shown in this drawing.

- B. the aft part of the ET contains 1515 m^3 (106 Mg) of liquid hydrogen; and
- C. the Centaur tanks contain 19.5 Mg of liquid oxygen and liquid hydrogen in a ratio of 5:1, respectively.

These cryogenic inventories would, depending on accident sequence and probability, result in environments depicted in Figures 4 through 7. These intensity values are defined as:

- A. Shock Overpressure - The peak pressure of the shock front as defined in Reference 1;

FIGURE 4 - The ET Explosion Mode results in these curves; the abscissa is the percentage of time that variable will exceed value selected.

B. Static Impulse - The areal momentum or the area under the curve of the pressure-time curve (values from Reference 1);

C. Shock Wave Velocity - Calculated from the expression $M^2 = 6/7 \times (P_s/P_o) + 1$ where M = Shock Mach Number, P_s = Overpressure and P_o = Atmospheric Pressure [4, p. A-14];

D. Flyer Plate Velocity - Values provided for this metallic debris distribution by JSC 08116 (Reference 1); and

E. LWRHU Velocity - Obtained by numerically integrating the basic force = mass x acceleration equation. The force in this case is the aerodynamic drag produced by the blast wind behind the incident shock; i.e., $F = q/AC_D$ where q , the dynamic pressure, is $1/2\rho_p (\mu_p - \mu)^2$. The terms μ_p and ρ_p are the local particle velocity and density, and are obtained by assuming a triangular blast pressure pulse; μ is the LWRHU velocity. The ballistic coefficient, $W/C_D \cdot A$, was taken

FIGURE 5 - Parameters associated with the Centaur 1D Spill Mode. Probability (in percent) is time that the parameter will exceed that value.

to be the average of the end-on and cylinder broadside values, 42.7 kg/m^2 .

Items A through E are thus given probabilistic occurrence frequencies in terms of the event severity. As the cryogenic explosion accidents would result in an LWRHU/debris interaction sequence, namely,

Shock Overpressure → LWRHU/Flyer Plate Collision → LWRHU/Fixed

Structure Collision → Fireball → Longer-Term Exposure,

a test sequence was envisioned to fill in the uncertain areas as discussed below.

FIGURE 6 - Parameters associated with the Centaur 2D Spill Mode. The abscissa is percent probability that the variable will exceed the corresponding value.

3. Testing

The major gap in the existing test information was the flyer plate/LWRHU clad (unconstrained) interactions and the LWRHU clad/fixed structure impacts. {NOTE: The aeroshell and pyrolytic graphite insulators are assumed to be stripped from the clad after the shock wave has passed [true for velocities >3.9 MPa (side-on) and 5.5 MPa (end-on), Ref. 5], and the clad is up to its maximum velocity for the specific probability.]

To model this event, support was received from the Development and Environmental Testing Group at Mound.

The test LWRHUs were of an early developmental test configuration as manufactured and furnished to Mound by the Los Alamos National Laboratory. The test units weigh about 8.4 g each and contain a UO_2 pellet weighing about 2.5 g to simulate the PuO_2 which would be in the prime configuration. The size

FIGURE 7 - Parameters associated with the Centaur CBM Mode are given as a function of "greater-than" probability percentage.

dimensions of the LWRHU clad are 8.65 mm in diameter by 12.6 mm long.

The energy source used to propel the 3-g aluminum 6061 flyer plate into the test clad was a modified SE-1 detonator manufactured at Mound. The detonators used here were loaded with 260 mg PETN [pentaerythritol tetranitrate, $C(CH_2ONO_2)_4$], the material having a density of 0.68 mg/mm³.

The localized test setup is illustrated in Figure 8. The Plexiglas box contained the impacted LWRHU clad and the flyer plate after the event for easy retrieval. The scale provided (on the streak still shot) a reference distance from which the dx portion of dx/dt (velocity) could be determined. For normal firings, the flyer plate would travel about 20 mm, strike the LWRHU clad, and both clad and flyer plate

FIGURE 8 - The test setup for high-velocity flyer plate experiments is shown above. In operation, the SE-1 detonator fires, propelling the flyer plate to the left, striking the LWRHU clad and impulsing it into the impact plate at the left.

would collide with the stationary impact plate (aluminum, $R_b = 48$) after traversing about 150 mm.

The event is recorded on a Cordin Model 132 Streak Camera (Figure 9). The rotating mirror was integrated into the firing and magnetic foil lens system to trigger the events at a mirror period of 2 ms (500 rotations per second). This mirror angular velocity yielded a writing speed of 2 km/s (2 mm/ μ s). The streak film records for the three runs are given in Figure 10.

4. Test Results

The three LWRHU clads that were subjected to the 1.1 km/s flyer plates were significantly deformed as may be noted in Figures 11 through 13. The test

variables are provided in Table 1.

The urania (simulated fuel) from the two clads which were destructively evaluated after the flyer plate testing (Nos. 035 and 046) was analyzed for the size/quantity relationship. The general appearance of the urania from these two clads is shown in Figure 14. Table 2 gives weight fractions from these two clads.

The aluminum impact plate recorded the LWRHU clad and flyer plate impacts. The appearances of these imprints are provided in Figure 15.

Two additional tests were performed at the University of Dayton Research Institute (UDRI): high-velocity impacts

FIGURE 9 - The streak camera views the detonation events from outside the test cell. In this case, a period of 2 ms mirror rotation (500 Hz) was used; this gave a writing speed of 2 km/s.

on structural steel plates ($R_b = 75$, ~ 12 mm thick). (See Appendix for details.)

Test 1: The virgin urania-fueled, Clad 043, was fired into a steel plate that was perpendicular to the flight path. The clad axis was parallel to the flight path with the vent end forward. An overview of the impact area is given in Figure 16. More detailed metallographic cross sections are given in Figure 17. The fines distribution of the urania was measured for this tested clad. These data are presented in Column 4, Table 2.

Test 2: The already impacted Clad 039 was fired onto a similar steel plate that was oriented 45° to the flight path. The clad "flew" as a result of its previously incurred deformation, going through two 1-in. (25-mm) thick plywood structural components before striking the target. The measured impact velocity

was 593 m/s (after passing through one of the plywood pieces. The clad failed catastrophically as can be noted in Figure 18. The fuel released appeared very fine; the estimate is that the majority was less than 100 μm in size. No further analyses other than visual examination (Figure 19) were deemed appropriate due to the magnitude of the failure.

Some general observations relating to these tests should be made:

1. The specimens were fairly early development units that were employed as practice items by Los Alamos National Laboratory. The GTA welds were not radiographed, nor was the vent activation inspected. These anomalies would not be present in flight LWRHUs, as inspections to verify quality would have identified these conditions.

FIGURE 10 - Streak camera records of the flyer plate events.

That the LWRHU clads did not release detectable urania after the flyer plate tests speaks well for the base design.

2. The clads were not heated prior to testing. Dr. Gary Rhinehart

(LANL) performed some measurements on a fueled clad inside the graphites and recorded a clad temperature of 50-53°C. The responses of the clad at 25°C would be insignificantly different from responses at 50°C.

FIGURE 11 - Macroscopic views of the Flyer Plate impacted articles give an idea of the damage extent. All figures are 1.3X.

FIGURE 12 - Photomacrographs of two of the Flyer Plate-Tested LWRHU Clads (O35 at left and O46 at right) show that little or no wall thinning occurred in these test environments. Some GTA closure weld anomalies are noted in O46 with some porosity and the residual step apparent in one location. Both shots at 6.0X.

FIGURE 13 - Although distorted, there were no failures noted in the vents of the two Flyer Plate-Tested LWRHU Clads. LWRHU 035 at 26X (left) shows a small intrusion into the vent with the activation drill. LWRHU 046 (right) at 20X was not sliced to show the hole, but the considerable deformation with no failure speaks well of the design and manufacturing techniques.

FIGURE 14 - The urania pellets contained in LWRHU Clads 035 (left) and 046 (right) have incurred significant breakup in the 1100 m/s flyer plate followed by 330 m/s impacts on thick aluminum plate (8.2X, bar = 1 mm).

Table 1 - VARIABLE DATA RELEVANT TO THE THREE HIGH-VELOCITY LWRHU/FLYER PLATE EXPERIMENTS.

	<u>Clad 035</u>	<u>Clad 039</u>	<u>Clad 046</u>
1. Velocities (m/s)			
a. Flyer Plate (FP)	1100	1100	1100
b. LWRHU	50	50	50
c. LWRHU/FP	1000	1000	1000
d. LWRHU at Impact	330	330	330
2. Orientation (° to Normal)			
a. Flyer Plate	0°	0°	0°
b. LWRHU	0°	0°	45°
c. Impact Plate	0°	25°	0°
3. $^{238}\text{UO}_2$ Detected	0	0	0
4. External Cracking	0	2 small at vent end face	0

Table 2 - URANIA SIZE DISTRIBUTIONS FROM IMPACTED LWRHU CLADS.

	<u>Weight Fraction in</u>		
<u>Size Range, μm</u>	<u>Clad 035</u>	<u>Clad 046</u>	<u>Clad 043</u>
>850	0.135	0.034	0.094
420-850	0.183	0.127	0.131
149-420	0.327	0.327	0.257
105-149	0.070	0.094	0.062
88-105	0.036	0.056	0.044
63-88	0.050	0.059	0.056
44-63	0.072	0.099	0.080
30-44	0.080	0.114	0.168
20-30	0.030	0.049	0.052
10-20	0.015	0.033	0.055
<10	0.002	0.008	0.001

FIGURE 15 - The aluminum impact plate suffered some localized permanent deformations upon being struck by the accelerated LWRHUs and flyer plates. The overall view at left is at 1.3X, whereas the three clad impact areas are enlarged by 2.2X.

FIGURE 16 - LWRHU Clad 043 (previously untested) was impacted on the vent and onto a 12 mm steel plate at 607 m/s. Note some clad cracking on the lower left picture (5.0X) and failure on the steel plate back side, above (5.0X).

FIGURE 17 - Polished and etched cross section of LWRHU Clad 043 imbedded in the cold-rolled steel impact plate. Note that there is a ductile failure at the GTA closure weld and the vent has apparently been pulverized.

FIGURE 18 - The previously-tested Clad 039 (flyer plate and aluminum-impact plate collisions) was fired at 593 m/s onto a steel plate (impact crater at left) at 45° to the direction of flight. Three fragments from this catastrophically-failed clad are given below at 5.0X.

FIGURE 19 - Two views at 20X of the broken-up uranium released in the catastrophic failure of Clad 043. There is evidence of many slivers from the clad penetrating the plywood catch box. These photomicrographs imply a highly-divided fuel form release with an average diameter of about 50 μm .

5. Summary

From these tests, it appears that clad impacted on essentially unyielding surfaces will remain intact up to impact velocities of 330 m/s. One can expect clad failure with fuel release at a 50% level if the clad velocity is in excess of 330 m/s, and it strikes an essentially unyielding surface.

These data were successfully employed in filling in the test data gaps and enabled completion of the relevant sections of the Safety Analysis Report for the LWRHU on schedule.

6. Acknowledgements

Mound personnel who contributed to this report are as follows:

M. L. Fortner of Energetic Components Development Group who designed and directed the fabrication of the flyer plate acceleration system; T. E. Tayse, M. R. Donohue, and D. E. Benner of the Environmental Testing Group who actually performed the flyer plate tests; K. J. Hudson, E. F. Murray, and M. L. Rivers who performed the powder loadings in the Production area; T. B. Sheidler and L. J. Wise of the Energetic Components Group who performed the final assembly; V. P. Willson and C. R. Taylor for manufacturing the

pellets; J. R. McKendree and D. A. Sohn for metallographic work; and N. Bonekowski for performing the fines analyses.

7. References

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3. Bradshaw, C. T., Presentation at NUS, Gaithersburg, Maryland, on June 5, 1985.
4. "Updated Safety Analysis Report for the Galileo Mission and the International Solar-Polar Mission," GESP-7186, General Electric Company, April, 1984.
5. Schumann, F. A., "A Study of the Blast Overpressure Capability for the RHU Heat Shield," TES-3203, Teledyne Energy Systems, (June 3, 1985).

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Appendix

The University of Dayton

2 July 1985

Monsanto Research Corporation
ATTN: Mr. E. W. Johnson, Bldg. 88
P.O. Box 32
Miamisburg, OH 45352

SUBJECT: LWRHU High-Velocity Impact Tests at University
of Dayton Research Institute (UDRI)--Purchase
Order No. 43740

Dear Mr. Johnson:

The LWRHU high-velocity impact tests under P.O. No. 43740 were completed on July 1, 1985. The testing was conducted at UDRI on Range #9 of the Impact Physics Group. MRC provided Health Physics verification along with Mr. R. Harmer (Radiation Safety Officer) of UDRI to make sure that localized contamination of UO_2 of the shooting was less than 20 dpm/100 cm^2 surface. The two shots conducted onto 6x6x0.5 inch cold rolled steel plates by the LWRHU clad projectiles were considered clean of local contamination for the testing.

Catch boxes fabricated of 0.75-inch thick plywood were made by UDRI for the two data shots. The boxes were about 12.0 inch cubes with the steel target plate being mounted within the box at the proper incidence angle. Both boxes had additional protection to contain the deformed projectiles after impact. The 45 degree impact box had a 1.5 inch hole for the projectile to enter while the 90° (normal) impact box had a 1.0 inch hole for the projectile entrance. Each catch box was placed inside a thick plastic bag before the impact for transport back to MRC after testing. Mr. Johnson taped the holes made by the projectile entrance in each case to minimize any potential rebase possibility of UO_2 dust after each shot.

MRC also provided four lead cylinders to UDRI for velocity curve development and projectile trajectory. These shots were conducted in the morning of July 1 with Table 1 giving the

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Experimental and Applied Mechanics Division
300 College Park Dayton, Ohio 45469-0001

2 July 1985

results of the preliminary testing. A .50 caliber rifled barrel 42.0 inches long was used along with a 30-30 caliber Winchester case (breech) and 2400 powder in the testing. Each projectile fired was launched in a two piece (.50 caliber) lexan sabot for protection in the testing. All of the lead (preliminary) shots had an identical trajectory and impacted a thick aluminum plate at the same location. Precise impact location should have been accomplished in the two data shots since an alignment laser was used to project a laser beam through the bore of the launch tube onto the impact site location of the lead projectiles.

Table 2 gives the results of the two data shots. Several barrel warm-up shots using plastic sabots were conducted prior to the data shots to receive consistent velocities in the testing. The 45 degree impact using LWRHU projectile 039 was initially deformed and did not fly the same trajectory as the lead projectiles. The UO_2 clad projectile hit the plywood box at the two o'clock position about 0.5 inches out from the outer edge of the 1.5 inch entrance hole. This off-trajectory shot was probably caused by the deformed shape of the projectile flying in the air or maybe one mashed end caught on one of the sabot pieces.

The 90 degree (normal) LWRHU projectile 043 shot hit directly in the center of the 1.0 inch entrance hole in the catch box. The measured impact velocity for the 45 degree shot was 1944 ft/sec (592.7 m/s) and for the 90 degree shot it was 1993 ft/sec (607.6 m/s). After each shot, duct tape was used to close the hole made by the projectile through the plastic bag.

Photographs of the test set-up are included with this summary letter report. Should any additional information be required on the testing, please give the undersigned a call at (513) 229-3546.

Sincerely,

Robert S. Bertke

Robert S. Bertke
Research Engineer

RB/tw

Enclosures

cc: UDRI
93143-13 file

TABLE 1. PRELIMINARY SHOOTING WITH LEAD PROJECTILES

Shot #	Projectile Dimensions (in)	Projectile Mass (gm)	Package Mass (Projectile) plus sabot (gm)	Impact Velocity (ft/sec)	Comments
9-0107	Dia. ~ 0.338 L ~ 0.498	8.00	10.58	1594	Good Impact (Sabot separated cleanly)
9-0108	Dia. ~ 0.338 L ~ 0.498	8.03	10.62	1907	Good Impact (Hit same location as previous shot)
9-0109	Dia. ~ 0.338 L ~ 0.498	8.06	10.65	1928	Good Impact (Hit same location as previous shots)
9-0110	Dia. ~ 0.338 L ~ 0.498	8.06	10.64	1997	Good Impact (Hit same location as previous shots)

TABLE 2. RESULTS OF UO₂ CLAD PROJECTILE SHOTS

Shot #	Projectile Dimensions (in)	Impact Angle (Deg)	Impact Velocity (ft/sec)	Comments
9-0111	LWRHU #039 (deformed) Dia. = 0.362 L = 0.517	45°	1944	Hit @ two o'clock position about 0.5 inches from outside of entrance hole. (Trajectory inaccuracy probably due to projectile deformed shape)
9-0112	LWRHU #043 Dia. = 0.340 L = 0.497	90° (Normal)	1993	Projectile hit cleanly through 1.0 inch entrance hole of catch box.

The experimental setup at UDRI is shown above. The clad-containing split sabot is fired from the right, through the timing screens and then through the hole in the plywood catch box (photo on left). For these tests, the box was wrapped in a plastic bag to minimize the spread of uranium dust, should a clad fail.

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