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General-Purpose

Heat Source Development:

Extended Series Test Program

Large Fragment Tests

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*Edited by Paul W. Henriksen, Group IS-11
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Theresa A. Cull

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**GENERAL-PURPOSE HEAT SOURCE DEVELOPMENT:
EXTENDED SERIES TEST PROGRAM
LARGE FRAGMENT TESTS**

by

Theresa A. Cull

ABSTRACT

General-Purpose Heat Source radioisotope thermoelectric generators (GPHS-RTGs) will provide electric power for the NASA Galileo and European Space Agency Ulysses missions. Each GPHS-RTG comprises two major components: GPHS modules, which provide thermal energy, and a thermoelectric converter, which converts the thermal energy into electric power. Each of the 18 GPHS modules in a GPHS-RTG contains four $^{238}\text{PuO}_2$ -fueled capsules. LANL conducted a series of safety verification tests on the GPHS-RTG before the scheduled May 1986 launch of the Galileo spacecraft to assess the ability of the GPHS modules to contain the plutonia in potential accident environments. As a result of the Challenger 51-L accident in January 1986, NASA postponed the launch of Galileo; the launch vehicle was reconfigured and the spacecraft trajectory was modified. These actions prompted NASA to reevaluate potential mission accidents, and an extended series safety test program was initiated. The program included a series of large fragment tests that simulated the collision of solid rocket booster (SRB) fragments, generated in an SRB motor case rupture or resulting from a range safety officer SRB destruct action, with the GPHS-RTG. The tests indicated that fueled clads, inside a converter, will not breach or release fuel after a square (142 cm on a side) SRB fragment impacts flat-on at velocities up to 212 m/s, and that only the leading fueled capsules breach and release fuel after the square SRB fragment impacts the modules, inside the converter, edge-on at 95 m/s.

I. BACKGROUND

General-Purpose Heat Source radioisotope thermoelectric generators (GPHS-RTGs) will provide electric power for the NASA Galileo and European Space Agency Ulysses missions. Each GPHS-RTG comprises two major components: GPHS modules, which provide thermal energy from ^{238}Pu α -decay, and a thermoelectric converter which converts the thermal energy into electric power. Each GPHS module generates about 250 W_t. The total thermal energy of each GPHS-RTG

(4410 W_t) results in about 285 W_e at the beginning of the mission. Two GPHS-RTGs will be required to power the Galileo spacecraft, and one GPHS-RTG will power the Ulysses spacecraft.

Each GPHS-RTG contains 18 GPHS modules. Each module (Fig. 1) has a Fine-Weave Pierced Fabric* (FWPF) graphite composite aeroshell to protect it from the ablation, thermal shock, and thermal response of reentry. Within the aeroshell are two FWPF graphite impact shells (GISs) to provide impact protection; each GIS is inserted in a carbon-bonded carbon fiber sleeve for additional thermal insulation. The two $^{238}\text{PuO}_2$ pellets in each GIS are encapsulated in high-temperature iridium-alloy cladding designed to contain the fuel after impact. Each clad contains a fritted vent to allow the helium gas generated during the decay of ^{238}Pu to escape.

The thermoelectric converter (Fig. 2) is approximately 114 cm long and 42 cm in diameter. It includes an outer aluminum case that serves as the main support for the thermoelements and the heat source stack, axial and midspan heat source supports, 572 silicon-germanium thermoelectric couples, and multifoil insulation. The thermoelectric couples are supported in a cantilever fashion from the outer case and the couples in turn partially support the insulation packet.

In addition to the GPHS-RTGs on the Galileo spacecraft, lightweight radioisotope heater units (LWRHUs) will provide thermal energy to temperature-sensitive components on the spacecraft so that the components will function reliably in space. Each LWRHU (Fig. 3) is composed of a $^{238}\text{PuO}_2$ pellet encapsulated in a platinum-alloy (30% Rh) shell surrounded by three pyrolytic graphite tubes and an FWPF graphite aeroshell. The exterior of the LWRHU is designed to provide 1 W_t 7 years after fueling.¹ At least 129 LWRHUs will be used on the Galileo spacecraft; Ulysses uses no LWRHUs.

LANL conducted a series of safety verification tests (SVTs) on the GPHS-RTG and the LWRHU before the scheduled May 1986 launch of Galileo to assess the ability of the GPHS modules and the LWRHU to contain the plutonia in potential accident environments.^{2,3} At that time a liquid-fueled Centaur rocket would have served as the spacecraft propulsion unit and been transported with each spacecraft in the cargo bay of the Shuttle Orbiter. A launch explosion, fueled by the Shuttle and Centaur propellants, could have exposed the GPHS-RTG and LWRHUs to high overpressures and to a field of high-velocity Shuttle fragments.⁴ As a result of the Challenger 51-L accident in January 1986, NASA postponed the launch of Galileo; the Centaur was replaced with a solid propellant inertial upper stage (IUS) and the spacecraft trajectory was modified. The changes prompted both a reevaluation of potential mission accidents⁵ and the initiation of an extended series safety test program.⁶

II. INTRODUCTION

A primary concern in the extended series test program is the interaction of the GPHS-RTG and LWRHUs with large, heavy-walled SRB fragments that an SRB motor case rupture or a range safety officer (RSO) SRB destruct action would generate. To determine the severity of such an interaction the velocity and orientation of the fragments, when they reach the GPHS-RTG, must be reasonably known. A separate series of tests evaluated the interaction of SRB fragments with Orbiter structural components.⁷

III. TEST PROGRAM

Test personnel at LANL and Sandia National Laboratory Albuquerque (SNLA) conducted three large fragment tests (LFTs) to simulate flat-on and edge-on collisions of SRB fragments with the GPHS-RTG and flat-on collisions with the LWRHU. The tests were conducted at SNLA's Area III Rocket Sled Facility. In the tests, SNLA test personnel propelled a square (142-cm on a side) SRB fragment (1.27-cm-thick D-6ac steel) on a rocket sled into the test assembly. In the first two

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

tests (LFT-1 and LFT-2) they propelled the fragment flat-on, convex side forward and major axis vertical, at velocities of 115 m/s and 212 m/s; in LFT-3 they propelled the fragment edge-on, major axis vertical, at a velocity of 95 m/s.

LANL test personnel acquired and assembled the test items, collaborated with General Electric Company (GE) personnel to specify the test parameters, designed and assembled the test support apparatus, heated the GPHS module stack and translated it into the converter, performed posttest recovery and analyses, and communicated the results to the appropriate organizations. SNLA fabricated the rocket sleds and catch tubes, propelled the sled at the desired velocity, measured the sled velocity, and provided high-speed photographic coverage.

A. Components

Each test assembly included a half-length GPHS-RTG containing a stack of eight GPHS modules (Fig. 4). We placed two simulant-fueled (depleted $^{238}\text{UO}_2$) modules in the second and fifth positions of the module stack and six polycrystalline graphite modules (Fig. 5), each containing four molybdenum slugs to simulate the module mass and mass distribution, in the remaining positions. All components of the two test modules, except the fuel simulant, were of flight-quality. We used a simulant fuel because the test facility was not equipped to contain plutonium oxide. We adjusted the bulk density of each UO_2 pellet to match the mass and configuration of an average plutonia fuel pellet. LANL made the pellets and Savannah River Laboratory personnel encapsulated them in containment shells. The Mound Facility provided flight-quality iridium-alloy containment shells. Table I presents data describing the iridium and UO_2 components. LANL fabricated the mass simulant modules and marked the molybdenum slugs in each module before each test, so they could be identified after the test.

GE provided the converters for the tests. For the first two tests, the engineering unit converter, which was used for power system life testing at Mound, was sectioned into half units (Fig. 6). The outboard half, containing the actual midspan support ring, was used in LFT-1; a simulated midspan ring was welded on the inboard half for use in LFT-2. Simulant half-length converters (Fig. 7), each consisting of an aluminum case with layers of molybdenum and nickel foil fastened inside, were used for the second calibration test and for LFT-3. LANL also constructed and tested three simulant-fueled (depleted $^{238}\text{UO}_2$) LWRHUs. (See Table II).

Morton-Thiokol supplied the SRB fragments, which were flame cut from 3.66-m-diam sections of SRB casing suitable for mechanical tests, but not for flight. Table III summarizes the mechanical properties of D-6ac steel. Plasma torch trimming at LANL produced the final configuration of the fragments (142 cm on a side, approximately 193 kg).

B. Equipment and Procedures

In each test with simulant-fueled modules, we heated the module stack in the inert atmosphere of an electrical resistance-type furnace on a 3-m-high platform straddling the rocket sled track. Figs. 8 and 9 show the schematics of the flat-on and edge-on tests. We measured the furnace temperature with two calibrated Type K thermocouples suspended in the furnace on opposite sides of the module stack. A calibrated Biddle (Model 750350-2) thermocouple test set monitored the temperature up to about 500°C. A calibrated Yokogawa (Model 3087-21) DVM/chart recorder then recorded the temperature up to 1127°C or 1113°C. Tests at LANL showed that the temperature of the fueled clads decreased by about 18°C during translation of the module stack into the converter, which was suspended from the platform about 0.9 m below the furnace. The temperature of the fueled clads decreased an additional 4°C after the stack had been in the converter for 20 seconds (the approximate time that would elapse before fragment impact). We wanted the fueled clad temperature at impact to be 1091°C, the average temperature of fueled clads in an on-pad GPHS-RTG. We could not measure the fueled clad temperature in the tests, so we assumed, from the temperature tests, that the clad temperatures at impact were $1091^\circ \pm 5^\circ\text{C}$.

When the furnace reached the desired temperature, a switch in the instrumentation bunker cut the power to an electromagnet, thereby opening the furnace door (Fig. 10). A remote-controlled winch lowered the heated module stack from the furnace into the converter. We keyed the base plate of the module stack to the pressure plate (or lower cover) on the converter to position the stack in the proper orientation (A-GIS on the impact side). A counterweighted graphite hook (Fig. 11) automatically released the stack when it was in place in the converter. We visually verified each step and used a video camera to transmit the information to a video monitor and recorder in the instrumentation bunker. After releasing the stack, we raised the graphite hook and support rod out of the path of the fragment by reversing the winch.

As soon as the stack was in place in the converter, LANL signalled SNLA to fire the rockets. SNLA had previously determined the number of Zuni (12.7-cm-o.d., 6000-lb thrust) rockets required on the sled and the starting position of the sled so that the fragment would impact the test article at the desired velocity. SNLA measured the velocity of the fragment from the time intervals between three break wires spaced at 1.52-m intervals on the sled track near the test article location. A laser tracker and high-speed camera were backup velocity measurement systems if the break wire signals were not sensed. The break wire system functioned in all tests.

When the fragment was approximately 1.5 m from the test article, explosive bolts detonated to release the fragment from the rocket sled. In the first two tests, explosive cable cutters released a 1.1-m-o.d., 4.6-m-long corrugated steel catch tube from its support frame, shortly after the bolts were fired. In LFT-1 and LFT-2, the fragment impacted the test article and propelled it into the catch tube, partially filled with sawdust and/or vermiculite. The catch tube also decelerated the fragment while the sled passed the entire assembly without contact, and continued down the track. The catch tube and fragment came to rest on or near the track.

In LFT-3, calibration tests indicated that a catch tube would not be useful. Instead, SNLA placed 3.7-m-high mounds of dirt and sand, separated by about 3 m, at the end of the track. The dirt mounds extended 30 m south from the end of the sled track and we covered the first 9 m of the mounds closest to the end of the track with plastic to mark the penetration of the test debris scattered by the edge-on impact. About 9 m from the end of the track, we stacked bags of sawdust about 1.5 m high on each side with an opening in the center to allow the sled and fragment to pass through. SNLA placed a 3.7-m-high mound of dirt and sawdust between the dirt/sand mounds about 18 m from the end of the track to decelerate the sled and fragment. To ensure recovery of the simulant-fueled clads, we irradiated them at LANL to activate the iridium before the test.

SNLA used several high-speed cameras to record the tests. The camera coverage varied from test to test, but typically consisted of the following: an overall view of the test at 400 frames per second (fr/s); several side views of the impact at 100 fr/s; and a closeup of the impact at about 4000 fr/s. We also photographed the test setup and results with a 35-mm camera.

We recovered the test articles by sifting the sawdust and/or vermiculite through 1.27-cm screens. After LFT-3, portable survey instruments quickly located the irradiated simulant-fueled clads. We then shipped the recovered items back to LANL for postmortem analysis.

IV. RESULTS

We conducted calibration tests (LFT-ENGs) before each of the LFTs to verify fragment velocity, release of the fragment from the rocket sled, the location of the fragment at impact, and the test article catch method. One of these tests, LFT-ENG-2, also involved a mock GPHS-RTG and two LWRHUs. The results of this test and the LFTs are given below.

A. Large Fragment Calibration Test 2

In LFT-ENG-2, we propelled the SRB fragment flat-on into a simulant half-length GPHS-RTG, containing eight mass-simulant modules, at a velocity of 117 m/s. A ninth mass-simulant module and two simulant-fueled LWRHUs hung from 0.95-cm-thick, 0.16-cm-walled aluminum tubes below

and above the GPHS-RTG, respectively. LWRHU 130 hung with its major axis vertical and LWRHU 131 was tilted back 45°.

The fragment propelled the test articles into the catch tube (filled to about 4 m with sawdust) crushing it to a length of about 3 m before it contacted the catch tube support frame and sled track rails and tumbled off to one side of the track. The catch tube slid along the sled track rails for about 30 m, leaving a trail of test debris behind it.

We recovered the GPHS-RTG from between the sled track rails about 8 m from its original position. The collision flattened the simulant converter (Fig. 12) on the impact face, and conformed the downstream side to the six modules still inside. We recovered the molybdenum slugs and the graphite fragments from the top and bottom modules in the sawdust near the GPHS-RTG. The fragment impact did not measurably deform the slugs.

We also recovered the slugs from the ninth mass-simulant module in the sawdust near the GPHS-RTG. The slugs on the impact side (A-GIS) were split in half by, we believe, a secondary impact with the front edge of the catch tube. We also recovered some small fragments of the A-GIS slugs from the catch tube. The impact did not measurably deform the slugs on the downstream side. We could not determine if the converter casing affected the deformation of the slugs.

The LWRHUs were recovered about 15 m from their original test position in sawdust to one side of the track. The aluminum casing was noticeably deformed on the impact side of both LWRHUs (Fig. 13). Neither of the LWRHUs was breached. We sent the LWRHUs to Mound for further postmortem examination.⁸

B. Large Fragment Test 1

In LFT-1, we propelled the SRB fragment flat-on into the half-length GPHS-RTG at a velocity of 114.9 m/s. The test articles were thrown into the catch tube, which was filled to about 4 m with vermiculite. The fragment crushed about 2 m of the catch tube before it propelled the catch tube along the sled track rails. The catch tube ruptured in two regions and spilled most of the vermiculite before it came to a stop on the sled track about 135 m from its original position. The fragment contacted the catch tube support frame and the sled track and then tumbled off to the side.

The converter separated into two major sections (Fig. 14) which we recovered from between the sled track rails about 30 m from the original test position. The module that had been located in stack position 5 (module 5) was recovered integral from between the sled rails near the converter sections (Fig. 15). Module 2 was recovered about 6 m to the west of the sled track on a concrete pad (Fig. 16). Both of the GISs had been expelled from the aeroshell. The C-GIS landed near the aeroshell; the A-GIS was about 10 m north. The module experienced a secondary impact that left a penetrating corner deformation matching the steel tie-down pads on the rocket sled track. We believe that this secondary impact prompted the GIS releases.

In spite of the secondary impact, the graphite contained all of the fueled clads. None of the clads breached (Figs. 17 and 18) and no fuel was released in the test. Fueled clad deformations in module 5 ranged from +1.0% to +8.2%; in module 2, the deformations ranged from +0.9% to +8.8% (Table IV). We sectioned the simulant-fueled clads from the closure side of the A-GIS (A-GIS (open)) from each module (Q-23 and Q-17) and particle sized the total fuel contents. The results are shown in Table V.

C. Large Fragment Test 2

In LFT-2, we propelled the SRB fragment into a half-length GPHS-RTG and a simulant-fueled LWRHU (suspended about 11 cm below the GPHS-RTG) at a velocity of 212 m/s. The test articles were thrown into the catch tube containing about 1.2 m of sawdust followed by about 1.8 m of vermiculite at the open end. In addition, we loaded the front of the catch tube with about 227 kg of lead sheet to assist in decelerating the fragment. The catch tube was severely damaged and separated into two sections when the fragment propelled it onto the concrete pad on one side of the

track, about 40 m from its original position. One section of the catch tube remained there while the other, larger section travelled an additional 40 m before coming to rest on the same side of the track. Test article debris scattered throughout that area.

The converter was severely fragmented (Fig. 19). We recovered most of the converter fragments from the larger portion of the catch tube.

All of the fueled clads, except one (Q-27) that we recovered in a GIS remnant (Fig. 20), were recovered (bare) in or near the larger portion of the catch tube (Figs. 21 and 22). Four of the eight clads appeared to have experienced secondary impacts. Sharp edge secondary contacts breached two of these clads (Q-33 and Q-25); one clad, Q-34 from the A-GIS(open) position of module 2, experienced a large indentation, but was not breached. Clad Q-33, from the non-closure side of the A-GIS (A-GIS(blind)) of module 2 released 1.773 g of fuel; clad Q-25, from the A-GIS (blind) position of module 5 released 0.023 g. The unbreached fueled clad deformations in module 5 ranged from +2.9% to +7.0%; the deformations ranged from +1.9% to +14.0% in module 2 (Table VI).

The SRB fragment shattered into four segments (Fig. 23); two followed the test articles into the catch tube. SEM analysis indicated that these segments were the source of the secondary impacts that caused the clad breaches. We sectioned clads Q-26 and Q-34 from the A-GIS(open) positions of module 5 and module 2 and particle sized the total fuel contents. Particle size data are shown in Table V.

The impact removed the LWRHU capsule (Fig. 24) from its housing; the capsule was recovered on the concrete on the side of the sled track, about 26 m from its original position. The housing (Fig. 25) was recovered about 19 m from its original position on the other side of the track. The capsule was moderately deformed and slightly abraded, but it was not breached. We sent the LWRHU to Mound for further postmortem examination.⁸

D. Large Fragment Test 3

In LFT-3, we propelled the SRB fragment edge-on into a simulant half-length GPHS-RTG at 95.4 m/s. The fragment cut through the converter about 2.9 cm to the right of the converter centerline and impacted the simulant-fueled clads on the A-GIS(open) and the C-GIS(blind) position of each module. The fragment did not penetrate the downstream (back) side of the converter, but the upper and lower flanges and the lower cover separated from the major portion of the converter (Fig. 26). The fragment travelled straight through the trench, between the two 3.7-m-high mounds of dirt and sand, and impacted a pile of dirt and sawdust about 18 m away. The fragment was not noticeably deformed.

The A-GIS side of the aeroshell from module 2 was severely damaged (Fig. 27). We recovered the C-GIS clads integral inside the trench in a cracked, but intact, GIS (Fig. 28a) about 12 m away from their original position. We recovered the A-GIS(blind) clad integral in a GIS remnant (Fig. 29) inside the trench about 12 m from its original position. Fueled clad Q-46 from the A-GIS(open) position breached and released approximately 49 g of fuel. We recovered it bare in the sawdust about 9 m from its original position. All of the clads from module 2 are shown in Figure 30. Fueled clad deformations ranged from -0.2% to +3.2% in the three unbreached clads (Table VII).

The aeroshell from module 5 was extensively damaged on the A-GIS side (Fig. 31). We recovered the C-GIS(blind) clad (Fig. 28b) inside the GIS with the floating membrane about 12 m from its original position (outside the trench). We recovered the C-GIS(open) clad (bare) outside the trench about 60 m from its original position. Both of the C-GIS clads were integral. We recovered the A-GIS(blind) clad (Fig. 29b) integral in a GIS remnant about 18 m away from its original position. We recovered fueled clad Q-50, the A-GIS(open) clad, from the sawdust in the trench about 9 m from its original position. It breached and released approximately 7.5 g of fuel. All of the clads from module 5 are shown in Figure 32. Clad deformations ranged from +0.2% to +3.2% in the three unbreached clads (Table VII).

We sectioned clads Q-29 and Q-43 from the C-GIS(blind) positions of module 2 and module 5, and particle sized the total fuel contents. Particle size data are shown in Table V.

V. CONCLUSIONS

On the basis of the test results described above, we can conclude the following about the interaction of large SRB fragments with the GPHS-RTG:

1. Simulant-fueled clads, inside a converter, do not breach or release fuel after a square (142-cm on a side) SRB fragment impacts flat-on at velocities up to 212 m/s.
2. Only the leading fueled clads breach and release fuel after a square (142-cm on a side) SRB fragment impacts the modules, inside the converter, edge-on at 95 m/s.

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REFERENCES

1. R. E. Tate, "The Light Weight Radioisotope Heater Unit (LWRHU): A Technical Description of the Reference Design," Los Alamos National Laboratory report LA-9078-MS (January 1982).
2. "Final Safety Analysis Report for the Galileo Mission and Ulysses Mission," General Electric report GESP 7200 (October 1985).
3. R. E. Tate and C. C. Land, "Environmental Safety Analysis Tests on the Light-Weight Radioisotope Heater Unit (LWRHU)," Los Alamos National Laboratory report LA-10352-MS (May 1985).
4. A. B. Willoughby, C. Wilton, and J. Mansfield, "Liquid Propellant Explosive Hazards," URS Corporation document AFRPL-TR-68-92 (December 1968).
5. "Space Shuttle Data for Planetary Mission Radioisotope Thermoelectric Generator (RTG) Safety Analysis," National Aeronautics and Space Administration report NSTS 08116 Revision B (September 1988).
6. T. A. Cull and R. W. Zocher, "General-Purpose Heat Source Master Safety Test Plan for Reconfigured Galileo/Ulysses Missions," Los Alamos National Laboratory document LA-UR-87-3064 (September 1987).
7. T. A. Cull, "General-Purpose Heat Source Development: Extended Series Test Program SRB Fragment/Fuselage Tests," Los Alamos National Laboratory report LA-11574 (June 1989).
8. E. W. Johnson, "Light-Weight Radioisotope Heater Unit Final Safety Analysis Report (LWRHU-FSAR)," EG&G Mound Applied Technologies document MCM-3540 (October 1988).

TABLE I. Iridium and UO₂ Test Components Used in Large Fragment Tests.

Test	Capsule	Iridium Clad		UO ₂ Pellet	Fueled Clad Weight (g)	Module Weight(g)
		Vent Cup	Shield Cup			
LFT-1	Module 2					
	Q-17	ZR581RR2	ZR587-3	J-13	206.7091	1430.27
	Q-15	ZR589-1	ZR589-4	J-5	202.8373	
	Q-18	ZR587-6	Z556-4	J-14	207.4938	
	Q-16	ZR589-6	Z551-1	J-11	203.8833	
	Module 5					1430.09
	Q-23	Z551-6	Z551-5	J-23	206.5570	
	Q-19	ZR573-2	ZR568-3	J-16	203.4858	
	Q-22	Z551-2	Z551-3	J-21	205.1747	
	Q-20	ZR587-2	ZR590-3	J-18	206.6626	
LFT-2	Module 2					1415.22
	Q-34	YR430-2	Z556-3	O-9	201.2008	
	Q-33	TR134-5	Z564-3	O-8	200.9556	
	Q-32	ZR568-2	ZR568-4	O-7	204.0155	
	Q-31	ZR567-4	ZR568-1	O-6	201.7130	
	Module 5					1427.21
	Q-26	Z564-4	TR134-4	O-1	203.3858	
	Q-25	Z564-2	TR134-2	J-26	206.2180	
	Q-28	Z565-5	YR430-5	O-3	200.9988	
	Q-27	Z564-6	YR430-1	O-2	204.4232	
LFT-3	Module 2					1423.9
	Q-46	XR372-1	XR362-2	B-29	205.2	
	Q-49	ZR592-1	XR368-1	D-19	201.6	
	Q-30	ZR566-5	ZR567-1	O-5	205.2	
	Q-29	ZR566-1	ZR566-2	O-4	202.9	
	Module 5					1422.6
	Q-50	ZR592-3	XR369-1	D-23	202.9	
	Q-51	ZR597-1	XR369-5	D-24	199.2	
	Q-41	XR366-2	ZR591-6	O-17	203.1	
	Q-43	XR367-4	ZR596-5	B-18	208.4	

TABLE II. LWRHUs Used in Large Fragment Tests.

	LFT-ENG-2		LFT-2
	130	131	366
Pt-Rh Clad	130	131	366
Aeroshell Body	LRF153	012	
Aeroshell End Cap	153	090	
Outer Insulator Body	2-61	3-183	
Middle Insulator Body	2-61	528	
Inner Insulator Body	2-61	3-138	
Insulator Caps	61A, 61B	80, 80B	
Pt-Rh Clad Weight (g)	5.110	5.605	5.70
Fueled Capsule Weight (g)	7.7	8.2	8.3

TABLE III. Mechanical Properties of D-6ac Steel

Property	Parent Material Limits	
	Minimum	Maximum
Ultimate Strength, uniaxial (psi)	200 000	225 000
Yield Strength, uniaxial 0.2% offset (psi)	180 000	—
Elongation (%)	8	—
Reduction in Area, (%)	25	—
K_{IC} (fracture toughness parameter)	90 ksi $\sqrt{\text{in.}}$	—

TABLE IV. Clad Deformations After Large Fragment Test 1.

Clad		Strains (%)			Deformation Parameter (%)
		Diameter	Height	Length	
Module 2					
Q-17	vent	+0.9	-2.9	+1.0	+3.9
	shield	+0.9	-2.1		+3.1
Q-15	vent	+0.2	-2.6	+0.6	+2.9
	shield	+0.9	-2.3		+3.2
Q-18	vent	+2.9	-1.5	+2.1	+4.4
	shield	+2.6	-5.7		+8.8
Q-16	vent	+0.3	-0.6	-1.3	+0.9
	shield	+0.2	-1.3		+1.5
Module 5					
Q-23	vent	+2.9	-2.8	+2.0	+5.9
	shield	+3.1	-2.8		+6.1
Q-19	vent	+2.8	-4.9	+1.8	+8.2
	shield	+2.2	-2.1		+4.4
Q-22	vent	+0.6	-0.1	+0.9	+1.6
	shield	+0.8	-2.6		+3.6
Q-20	vent	+0.4	-0.6	-0.7	+1.0
	shield	+0.3	-0.9		+1.1

TABLE V. Large Fragment Tests—Urania Particle Size Analyses

Particle Size (μm)	LFT-1(Q-23) 114.9 m/s	LFT-1(Q-17) 212m/s	LFT-2(Q-26) 212m/s	LFT-2(Q-34) 212m/s	LFT-3(Q-29) 95.4m/s	LFT-3(Q-43) 95.4m/s
+6000	0.8893	0.9136	0.7637	0.5543	0.9173	0.9275
-6000 to +2000	0.0660	0.0559	0.0986	0.1440	0.0513	0.0501
-2000 to +841	0.0306	0.0195	0.0770	0.1800	0.0189	0.0151
-841 to +420	0.0083	0.0062	0.0300	0.0658	0.0059	0.0041
-420 to +177	0.0038	0.0032	0.0189	0.0374	0.0037	0.0021
-177 to +125	0.0004	0.0005	0.0024	0.0052	0.0006	0.0002
-125 to +74	0.0006	0.0004	0.0035	0.0054	0.0010	0.0004
-74 to +44	0.0002	0.0003	0.0017	0.0021	0.0005	0.0001
-44 to +30	0.0002	0.0001	0.0012	0.0019	0.0003	0.0001
-30 to +20	0.0001	0.0001	0.0006	0.0008	0.0002	0.0001
-20 to +10	0.0001	0.0001	0.0007	0.0010	0.0002	0.0001
-10	0.0002	0.0001	0.0016	0.0023	0.0002	0.0001
1.00(max)	0.000004	0.000011	0.000083	0.000248	0.000022	0.000006
2.00(max)	0.000016	0.000022	0.000387	0.000420	0.000057	0.000018
3.00(max)	0.000036	0.000023	0.000413	0.000343	0.000049	0.000020
4.00(max)	0.000034	0.000011	0.000254	0.000274	0.000030	0.000014
5.00(max)	0.000028	0.000010	0.000144	0.000232	0.000018	0.000008
6.00(max)	0.000014	0.000006	0.000078	0.000154	0.000006	0.000004
7.00(max)	0.000016	0.000005	0.000074	0.000098	0.000015	0.000003
8.00(max)	0.000018	0.000004	0.000037	0.000146	0.000007	0.000009
9.00(max)	0.000026	0.000005	0.000105	0.000104	0.000021	0.000007
10.00(max)	0.000018	0.000007	0.000072	0.000286	0.000014	0.000023

TABLE VI. Clad Deformations After Large Fragment Test 2.

		Strains (%)			Deformation
Clad		Diameter	Height	Length	Parameter (%)
Module 2					
Q-34	vent	+1.3	-10.8		+13.5
				+10.3	
	shield	+1.3	-11.2		+14.0
Q-33	vent	+0.6	-5.1		+6.0
				+8.1	
	shield	Not measured ^a			
Q-32	vent	+0.1	-1.8		+1.9
				-1.1	
	shield	-0.1	-2.4		+2.4
Q-31	vent	+0.9	-2.6		+3.7
				+0.2	
	shield	+0.6	-3.2		+4.0
Module 5					
Q-26	vent	+0.3	-8.5		+9.7
				+4.8	
	shield	+0.9	-3.4		+4.4
Q-25	vent	+2.4	-4.3		+7.0
				+8.4	
	shield	+0.3	-4.3		+4.8
Q-28	vent	+0.7	-2.6		+3.4
				0.0	
	shield	+1.0	-3.1		+4.2
Q-27	vent	+0.5	-2.3		+2.9
				-0.9	
	shield	+0.9	-3.3		+4.3

^aSecondary impact with sharp-edged fragment located to modify as-impacted dimensions

TABLE VII. Clad Deformations After Large Fragment Test 3.

Clad	Strains (%)			Deformation Parameter (%)
	Diameter	Height	Length	
Module 2				
Q-46	Indeterminate ^a			
vent	-0.6	-0.8		+0.1
Q-49			-0.4	
shield	0.0	-1.0		+1.0
vent	-0.8	-0.7		-0.2
Q-30			-0.5	
shield	-0.9	-0.8		-0.2
vent	+0.8	-2.2		+3.1
Q-29			+0.9	
shield	+1.1	-2.0		+3.2
Module 5				
vent	+2.9	-3.5		+6.7
Q-50			+25.9/+11.7 ^b	
shield	+9.4	-17.0		+32.0
vent	-0.5	-0.8		+0.3
Q-51			-0.4	
shield	-0.6	-0.8		+0.2
vent	+0.3	-0.3		+0.5
Q-41			-0.6	
shield	0.0	-0.7		+0.7
vent	+0.3	-2.8		+3.1
Q-43			+0.1	
shield	+1.2	-2.0		+3.3

^aFueled clad separated in half at the weld joint. Secondary impact deformations preclude accurate deformation measurements.

^bIncludes breach width/excludes breach width

Fig. 1. The General-Purpose Heat Source.

Fig. 2. The thermoelectric converter for the GPHS-RTG.

Fig. 3. The light-weight radioisotope heater unit.

(Front view)

(Side view)

Fig. 4. The stack of eight GPHS modules for the large fragment tests containing flight-quality modules in the second and fifth positions.

Assembly

Layout

Fig. 5. The polycrystalline graphite modules each containing four molybdenum slugs.

Fig. 6. Half sections of the engineering unit converter used in LFT-1 and LFT-2.

Fig. 7. Simulant half-length converters used in the second calibration test and in LFT-3.

Fig. 8. Schematic of the flat-on large fragment tests.

Fig. 9. Schematic of the edge-on large fragment test.

Fig. 10. Electromagnet used to hold the lower furnace door closed during heating.

Fig. 11. A counterweighted graphite hook automatically released the module stack when it was in place in the converter.

(a)

(b)

Fig. 12. (a) After LFT-ENG-2, the simulant converter was flattened on the impact face, and (b) the downstream side was conformed to the six GPHS modules still inside.

(LWRHU 130 (flat-on))

(LWRHU 131 (45°))

Fig. 13. After LHT-ENG-2, the aluminum casing was noticeably deformed.

Fig. 14. The converter separated into two major sections after a flat-on impact at 114.9 m/s in LFT-1.

(a)

(b)

Fig. 15. (a) Module 5 (077) recovered integral from between the sled track rails after LFT-1; (b) the GIS's from module 5 cracked, but intact.

(a)

(b)

Fig. 16. (a) Module 2 (076) experienced a penetrating corner deformation after LFT-1; (b) both GIS's were expelled from the module and were recovered cracked, but intact.

MODULE 076: A-GIS CLADS

OPEN END/Q-17

BLIND END/Q-15

MODULE 076: C-GIS CLADS

OPEN END/Q-18

BLIND END/Q-16

Fig. 17. The clads from module 5 were not breached after LFT-1.

MODULE 077: A-GIS CLADS

OPEN END/Q-23

BLIND END/Q-19

MODULE 077: C-GIS CLADS

OPEN END/Q-22

BLIND END/Q-20

Fig. 18. The clads from module 2 were not breached after LFT-1.

Fig. 19. The converter was severely fragmented after a flat-on impact at 212 m/s in LFT-2.

Fig. 20. Clad Q-27 was recovered in a GIS remnant after LFT-2.

MODULE PAL-0078: A-GIS

Q-34/OPEN END

Q-33/BLIND END

MODULE PAL-0078: C-GIS

Q-32/OPEN END

Q-31/BLIND END

Fig. 21. The clads from module 2 (PAL-0078) were recovered bare after LFT-2; Q-33 was breached as a result of a secondary impact, Q-34 experienced a large indentation that did not result in a breach, and the C-GIS clads were integral.

MODULE PAL-0080: A-GIS

Q-26/OPEN END

Q-25/BLIND END

MODULE PAL-0080: C-GIS

Q-28/OPEN END

Q-27/BLIND END

Fig. 22. All of the clads in module 5 (PAL-0080), except Q-27, were recovered bare after LFT-2; Q-25 was breached and Q-26 experienced secondary impacts, but did not breach, and the C-GIS clads were integral.

Fig. 23. The SRB fragment shattered into four segments in LFT-2.

Fig. 24. The LWRHU capsule was removed from its housing upon impact in LFT-2, but it was not breached.

Fig. 25. The LWRHU housing was flattened on the impact side in LFT-2.

Fig. 26. The fragment did not penetrate the downstream side of the converter in LFT-3, but the upper and lower flanges and the lower cover were separated from the major portion of the converter.

Fig. 27. The A-GIS side of the aeroshell from module 2 was severely damaged after an edge-on impact at 95.4 m/s in LFT-3.

Fig. 28. The C-GIS clads (left cylinder) from module 2 were recovered integral in a cracked, but intact, GIS after LFT-3; the C-GIS(blind) clad (right cylinder) from module 5 was recovered inside the GIS with the floating membrane after LFT-3.

Fig. 29. The A-GIS(blind) clads from module 2 (left side) and module 5 (right side) were recovered integral after LFT-3

MODULE STACK 2: A-GIS

Q-46/OPEN END

Q-49/BLIND END

MODULE STACK 2: C-GIS

Q-30/OPEN END

Q-29/BLIND END

Fig. 30. Q-46 from the A-GIS(open) position of module 2 was breached and Q-49 from the A-GIS(blind) position was integral after LFT-3, upper photos; the C-GIS clads from module 2 were not breached in LFT-3, lower photos.

Fig. 31. The aeroshell from module 5 was extensively damaged on the A-GIS side in LFT-3.

MODULE STACK 5: A-GIS

Q-50/OPEN END

Q-51/BLIND END

MODULE STACK 5: C-GIS

Q-41/OPEN END

Q-43/BLIND END

Fig. 32. Q-50 from the A-GIS(open) position of module 5 was breached and Q-51 from the A-GIS(blind) position was integral after LFT-3; the C-GIS clads from module 5 were not breached in LFT-3.