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GENERAL-PURPOSE HEAT SOURCE SAFETY VERIFICATION TEST SERIES: SVT-7 THROUGH SVT-10

by

T. G. George and D. Pavone

ABSTRACT

The General-Purpose Heat Source (GPHS) is a modular component of the radioisotope thermoelectric generator that will supply power for the Galileo and Ulysses (formerly ISPM) space missions. The GPHS provides power by transmitting the heat of $^{238}\text{PuO}_2$ α -decay to an array of thermoelectric elements. Because the possibility of an orbital abort always exists, the heat source was designed and constructed to minimize plutonia release in any accident environment. The Safety Verification Test (SVT) series was formulated to evaluate the effectiveness of GPHS plutonia containment after atmospheric reentry and Earth impact. The first report (covering SVT-1 through SVT-6) described the results of flat and side-on module impacts. This report describes module impacts at angles of 15° and 30° .

I. INTRODUCTION

The General-Purpose Heat Source (GPHS) is a modular component of the radioisotope thermoelectric generator (RTG) that will provide power for the NASA Galileo and ESA Ulysses (formerly ISPM) space missions. The RTG generates electric power by using the heat of $^{238}\text{PuO}_2$ α -decay to create a temperature differential across a thermoelectric array. The Galileo mission will require two RTGs, and Ulysses will use a single RTG. Each RTG will contain 18 GPHS modules.

The GPHS module was designed by Los Alamos National Laboratory and modified by the General Electric Company, Inc., (system contractor for the RTG) to meet weight requirements of the Galileo and Ulysses missions. Each GPHS module contains four $^{238}\text{PuO}_2$ fuel pellets that provide a total thermal output of 250 W. Each fuel pellet is encapsulated in a vented, DOP-26 iridium alloy shell. Two capsules are held in a Fineweave-Pierced Fabric* (FWPF) graphite impact shell (GIS), and two GISs are contained within a FWPF graphite zeroshell. A schematic of the GPHS module is

shown in Fig. 1. Because the possibility of an orbital abort always exists, the GPHS module has been designed to minimize plutonia release during atmospheric reentry and Earth impact.

Accident analyses have shown that in any orbital abort, the GPHS modules would be released from the RTG early in reentry and would strike the Earth singly and intact.¹ The responses of GPHS modules with various processing histories to a variety of reentry and impact conditions were investigated in the Design Iteration Tests (DIT). With the conclusion of the DITs, emphasis shifted to verifying the survivability of GPHS modules in probable accident environments. The objective of the Safety Verification Test (SVT) series was to determine the response of the GPHS module and its components to atmospheric reentry, and Earth impact.²

The first six SVTs investigated the module response in a series of flat and side-on impacts; these tests were described in a previous report.³ Because the DIT results indicated a significant difference in the degree of capsule damage produced by various impact angles, the next four SVTs (tests 7 through 10) were designed to evaluate the system response to impact orientations of $\alpha = 15^\circ$ and 30° (schematics of the 15° and 30° impact orientations are shown in Figs. 2 and 3).

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

Fig. 1. The GPHS module.

Fig. 2. The SVT-7 and SVT-8 test assemblies were impacted in the $\alpha = 15^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ module orientation.

Fig. 3. The SVT-9 and SVT-10 test assemblies were impacted in the $\alpha = 30^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ module orientation.

II. TEST PROGRAM

The SVT test program was designed to simulate the atmospheric reentry and subsequent Earth impact experienced by a GPHS module in the aftermath of an orbital abort. The impact orientation of each test module was determined by a technical review board consisting of R. W. Zocher (Los Alamos National Laboratory), C. T. Bradshaw (GE), and R. W. Englehart (NUS). A total of 13 GPHS modules were allocated for the test series.

The test modules were assembled at the Monsanto Research Corporation (MRC) and were treated (to reduce the excess oxygen content of the plutonia fuel) in the Mound Reduction and Monitoring Facility (MRMF). The treated modules were then subjected to two cycles of flight-acceptance vibration spectra and transient accelerations, radiographed, and shipped to

Los Alamos. Components of the GPHS modules used in SVT-7 through SVT-10 are identified in Table I.

The plutonia fuel pellets required for the SVT impacts were fabricated and encapsulated in iridium at the Savannah River Plant (SRP). The iridium shells were fabricated by the Mound Plant, from iridium alloy blanks supplied by the Oak Ridge National Laboratory (ORNL). Because of a process change, two classes of plutonia pellets (fired either in an Ar or Ar/O₂ atmosphere) were provided. Both types of pellets were considered to be flight quality; production histories of the fuel pellets used in SVT-7 through SVT-10 are presented in Table II.

All graphite module components were also composed of flight-quality material. ORNL produced the carbon-bonded carbon filament (CBCF) graphite insulation and MRC provided the FWPF graphite aeroshells and GISs. To simulate the ablation resulting from an orbital decay

TABLE I. GPHS Module Components

Component	SVT-7	SVT-8	SVT-9	SVT-10
Aeroshell	PAT-1010	PAL-011	PAI-034	PAL-045
Primary Impact Assembly				
Impact shell	PGT-1020	PGL-009	PGL-093	PGL-089
Insulation cylinder	C-40-9	C-40-2	C-43-6	C-56-2
Insulation discs	P-11-1-32	P-8-2-3	P-12-2-53	P-13-2-4
	P-12-1-4	P-8-2-5	P-12-1-8	P-13-2-28
Fueled clad 1 (closure end)	FC-364	FC-437	FC-591	FC-589
fuel pellet	HF-364	HF-437	HF-591	HF-589
vent cup	PR726-5	MER41-1	S35-2	T115-2
shield cup	PR726-7	MER41-2	S37-2	T113-2
Fueled clad 2 (blind end)	FC-368	FC-436	FC-592	FC-590
fuel pellet	HF-368	HF-436	HF-592	HF-590
vent cup	PR727-7	R919-4	SR-65-3	V203-5
shield cup	NR529-5	R901-2	SR-64-6	V202-3
Secondary Impact Assembly				
Impact shell	PGT-1021	PGL-010	PGL-091	PGL-092
Insulation cylinder	C-38-3	C-33-1	C-39-5	C-52-9
Insulation discs	P-12-1-3	P-8-2-61	P-8-1-19	P-13-2-2
	P-11-2-34	P-8-2-63	P-12-1-9	P-13-2-39
Fueled clad 3 (closure end)	FC-165	FC-391	FC-473	FC-152
fuel pellet	HF-165	HF-391	HF-473	HF-152
vent cup	NR508-4	RR925-3	S39-4	N512-5
shield cup	NR507-3	RR920-5	S14-2	N516-1
Fueled clad 4 (blind end)	FC-112	FC-441	FC-501	FC-185
fuel pellet	HF-112	HF-441	HF-501	HF-185
vent cup	NR509-1	MER21-6	SR52-1	PR714-3
shield cup	N505-3	MER21-1	SR51-6	PR716-3

TABLE II. Fuel Pellet Data

Pellet No.	Weight (g)	Processing Atmosphere	
		Ar	Ar/O ₂
HF-364	149.7	*	
HF-368	150.3	*	
HF-165	148.0		*
HF-112	148.0		*
HF-437	149.8	*	
HF-436	150.1	*	
HF-391	150.3	*	
HF-441	150.6	*	
HF-591	150.2	*	
HF-592	150.4	*	
HF-473	150.4	*	
HF-501	150.3	*	
HF-589	150.1	*	
HF-590	150.4	*	
HF-152	148.9		*
HF-185	148.7		*

reentry, each FWPF aeroshell was machined (at Los Alamos) to remove 1.27 mm of graphite from all external surfaces (a thickness equivalent to twice the predicted ablation for an orbital decay reentry).

Each GPHS module contained two flight-quality and two non-flight-quality fueled clads. The flight-quality and non-flight-quality clad designations were provided by SRP. Because cracking occurred in a number of early test welds, SRP developed an ultrasonic nondestructive evaluation (NDE) technique that rated weld defects by comparison with a standard defect of known dimensions. Fueled clads with NDE ratings ≤ 8 (arbitrary units) were designated as flight quality, and capsules with NDE ratings > 8 were reserved for terrestrial applications, where the abort environments are not as severe. In each test module, the flight-quality clads were loaded into a FWPF GIS (the primary impact assembly) and positioned in the module GIS cavity expected to receive the greatest deformation. Non-flight-quality clads were loaded into a GIS (secondary impact assembly) and positioned in the remaining GIS cavity.

III. EXPERIMENTAL PROCEDURES

A. Pretest Data

The assembled test modules were shipped to Los Alamos in welded stainless steel containers. When received, each container was radiographed to document the condition of the fuel pellets. After radiography the

module was removed from the shipping container, disassembled, and macroscopically examined. A 1.5875-mm (0.0625-in.) pyrometer sight hole was drilled into the cap of the primary impact assembly (PIA), and both GISs were loaded into a high-vacuum furnace for an aging heat treatment.

The aging treatment simulated the temperature of a GPHS module during the orbital decay of an aborted mission. The fueled clads used in SVT-7 through SVT-10 were aged for 90 days at 1287°C; the predicted time interval for orbital decay of a Galileo abort is 90 days, and the operating temperature of an orbiting RTG is 1287°C. Although an abort of the Ulysses mission would result in a 38-day orbital decay, a 90-day orbital decay was selected to represent both missions.⁴ Helium release from the SVT-8 and SVT-9 test components was monitored throughout the heat treatments; there was no evidence that any of the vents plugged during the 90-day period.

After aging, the GISs were prepared for reentry simulation. Holes for a split-junction thermocouple were drilled into the GIS caps. Each GIS was placed in an electron beam furnace and heated through an orbital decay reentry cycle (a schedule of the orbital decay reentry temperatures is presented in Table III). After

TABLE III. Orbital Decay Reentry Schedule

Time (min)	Temperature (°C)	Time (min)	Temperature (°C)
0.00	1294	10.25	1364
0.50	1291	10.50	1371
1.00	1285	10.75	1374
1.50	1278	11.00	1372
2.00	1269	11.25	1368
2.50	1259	11.50	1360
3.00	1248	11.75	1350
3.50	1237	12.00	1333
4.00	1228	12.25	1307
4.50	1221	12.50	1275
5.00	1216	12.75	1242
5.50	1214	13.00	1214
6.00	1212	13.25	1186
6.50	1211	13.50	1158
7.00	1213	13.75	1134
7.50	1216	14.00	1114
8.00	1227	14.25	1090
8.50	1246	14.50	1069
8.75	1255	14.75	1047
9.00	1271	15.00	1025
9.25	1287	15.25	1005
9.50	1312	15.50	983
9.75	1333	15.75	964
10.00	1349		

reentry simulation, the GISs were radiographed a second time and prepared for impact testing.

B. Impact Testing

After reentry simulation, the GISs were reloaded into the FWPF aeroshell. Holes were drilled through the aeroshell and impact shell walls to accommodate additional instrumentation. A calibrated split-junction thermocouple was placed in contact with one of the flight-quality clads, and two beaded-junction thermocouples were attached to the surface of the PIA (the GIS containing the flight-quality clads). The module was then transferred to the Los Alamos Isotope Fuels Impact Test Facility (a 185-mm gas gun that contains the impacted test article within a sealed catch tube).⁵

All of the test modules were impacted against a hardened steel plate, at a nominal velocity and temperature of 54 m/s and 975°C. The thermal output of the GPHS module was sufficient to permit self-heating to the test temperature. Specific conditions for each test are listed in Table IV.

C. Postmortem Examination

The principal objectives of the postmortem examination were to determine the quantity and particle size of the plutonia release, document the damage sustained by all test components, and characterize the iridium and plutonium impact responses.

After each test, the impacted module (contained within a sealed catch tube) was transferred to Wing 2 of the CMR building (at Los Alamos), and opened. All test components were photographed and the fueled clads were measured to determine the postimpact capsule strains. The size and location of all clad failures and cracks were recorded.

After macroscopic examination, the fueled clads were opened and the patterns of fuel fracture were photographed. At least one unbreached capsule was selected for a particle size analysis; this capsule was opened under water to prevent the loss of small fuel particles.

The capsules were defueled and specimens of each fuel pellet were taken for metallographic and chemical analyses. Fuel pellets selected for particle size analyses were not sampled until after the sieve analyses.

The iridium clads were also sampled to provide specimens for metallographic and chemical analyses. The SVT test plan required that each primary clad (the capsules contained within the PIA) be sampled to provide axial and transverse sections of the vent and weld shield cups, a vent cross section, and a weld (single pass region) cross section. In addition, all clad failures and areas of severe localized deformation were sectioned for metallography. The secondary clads were also sampled when there was clad failure or severe deformation.

All graphite test components, including the catch tube debris, were analyzed to determine the amount and particle size of plutonia release. The graphite aeroshell, impact shells, and all large pieces of CBCF insulation were ultrasonically cleaned in ethyl alcohol, dried, and burned in air at 850 to 900°C. The resulting ash was dissolved in acid and radioanalyzed for plutonium. The plutonium content of the graphite test components was assumed to be present as small plutonia fragments (<10 μm) trapped within the pores of the FWPF graphite.

The ultrasonic cleaning solution was combined with the debris remaining in the catch tube, dried, and burned in oxygen in a plasma-assisted combustion furnace. The plasma-assisted furnace was used because its low operating temperature ($\approx 50^\circ\text{C}$) minimized particle agglomeration (sintering). The resulting ash was macroscopically examined, and all large pieces of non-combustible material (such as thermocouple wiring, alumina insulation, etc.) were removed. The remaining material was then sized and submitted for radioanalysis.

The plutonia release in SVT-8 was determined by a different method. The large graphite components were processed as usual, but the ultrasonic cleaning solution and catch tube debris were combined, dried, sized into three fractions ($-10\ \mu\text{m}$, $10\ \mu\text{m}$ to $-420\ \mu\text{m}$, and $420\ \mu\text{m}$ and above), burned at high temperature (850 to 900°C), and radioanalyzed. It was felt that the time required for low-temperature ashing was not warranted for a plutonia release resulting from the failure of a non-flight-quality weld.

TABLE IV. Test Parameters

Test	Module Orientation	Temperature (°C)	Velocity (m/s)	Target Material
SVT-7	$\alpha = 15^\circ, \beta = 0^\circ, \gamma = 0^\circ$	975	53.5	steel
SVT-8	$\alpha = 15^\circ, \beta = 0^\circ, \gamma = 0^\circ$	975	54.6	steel
SVT-9	$\alpha = 30^\circ, \beta = 0^\circ, \gamma = 0^\circ$	975	54.6	steel
SVT-10	$\alpha = 30^\circ, \beta = 0^\circ, \gamma = 0^\circ$	975	54.3	steel

IV. RESULTS

The individual tests and postmortem examinations are summarized below. Analytical results are tabulated as follows:

Table V. SVT Summaries

Table VI. SVT Fuel Release Data

Table VII. Sieve Analyses of Fuel in Unbreached SVT Clads

Table VIII. Iridium Grain Size of Selected SVT Capsules

Table IX. SVT Iridium AES Analyses

Table X. Spectrographic Analyses of SVT Iridium Clads

Table XI. SVT Plutonia Analyses

TABLE V. SVT Summaries

Test	Reentry Mode	Impact Orientation	Fueled Clads	Clad NDE Values	Postimpact Capsule Strains			Failures	
					Diam (%)	Height (%)	Axial (%)	Number	Total Area (mm ²)
SVT-7	Orbital Decay	$\alpha = 15^\circ$	FC-364	2.0	+ 9.9	-13.5	+5.3	1	53.0
		$\beta = 0^\circ$	FC-368	1.6	+ 9.5	- 9.9	+5.4	0	
		$\gamma = 0^\circ$	FC-165	13.0	+10.7	-10.0	+5.7	2	
			FC-112	11.0	+ 8.0	- 9.5	+4.0	2	
SVT-8	Orbital Decay	$\alpha = 15^\circ$	FC-436	1.0	+ 6.2	- 5.2	+3.6	0	54.0*
		$\beta = 0^\circ$	FC-437	1.0	+ 8.8	- 7.9	+5.4	0	
		$\gamma = 0^\circ$	FC-391	9.8	+10.4	-10.0	+6.5	1	
			FC-441	9.6	+ 8.9	- 8.9	+5.3	0	
SVT-9	Orbital Decay	$\alpha = 30^\circ$	FC-592	3.0	+ 6.0	- 6.1	+2.4	0	0
		$\beta = 0^\circ$	FC-591	1.6	+ 7.1	- 8.9	+3.7	0	
		$\gamma = 0^\circ$	FC-473	10.3	+ 6.0	- 5.1	+2.0	0	
			FC-501	11.4	+ 6.7	- 5.7	+4.3	0	
SVT-10	Orbital Decay	$\alpha = 30^\circ$	FC-589	1.7	+ 4.2	- 3.5	+2.5	0	0
		$\beta = 0^\circ$	FC-590	3.7	+ 5.4	- 6.6	+5.0	0	
		$\gamma = 0^\circ$	FC-152	11.0	+ 6.9	- 7.3	+3.6	0	
			FC-185	1.5	+ 6.5	- 6.8	+3.7	0	

*Capsule FC-391 failed along the weld centerline; the weld shield band remained in place and limited fuel release.

TABLE VI. SVT Fuel Release Data*

Test	Impact Orientation	²³⁸ Pu Release (g)		
		Total	<10- μ m fraction	>10- μ m fraction
SVT-7	$\alpha = 15^\circ$	0.2227	0.1390	0.0837
	$\beta = 0^\circ$			
	$\gamma = 0^\circ$			
SVT-8	$\alpha = 15^\circ$	0.0860	0.0687	0.0173
	$\beta = 0^\circ$			
	$\gamma = 0^\circ$			
SVT-9	$\alpha = 30^\circ$	0.0024	0.0024	0
	$\beta = 0^\circ$			
	$\gamma = 0^\circ$			
SVT-10	$\alpha = 30^\circ$	0.0026	0.0026	0
	$\beta = 0^\circ$			
	$\gamma = 0^\circ$			

*No clad failures occurred in SVT-9 or SVT-10; all fuel release resulted from transport through the capsule vents.

TABLE VII. Sieve Analyses of Fuel in Unbreached SVT Clads^a

Particle Size Range (μm)	FC-437 (SVT-8)	FC-473 (SVT-9)	FC-590 ^b (SVT-10)	FC-152 ^c (SVT-10)
+6000	0.15850	0.50250	0.25090	0.14470
+2000 to 6000	0.46630	0.33770	0.52880	0.58690
+ 841 to 2000	0.22240	0.10960	0.14330	0.18050
+ 420 to 841	0.08070	0.02780	0.04230	0.04820
+ 177 to 420	0.04080	0.01220	0.01990	0.02280
+ 125 to 177	0.00650	0.00180	0.00300	0.00370
+ 74 to 125	0.00640	0.00190	0.00300	0.00350
+ 44 to 74	0.00470	0.00160	0.00230	0.00280
+ 30 to 44	0.00340	0.00130	0.00160	0.00190
+ 20 to 30	0.00470	0.00190	0.00220	0.00250
+ 10 to 20	0.00270	0.0070	0.00080	0.00100
+ 9 to 10	0.00096	0.00015	0.00053	0.00047
+ 8 to 9	0.00018	0.00006	0.00027	0.00019
+ 7 to 8	0.00019	0.00012	0.00015	0.00027
+ 6 to 7	0.00025	0.00016	0.00013	0.00018
+ 5 to 6	0.00023	0.00008	0.00023	0.00010
+ 4 to 5	0.00014	0.00010	0.00012	0.00007
+ 3 to 4	0.00025	0.00007	0.00012	0.00006
+ 2 to 3	0.00016	0.00008	0.00007	0.00008
+ 1 to 2	0.00014	0.00009	0.00008	0.00007
0 to 1	0.00027	0.00016	0.00016	0.00010
Weight Fraction				
<10 μm	0.00277	0.00107	0.00183	0.00159

^aAll values are expressed as a fraction of total pellet weight.

^bCapsule FC-590 was contained within the primary impact assembly.

^cCapsule FC-152 was contained within the secondary impact assembly.

A. SVT-7

The test module was impacted on a steel target at 53.5 m/s and 975°C. The impact orientation was $\alpha = 15^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$. Postimpact examination revealed that the aeroshell fractured along the axial contact lines of the leading GIS (Fig. 4). The lead narrow face of the aeroshell separated from the aeroshell body and broke into two pieces. Impact shell damage was moderate, similar to that observed in $\alpha = 0^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ impacts. Axial cracks (approximately 80% of the GIS length) occurred on the impact faces of both GISs.

Clad damage was extensive. Breaching cracks, apparently caused by the differential displacement of large fuel fragments, were observed on the impact face of capsule FC-364 (Fig. 5) and on the trailing face of FC-165 (Fig. 6). A centerline weld crack (10 mm long) was also observed on capsule FC-165, 90° to the impact face.

Small fractures were observed on the exteriors of capsules FC-368 and FC-112, and two small weld cracks perpendicular to the weld centerline were found on the trailing face of capsule FC-112 (Fig. 7). A small fracture

was also observed on the FC-368 vent cup radius (Fig. 8). However, full penetration of the crack on the FC-368 vent cup was not confirmed by subsequent metallography.

Examination of wall sections removed from the FC-364 vent and weld shield cups (Figs. 9 and 10) revealed a brittle intergranular failure. The breaching crack apparently resulted from the differential displacement of a large fuel fragment. As is frequently observed in this type of breach, the fracture occurred in a reverse bend region adjacent to the fuel fragment imprint. The limited ductility of DOP-26 iridium and its dependence on strain state are illustrated by the reduction in wall thickness at the fracture (5% in the vent cup, 9% in the shield cup) and at the point of fuel fragment indentation (approximately 18% in both cups).

Metallographic examination of the breach in capsule FC-165 revealed the same intergranular crack morphology observed in the FC-364 failure (Figs. 11 and 12). Because the FC-165 breach occurred on the trailing capsule face, the fuel fragment imprint was not as sharply defined as it was in the FC-364 failure. However, as in capsule FC-364, the FC-165 breach

TABLE VIII. Iridium Grain Size of Selected SVT Capsules^a

Fueled Clad	Test	Iridium Cup	Grain Size		Comments
			Transverse	Axial	
FC-165	SVT-7	PR507-3	21	16	Large internal grains 20 to 30% of thickness
		PR508-4	16	13	Large internal grains 20 to 30% of thickness
FC-364	SVT-7	PR726-5	15	15	Large internal grains 25 to 30% of thickness
		PR726-7	16	15	Large internal grains 25 to 30% of thickness
FC-368	SVT-7	PR727-7	15	17	Large internal grains 20 to 35% of thickness
		MR529-5	14	13	Large internal grains 25 to 30% of thickness
FC-391	SVT-8	RR920-5	15	ND ^b	Typical microstructure
		RR925-3	ND	13	Typical microstructure
FC-436	SVT-8	R901-2	13	13	Large internal grains 20 to 30% of thickness
		R919-4	14	12	Large internal grains 20 to 30% of thickness
FC-437	SVT-8	MER41-1	14	13	Large internal grains 20 to 30% of thickness
		MER41-2	13	13	Large internal grains 20 to 30% of thickness
FC-473	SVT-9	S39-4	13	15	Large internal grains up to 25% of thickness, and isolated large external grains
		S14-2	16	17	Large internal grains up to 25% of thickness
FC-501	SVT-9	SR51-6	15	18	Large internal grains 20 to 30% of thickness
		SR52-1	14	14	Large internal grains up to 25% of thickness, and isolated large external grains
FC-152	SVT-10	N512-5	16	ND	Typical microstructure
		N516-1	14	ND	Typical microstructure
FC-589	SVT-10	T113-2	14	11	Numerous delaminations observed along inner surface
		T115-2	14	12	Numerous delaminations observed along inner surface
FC-590	SVT-10	V202-3	4	10	Isolated large grains observed throughout the microstructure
		V203-5	11	11	Typical microstructure

^aGrain sizes are given as an average of grains/0.535-mm nominal wall thickness.^bNot determined.

TABLE IX. Iridium AES Analyses

Specimen	Th ₆₅ /Ir ₂₂₉				P ₁₂₀ /Ir ₂₂₉ (Av)	C ₂₇₀ /Ir ₂₂₉ (Av)	O ₅₁₀ /Ir ₂₂₉ (Av)	S ₁₅₀ /Ir ₂₂₉ (Av)	Cl ₁₈₀ /Ir ₂₂₉ (Av)
	Int.	Center	Ext.	(Av)					
FC-364 V ^a -cup 1	0.27	0.59	0.54	0.47	0.02	0.52	0.80	0.02	0.10
V-cup 2	0.27	0.53	0.42	0.41	0.03	0.33	0.63	ND ^b	0.09
S ^c -cup 1	0.21	0.68	0.62	0.50	ND	0.14	0.39	ND	ND
S-cup 2	0.34	0.68	0.48	0.50	ND	0.19	0.35	0.01	ND
FC-358 V-cup 1	0.31	0.54	0.63	0.50	ND	0.78	0.98	VS ^d	0.02
V-cup 2	0.70	0.84	0.59	0.71	ND	0.10	0.22	ND	ND
S-cup 1	0.29	0.85	0.68	0.61	0.07	0.16	0.34	0.01	ND
S-cup 2	0.19	0.55	0.64	0.46	0.04	0.20	0.30	0.02	ND
FC-165 V-cup 1	0.37	0.53	0.13	0.34	ND	0.51	0.95	VS	ND
V-cup 2	0.06	0.44	0.37	0.29	ND	5.68	1.73	VS	ND
S-cup 1	0.19	0.35	0.40	0.21	ND	1.08	1.14	VS	0.12
S-cup 2	0.68	1.47	0.45	0.87	ND	0.08	0.10	ND	ND
FC-436 V-cup 1	0.14	0.67	0.39	0.40	ND	0.02	0.51	0.02	ND
V-cup 2	0.18	0.39	0.46	0.34	ND	0.08	0.92	0.05	0.16
S-cup 1	0.31	0.43	0.44	0.39	ND	0.05	1.32	0.05	0.14
S-cup 2	0.39	0.92	0.60	0.64	ND	0.03	0.26	0.01	0.01
FC-437 V-cup 1	0.39	0.82	0.77	0.66	ND	ND	ND	ND	ND
V-cup 2	0.15	0.50	0.59	0.41	ND	0.05	0.54	ND	ND
S-cup 1	0.21	0.96	0.62	0.60	ND	ND	0.13	ND	ND
S-cup 2	0.11	0.40	0.33	0.28	ND	0.06	0.68	ND	ND
FC-473 V-cup 1	0.08	0.48	0.54	0.37	0.03	0.57	0.99	0.06	0.09
V-cup 2	0.38	0.45	0.42	0.42	ND	0.81	1.13	0.12	ND
S-cup 1	0.05	0.51	0.37	0.31	0.07	0.40	0.78	ND	0.03
S-cup 2	0.23	0.63	0.51	0.46	0.08	0.46	0.91	0.04	ND
FC-501 V-cup 1	0.24	0.38	0.59	0.40	0.02	1.20	0.88	0.18	0.28
V-cup 2	0.09	0.24	0.15	0.16	ND	0.77	1.32	VS	0.03
S-cup 1	0.41	0.37	0.62	0.47	0.05	0.88	0.93	0.04	0.04
S-cup-2	0.31	0.50	0.56	0.46	ND	0.74	1.04	VS	ND
FC-589 V-cup 1	0.05	0.44	0.38	0.29	ND	0.05	0.57	ND	ND
V cup-2	0.04	0.62	0.51	0.39	ND	0.07	0.65	0.06	0.02
S cup-1	0.04	0.37	0.37	0.26	ND	0.05	0.67	0.03	0.06
S cup-2	ND	0.30	0.28	0.19	ND	0.04	0.18	ND	ND
FC-590 V-cup 1	0.04	0.16	0.48	0.23	ND	0.08	1.24	0.87	0.14
V cup-2	0.04	0.55	0.54	0.38	ND	0.07	0.96	0.82	0.05
S cup-1	0.03	0.40	0.20	0.21	ND	0.05	0.94	0.76	0.05
S cup-2	0.04	0.08	0.47	0.20	ND	0.08	0.76	0.10	0.21

^aVent cup.^bNone detected.^cShield cup.^dVery strong elemental peak.

TABLE X. Spectrographic Analyses of the SVT Iridium Clads

Capsule	Cup	Selected Elements ^a (ppm)								
		Cu	Mg	Ca	Al	Si	Cr	Fe	Ni	Pt
FC-364	PR726-5	15	ND ^b	ND	50	ND	30	200	30	ND
	PR726-7	5	ND	ND	50	ND	20	200	30	ND
FC-368	PR727-7	5	ND	ND	50	20	40	200	50	30
	NR529-5	5	3	ND	50	10	30	200	50	50
FC-165	NR508-4	15	ND	ND	50	10	30	200	30	ND
	NR507-3	15	ND	ND	70	ND	30	200	30	30
FC-391	RR920-5	20	3	3	50	10	70	300	50	ND
	RR925-3	20	3	3	50	20	70	300	50	ND
FC-436	R901-2	20	3	10	70	15	80	500	150	ND
	R919-4	20	3	5	50	10	100	400	100	ND
FC-437	MER41-1	20	3	3	50	10	50	400	100	ND
	MER41-2	10	3	3	50	10	50	400	60	ND
FC-473	S39-4	5	ND	ND	30	ND	10	100	20	ND
	S14-2	20	ND	ND	30	ND	30	100	70	ND
FC-501	SR52-1	5	ND	ND	30	ND	10	100	20	ND
	SR51-6	5	ND	ND	30	ND	10	70	10	ND
FC-152	N512-5	10	15	ND	70	15	80	500	100	30
	N516-1	10	5	ND	100	15	60	400	80	30
FC-589	T113-2	4	ND	3	25	ND	20	275	10	ND
	T115-2	5	7	3	50	15	25	300	25	ND
FC-590	V202-3	45	20	10	225	85	200	450	200	30
	V203-5	60	20	10	200	125	200	550	225	30

^aElements are listed only if they exceed the detection limit in at least one cup.^bNot detected.

resulted from the differential displacement and subsequent push-through of a large fuel fragment.

The FC-112 closure weld was also examined metallographically. The two weld cracks (Fig. 13) occurred on the vent cup side of the weld bead and were located just beyond the "spear point" at the end of the overlap weld. Both cracks were intergranular and had propagated into relatively fine grained sections of the vent cup wall (Fig. 14). Additional grinding revealed the weld microstructures shown in Fig. 15. Both weld sections contained a large number of equiaxed grains, and the fractures followed the grain boundaries through the weld bead thickness. Although the metallography did not indicate whether the fractures resulted from mechanical deformation or the enlargement of preexisting defects, the fact that both cracks occurred on the vent cup side of the weld supports the latter theory.

The microstructures of the FC-165 and FC-368 weld beads are shown in Figs. 16 and 17. The FC-165 weld failure apparently occurred by fracture along the bound-

aries of elongated grains oriented normal to the wall thickness. Similar grain elongation (up to 40% of the weld thickness) was also observed in the FC-368 weld.

Cross sections of the FC-364 and FC-368 vent assemblies revealed that both vents were free of intermetallic deposits and vent effusates. Only small quantities of plutonia were observed on the inner surfaces of the vent frits. Excessive grain growth adjacent to the assembly and decontamination cover welds occurred in both vents (Figs. 18 and 19).

Indications of grain boundary sulfur contamination (from an unknown source) were detected in three iridium wall samples obtained from capsule FC-165 and in one specimen removed from FC-368. The AES results (Table VIII) also indicated thorium depletion on the clad interiors. Bulk impurity levels were within the expected ranges.

The microstructures of plutonia pellets HF-364 and HF-368 were typical of SRP material. No second phase impurities were observed.

TABLE XI. SVT Plutonium Analyses								
Fueled	Selected Elements ^a (ppm)							
Clad	P	Mg	Ca	Al	Si	Fe	Cr	Ti
FC-112	8	3	300	20	15	5	6	15
FC-165	9	10	50	30	40	10	15	15
FC-364	5	20	300	20	40	5	7	30
FC-368	15	1	25	15	30	ND ^b	10	20
FC-391	11	7	250	360	35	ND	9	15
FC-436	15	7	ND	50	15	ND	ND	15
FC-437	35	7	6	55	15	9	ND	15
FC-441	6	7	400	75	5	ND	7	10
FC-473	16	5	750	770	40	35	10	35
FC-501	14	5	750	145	40	7	7	35
FC-591	20	3	750	ND	15	ND	10	35
FC-592	4	2	750	85	15	20	8	35
FC-152	5	2	750	140	25	25	5	35
FC-185	6	1	400	ND	8	10	15	25
FC-589	6	1	500	ND	10	ND	7	35
FC-590	2	10	750	30	35	15	8	20

^aElements are listed only if they exceed the detectability limit in at least one pellet.

^bNot detected.

Fig. 4. The SVT-7 aeroshell fractured along the axial contact lines of the leading GIS; 0.4X.

(a)

(b)

Fig. 5. A wide axial crack was observed on the impact face of capsule FC-364. (a) Impact face and (b) vent end; both at 1.5X.

FC-165

(a)

FC-165

(b)

Fig. 6. The FC-165 impact face was also breached by a wide axial crack. (a) Impact face and (b) vent end; both at 1.5X.

FC-112

Fig. 7. Two small weld cracks (perpendicular to the weld centerline) were observed on the trailing face of capsule FC-112; 1.5X.

FC-368

Fig. 8. A small, nonpenetrating crack was observed on the FC-368 vent cup radius; 1.5X.

(a)

(b)

(c)

Fig. 9. Failure in the FC-364 vent cup occurred in a reverse bend region adjacent to the indentation of a large fuel fragment. (a) As polished, 6.5X; (b) and (c) etched, 50X.

(a)

(b)

(c)

Fig. 10. Failure in the FC-364 shield cup also occurred in a reverse bend region. (a) As polished, 6.5X; (b) and (c) etched, 50X.

(a)

(b)

Fig. 11. The vent cup portion of the FC-165 breach had a brittle intergranular appearance. (a) As polished, 6.5X; and (b) etched, 50X.

(a)

(b)

Fig. 12. The shield cup portion of the FC-165 breach also had a brittle intergranular morphology. (a) As polished, 6.5X; and (b) etched, 50X.

Fig. 13. Cracks in the FC-112 closure weld were located just beyond the "spear point" at the end of the overlap weld; 3.0X.

(a)

(b)

Fig. 14. The FC-112 weld cracks propagated into the vent cup; (a) and (b) etched, 50X.

(a)

(b)

Fig. 15. The cracked section of the FC-112 closure weld had a relatively coarse microstructure composed of large equiaxed grains; (a) and (b) etched, 50X.

Fig. 16. The FC-165 weld failure occurred in a coarse-grained section; etched, 50X.

Fig. 17. The FC-368 weld had an unusual microstructure; etched, 50X.

(a)

(b)

Fig. 18. Excessive grain growth was observed adjacent to the FC-364 decontamination cover weld; (a) and (b) etched, 50X.

(a)

(b)

Fig. 19. Grain coarsening was also observed near the FC-368 decontamination cover weld; (a) and (b) etched, 50X.

B. SVT-8

During the 90-day orbital decay heat treatment, the SVT-8 test module was continuously monitored to determine the helium release; there were no indications of unplugging.

The SVT-8 test module was impacted on a steel target at 54.6 m/s and 975°C. The impact orientation was $\alpha = 15^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$. Postimpact examination revealed that the aeroshell walls fractured along the axial contact lines of the primary GIS (Fig. 20) and that both shell closures were released. Although the GISs were unrestrained, neither left the aeroshell.

Damage to the impact shells was significant but not unusual. Irregular axial cracks (up to 75% of the GIS length) were visible on the impact face of each GIS. Both GIS caps had come off, and capsule FC-437 (one of the primary clads) was released into the aeroshell.

Macroscopic examination revealed that the primary clads (FC-436 and FC-437) and one secondary clad (FC-441) were only moderately deformed. Capsule FC-391, however, was badly breached (Fig. 21). The FC-391 closure weld failed over a 120° arc, with the crack center 90° to the impact face. The crack size (30.0 mm $\times$ 1.8 mm) permitted excessive clad deformation and generated secondary cracks in the vent and weld shield cups (Fig. 22). The weld shield band remained in place and minimized fuel release.

Although the FC-391 closure weld had an SRP/NDE rating of 9.8, weld quality was poor. Metallographic examination revealed slight misalignment of the vent and weld shield cups (Fig. 23) and significant porosity in weld remnants on either side of the breaching crack (Fig. 24). In addition, two large voids (with maximum diameters of approximately 0.33 mm) were observed in a face on the weld section containing the terminus of the breaching crack (Fig. 25).

Examination of the FC-436 and FC-437 closure welds did not reveal any unusual features. Both welds had typical microstructures and were free of observable defects.

The iridium cups used in capsules FC-391, FC-436, and FC-437 had acceptable microstructures. Although all six cups contained isolated areas of abnormal grain growth, the microstructures were generally fine grained, with cup grain sizes ranging from 12 to 15 grains/0.635-mm nominal wall thickness. No significant chemical or microstructural anomalies were observed in any of the iridium cups.

Examination of the axial crack on the FC-391 shield cup (Fig. 26) revealed the same intergranular morphology observed in previous iridium fractures. There was no evidence to indicate that the crack resulted from anything other than excessive clad deformation permitted by the weld failure.

The FC-436 and FC-437 capsule vents did not contain any mechanical defects and were relatively undeformed. Although the vent frits were clear, glassy deposits were observed on the vent exteriors and center holes (Fig. 27). The deposits intergranularly attacked the iridium (Figs. 28 and 29) and promoted excessive grain growth. Microprobe analyses indicated that the deposits contained iridium, oxygen, silicon, and tungsten.

Metallographic examination of the FC-437 capsule vent revealed abnormally large iridium grains (up to 2 grains/0.635-mm nominal wall thickness) near the vent cover weld (Fig. 30). The grain coarsening was similar to that observed on the SVT-7 vent cover welds. The microstructure of the FC-436 vent cover weld was not affected.

All of the SVT-8 fuel pellets had typical microstructures; no second phase impurities were observed in any pellet. Although pellets HF-391 and HF-441 had elevated calcium contents, the slight variations in chemistry apparently did not affect the impact responses. The pellets all fractured in a brittle, entirely random manner.

C. SVT-9

During the orbital decay aging heat treatment (90 days), the test module was continuously monitored to determine helium release; there were no indications of vent unplugging.

After aging and reentry heat treatments, the module was impacted against a steel target at 54.6 m/s and

Fig. 20. The walls of the SVT-8 aeroshell fractured along the axial contact lines of the primary GIS; 0.4X.

(a)

(b)

(c)

(d)

Fig. 21. The FC-391 closure weld failed over a 120° arc. (a) Impact face, (b) profile, (c) trailing face, and (d) vent end; all at 1.5X.

(a)

(b)

Fig. 22. The deformation produced by the FC-391 weld failure propagated cracks into the vent and weld shield cups. (a) Small crack in the vent cup and (b) axial crack in the shield cup; both at 2.0X.

(a)

(b)

Fig. 23. The FC-391 vent and weld shield cups were slightly misaligned. (a) As polished and (b) etched; both at 50X.

(a)

(b)

Fig. 24. Remnants on either side of the FC-391 weld failure were slightly porous. (a) Vent cup side and (b) shield cup side; both at 50X.

(a)

(b)

Fig. 25. Large voids were observed in a face-on section of the FC-391 closure weld. (a) As polished, 7.0X; and (b) etched, 50X.

(a)

(b)

Fig. 26. The axial crack in the FC-391 shield cup had a brittle intergranular appearance. Opposite crack sides (a) and (b), etched, 50X.

Fig. 27. Glassy deposits were observed on the FC-436 and FC-437 vent exteriors. The FC-436 vent is shown here as polished, 50X.

Fig. 28. The deposits on the FC-436 vent intergranularly attacked the iridium; etched, 50X.

Fig. 29. Deposits on the FC-437 vent had a similar appearance, and they apparently promoted excessive grain growth; etched, 50X.

(a)

(b)

Fig. 30. Excessive grain growth was observed adjacent to the FC-437 vent decontamination cover weld. (a) Impact face side and (b) opposite side; both at 50X.

975°C. The impact orientation was $\alpha = 30^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$. Because of a loading error, the secondary impact assembly (containing capsules FC-473 and FC-501) was placed in the lead (primary) position. For purposes of the postmortem examination, capsules FC-473 and FC-501 were treated as "primary" clads.

Aeroshell damage was greater than that observed in either $\alpha = \beta = \gamma = 0^\circ$ or $\alpha = 15^\circ$, $\beta = \gamma = 0^\circ$ impacts. A photograph of the impacted aeroshell is shown in Fig. 31. Two fragments broke away from the leading broad face of the aeroshell, and the aeroshell body fractured on the trailing broad face, roughly parallel to the axis of the secondary impact shell. Although the impact faces of both GISs were cracked, with fractures running nearly the GIS length, the leading impact shell was significantly more deformed than the trailing GIS (Fig. 32).

There were no failures in any of the fueled clads. Capsule deformation was generally symmetric, and localized deformation of the iridium was mild. Figure 33 illustrates the deformation of fueled clads from the closure ends of the both impact shells. Capsule FC-591 was slightly more deformed than the other clads.

The microstructures of the FC-473 and FC-501 iridium cups were characterized by moderate grain growth on 25-30% of the inner wall thickness. However, large grains were also present in several locations on the FC-473 vent cup exterior (Fig. 34). Isolated areas of abnormal grain growth were also seen on the exterior of the FC-501 vent cup (Fig. 35) and in both weld shield

cups (Fig. 36). One section of the FC-501 weld shield cup contained a single grain that occupied 75% of the total wall thickness (Fig. 36b).

AES analyses indicated thorium depletion on the iridium cup interiors. Sulfur segregation to the grain boundaries was also found in all but one sample. Sulfur concentrations were low in the FC-473 cups (S_{150}/IR_{229} ratio < 0.15) but appeared to be significantly higher in both of the FC-501 cups. In two sections removed from the FC-501 cups, the sulfur peaks overloaded the instrument.

Spectrographic analyses of the iridium indicated low concentrations of iron (approximately 100 ppm) and aluminum contents (30 ppm) significantly lower than those observed in previous test clads.

Examination of cross sections from the FC-473 and FC-501 vents revealed that the vent orifices contained no intermetallic deposits. Only small quantities of plutonia were observed at the entrances to the vent filter elements. Abnormal grain growth occurred adjacent to the vent assembly and decontamination cover welds (Figs. 37 and 38).

The microstructures of the plutonia fuel pellets were typical. All of the pellets had calcium contents of 750 ppm and HF-373 had an aluminum content of 770 ppm. Although the aluminum and calcium contents exceeded the SRP guideline limits (150 and 300 ppm, respectively), there were no apparent differences between the impact responses of the SVT-9 fuel pellets and those of pellets used in previous SVT impacts.

Fig. 31. Damage to the SVT-9 aeroshell was more severe than that observed in the SVT-8 and SVT-7 impacts; 0.4X.

(a)

(b)

Fig. 32. Both of the SVT-9 impact shells were cracked on the impact face. (a) Primary GIS and (b) secondary GIS; both at 1.0X.

Fig. 33. Deformation of the SVT-9 fueled clads was symmetric. (a) FC-501 and (b) FC-591; both at 1.5X.

(a)

(b)

(c)

Fig. 34. Several coarse-grained areas were observed in the FC-473 vent cup, (a), (b), and (c). Etched, with interior surface at left; all at 50X.

(a)

(b)

(c)

(d)

Fig. 35. The microstructure of the FC-501 vent cup was variable, with isolated areas of excessive grain growth, (a), (b), (c), and (d). Etched, with interior surface at left. All at 50X.

(a)

(b)

Fig. 36. The FC-473 and FC-501 shield cups also contained areas of abnormal grain growth. (a) FC-473 shield cup and (b) FC-501 shield cup; etched, with interior surfaces at left. 50X.

(a)

(b)

Fig. 37. Grain coarsening was observed adjacent to the FC-473 vent assembly and decontamination cover welds. (a) Impact face side of vent and (b) opposite side; both at 50X.

(a)

(b)

Fig. 38. Grain growth was also observed near the FC-501 vent assembly and decontamination cover welds. (a) Impact face side of vent and (b) opposite side; both at 50X.

D. SVT-10

The SVT-10 test module was impacted against a steel target at 54.3 m/s and 975°C. The module orientation was $\alpha = 30^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$. Aeroshell breakup was severe (Fig. 39). The aeroshell walls fractured along the axial contact lines of the impact shells, and both GISs were released.

Impact shell damage was moderate. Thin longitudinal cracks, running the length of the impact shell, were observed on the impact face of the leading GIS (Fig. 40), and a wide axial crack extended over 75% of the secondary GIS impact face (Fig. 41). The cap on the secondary GIS had fallen off, and capsule FC-152 was released into the catch tube.

Macroscopic examination of the fueled clads did not reveal any exterior cracks or other defects. Clad deformation was relatively minor. Although capsule FC-152 was released into the catch tube, it was not significantly more deformed than capsule FC-185, which remained within the secondary GIS. A sharp crease on the FC-152 impact face (Fig. 42) was apparently caused by the differential displacement of a large fuel fragment. Because capsule FC-185 was only minimally deformed and contained no unusual features, it was not examined further.

Examination of the FC-152 closure weld revealed a slight wall misalignment (Fig. 43a) and evidence of incomplete weld penetration (Fig. 43b). The FC-590 closure weld contained significant porosity (Fig. 44a) and had a coarse but otherwise acceptable microstructure (Fig. 44b). The microstructure of the FC-589 closure weld was satisfactory.

Metallographic examination of wall sections removed from the FC-152, FC-589, and FC-590 iridium cups revealed generally fine grained microstructures. The FC-590 weld shield cup, however, contained several coarse-grained sections (Fig. 45). The cup grain sizes ranged from 4 to 16 grains/0.635-mm nominal wall thickness.

Because the fuel capsules experienced only moderate deformation, the capsule vents were unaffected by the impact. No mechanical defects were observed in the FC-589 and FC-590 vent assemblies and neither vent contained intermetallic or glassy deposits.

Examination of the FC-589 and FC-590 vent cover welds revealed evidence of abnormal grain growth (Figs. 46 and 47). Although large grains were observed near ooth cover welds, capsule FC-590 was worst affected; wall sections adjacent to the FC-590 cover weld contained only 2 grains/0.635-mm nominal wall thickness (Fig. 47b).

AES analyses of specimens removed from the FC-589 and FC-590 iridium cups revealed significant thorium depletion on the inner surfaces. The thorium concentration at the interior of one FC-589 shield cup section was

below the detection limit of the instrument. In addition, high sulfur levels were observed in all of the FC-590 cup specimens.

Spectrographic analyses of the SVT-10 iridium cups revealed unusually high iron contents (275-550 ppm) in the FC-589, FC-590, and FC-152 clads. In addition, the FC-590 vent and weld shield cups contained abnormal amounts of copper, aluminum, silicon, chromium, and nickel.

All of the SVT-10 fuel pellets had typical microstructures and fractured in a completely brittle manner. The FC-152 pellet was unusual in that it fractured cleanly along a plane 45° to the impact face (Fig. 48). Spectrographic and radiochemical analyses of the fuel pellets revealed that the compositions were similar to those of pellets used in previous SVT impacts. However, the calcium contents were somewhat elevated (400-750 ppm) and were above the SRP guideline limits.

V. DISCUSSION

The test results clearly indicate that the $\alpha = 15^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ impact orientation produced more severe damage than did the $\alpha = 30^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ orientation. The differences in capsule deformation illustrate the severity of the $\alpha = 15^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ impact; the SVT-7 and SVT-8 postimpact capsule strains (Table V) were approximately 50% higher than those observed in SVT-9 and SVT-10. In addition, while no failures occurred in SVT-9 and SVT-10, three clads breached in SVT-7. (The breach of capsule FC-391 in

Fig. 39. The SVT-10 aeroshell was severely broken up; 0.4X.

Fig. 40. The impact face of the leading GIS contained numerous longitudinal cracks.

Fig. 41. A wide axial crack was observed on the impact face of the SVT-10 secondary GIS; 1.0X.

Fig. 42. Although the SVT-10 fueled clads experienced only moderate deformation, a sharp crease was observed on the impact face of capsule FC-152; 1.5X.

(a)

(b)

Fig. 43. The FC-152 closure weld was not of good quality. (a) As polished and (b) etched: both at 50X.

(a)

(b)

Fig. 44. The FC-590 closure weld contained a significant amount of porosity. (a) As polished and (b) etched; both at 50X.

Fig. 45. The FC-590 weld shield cup contained several coarse-grained sections; etched, 50X.

(a)

(b)

Fig. 46. Grain coarsening was observed in wall sections adjacent to the FC-589 vent assembly and decontamination cover welds. (a) Impact face side of vent and (b) opposite side; both at 50X.

(a)

(b)

Fig. 47. Excessive grain growth was also observed in sections adjacent to the FC-590 vent assembly and decontamination cover welds. (a) Impact face side of vent and (b) opposite side; both at 50X.

Fig. 48. The FC-152 fuel pellet fractured cleanly along a plane 45° to the impact face; 1.5X.

SVT-8 is not considered, because it resulted from the failure of a non-flight-quality weld.) The failure rate of fuel capsules used in the $\alpha = 15^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ impacts was 43%.

In SVT-7, one primary (FC-364) and both secondary (FC-112 and FC-165) clads breached. The FC-364 and FC-165 failures (Figs. 5 and 6) apparently resulted from the differential displacement and subsequent push-through of large fuel fragments. Capsule FC-112 was breached by two small weld cracks (Fig. 7) that probably resulted from the propagation of preexisting weld defects.

Deformation of the SVT-8 clads was significant but somewhat less than that of the SVT-7 clads. Localized iridium deformation was generally mild, and only one secondary clad (FC-391) failed. The FC-391 breach resulted from extensive weld failure (the closure weld fractured over a 120° arc) and was related to the poor weld quality.

Metallographic examination of FC-391 weld sections revealed significant amounts of porosity (Fig. 24), vent and shield cup misalignment (Fig. 23), and two large voids (Fig. 25) at the edge of the fusion zone. Although the FC-391 weld was not flight quality, the presence of so many defects in a weld with an SRP/NDE rating of only 9.8 is disturbing; fueled clads with SRP/NDE ratings ≤ 8 are designated as flight quality.

Except for FC-391, the capsule welds were generally acceptable. However, the FC-165 and FC-152 closure welds had unusually coarse grained microstructures.

The FC-165 weld failure occurred in a section containing only 4 grains/0.635-mm wall thickness (Fig. 16); the grains were very elongated and the fracture followed the grain boundaries through the thickness. Although the FC-152 weld did not fail, the incomplete weld penetration (Fig. 43b) promoted excessive grain growth on the clad interior.

Results of the chemical and microstructural analyses indicate that the iridium cups used in SVT-7 through SVT-10 were similar to those used in previous SVT impacts. The cup microstructures were generally fine grained; with one exception the average grain sizes ranged from 11 to 21 grains/0.635-mm nominal wall thickness. Although all cups contained isolated areas of grain growth, excessively large grains were observed throughout the microstructure of the FC-590 weld shield cup.

The abnormal grain growth observed in the FC-590 weld shield cup and in isolated interior locations of several other cups may have been related to thorium depletion. The AES analyses (Table IX) revealed moderate thorium depletion on the interiors of the SVT-7 and SVT-8 iridium cups. Thorium concentrations on the interiors of three SVT-9 cup samples were very low, and the interiors of all SVT-10 cup samples were severely depleted. In one specimen removed from the FC-589 shield cup, the thorium concentration on the inner surface was below the detection limit of the instrument. Significant amounts of sulfur were also detected in several cup samples. Although the effects of grain

boundary segregation of sulfur are unclear, sulfur is suspected of promoting grain growth.

Abnormal grain growth was also observed in wall sections adjacent to nearly all the vent assembly and decontamination cover welds. Wall sections adjacent to the vent cover welds on capsules FC 437 and FC-590 contained only 2 grains/0.635-mm nominal wall thickness (Figs. 28 and 47). Such excessive grain growth at the same location in several capsules suggests a relation to some aspect of the production process. Whatever the cause, grain coarsening adjacent to the capsule vent could result in a capsule breach in any impact that significantly deformed the vent assembly.

Both the $\alpha = 15^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ and $\alpha = 30^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ module impacts produced negligible vent deformation. Postimpact examination revealed that all capsule vents were relatively undamaged; no mechanical defects were observed in any vent, and all vent frits were free of intermetallic deposits. Although no vent effusates were detected during macroscopic examination, cross sections of the FC-436 and FC-437 capsule vents revealed deposits on the vent exteriors and center holes (Fig. 27). The deposits intergranularly attacked the iridium and promoted excessive grain growth (Figs. 28 and 29). Microprobe analyses revealed that the deposits contained iridium, oxygen, silicon, and tungsten. Although impurities in the fuel would be an obvious silicon source, spectrographic analyses of the FC-436 and FC-437 fuel pellets indicated low silicon contents.

Spectrographic and radiochemical analyses (Table XI) indicated that the fuel pellets used in SVT-7 through SVT-10 contained acceptable amounts of impurities; however, calcium and aluminum contents of several pellets exceeded the SRP guideline limits. Although the effects of excess aluminum and calcium are unclear, there did not appear to be any relation between chemical composition and impact response. All pellets fractured in a brittle manner. The pellet microstructures were typical of SRP material and similar to the microstructures of the pellets used in previous SVT impacts.

VI. CONCLUSIONS

- (1) The $\alpha = 15^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ impact orientation produced markedly more severe clad damage than did the $\alpha = 30^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ orientation. The failure rate of fueled clads in the $\alpha = 15^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ impacts was 43%; no failures occurred in the $\alpha = 30^\circ$, $\beta = 0^\circ$, $\gamma = 0^\circ$ impacts.
- (2) Fuel fragment push-through was the dominant mode of clad failure. The large breaching cracks observed in SVT-7 were caused by the differential displacement and subsequent push-through of large fuel fragments.

- (3) The single clad failure in SVT-8, in which the FC-391 closure weld failed over a 120° arc, was related to poor weld quality. Because the weld had an SRP/NDE rating of only 9.8, the nondestructive evaluation apparently did not recognize the number or magnitude of weld defects.
- (4) Excessively large grains were observed adjacent to nearly all of the vent assembly and decontamination cover welds. Such unusual grain coarsening at the same location in several vents suggests a relation to some aspect of the production process.
- (5) Deposits that promoted grain growth and intergranularly attacked the iridium were seen on the exteriors of the FC-436 and FC-437 capsule vents. The deposits were composed of iridium, oxygen, silicon, and tungsten, and appeared to be a single phase compound.
- (6) AES analyses revealed significant thorium depletion on the interiors of nearly all the iridium cups. The cups used in SVT-9 and SVT-10 were worst affected; the thorium content on the interior of one FC-589 shield cup sample was below the detection limit of the instrument.
- (7) Chemical and metallographic analyses of the iridium cups and plutonia fuel pellets revealed that they were typical and representative of flight-quality components. The few chemical and microstructural anomalies observed would not have affected the impact responses.

VIII. RECOMMENDATIONS

- (1) Because excessive grain growth at the vent cover weld appears to be characteristic of the clad microstructures, several capsules should be impacted in a configuration that produces significant vent end deformation.
- (2) Efforts should be made to identify the mechanism responsible for grain growth at the vent cover welds and to determine the time and temperature required.

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REFERENCES

1. "Updated Safety Report for the Galileo Mission and the International Solar-Polar Mission," General Electric document GESP-7186, Sec. 3.4 (April 1984)(GPHS Reentry Response).

2. "GPHS Safety Verification Test Series Procedure Manual," Los Alamos National Laboratory document MST-5-C-83-19, Sec. 1.0 (April 14, 1983).
3. D. Pavone, T. G. George, and C. E. Frantz, "General-Purpose Heat Source Safety Verification Test Series: SVT-1 Through SVT-6," Los Alamos National Laboratory report LA-10353-MS (June 1985).
4. "Estimates for the Orbital Lifetimes for Galileo and Solar Polar," Applied Physics Laboratory document ATD-RL-82-081/ANSP-L-662 (November 18, 1982).
5. C. E. Frantz, J. W. Taylor, and D. B. Court, "Isotope Fuels Impact Tester (IFIT)," Los Alamos Scientific Laboratory report LA-6013 (January 1976).