LA--10353-MS

DE85 017956

LA-10353-MS

UC-33A

Issued: June 1985

General-Purpose Heat Source Safety Verification Test Series: SVT-1 Through SVT-6

D. Pavone
T. G. George
C. E. Frantz

MAILED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

26

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

memorandum

TO Holders of LA-10353-MS

FROM IS-11

SYMBOL

SUBJECT Addendum

DATE July 26, 1985

MAIL STOP/TELEPHONE D418/7-5469

Addendum, p. 37.

Fig. A-1. Particle-size distributions of selected
impacted plutonia pellets.

GENERAL-PURPOSE HEAT SOURCE SAFETY VERIFICATION TEST SERIES: SVT-1 THROUGH SVT-6

by

D. Pavone, T. G. George, and C. E. Frantz

ABSTRACT

The General-Purpose Heat Source (GPHS) is a modular heat source that will supply energy for Radioisotope Thermoelectric Generators (RTGs) in space missions. The Safety Verification Tests (SVTs) are performed to assess the plutonia containment capability of heat source modules subjected to certain accident environments. This interim report describes the GPHS module configuration, the test environment, and the response of the module components following simulated reentry and solid Earth impact. The specific test environment of these initial six tests results from failure of the booster rocket to place the spacecraft in a proper trajectory and subsequent reentry of the GPHS modules from Earth orbit.

I. INTRODUCTION

The General-Purpose Heat Source (GPHS) is a modular radioisotopic heat source that produces heat from the α -decay of the 238 isotope of plutonium. The heat-source modules have been designed so that they may be used as individual heat sources in Radioisotope Thermoelectric Generators (RTGs) of various final power outputs and as a heat source for turbine-type generators if such equipment were developed. The initial application of the GPHS will be in RTGs to furnish electric power for the NASA Galileo mission and the Ulysses mission (formerly the International Solar-Polar mission). The RTGs for these missions each use eighteen 250-W(t) modules.

The GPHS module was primarily designed at the Los Alamos National Laboratory; however, that design was modified by the General Electric Company, system contractor for the RTG, to reduce the weight for the above-mentioned missions. A short series of Design Iteration Tests (DITs) was conducted in the modified design configuration and then the design was accepted for use in the Galileo and Ulysses missions. An extensive series of tests is being conducted to assess the capability of the system to contain plutonium in the event of an aborted mission from orbit with subsequent reentry and Earth impact. This interim report describes

the planned Safety Verification Test (SVT) series and the results of the initial six impact tests.

The GPHS module contains four right circular cylindrical pellets of 238-plutonia nominally 27.7-mm diam $\times$ 27.7-mm height, which weigh approximately 150 g and generate 62.5 W(t). Each plutonia pellet is clad in a welded DOP-26 iridium-alloy capsule 29-mm diam $\times$ 29.4-mm height $\times$ 0.64-mm wall thickness. One end of the iridium capsule is fitted with a vent of sintered iridium powder through which the decay product helium is released. This assembly, referred to as a fueled clad (FC), is the basic unit of plutonia containment. Two fueled clads are loaded into a cylindrical, Fine-weave-Pierced Fabric* (FWPF) composite graphite impact shell (GIS), 39.4-mm diam $\times$ 78.7-mm length. To complete the GPHS module, two GISs, each surrounded by a cylinder and two disks of carbon-bonded carbon-fiber (CBCF) insulation, are contained within cavities of a rectangular parallelepiped FWPF aeroshell (A/S) 98 mm $\times$ 94 mm $\times$ 54 mm. A schematic view of the module is shown in Fig. 1.

Reentry analysis¹ indicated that if an RTG reentered the atmosphere, the RTG case and thermoelectric modules would be stripped from the heat source and the heat

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

source modules would reenter as single entities. Thus, individual modules were selected for testing in the test program.

II. TEST OBJECTS

Objects to be tested in this phase of the program were complete GPHS modules assembled from flight-quality components except as noted below. The source and fabrication responsibilities of the components were as follows:

A. Iridium Clad

Iridium-alloy sheet for the cladding was produced by Oak Ridge National Laboratory. Circular blanks and foil were supplied to Monsanto Research Corporation Mound Plant (MRC-Mound).

MRC-Mound formed cups from the blanks; formed vent assemblies, decontamination covers, and weld shields from the foil; and assembled these pieces to constitute the pellet cladding.

B. Plutonia

Plutonia pellets were fabricated at the Savannah River Plant (SRP) and were encapsulated in the iridium

clad at that site. A process change during the production run resulted in two classes of plutonia pellets, one which had been fired in an argon atmosphere and other in an Ar/O₂ atmosphere. Both pellet groups considered to be of flight quality. Table I lists production history of the pellets.

Because weld cracking occurred in some test vessels, SRP developed an ultrasonic, nondestructive evaluation procedure (NDE). An arbitrary scale, calibrated against standard defects, was established. Those FCs with ultrasonic reflections <8 were designated as flight quality.

C. CBCF Insulation

Carbon-based carbon-fiber insulation components were manufactured to final configuration at Oak Ridge National Laboratory and were supplied directly to MRC-Mound.

D. Aeroshell and Impact Shell

Fineweave-Pierced Fabric composite graphite components were machined at two locations, Los Alamos National Laboratory and Teledyne Isotopes, Timonium, Maryland. Items produced by Teledyne carry an identification code of PAT or PGT followed by a four-digit number, PAT-XXXX or PGT-XX

Fig. 1. Schematic diagram of a GPHS module.

TABLE I. Production History of the SVT Fuel Pellets

Pellet No.	Firing Atmosphere	Test
HF-232	Ar/O ₂	SVT-1
HF-238	Ar/O ₂	SVT-1
HF-261	Ar/O ₂	SVT-1
HF-410	Argon	SVT-1
HF-273	Ar/O ₂	SVT-2
HF-355	Argon	SVT-2
HF-369	Argon	SVT-2
HF-449	Argon	SVT-2
HF-343	Argon	SVT-3
HF-350	Argon	SVT-3
HF-454	Argon	SVT-3
HF-457	Argon	SVT-3
HF-139	Ar/O ₂	SVT-4
HF-162	Ar/O ₂	SVT-4
HF-348	Argon	SVT-4
HF-354	Argon	SVT-4
HF-260	Ar/O ₂	SVT-5
HF-267	Ar/O ₂	SVT-5
HF-415	Ar/O ₂	SVT-5
HF-426	Argon	SVT-5
HF-189	Ar/O ₂	SVT-6
HF-225	Ar/O ₂	SVT-6
HF-361	Argon	SVT-6
HF-373	Argon	SVT-6

Those produced at Los Alamos are identified with a code of PAL or PGL followed by a three-digit number, PAL-XXX or PGT-XXX. Aeroshells used in the test modules of this series were machined at Los Alamos to remove twice the thickness of expected ablation for the reentry mode of the test. The RTG contractor, General Electric Company, described two reentry configurations: a minimum-gamma and an orbital-decay reentry mode.

E. Module Assembly

Components of the test modules were assembled at MRC-Mound. After the vents of the fueled clads were activated and the module was assembled, the assembled module was treated in the Mound Reduction and Monitoring Facility (MRMF). Then the module was subjected to two cycles of flight-acceptance vibration spectra and transient accelerations, radiographed, and shipped to Los Alamos in welded stainless steel containers. Table II identifies the components of the modules SVT-1 through SVT-6.

III. TEST PROGRAM

The test program was designed to simulate the sequence of environments and events that a module would experience during an aborted mission.

Thirteen modules were allocated for testing in the SVT series. Each module was fueled with two GISs: one GIS, designated the primary impact assembly (PIA), contained flight-quality FCs, and the other GIS, or secondary impact assembly (SIA), contained non-flight-quality FCs. The FCs in the SIA are not flight-quality because weld-inspection NDE indications exceeded 8 (arbitrary units). No FC with an NDE indication >14 was used in the SVT series.

In addition to the reentry mode and the fuel processing variables, various impact orientations of the module were included. Schematic representation of possible orientations is depicted in Fig. 2, and the Impact Test Plan is depicted in Fig. 3. Orientations of tests following the initial five (SVT-1 through 5) were determined by a Technical Review Board consisting of R. W. Zocher (Los Alamos National Laboratory), C. T. Bradshaw (General Electric Company), and R. W. Englehart (NUS).

IV. EXPERIMENTAL PROCEDURES

A. Receiving and Inspection

Assembled modules were received from MRC-Mound in welded stainless steel containers. Three of the modules had been disassembled at MRC-Mound and the impact assemblies shipped in stainless steel containers separate from the aeroshell/insulation components.

The test articles were radiographed to establish the condition of the fuel pellet before further test operations. Test modules were removed from the shipping can in an argon-atmosphere glove box ($O_2 = <150$ ppm), were disassembled to the extent of removal of the impact assemblies from the aeroshell, and were visually examined.

B. Aging

A 1/16-in.-diam optical pyrometer sight hole was drilled through the cap of the primary impact assembly, and both GISs were loaded into an ATJ graphite furnace fixture. The aging assembly was transported to the furnace in a covered can and loaded into the furnace with minimum exposure to air.

Aging treatments were performed in high-vacuum furnaces with tungsten mesh heating elements and tantalum radiation shields. Most of the GISs were aged in Brew Model 424C furnaces, which have a 4-in.-diam hot

TABLE II. Components of GPHS SVT Series Test Modules

Component	SVT-1	SVT-2	SVT-3	SVT-4	SVT-5	SVT-6
Aeroshell	PAL-012	PAL-015	PAL-014	PAT-1007	PAT-1008	PAT-1009
Prime impact assembly						
Insulation cylinder	C40-4	C40-5	C40-7	C40-6	C41-3	C40-8
Insulation discs	P8-2-4; P8-2-15	P8-2-44; P12-1-17	P8-2-59; P8-2-60	P8-2-51; P8-2-54	P11-2-12; P11-2-20	P11-1-30 P11-2-8
Impact shell	PGL-013	PGL-018	PGL-020	PGT-1015	PGT-1027	PGT-1023
Fueled clad—open end	FC-232	FC-355	FC-343	FC-348	FC-267	FC-361
Fuel pellet	HF-232	HF-355	HF-343	HF-348	HF-267	HF-361
Vent cup	LR-313-1	Q806-2	PR718-5	QR820-1	P701-5	PR726-1
Shield cup	LR-316-1	Q806-5	PR719-5	QR820-6	P708-5	PR725-5
Fueled clad—blind end	FC-238	FC-369	FC-350	FC-354	FC-260	FC-373
Fuel pellet	HF-238	HF-369	HF-350	HF-354	HF-260	HF-373
Vent cup	LR-315-2	NR528-2	R904-7	QR820-3	PR717-3	PR727-3
Shield cup	LR-318-6	NR528-3	R904-5	QR820-2	PR717-4	Q803-6
Secondary impact assembly						
Insulation cylinder	C31-3	C33-9	C30-4	C30-8	C34-2	C29-5
Insulation discs	P8-2-2; P12-1-18	P11-1-10; P11-1-11	P11-1-24; P11-1-31	P11-11-12; P11-1-23	P11-2-18; P11-2-29	P11-2-7 P11-2-9
Impact shell	PGL-014	PGL-018	PGL-027	PGT-1017	PGT-1029	PGT-1026
Fueled clad—open end	FC-261	FC-449	FC-457	FC-139	FC-415	FC-189
Fuel pellet	HF-261	HF-449	HF-457	HF-139	HF-415	HF-189
Vent cup	P709-6	S27-2	P40-5	N510-C	S8-3	P705-3
Shield cup	Q804-1	S25-3	P41-4	MER14-5	S7-2	P705-5
Fueled clad—blind end	FC-410	FC-273	FC-454	FC-162	FC-426	FC-225
Fuel pellet	HF-410	HF-273	HF-454	HF-162	HF-426	HF-225
Vent cup	S2-4	PR718-4	S36-4	MER19-2	S25-4	MER1-4
Shield cup	S2-5	MER19-4	S39-5	MER1-5	S25-5	MER7-4

Fig. 2. Three angles describe the orientation sensitivity of the GPHS module to impact.

zone and accommodate the two GISs from a single module. A 6-in.-diam Brew Model 426C, which could accommodate four GISs from two modules, was used for the aging heat treatment of some test pieces.

Two of the 4-in.-diam furnaces were equipped to monitor the helium released from the FCs during the aging treatment. Those modules treated in these furnaces were continuously monitored, but modules to be handled in this manner were not preselected.

Aging treatments were conducted at a pressure of $<1 \times 10^{-6}$ torr and a clad temperature of 1287°C as measured with a calibrated optical pyrometer sighted on the end of one of the GIS fueled clads. This temperature represented a weighted average of the iridium-clad temperature at the operating conditions of the heat source in the Galileo and Ulysses RTGs. Aging time was 200 h for GISs from modules to be tested in the minimum-gamma reentry mode, and 90 days for GISs from modules to be tested in the orbital-decay reentry mode. The 90-day aging reflects the expected elapsed time for an aborted Galileo mission;² however, the data obtained are considered applicable to the Ulysses mission as well, which would have a 38-day operational period before an orbital-decay reentry.

C. Reentry Simulation

When the aging treatment was completed, the GISs were returned to the inert-atmosphere glove box, and two additional holes were drilled in the cap of the impact shells to accommodate the legs of a split-junction thermocouple. The appropriate reentry temperature profile was applied in an electron-beam furnace. Figure 4 illustrates the temperature profiles for the minimum-gamma and orbital-decay reentry conditions.

D. Preimpact Inspection

Before the GISs were reassembled into the aeroshell, they were again radiographed to document the pre-impact condition of the plutonia pellet.

E. Impact Test

Holes were drilled in the aeroshell and the primary GIS for thermocouples used to monitor the temperature of the impact assembly. A split-junction, Chromel-Alumel thermocouple was installed with its legs contacting a primary FC, and two beaded-junction thermocouples were placed in contact with the outer surface of the primary GIS. The instrumented module was transported to the test site in a helium-filled container that was cooled by forced air.

Test modules in these reported tests were impacted at the Los Alamos Isotope Fuels Impact Test Facility (IFIT) against a hardened steel target at the designated temperature and velocity corresponding to the reentry mode of the test. The impact test conditions, specified by General Electric Company, were a velocity of 54 m/s and a clad impact temperature of 919°C for minimum-gamma reentries and 975°C for orbital-decay entries.

The IFIT, a 178-mm-diam gas gun with provision for containment of the impacted test article in a catch tube, is described in detail in Los Alamos Scientific Laboratory report LA-6013 (January 1976), entitled "Isotope Fuels Impact Tester." Tests of GPHS SVT modules differed from that shown for the Multihundred-Watt Fuel Sphere Assemblies (MHW FSAs): The modules were not enclosed in an impact can, iridium-clad temperatures were measured directly, and the desired impact temperatures and thermal inventory of a module

Fig. 3. Test scheme for aging reentry-impact portion of GPHS SVT series.

Fig. 4. Clad temperature histories during reentry of a GPHS module.

were such that the impact temperatures were reached by self-heating.

For modules in the $\alpha = \beta = 0^\circ$ (broad-face) impact orientation, geometric considerations prevented the direct use of split-junction thermocouple measurement of the clad temperature. In these cases, a temperature calibration was made in the gun, in which the surface temperature of the impact shell was determined to correspond to the iridium-clad temperature measured with the split-junction thermocouple. The split-junction thermocouple was removed, and the test was conducted at the calibrated impact-shell surface temperature.

F. Postmortem Examination

Because the schedule for Safety Analysis Reviews allowed only a limited time to complete the impact tests and postmortem examinations, we adopted the protocol of performing complete postmortem examinations only of the primary FCs. This protocol was later amended to include investigation of failures of the secondary FCs, and since the fuel pellet would be processed for plutonia recovery, chemical analyses of the secondary fuel pellets were obtained.

The principal objectives of the postmortem examination were to determine the quantity of plutonium released, if any, and the fraction in the $<10\text{-}\mu\text{m}$ particle-size range; to document the damage sustained by all components; and to characterize the iridium and plutonia with respect to chemical composition and microstructure. The following nine steps summarize the postmortem examination.

- (1) Obtain documentary photographs of the post-impact condition of the aeroshell, the impact shells, and the fueled clads.
- (2) Recover all graphitic components, including the catch-tube debris, and determine the total plutonium content and the fraction in the particle-size range $<10\text{-}\mu\text{m}$.
- (3) Measure the principal dimensions of the impacted FCs.
- (4) Estimate the area of fractures from suitably oriented photographs.
- (5) Defuel the FCs, obtain documentary photographs of the plutonia fracture pattern, and perform sieve analysis of the impacted plutonia pellets of selected unfailed FCs.
- (6) Select a sample of each cup of the iridium clad for emission spectrographic analysis and select two samples for Auger electron spectroscopy (AES) analysis.
- (7) Select metallographic cross sections through any failures or severe localized deformation of the iridium clad, select an axial cross section through the weld, and select other cross sections so that

both transverse and axial microstructure and the grain size of each cup may be determined.

- (8) Cross section the vent assembly and metallographically examine the vent-assembly weld microstructures, vent deposits, and vent effusates.
- (9) Select samples of the plutonia fuel pellet for emission spectrographic analysis, colorimetric phosphorus analysis, and ceramographic microstructural examination.

The experimental procedures for conducting most of the postmortem operations involve generally well known equipment and techniques and need not be described in any further detail. However, the procedure for obtaining the total plutonium and the $<10\text{-}\mu\text{m}$ fraction contained in the graphitic materials warrants further discussion.

In previous test programs involving the MHW FSAs, the FSAs were impacted with the FSA contained within a welded tantalum can. All graphite debris was recovered after sawing the can open, and the debris was burned in air at about $850\text{--}900^\circ\text{C}$. The resulting ash was dissolved in acid, and the solution was analyzed for plutonium by radiochemical techniques.

For most of the initial tests (SVT-1 through 5) described here, the debris remaining in the catch tube was recovered by washing with ethyl alcohol, then was dried and combined with the aeroshell and impact shells. Processing of this material then followed the technique used previously, except that the ash resulting from the combustion was sieved into fractions greater than and less than $10\text{ }\mu\text{m}$, and each fraction was analyzed separately.

To investigate possible agglomeration of plutonia particles into larger aggregates by sintering at the combustion temperature of graphite, an extraction replica was made of a sample from the $<20\text{-}\mu\text{m}$, $>10\text{-}\mu\text{m}$ fraction of the ash, and this replica was examined by electron microscopy. Figure 5 shows that very small particles, a few tenths of a micron in diameter, did indeed form aggregates larger than $10\text{ }\mu\text{m}$. To circumvent this problem, the procedure for handling the graphitic materials was modified according to a scheme suggested by E. W. Johnson (MRC). In this procedure, large pieces of aeroshell, impact shells, and insulation were cleaned ultrasonically in ethyl alcohol before combustion in the usual manner. Material recovered from the washing operation was combined with the catch-tube debris and burned in oxygen in a plasma-assisted combustion furnace. The rate of oxidation is very slow in this apparatus, but the temperature remains low ($\sim 50^\circ\text{C}$) so that particle sintering is not a problem. The ash is sieved into $<10\text{-}\mu\text{m}$ and $>10\text{-}\mu\text{m}$ fractions and analyzed as before. The plutonium remaining on the

Fig. 5. Agglomerates of plutonia particles and ash were formed during combustion of the graphitic materials. 10,000X.

aeroshell and impact shells is considered to be $<10\text{-}\mu\text{m}$ material.

V. TEST RESULTS

Results will be presented narratively as a description of observations, with illustration of significant features. For ease of comparison and ready reference, analytical results are tabulated as follows in the Appendix:

Table A-I. Impact Test Summary—GPHS SVT Series

This table lists the NDE value, the gross deformation of each FC, the number of failures, and the estimated area of the fractures.

Table A-II. GPHS SVT Fuel Release

This table lists the total plutonium released in the test and the distribution between the $<10\text{-}\mu\text{m}$ and $>10\text{-}\mu\text{m}$ size range.

Table A-III. Particle-Size Distribution of the $<10\text{-}\mu\text{m}$ Fraction of Selected Impacted Pellets

The size distribution of the $<10\text{-}\mu\text{m}$ fraction of the plutonia pellets from selected unfailed fuel clads is shown in this table. Figure A-1 graphically shows the results of the sieve analysis of these pellets.

Table A-IV. Iridium Grain Size—GPHS SVT Series

This table lists the grain size of the iridium cups in axial and transverse cross section expressed as grains/640 μm thickness.

Table A-V. Summary of AES Analyses of GPHS SVT Iridium

This table summarizes the results of AES analysis of the primary iridium clads and a few of the secondary clads. The $\text{Th}_{65}/\text{Ir}_{229}$ intensity ratios are given for the interior, center, exterior, and for the average. The average intensity ratios are given for other elements.

Table A-VI. Results of Spectrographic Analysis of GPHS SVT Iridium

The concentrations are tabulated for impurity elements present in the individual iridium cups as determined by emission spectroscopy.

Table A-VII. Plutonia Analyses, GPHS SVT Series

This table summarizes the results of emission spectrographic analysis of the plutonia pellets and gives the phosphorus content as determined by a colorimetric procedure.

A. SVT-1

This assembly was tested to simulate minimum-gamma reentry conditions in a broad-face ($\alpha = \beta = 0^\circ$) orientation. The impact temperature was 919°C (clad) and the impact velocity was 54.4 m/s. The target was hardened 4340 steel.

Figure 6 shows the module as recovered from the catch tube. There were nearly full length cracks on both nonclosure narrow faces of the aeroshell and two cracks parallel to the axes of the impact assemblies on the impact face. The back face was dented and cracked. Although forces exerted on the back face during impact may account for the deformation and cracking of the aeroshell back face, the observed deformation and cracking might also result when the module rebounds against thermocouple extension wires that are fed through the center of the inner projectile cylinder. The condition of the PIA impact shell is shown in Fig. 7. Both of the GISs had slightly bowed profiles and irregular cracks on the impact face extending about 85% of the length from the closure end. These postimpact features are typical of the FWPF components of a module impacted in the $\alpha = \beta = 0^\circ$ orientation.

No failures were observed in either of the FCs of the PIA, FC-232 and FC-238. The overall deformation was symmetrical and only modest localized iridium deformation was observed, principally on the impact face.

Failures occurred in both fueled clads of the SIA. Figure 8 illustrates a major failure located on the back side in both cups of the iridium clad of FC-261 and shows a small failure on the impact face of the shield cup about 180° from the back-side fracture. The vent-end profile view shows the overall distortion of the iridium clad caused by plutonia fragments sliding along a plane oriented at an angle near 45° to the impact plane. The failure in FC-410 apparently originated at the corner of the shield-cup back side and extended axially through

(a)

(b)

Fig. 6. The aeroshell of SVT-1. There were cracks on the impact face, on both nonclosure narrow faces, and on the back. (a) Impact face forward, (b) back forward.

(a)

(b)

Fig. 7. The graphite impact shell of the PIA of SVT-1 was cracked on the impact face and had a slightly bowed profile. (a) Impact face, (b) profile view.

(a)

(b)

(c)

Fig. 8. Fuel push-through failures occurred on the impact face of FC-261 and on the back side of FC-261. (a) Impact face, (b) back side, and (c) vent-end view.

the weld into the vent-cup wall, as well as into the edge of the shield-cup bottom. Figure 9 illustrates the location and the extent of the failure.

Metallographic transverse cross sections through the failures in FC-261 are shown in Figs. 10 and 11. The fracture mode at the fracture site on the vent-cup back side (Fig. 10) was intergranular, although a small reduction in thickness, about 4%, indicates limited ductility. The radial displacement of opposite sides of the fracture indicates the effect of fuel-fragment push-through. The photomicrograph of the cross section through the impact-face fracture of the shield cup (Fig. 11) shows a sharp bend at the point of the fuel-fragment push-through and the fracture nearby in the reverse-bend

region. The etched microstructure indicates that the failure occurred where some relatively large, columnar grains normal to the surface were present. This microstructure is similar to that observed in some vent-assembly welds and is probably the location at which the weld-shield tab was welded to the cup interior.

Transverse metallographic cross sections through the shield-cup failure of FC-410 are shown in Fig. 12. Again, the effect of fuel-fragment push-through is evident. The fracture mode was intergranular, but the reduction of thickness of about 6% indicates modest ductility.

Auger electron spectroscopy analysis of fracture surfaces indicated that small quantities of grain-boundary sulfur were present in both samples of the FC-261 vent cup.

(a)

(b)

Fig. 9. The failure in FC-410 originated at corner on the shield-cup back side, and it extended axially through the wall of the shield cup into the vent cup as well as into the edge of the capsule bottom.

(a)

(b)

Fig. 10. Radial displacement of the two sides of the fracture on the back side of the FC-261 vent cup indicates the effect of fuel-fragment push-through. The fracture mode was intergranular.

(a)

(b)

Fig. 11. The fracture on the shield-cup impact face occurred in the reverse-bend region near the point of fuel-fragment indentation. Large grains on the interior of the wall thickness result from welding of the weld-shield tab to the capsule wall. (a) 7 $\times$, (b) 50 $\times$.

The calcium content of the plutonia pellets HF-238, HF-261, and HF-410 exceeded the SRP guideline limits. The microstructures of pellets HF-238 and HF-239 were typical of SRP material.

The iridium microstructure was uniform; however, the grain size varied from 20 grains/640 μm thickness for cup LR315-2 to 28 grains/640 μm thickness for cup LR318-6.

Metallographic examination of an axial cross section through the weld bead indicated that the microstructure consisted of randomly oriented, equiaxed grains in the center of the weld bead, that there was no porosity, and that the penetration was complete.

Metallographic examination of the vent-assembly cross sections of FC-232 and FC-238 showed that both vent orifices were free of deposits, that the entrance to the filter element of the vents contained only a small quantity of plutonia, and that the decontamination cover and vent-assembly welds were sound.

B. SVT-2

This module was also tested in the minimum-gamma reentry mode at an orientation of $\alpha = \beta = 0^\circ$. The impact temperature was 919°C (clad) and the velocity was 55 m/s against a target of hardened steel.

The condition of the graphitic components was similar to that of graphitic components in SVT-1. The aeroshell had impact-face cracks about parallel to the GIS axes, and it was fractured on both nonclosure narrow faces. Both impact shells had bowed profiles and irregular impact-face cracks along about 80% of the length.

There were no failures or severe localized iridium deformation in either FC-355 or FC-369, the fueled clads of the primary impact assembly, or in clad FC-273 of the secondary impact assembly.

The fueled clad positioned in the closure end of the secondary impact shell, FC-449, suffered three failures:

(a)

(b)

Fig. 12. The fracture on the back side of the shield cup of FC-410 was also of the fuel-fragment push-through type. (a) 7X, (b) 50X.

an axial failure on the back side, a failure on the centerline of the weld bead, and a failure on the vent-cup radius on the back side. Figure 13 illustrates the observed failures. The weld-bead failure was in a single-pass region of the weld bead, about 180° from the weld overlap and about 90-100° from the center of the impact face.

Metallographic cross sections through the failures of both cups on the back side of FC-449 (Fig. 14) show that the fracture mode was intergranular with no significant reduction of thickness; however, radial displacement of the sides of the fractures indicates fuel-fragment push-through.

Figure 15 shows the metallographic cross section through the fractured weld bead. The microstructure of the weld consists of small, randomly oriented grains that would not be particularly subject to failures along the centerline of the bead; however, relative displacement of the two sides of the fracture suggests that the failure

was caused by fuel push-through effects similar to those seen on the impact face and back side of the cylinder portion of other assemblies. An AES analysis of the weld bead did not show any unusual impurities, though the thorium content on the vent-cup side of the weld was higher than that on the shield-cup side.

The metallographic cross section through the fracture in the vent-cup corner is shown in Fig. 16. The fracture mode is intergranular with no indication of reduced thickness and no displacement of the two sides of the fracture. This is a low-strain region of the capsule, so the reason for failure at this location is not evident.

Examination of the microstructure of the FC-355 weld bead (Fig. 17) revealed a crack that extended about 25% of the thickness from the interior surface. The weld sample cross section was located on the side of the impacted fuel clad and by chance included the weld overlap region. The observed crack is doubtlessly a pre-existing fabrication defect and not an impact-induced

Fig. 13. Three failures occurred in FC-44: an axial failure on the back side, a centerline weld-bead failure, and a failure on the vent-cup radius on the back side. (a) Back side, (b) side profile, and (c) vent-end view.

failure. The microstructure of the center of the weld bead includes undesirable elongated grains oriented approximately normal to the thickness of the capsule wall.

The microstructures of the iridium clads were uniform. The observed grain sizes ranged from 28 grains/640 μm thickness for cup NR528-3 to 21 grains/640 μm thickness for cup Q806-2.

Vent-assembly metallographic examination of FC-355 and FC-369 showed that the vent orifices were free of deposits and that only a small quantity of plutonia was deposited in the entrance to the vent filter element. The decontamination cover and vent-assembly welds to the clad were free of defects.

AES analysis of the grain-boundary chemistry of the iridium clad revealed expected concentrations of

thorium. Small amounts of phosphorus were present in samples from FC-355 and FC-369 (prime). Iron was the principal impurity element detected by emission spectroscopy.

The microstructure of the prime plutonia pellets was normal, and no impurities exceeding the SRP guidelines were present.

C. SVT-3

This assembly was processed for simulation of an orbital-decay reentry and was impacted in the $\alpha = \beta = 0^\circ$ orientation. The impact temperature was 975°C (clad) and the impact velocity was 54.4 m/s against a steel target. Continuous monitoring of the heat flux released

(a)

(b)

(c)

(d)

Fig. 14. Failures on the back side of FC-449 occurred in areas of mild localized iridium deformation. Shield cup (a) 7 $\times$ and (b) 50 $\times$. Vent cup (c) 7 $\times$ and (d) 50 $\times$.

Fig. 15. The microstructure of the center of the FC-449 weld bead consisted of small, randomly oriented grains. Radial displacement of the two sides of the fracture suggests unequal strain across the weld. 50X.

(a)

(b)

1. The failure on the vent-cup radius of FC-449 exhibited no evidence of fuel-fragment push-through, and the fracture occurred with no indication of ductility. (a) Photomicrograph 7X, (b) 50X.

Fig. 17. The microstructure of the weld head of FC-355 contained elongated grains oriented normal to the wall thickness; a crack extending about 25% of the thickness in the weld overlap was present. 50X.

from the test assembly showed that there were several periods during the initial 680 h of the 90-day aging exposure in which the helium released was equivalent to 75% of the generation rate, indicating intermittent vent plugging of one fueled clad.

There were no fractures on the impact face or narrow faces of the aeroshell, but a diagonal crack was present on the back side. Both impact shells had bowed profiles and impact-face cracks spanning about 70% of the length.

No fractures of the iridium clads of the primary impact assembly, FC-343 and FC-350, or of the secondary impact assembly clad, FC-457, were observed.

Figure 18a shows a small fracture in the center of the back side of the FC-454 shield cup. This capsule also displayed a significant quantity of vent effusate surrounding the vent hole as shown in Fig. 18b.

Metallographic examination of a transverse cross section through the back-side fracture of the FC-454 shield cup revealed that the fracture mode was intergranular with a small reduction in thickness of about 4% near the fracture. The photomicrographs of Fig. 19 show no severe localized deformation of the iridium in this clad area and no radial displacement by fuel fragments to account for the fracture.

Auger electron spectroscopy analysis of the grain-boundary chemistry of samples taken adjacent to the fracture in the FC-454 shield cup revealed high sulfur

concentrations. Small quantities of sulfur were also observed at some locations in samples from FC-355 and FC-369. Thorium concentrations at all sample interiors were lower than in the center and exterior locations. The principal impurity element detected by emission spectroscopy was iron.

Figure 20 shows a metallographic cross section through the vent orifice and the intermetallic reaction products on the exterior surface surrounding the orifice of FC-454. A porous deposit of iridium-tungsten alloy was present on the wall of the orifice, particularly near the interior. The four phases on the clad exterior were identified as (1) iridium, tungsten, and iron; (2) iridium, plutonium, and titanium; (3) iridium and plutonium; and (4) iridium and iron. The vent orifices of the other fueled clads did not show any effused materials, therefore FC-454 probably was responsible for the observed periods of vent plugging.

The vent orifices of FC-343 and FC-350 were free of vapor-transported material, and only small quantities of plutonia were deposited at the vent entrance. The decontamination cover and vent-assembly welds of FC-350 were free of defects or abnormal microstructures. The weld areas of FC-454 exhibited a large grain size, and in FC-343 large grains were observed on one side of the sample while normal microstructure existed on the other. These features are illustrated in Fig. 21.

(a)

(b)

Fig. 18. A small fracture in the center of the back side of FC-454 was the only failure in SV T-3 (a). Effusate surrounding the vent orifice indicates that this vent was plugging during the aging treatment (b).

(a)

(b)

Fig. 19. Failure in the shield cup of FC-454 occurred in an area without severe localized iridium deformation or indications of fuel-fragment push-through. (a) 7X. (b) 50X.

(a)

(b)

Fig. 20. The orifice of the FC-454 vent had a deposit of iridium-tungsten alloy. Intermetallic reaction products were present on the clad exterior. (a) 50 $\times$, (b) 250 $\times$.

(a)

(b)

(c)

(d)

Fig. 21. Abnormal grain growth occurred in the vent-assembly welds of FC-454 (a,b) and FC-343 (c,d). 50X.

Fig. 22. The microstructure of iridium cup S39-5 had isolated large grains on the exterior in addition to large interior grain size, 50 $\times$.

The iridium microstructures observed were nonuniform across the thickness. Typically, the interior 20-25% of the thickness showed a large grain size. Isolated occurrences of large grain size were also observed on the exterior of cup S39-5 (FC-454), as illustrated in Fig. 22.

Metallographic examination of the cross section through the welds of FC-343 and FC-350 indicated that the welds were free of porosity, had penetrated completely, and had microstructures consisting of randomly oriented grains in the center of the weld bead.

The microstructure of the primary fueled-clad plutonia pellets was typical. Pellets HF-350 and HF-454 each had a calcium concentration of 200 ppm, which slightly exceeds the SRP guideline.

D. SVT-4

This test duplicated SVT-3, that is, with orbital-decay aging and reentry and impact in an $\alpha = \beta = 0^\circ$ orientation against a steel target. The impact temperature was 774 $\pm$ 31 and the impact velocity was 54 m/s.

Fig. 23. FC-348 sustained a fuel-fragment push-through crack on the impact face, principally in the shield cup.

Continuous monitoring of the helium released from the four fueled clads showed no evidence of vent plugging throughout the 90-day aging exposure.

Damage sustained by the aeroshell was similar to that observed in the previous three tests conducted in the $\alpha = \beta = 0^\circ$ orientation. There were irregular cracks on the impact face near both edges of the aeroshell body and a fracture the full length of the narrow face on the PIA side of the aeroshell. The fracture on the other narrow side extended only about 50% of the length. A dent was present on the back side with cracks radiating to the corners. Several longitudinal cracks distributed over the impact face occurred in the impact shell of the primary impact assembly. This failure mode differs from the single crack on the center of the impact face usually observed. Both impact shells exhibited the typical bowed profiles.

No failures occurred in the iridium clad of FC-354 of the PIA or in either of the fueled clads, FC-139 and FC-162, of the SIA. Only mild to moderate localized iridium deformation was observed in these units.

A longitudinal fuel push-through failure in a reverse-bend area was present on the impact face of FC-348. The fracture extended nearly the full length of the shield cup and a short distance into the vent cup, with a discontinuity at the weld; Fig. 23 illustrates the location and extent of the failure.

Metallographic cross-sections taken transversely through the fractures of the shield cup and the vent cup are shown in Figs. 24 and 25, respectively. The

(a)

(b)

(c)

Fig. 24. The impact-face failure in the shield cup of FC-348 occurred in a region of severe reverse bending near a fuel-fragment indentation. (a) 7X, (b) and (c) 50X.

(a)

(b)

Fig. 25. Deformation in the vent cup of FC-348 also exhibited the fuel-fragment push-through characteristics. Failure occurred after modest reduction in thickness.

photomicrographs clearly illustrate the point of fuel-fragment indentation, with failure occurring in the reverse-bend region nearby. The shield-cup cross section also shows a crack progressing from the exterior surface through about two-thirds of the wall thickness. The primary fracture in the shield cup exhibits negligible reduction of thickness at the fracture site and about 15% reduction of thickness at the point of fuel-fragment indentation. A reduction of thickness of about 9-10% at the fracture site in the vent cup indicates a limited amount of ductility. The fracture appears to lack about one grain thickness of full penetration on this plane, but quite likely penetrated through the thickness somewhere along its length.

Though no failures were observed in FC-354 of the primary impact assembly, a crack progressing through about 40% of the wall thickness occurred in the reverse-bend region of the impact face, as illustrated in Fig. 26. The degree of fuel-fragment indentation and reverse bending at this location was comparatively mild.

AES analysis of the iridium grain-boundary chemistry of FC-345 and FC-354 showed that in most samples, the thorium concentration was depleted at the interior surface. Small concentrations of sulfur were detected in samples from the shield cup of FC-354. Cup QR820-2 had higher concentrations of chromium, iron, and nickel impurities than did the other cups of the primary fueled clads.

The iridium microstructures observed were similar to those of cups in SVT-3, with large interior grains occupying 20-25% of the wall thickness. The range of observed grain sizes was 18 grains/640 μm thickness for cup QR820-1 to 15 grains/640 μm thickness for cup QR820-6.

Examination of vent-assembly cross sections indicated similar conditions for both FC-343 and FC-350. The vent orifices were free of vapor-transported deposits, a small quantity of plutonia was deposited at the entrances to the vent assemblies, and the decontamination cover and vent-assembly welds were free of defects.

Fig. 26. A crack observed in FC-354 traversed about 40% of the wall thickness from the interior at a location of mild reverse bending. (a) 7X, (b) 50X.

Axial cross sections through the capsule closure welds showed that these welds were of high quality. There was no porosity, the weld penetrated completely, and the microstructure did not contain any undesirable characteristics.

All impurity elements in the plutonia pellets were well below SRP guidelines. The microstructures were typical, though HF-354 had a somewhat smaller grain size.

E. SVT-5

This test module was designated for impact testing in the orbital-decay reentry mode with impact against a steel target on the narrow, nonclosure face of the aeroshell ($\alpha = 90^\circ$, $\gamma = 0^\circ$). The impact temperature was 975°C and the impact velocity was 54.0 m/s .

Figure 27 shows the module in the catch tube and the aeroshell after the impact assemblies have been removed. The impact face of the aeroshell was separated

from the body along fractures parallel to the axis of the lead impact assembly. The aeroshell closure cap of the lead impact assembly was not retained and a circular disk was torn from the opposite end, leaving the lead impact assembly free to be ejected from the aeroshell. The closure cap of the lead impact shell was not retained in the body, and one of the fueled clads was partially out of the impact shell. Damage to the lead impact shell was greater than that sustained in the $\alpha = \beta = 0^\circ$ orientation. In addition to a crack on the impact-face centerline that was wider than is usually observed, there were cracks on each side about midway between the centerline and edge of the impact face. The trailing impact shell had a typical irregular crack on the impact face and a transverse crack on the back side about 8 mm from the closure end.

No failures were observed in any of the fueled clads. As expected, the gross deformations of the fueled clads in the lead impact assembly were greater than (about twice) those of the clads in the trailing impact assembly.

(a)

(b)

Fig. 27. The narrow impact face was torn from the aeroshell, permitting the lead IA to be ejected in SVT-5. A crack was present on the impact face.

(a)

(b)

Fig. 28. Fuel-fragment push-through deformation occurred on the back of the shield cup of FC-267. The crack in the reverse-bend location progressed only three grains.

Localized iridium deformation of the clads was moderate, occurring principally on the center of the FC-260 and FC-267 impact faces. Figure 28 illustrates the most severe localized iridium deformation, which occurred on the back side of the FC-267 shield cup. A small crack was initiated at the interior surface, but it progressed only three grains into the wall.

AES analyses showed that thorium concentrations at the iridium grain boundaries were lower at the interior than at the center and exterior. Low levels of sulfur were found in one sample of the shield cup of FC-267. Emission spectroscopy analysis showed iron to be the principal impurity element in the iridium clads.

The microstructure of the iridium clads was nonuniform across the thickness. Large interior grains occurred to a depth of 20-25% of the thickness. The average grain-size range was narrow at 14 grains/640 μm thickness for cup P701-5 to 16 grains/640 μm thickness for cups P708-5 and PR717-4.

Axial cross sections through the welds of FC-260 and FC-267 showed that the weld beads had a desirable microstructure, no porosity, and full penetration.

Emission spectrographic analysis of samples of the plutonia pellets showed that pellet HF-260 had an aluminum content of 320 ppm, which exceeds the SRP guideline. Colorimetric phosphorus analysis for samples of HF-260 and HF-267 showed 40 to 55 ppm, respectively. Subsequent γ -scan analysis of these two pellets indicated that phosphorus content was below the detection limit (20 ppm). The chemical samples were possibly contaminated inadvertently. The absence of phosphorus in the grain boundaries of the iridium would support this hypothesis.

The microstructure of the plutonia pellets HF-260 and HF-267 was typical of SRP material.

F. SVT-6

The SVT-6 test assembly was aged for 90 days at 1287°C; monitoring of the helium release revealed no evidence of vent plugging. Following the aging heat treatment, the module was given a simulated reentry at 1375°C. Post-reentry radiography indicated that all four fuel pellets were badly cracked.

The test module impacted "side-on" at 54.6 m/s and 975°C against a hardened 4340 steel plate (Fig. 29). The aeroshell walls fractured along the axial contact lines of the prime GIS, 90° to the impact face (Fig. 30). Damage to the impact shells was moderate. Both GISs had a bowed profile and were partially fractured on the impact face.

The primary clads (HF-361 and HF-373) deformed, and capsule HF-373 breached (Fig. 31). The impact face of HF-373 contained a large axial crack (22.5 mm × 1.7 mm) and a smaller parallel crack (3.7 mm × 0.3 mm) on the vent-cup radius. Both cracks apparently resulted from the differential displacement of a large fuel fragment.

Metallographic examination of sections removed from the primary clads revealed localized excessive grain growth. Although the average grain sizes were acceptable (see Table A-IV), areas in both vent cups contained as few as 2 grains/thickness. The largest grains were observed on the vent-cup radii (Figs. 32 and

33) and adjacent to the vent-cover welds (Figs. 34 and 35). Although the breach in HF-373 did not occur in a coarse-grained region, cracks on the vent-cup radii were associated with excessively large grains (Fig. 36).

The plutonia in the primary clads was broken into massive chunks that were held tightly by the deformed iridium. Fuel in the trailing capsules fractured into numerous small fragments. Particle-size analyses of the fuel in capsule HF-361 is given in Fig. A-1 and Table A-III, and the fines released by HF-373 are given in Table A-II.

VI. DISCUSSION OF RESULTS

In the four modules tested in the $\alpha = \beta = 0^\circ$ orientation, failures were observed in five fueled clads for an overall failure rate of 31%. One failure of a PIA fueled clad occurred for a failure rate of 12.5%, and four failures occurred in a SIA fueled clad for a failure rate of

Fig. 29. SVT-6 impact orientation.

Fig. 30. The SVT-6 aeroshell fractured along the axial contact lines of the prime GIS.

Fig. 31. A wide axial crack was present on the impact face of capsule FC-373; 2X.

Fig. 32. Abnormal grain growth was observed on the FC-361 vent-cup radius; 100X.

Fig. 33. Grain coarsening also occurred on the FC-373 vent-cup radius; 100X.

Fig. 34. Abnormal grain growth was also observed on the impact-face side of the FC-361 vent-cover weld; 40X.

(a)

(b)

Fig. 35. Excessive grain growth was observed on the FC-273 vent-cover weld. (a) Impact-face side and (b) opposite face; both at 40X.

(a)

(b)

Fig. 36. Cracks on the FC-373 vent-cup radius were associated with abnormally large grains. (a) As polished and (b) etched: both at 50 $\times$.

50%. The principal cause of failures was fuel-fragment push-through. For a few of the failures, a direct cause could not be identified; however, these were small fractures and did not significantly contribute to the total fracture area. Except for axial failures that traversed the girth weld, only one weld failure was observed. The failure occurred about 180° from the weld-overlap region, a common site of weld cracking, and therefore fabrication defects probably were not involved in the failure. In the two modules tested in the $\alpha = 90^\circ$, $\gamma = 0^\circ$ orientation, one failure was observed for an overall failure rate of 12.5%. The single failure occurred in the primary impact assembly for a failure rate of 25% in the leading impact assembly. The failure was of the fuel-fragment push-through type.

Evidence of vent plugging was observed in 1 of 3 modules that were subjected to continuous monitoring of the helium release; only 1 capsule of the 12 exhibited significant vent effusate. Performance was good primarily because the impurity content of the plutonia was generally low. Positioning the vents of the two fueled clads in opposition at the center of the IA (highest temperature) probably helped avoid deposits that would plug the vent.

Iridium transport was not significant in the FCs examined (except FC-454). Processing the modules in the MRMF to slightly reduce the stoichiometry of the plutonia appears to have been beneficial in lowering the partial pressure of oxygen within the fueled clad and limited the tendency for iridium transport.

The concentration of impurity elements found in the iridium-alloy capsules was, in general, low. Iron was the principal impurity found, but only at levels of a few hundred parts per million, which is not expected to significantly affect the mechanical properties. A few samples showed sulfur contamination at the grain boundaries. These instances were not consistent in all samples from a given capsule, and therefore it is difficult to account for their source. The effect of sulfur segregation to grain boundaries is not well established, but it may have contributed to the minor failure of FC-454.

The average grain size of the iridium in capsules aged for 90 days was smaller than that which would be predicted from prior MHW data (7-8 grains/640 μm). Though the iridium-clad temperature during aging was slightly lower (1287°C vs 1310°C), the absence of phosphorus contamination at the grain boundaries may also

have helped restrict the abnormal grain growth to the clad interior where thorium depletion inevitably occurs. The excessive grain growth associated with the decontamination cover and the vent-assembly welds in some capsules suggests that this effect is a function of welding procedures and is not an inherent property of the design or the materials.

ACKNOWLEDGMENT

The authors gratefully acknowledge the cooperation and contributions of the following to the conduct of the test program reported herein:

- G. H. Brooks and J. P. Lucero—Radiographic inspection.
- M. D. Anstey and A. R. Herrera—Impact Tests.
- L. R. Bergamo and J. I. Archuleta—Postmortem assistance and metallography.
- O. R. Simi, D. L. Gallimore, and J. D. Montoya—Emission spectrographic analysis of iridium.
- J. D. Farr—Auger electron spectroscopy of iridium.
- W. M. Myers, C. B. Collier, and D. Hedrick—Emission spectrographic analysis of plutonia.
- T. K. Marshall and T. R. Hahn—Colorimetric phosphorus analysis.
- T. R. Hahn, J. Bubernak, and E. M. Hodge—Analysis of plutonium in graphitic materials.
- Helen Bustos for manuscript preparation.

REFERENCES

1. "Updated Safety Analysis Report For The Galileo Mission and The International Solar-Polar Mission." General Electric document GEST-7186 (April, 1984), Section 3.4 (GPHS Reentry Response).
2. "Estimates for the Orbital Lifetime for Galileo and Solar Polar." Applied Physics Laboratory document ATD-RL-82-081/ANSP-L-662 (November 18, 1982).

APPENDIX

Tabulation of Analytical Results for the GPHS SVT Test Series

TABLE A-I. Impact Test Summary, GPHS SVT Series

Test No.	Reentry Mode	Fueled Clads	NDE Value	Gross Deformation			Failures	
				Diam (%)	Height (%)	Axial (%)	Number	Area (mm ²)
SVT-1	Min-γ ^a	FC-232	3.0	+13.5	-11.1	+5.8	0	25.4
		FC-238	5.0	+9.6	-7.3	+3.8	0	
	Face-on	FC-261	8.7	+11.7	-11.1	+5.6	2	
		FC-410	12.6	+9.8	-9.6	+1.4	1	
SVT-2	Min-γ ^a	FC-355	6.8	+10.0	-10.4	+4.1	0	8.4
		FC-369	6.0	+9.1	-9.3	+4.1	0	
	Face-on	FC-449	13.7	+12.5	-10.3	+5.6	3	
		FC-273	10.7	+10.3	-10.5	+4.4	0	
SVT-3	Orbital	FC-343	2.9	+12.3	-9.0	+5.7	0	0.4
	Decay ^b	FC-350	1.1	+10.0	-8.5	+2.6	0	
	Face-on	FC-457	9.8	+10.8	-7.2	+5.6	0	
		FC-454	12.8	+9.5	-6.4	+2.9	1	
SVT-4	Orbital	FC-348	1.0	+11.5	-11.3	+6.4	1	1.8
	Decay ^b	FC-354	3.2	+8.5	-8.2	+4.0	0	
	Face-on	FC-139	13.7	+12.5	-8.5	+5.1	0	
		FC-162	10.7	+10.3	-9.3	+3.4	0	
SVT-5	Orbital	FC-267	3.0	+10.4	-9.1	+5.5	0	0
	Decay ^b	FC-260	4.0	+10.9	-13.7	+4.1	0	
	Side-on	FC-415	9.4	+5.5	-4.5	+1.2	0	
		FC-426	9.6	+5.0	-6.9	nil	0	
SVT-6	Orbital	FC-373	4.1	+11.2	-14.9	+6.2	2	24.1
	Decay ^b	FC-361	4.4	+12.3	-17.6	+8.8	0	
	Side-on	FC-225	13.2	+7.8	-8.8	+3.7	0	
		FC-189	13.3	+6.4	-7.2	+2.9	0	

^aAged 200 h at 1287°C (clad); impact 919°C and 54 m/s.

^bAged 90 days at 1287°C (clad); impact 975°C and 54 m/s.

Table A-II. GPHS SVT Fuel Release

Module	Reentry Mode	Pu Content (g) ^a		
		<10 μm	>10 μm	Total
SVT-1	Min- γ	0.0128	0.0972	0.1100
SVT-2	Min- γ	0.0041	0.0248	0.0289
SVT-3	0-Decay	0.0051	0.0126	0.0177
SVT-4	0-Decay	0.0076	0.0181	0.0257
SVT-5	0-Decay	0.0020	0	0.0020
SVT-6	0-Decay	0.0091	0.0056	0.0147

^aSVT-1 to -5: Combust graphitics at 850-900°C, sieve ash, and analyze.

SVT-6: Ultrasonic wash of A/S and GIS, plasma-assisted combustion of small fragments and fines, sieve ash, and analyze.

Table A-III. Particle-Size Distribution of the <10- μm Fraction of Selected Impacted Pellets

Max. Size (μm)	Weight Fraction				
	SVT-1 HF-232	SVT-3 HF-343	SVT-4 HF-139	SVT-5 HF-260	SVT-6 HF-361
1.00	0.001593	0.000511	0.000309	0.000417	0.000846
2.00	0.000398	0.000260	0.000387	0.000243	0.000492
3.00	0.000579	0.000235	0.000336	0.000253	0.000635
4.00	0.000441	0.000341	0.000344	0.000313	0.000800
5.00	0.000382	0.000315	0.000428	0.000229	0.001000
6.00	0.000992	0.000242	0.000422	0.000308	0.000972
7.00	0.000263	0.000192	0.000419	0.000140	0.000172
8.00	0.000784	0.000861	0.000375	0.000417	0.000768
9.00	0.001116	0.001430	0.000534	0.000594	0.001094
10.00	0.001531	0.002523	0.001955	0.001834	0.003001
Acc. Wt. Frac. <10 μm	0.00808	0.00691	0.00551	0.00475	0.00978

TABLE A-IV. Iridium Grain Size—GPHS SVT Series, Grains per Nom. 640 μm

FC No.	Cup No.	Transverse	Axial	Comments
SVT-1				
232	LR313-1	25	20	Uniform
232	LR316-1	21	22	Uniform except for tab weld
238	LR315-2	20	20	Uniform
238	LR318-6	28	28	Uniform
261	P709-6	22	na ^a	Uniform
261	Q804-1	22	22	Uniform
410	S205	20	na	Uniform
SVT-2				
355	Q806-2	21	19	Uniform
355	Q806-5	25	23	Uniform except for tab weld
369	NR528-2	22	22	Uniform
369	NR528-3	28	29	Uniform except for tab weld
449	S27-2	23	na	Uniform
449	S25-3	23	na	Uniform
SVT-3				
343	PR718-5	20	17	Lg. interior grains, 20-25% of thk.
343	PR719-5	16	18	Lg. interior grains, 20-25% of thk.
350	R704-7	18	16	Lg. interior grains, 20-25% of thk.
350	R904-5	18	17	Lg. interior grains, 20-25% of thk.
454	S39-5	15	na	Lg. interior grains, 20-25% of thk. + isolated lg. exterior grains.
SVT-4				
348	QR820-1	18	16	Lg. interior grains, 20-25% of thk.
348	QR820-6	15	17	Lg. interior grains, 20% of thk.
354	QR820-3	19	17	Lg. interior grains, 20% of thk.
354	QR820-4	17	16	Lg. interior grains, 20% of thk.
SVT-5				
267	P701-5	14	15	Lg. interior grains, 30-35% of thk.
267	P708-5	16	16	Lg. interior grains, 20-25% of thk.
260	PR717-3	15	15	Lg. interior grains and isolated lg. exterior grains.
260	PR717-4	16	14	Lg. interior grains, 20-25% of thk.
SVT-6				
361	PR725-5	16	15	Lg. interior grains to 30% of thk.
361	PR726-1	14	13	Lg. interior grains to 30% of thk.
373	Q803-6	15	16	Lg. interior grains to 30% of thk.
373	PR727-3	16	17	Lg. interior grains to 30% of thk.

^ana = not analyzed.

TABLE A-V. Summary of AES Analyses of GPHS SVT Iridium

Specimen	Th ₆₅ /Ir ₂₂₉				P ₁₂₀ /Ir ₂₂₉	C ₂₇₀ /Ir ₂₂₉	O ₅₁₀ /Ir ₂₂₉	S ₁₅₀ /Ir ₂₂₉	Cl ₁₈₀ /Ir ₂₂₉
	Int.	Center	Ext.	Ave.	Ave.	Ave.	Ave.	Ave.	Ave.
SVT-1									
FC-232: Vent cup-1	0.07	0.40	0.16	0.21	nd ^a	0.47	0.65	nd	nd
Vent cup-2	0.46	0.56	0.61	0.54	nd	0.35	0.76	nd	nd
Shield cup-1	0.36	0.65	0.57	0.53	nd	0.17	0.43	nd	nd
Shield cup-2	0.71	0.75	0.60	0.69	nd	0.12	0.20	nd	nd
FC-238: Vent cup-1	0.45	0.76	0.44	0.55	nd	0.44	0.69	nd	nd
Vent cup-2	0.55	0.65	0.41	0.56	nd	0.30	0.59	nd	nd
Shield cup-1	0.41	0.50	0.43	0.45	nd	1.45	1.17	0.04	0.04
Shield cup-2	0.80	0.88	0.80	0.83	nd	0.17	nd	nd	nd
SVT-2									
FC-449: Vent cup-1	0.60	0.69	0.64	0.61	nd	0.16	0.47	nd	nd
Vent cup-2	0.82	0.97	0.66	0.82	nd	0.09	0.08	nd	nd
Shield cup-1	0.43	0.32	0.43	0.39	nd	0.59	1.01	nd	nd
Shield cup-2	0.45	0.68	0.65	0.59	nd	0.32	0.57	nd	nd
Weld VC side	—	—	—	0.62	nd	0.19	0.49	nd	nd
Weld SC side	—	—	—	0.23	nd	0.92	0.88	nd	nd
FC-335: Vent cup-1	0.82	0.93	0.76	0.84	0.05	0.10	0.31	nd	nd
Vent cup-2	0.65	0.85	0.63	0.71	0.08	0.11	0.11	nd	nd
Shield cup-1	0.55	0.86	0.56	0.66	0.05	0.12	0.36	nd	nd
Shield cup-2	0.37	0.53	0.54	0.48	0.04	0.24	0.54	nd	nd
FC-369: Vent cup-1	0.48	0.63	0.40	0.50	0.03	0.31	0.74	nd	nd
Vent cup-2	0.46	0.53	0.46	0.48	0.05	0.39	0.79	nd	nd
SVT-3									
FC-343: Vent cup-1	0.38	0.68	0.41	0.49	nd	0.23	0.46	nd	nd
Vent cup-2	0.17	0.48	0.39	0.35	nd	0.48	0.70	nd	nd
Shield cup-1	0.21	0.35	0.41	0.32	nd	0.33	0.85	nd	nd
Shield cup-2	0.35	0.76	0.55	0.55	nd	0.35	0.01	nd	nd
FC-350: Vent cup-1	0.19	0.63	0.47	0.43	nd	0.87	0.70	nd	nd
Vent cup-2	0.46	0.74	0.84	0.68	nd	nd	nd	nd	nd
Shield cup-1	0.20	0.44	0.41	0.35	nd	1.54	0.96	0.01	nd
Shield cup-2	0.14	0.75	0.65	0.51	nd	0.06	0.09	nd	nd
FC-454: Shield cup-1	0.32	0.48	0.59	0.46	nd	0.98	0.81	0.15	nd
Shield cup-2	0.16	0.28	0.36	0.24	nd	0.72	0.95	vs ^b	nd
SVT-4									
FC-348: Vent cup-1	0.19	0.49	0.42	0.40	nd	0.95	1.19	nd	nd
Vent cup-2	0.35	0.56	0.24	0.38	nd	0.13	0.53	nd	nd
Shield cup-1	0.63	0.76	0.63	0.67	nd	nd	nd	nd	nd
Shield cup-2	0.44	0.49	0.39	0.44	nd	0.37	0.82	nd	nd
FC-354: Vent cup-1	0.11	0.52	0.71	0.45	nd	0.46	0.94	nd	nd
Vent cup-2	0.27	0.36	0.47	0.37	nd	0.40	0.75	nd	nd
Shield cup-1	0.34	0.46	0.52	0.44	nd	0.31	0.83	0.04	nd
Shield cup-2	0.37	0.68	0.43	0.49	nd	1.91	1.19	0.04	nd

^and—not detected.^bvs—very strong

TABLE A-V (cont). Summary of AES Analyses of GPHS SVT Iridium

Specimen	Th ₆₅ /Ir ₂₂₉				P ₁₂₀ /Ir ₂₂₉	C ₂₇₀ /Ir ₂₂₉	O ₅₁₀ /Ir ₂₂₉	S ₁₅₀ /Ir ₂₂₉	Cl ₁₈₀ /Ir ₂₂₉
	Int.	Center	Ext.	Ave.	Ave.	Ave.	Ave.	Ave.	Ave.
SVT-5									
FC-260: Vent cup-1	0.20	0.56	0.38	0.39	nd	0.46	0.17	nd	nd
Vent cup-2	0.36	0.77	0.49	0.54	nd	0.12	0.25	0.02	nd
Shield cup-1	0.35	0.36	0.52	0.43	nd	0.21	0.43	nd	nd
Shield cup-2	0.05	0.37	0.42	0.28	nd	0.79	1.07	nd	nd
FC-267: Vent cup-1	0.21	0.76	0.81	0.59	nd	nd	0.22	nd	nd
Vent cup-2	0.38	0.97	0.96	0.77	nd	nd	nd	nd	nd
Shield cup-1	0.34	0.35	0.53	0.41	nd	0.74	1.08	0.05	nd
Shield cup-2	0.19	0.22	0.46	0.29	nd	0.91	1.10	0.29	0.05
SVT-6									
FC-361: Vent cup-1	0.33	0.52	0.63	0.49	nd	0.09	0.52	nd	nd
Vent cup-2	0.19	0.44	0.53	0.39	nd	0.11	0.98	0.08	nd
Shield cup-1	0.38	0.49	0.56	0.48	nd	0.09	0.68	nd	nd
Shield cup-2	0.14	0.42	0.31	0.29	nd	0.78	0.86	nd	0.11
FC-373: Vent cup-1	0.07	0.78	0.54	0.46	nd	0.18	0.56	nd	nd
Vent cup-2	0.02	0.54	0.58	0.38	nd	0.12	0.57	nd	nd
Shield cup-1	0.15	0.64	0.36	0.38	nd	0.23	0.63	nd	nd
Shield cup-2	0.40	0.42	0.40	0.41	nd	1.25	0.60	0.30	nd

TABLE A-VI. Results of Spectrographic Analysis of GPHS SVT Iridium

FC No.	Cup No.	Selected Elements ^a (ppm)								
		Cu	Mg	Ca	Al	Si	Cr	Fe	Ni	Pt
SVT-1										
232	LR313-1	3	nd ^b	nd	40	nd	nd	80	10	nd
	LR316-1	20	7	5	50	25	30	150	40	nd
238	LR315-2	15	10	20	50	25	nd	120	40	nd
	LR318-6	15	7	15	50	10	10	120	45	nd
261	P709-6	15	15	20	50	50	nd	150	45	50
	Q804-1	15	15	25	50	30	nd	150	35	150
410	S2-4	3	15	20	50	100	nd	150	50	nd
	S2-5	5	20	30	50	140	nd	120	20	100
SVT-2										
355	Q806-2	nd	3	nd	50	nd	nd	200	30	nd
	Q806-5	10	5	3	60	150	15	200	40	nd
369	NR528-2	3	nd	nd	40	nd	nd	100	nd	nd
	NR528-3	nd	nd	nd	50	nd	nd	150	10	nd
449	S27-2	20	nd	nd	40	nd	10	200	30	nd
	S25-2	10	nd	nd	50	nd	15	200	30	nd
SVT-3										
343	PR718-5	40	nd	nd	40	nd	nd	150	30	nd
	PR719-5	20	nd	nd	50	nd	15	200	60	nd
350	R904-7	6	nd	nd	60	nd	15	300	50	nd
	R904-5	6	nd	nd	60	nd	15	300	40	nd
SVT-4										
348	QR820-1	5	nd	nd	50	nd	10	200	40	nd
	QR820-6	nd	nd	nd	50	nd	10	200	30	nd
354	QR820-3	15	nd	nd	40	10	15	150	30	nd
	QR820-2	40	nd	3	60	10	50	400	80	30
SVT-5										
267	P701-5	15	7	4	50	50	nd	150	60	nd
	P708-5	15	nd	3	60	nd	10	150	50	nd
260	PR717-3	20	nd	nd	60	nd	10	120	50	nd
	PR717-4	20	nd	nd	70	nd	nd	120	50	nd
SVT-6										
361	PR725-5	15	nd	nd	60	10	30	150	40	30
	PR726-1	5	nd	nd	50	nd	15	200	40	nd
373	Q803-6	3	nd	nd	50	nd	40	200	40	nd
	PR727-3	3	nd	3	50	30	30	200	40	nd

^aElements present in excess of the detection limit.

^bnd—not detected.

TABLE A-VII. Plutonia Analyses, GPHS SVT Series

Pellet No.	Selected Elements (ppm)								
	P ^a	Mg	Ca	Al	Si	Fe	Cr	Ni	Ti
SVT-1									
HF-232	5	1	130	20	15	60	15	nd	5
HF-238	5	1	200	25	70	70	15	5	5
HF-261	5	nd	200	20	25	85	40	nd	7
HF-410	2	3	400	25	45	110	35	5	7
SVT-2									
HF-355	4	2	40	25	30	65	30	nd	10
HF-369	3	2	30	15	15	45	10	nd	5
HF-273	3	2	40	25	70	55	25	7	5
HF-449	2	2	40	35	50	80	30	nd	10
SVT-3									
HF-350	3	nd	200	35	20	35	10	nd	20
HF-343	5	10	100	35	30	20	10	nd	15
HF-454	2	nd	200	60	50	70	60	nd	20
HF-457	3	nd	150	35	10	20	15	nd	3
SVT-4									
HF-348	4	3	40	40	10	30	15	nd	7
HF-354	3	3	50	40	15	35	25	nd	7
HF-139	3	2	30	25	8	20	25	nd	10
HF-162	2	2	30	20	8	25	9	nd	5
SVT-5									
HF-260	40 ^b	nd	30	320	15	20	5	nd	15
HF-267	55 ^b	2	40	75	35	30	6	nd	15
HF-415	6	nd	20	40	8	7	nd	nd	15
HF-426	6	nd	30	60	10	10	15	nd	20
SVT-6									
HF-189	3	3	nd	65	25	20	nd	nd	20
HF-225	9	10	60	45	30	15	nd	nd	10
HF-361	8	20	150	30	35	10	15	nd	20
HF-373	2	4	130	15	45	20	nd	nd	20

^aColorimetric Analysis.

^bγ-Scan indicates <20 ppm for HF-260 and HF-267.