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Space Nuclear Safety Program

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

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Compiled by
S. E. Bronisz

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SPACE NUCLEAR SAFETY PROGRAM

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ABSTRACT

This technical monthly report covers studies related to the use of $^{238}\text{PuO}_2$ in radioisotope power systems carried out for the Office of Special Nuclear Projects of the US Department of Energy by Los Alamos National Laboratory. Most of the studies discussed here are ongoing. Results and conclusions described may change as the work continues.

I. GENERAL-PURPOSE HEAT SOURCE (GPHS)

A. Safety-Verification Impact Test: SVT-4 (D. Pavone)

The fourth GPHS module in the safety verification test series, SVT-4, was aged for 90 days at 1287°C in a vacuum below 10^{-6} torr, subjected to a simulated orbital-decay reentry thermal pulse to 1375°C, and impacted at 54 ms^{-1} and 975°C in the face-on orientation. One prime fueled clad was deformed and failed; the other prime clad and the two secondary clads were deformed but remained intact.

The components of SVT-4 are listed in Table I. During aging, the helium released from the fueled clads was monitored continuously. There was no evidence of vent plugging throughout the 90-day exposure. After their reentry heat treatments, the two impact assemblies were radiographed. All four fuel pellets were cracked randomly, and HF-348 also was cracked axially along two thirds of its length.

The impacted aeroshell is shown in Fig. 1. One aeroshell cap was displaced by the impact, and the prime impact assembly that it had retained was out of the aeroshell. The impact face was cracked longitudinally in two places (Fig. 1a). The nonpenetrated sides were both cracked, the crack adjacent to the prime assembly extended the full length of the aeroshell (Fig. 1a), but the crack adjacent to the secondary assembly extended only ~50% of the aeroshell's length (Fig. 1b). The dent from which the back-surface cracks radiate (Fig. 1b) is believed to have occurred when the impacted module

rebounded and struck the extended thermocouple lead wires in the projectile.

The impacted sides of both impact assemblies were cracked, and both assemblies exhibited the usual bowed profile (Fig. 2). The failure in the prime assembly, PGT-1015, was distributed over several cracks across the impact surface (Fig. 2a), but the failure in the secondary assembly, PGT-1017, was confined to a single, wide crack (Fig. 2c). A partial circumferential

TABLE I. SVT-4 Components

Component	Serial No.
Aeroshell	PAT-1007
Prime impact assembly	
Impact shell	PGT-1015
Fueled clads	FC-348, FC-354
Fuel pellets	HF-348, HF-354
Insulation sleeve	C40-6
Insulation disks	P8-2-51, P8-2-54
Secondary impact assembly	
Impact shell	PGT-1017
Fueled clads	FC-139, FC-162
Fuse pellets	HF-139, HF-162
Insulation sleeve	C30-8
Insulation disks	P11-11-12, P11-1-23

crack occurred ~ 8 mm from the closure end of the secondary impact shell (Figs. 2d and 2e).

The impacted fueled clads from the prime and secondary impact assemblies are shown in Figs. 3 and 4, respectively. All four were deformed by the impact, but only FC-348 failed. It was cracked longitudinally in the reverse-bend region of the impact face (Fig. 3a). The crack extended nearly the length of the shield (nonvented) cup, across the weld, and just into the vent cup. It was caused by a fuel fragment push-through. The area of the failure was 1.8 mm^2 . Other than this crack, the local deformations were only moderately severe. The gross strains are listed in Table II and compared there with the fueled-clad strains measured in the prior SVT impacts.

The plutonium released through the failure in FC-348 on impact and vaporized through the four vents during aging was determined by analysis of the recovered graphite components. The graphite was ashed, the resulting residues were separated into $>10\text{-}\mu\text{m}$ and $<10\text{-}\mu\text{m}$ fractions, dissolved, and analyzed radiochemically. The results are listed in Table III. The total amount of plutonium found was 25.7 mg, 7.6 mg of which was found in the $<10\text{-}\mu\text{m}$ fraction. The amount

found in the $<10\text{-}\mu\text{m}$ fraction undoubtedly underestimates the actual amount originally present in the graphite because some agglomeration occurred during the ashing procedure.

The fueled clads were cut circumferentially and the fuel pellets were exposed (Fig. 5). Pellets HF-348 and HF-354 broke into randomly oriented pieces with little evidence of the columnar fracture pattern usually seen in this impact orientation. The fuel movement that caused the failure in FC-345 is clearly visible (Fig. 5a). Pellets HF-139 and HF-162 broke into mixed large and small fragments, with the former showing some tendency to columnar fracture.

Cross sections through the fractures in the shield cup and the vent cup of FC-348 are shown in Figs. 6 and 7, respectively. The failure in the shield cup was in the reverse-bend region of the impact face and occurred with no plastic deformation (Fig. 6b). A secondary crack, which penetrated two-thirds of the capsule wall, occurred opposite the location of a fuel-fragment indentation that deformed the capsule wall by 15%. In the vent cup, the crack in the reverse-bend region occurred with $\sim 10\%$ plastic strain. In the section exposed (Fig. 7b), the crack is made up of two cracks, one connected to

TABLE II. Impact Summary, GPHS SVT Series

Test No.	Component	Clad No.	Deformation (%)		Failures ^a	
			Diametral	Axial	Number	Area (mm^2)
SVT-1	Prime assembly	FC-232	+13.5, -11.1	+5.8	0	25.4
		FC-238	+ 9.6, - 7.3	+3.8	0	
	Secondary assembly	FC-261	+11.7, -11.1	+5.6	2	
		FC-410	+ 9.8, - 9.6	+1.4	1	
SVT-2	Prime Assembly	FC-355	+10.0, -10.4	+4.1	0	8.4
		FC-369	+ 9.1, - 9.3	+4.1	0	
	Secondary assembly	FC-449	+12.5, -10.3	+5.6	3	
		FC-273	+10.3, -10.5	+4.4	0	
SVT-3	Prime assembly	FC-343	+12.3, - 9.0	+5.7	0	0.4
		FC-350	+10.0, - 8.5	+2.6	0	
	Secondary assembly	FC-457	+10.8, - 7.2	+5.6	0	
		FC-454	+ 9.5, - 6.4	+2.9	1	
SVT-4	Prime assembly	FC-348	+11.5, -11.3	+6.4	1	1.8
		FC-354	+ 8.5, - 8.2	+4.0	0	
	Secondary assembly	FC-139	+12.5, - 8.5	+5.1	0	
		FC-162	+10.3 - 9.3	+3.4	0	

^aThe number of failures in each fueled clad and the sum of the areas of all cracks in the four clads in an impacted module.

TABLE III. Fuel Release from SVT Modules

Module	Component ^a	Pu Content (g)		
		<10 μm	>10 μm	Total
SVT-1	GIS, intact ^b	0.0010	0.0034	0.0044
	GIS, failed ^c	0.0074	0.0710	0.0784
	A/S, insul.	0.0039	0.0196	0.0235
	C.T. debris	0.0005	0.0032	0.0037
	Totals	0.0128	0.1072	0.1100
SVT-2	GIS, intact	0.0001	0	0.0001
	GIS, failed	0.0029	0.0197	0.0226
	A/S, insul.	0.0010 ^d	0.0049	0.0059
	C.T. debris	0.0001	0.0002	0.0003
	Totals	0.0041	0.0248	0.0289
SVT-3	GIS, intact	0.0006	0.0004	0.0010
	GIS, failed and A/S	0.0018 ^d	0.0090	0.0108
	C.T. debris	0.0027	0.0032	0.0059
	Totals	0.0051	0.0126	0.0177
SVT-4	GIS, intact	0.0045	0	0.0045
	GIS, failed	0.0005	0.0160	0.0165
	A/S, C.T. debris	0.0026	0.0021	0.0047
	Totals	0.0076	0.0181	0.0257

^aGIS-graphite impact shell, A/S-aeroshell, C.T.-catch tube.

^bContained fueled clads without failures.

^cContained fueled clads with failures.

^dEstimated value, sample lost during dissolution.

the inner surface and the other connected to the outer surface. In this cup, too, a fuel indentation occurred; it caused a 17% reduction in thickness (Fig. 7a).

A small crack penetrating 40% of the iridium wall in the shield cup of FC-354 was also found. The crack connected to the inner surface and was located in the very mild reverse bend (Fig. 8d).

Typical microstructures of the iridium cups used in the prime fueled clads in SVT-4 are shown in Fig. 8. In each case, larger grains were present in a layer occupying ~20% of the thickness adjacent to the inner (fuel) surface. The grain sizes are listed in Table IV and compared there with those found in the previous SVT clads. The grain size in the shield cup is somewhat greater than that of any of the other prime capsules.

The welds of both of the prime capsules were fully penetrated, free of porosity, and had desirable microstructures (Fig. 9).

The results of the Auger electron spectroscopy (AES) analyses of the grain boundaries of the prime iridium used in SVT-4 are listed in Table V. The thorium concentrations were lower than those usually seen in the DOP-26 iridium alloy. No phosphorus or silicon was

detected. Sulfur was found only in the shield cup of FC-354. Carbon and oxygen in varying amounts were found in nearly all of the samples.

The results of the emission spectrographic analyses of the prime iridium cups are given in Table VI. Again, iron was the most prevalent impurity. In cup QR820-2 (FC-354 shield), copper, aluminum, chromium, iron, nickel, and plutonium are all higher than in cup QR820-3 (FC-354 vent). Both cups were exposed to the same fuel pellet, so it is unlikely that these impurities were introduced by the fuel pellet.

The results of the spectrographic analyses of the four fuel pellets used in SVT-4 are listed in Table VII. The concentrations of all of the impurities are low. In the case of silicon, they are the lowest yet seen in the SVT fuel pellets.

The chemistry results do not reveal any substantial impurity that could account for FC-348's failure. The metallographic results establish clearly that a fuel fragment push-through was the primary mechanical cause of the failure.

B. Fragment Impact Test (R. Tate)

The edge-on GPHS fuel-tank fragment test was conducted this month. The objective of this test was to simulate a worst-case condition in which a Shuttle launch explosion propels a defined plate fragment of external tankage at high velocity into heated GPHS modules. The defined fragment is a plate of the Shuttle's external tank alloy (2219-T87) 203 x 203 x 3.2 mm. The defined fragment velocity is 914.5 m/s (3000 ft/s). The target temperature is defined as 1091°C, the temperature of the GPHS clad units when loaded in the shuttle.

In the edge-on fragment test, the target was the center unit in a three-module stack. The top and bottom units were blocks of bulk graphite machined to the GPHS exterior configuration. The target unit (PAL003) was a fine-weave pierced fabric module of prime quality loaded with simulant (depleted UO₂) fueled clads. The module stack was supported on a hollow graphite pedestal so that the edge-on fragment would strike the target module at the centerline of a nonclosure side. A great deal of care was taken in adjusting the furnace base plate so that the plane of the fragment on the rocket sled and the plane of target module centerline were at the identical elevation. Calibrated sheathed Chromel-Alumel thermocouples, one in the target module/dummy module interface and one wired to the three-module stack, were used to measure and record the target and furnace temperatures.

To begin the test run, the vermiculite-filled catch box, 4.6 m long with a 254-mm wide by 356-mm high opening, was retracted, and the bell-shaped furnace was

TABLE IV. Iridium Grain Size, GPHS SVT Series

Test No.	Clad No.	Cup No.	Grain Size ^a		Comments
			Intercept Diam. (μm)	Nominal	
SVT-1	FC-232	LR313-1(v) ^b	25.7	25	Uniform
	FC-232	LR316-1(s)	30.7	21	Uniform except for tab weld
	FC-238	LR315-2(v)	32.3	20	Uniform
	FC-238	LR318-6(s)	23.3	28	Uniform
	FC-261	P709-6(v)	29.1	22	Uniform
	FC-261	Q804-1(s)	29.8	22	Uniform
	FC-410	S2-5(s)	31.6	20	Uniform
SVT-2	FC-355	Q806-2(v)	30.4	21	Uniform
	FC-355	Q806-5(s)	25.8	25	Uniform except for tab weld
	FC-369	NR528-2(v)	29.7	22	Uniform
	FC-369	NR528-3(s)	23.2	28	Uniform except for tab weld
	FC-449	S27-2(v)	28.5	23	Uniform
	FC-449	S25-3(s)	28.1	23	Uniform
SVT-3	FC-343	PR718-5(v)	32.7	20	Lg. int. grains, 20-25% of thk.
	FC-343	PR719-5(s)	38.9	16	Lg. int. grains, 20-25% of thk.
	FC-350	R904-7(v)	35.7	18	Lg. int. grains, 20-25% of thk.
	FC-350	R904-5(s)	36.4	18	Lg. int. grains, 20-25% of thk. and tab weld
	FC-454	S39-5(s)	42.3	15	Lg. int. grains, 20-25% of thk. + isolated lg. ext. grains
SVT-4	FC-348	QR820-1(v)	35.8	18	Lg. int. grains, 20-25% of thk.
	FC-348	QR820-6(s)	43.5	15	Lg. int. grains, 20% of thk. + tab weld
	FC-354	QR820-3(v)	34.1	19	Lg. int. grains, 20% of thk.
	FC-354	QR820-2(s)	36.8	17	Lg. int. grains, 20% of thk.

^aThe intercept size is the average diameter determined by the boundary intercept method. The nominal size is the number of grains across a 640- μm thickness.

^b(v) — vent cup; (s) — shield cup.

TABLE V. Results of AES Analysis of SVT-4 Iridium

Specimen		Location	Intensity Ratios			
			Th ₆₅	C ₂₇₀	O ₅₁₀	S ₁₅₀
			Ir ₂₂₉	Ir ₂₂₉	Ir ₂₂₉	Ir ₂₂₉
FC-348	Vent cup-1	Int. edge	0.19	1.11	1.09	nd ^a
		Center	0.49	0.90	1.29	nd
		Ext. edge	0.52	0.84	1.19	nd
		Average	0.40	0.95	1.19	nd
	Vent cup-2	Int. edge	0.35	0.18	0.60	nd
		Center	0.56	0.21	0.52	nd
		Ext. Edge	0.24	nd	0.47	nd
		Average	0.38	0.13	0.53	nd
	Shield cup-1	Int. edge	0.63	nd	nd	nd
		Center	0.76	nd	nd	nd
		Ext. edge	0.63	nd	nd	nd
		Average	0.67	nd	nd	nd
	Shield cup-2	Int. edge	0.44	0.34	0.79	nd
		Center	0.49	0.29	0.72	nd
		Ext. edge	0.39	0.48	0.94	nd
		Average	0.44	0.37	0.82	nd
FC-354	Vent cup-1	Int. edge	0.11	0.98	0.99	nd
		Center	0.52	0.49	0.69	nd
		Ext. edge	0.71	nd	1.14	nd
		Average	0.45	0.46	0.94	nd
	Vent cup-2	Int. edge	0.27	0.44	0.63	nd
		Center	0.36	0.46	0.84	nd
		Ext. edge	0.47	0.31	0.79	nd
		Average	0.37	0.40	0.75	nd
	Shield cup-1	Int. edge	0.34	0.18	0.72	0.06
		Center	0.46	0.28	0.80	nd
		Ext. edge	0.52	0.48	0.98	0.06
		Average	0.44	0.31	0.83	0.04
	Shield cup-2	Int. edge	0.37	1.85	1.04	0.13
		Center	0.68	2.33	1.55	nd
		Ext. edge	0.43	1.54	0.99	nd
		Average	0.49	1.91	1.19	0.04

^and—not detected.

TABLE VI. Results of Spectrographic Analysis of GPHS Iridium

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

^aElements present in excess of the detection limit.

TABLE VII. Plutonia Analyses, GPHS SVT Series

Pellet No.	P ^a	Mg	Selected elements (ppm)						Ni	Ti
			Ca	Al	Si	Fe	Cr			
<u>SVT-1</u>										
HF-232	5	1	130	20	15	60	15	nd ^b	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	
<u>SVT-2</u>										
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	
<u>SVT-3</u>										
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	
<u>SVT-4</u>										
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	

^aColorimetric analysis.
^bnd—not detected.

lowered over the module stack and support pedestal. Argon gas was piped into the furnace base to maintain an inert furnace atmosphere. The run was started the day after setup. The module stack was heated to ~315°C, but the test was delayed for 24 h because of snowy weather. The furnace was restarted on the following day, and the module reached 1121°C in early afternoon. The temperature was held at this level for 15 min. At T minus 30 s the furnace was raised, and at T minus 15 s the catch box was moved into position, ~25 mm from the module. At T = 0, the rocket sled propelled the plate toward the target module at a velocity later determined to be 918 m/s (3012 ft/s). Detonators on the rocket sled were fired to release the plate with two linear explosive charges when it was ~50 mm from the target. Inspection of the temperature recording indicated that the target module temperature dropped 14°C to 1107°C during the 30 s between the time the furnace started to

rise and target impact. Unfortunately, inspection of high-speed movies recording the plate/target interaction indicated that the linear explosive on one side of the plate failed to ignite, a failure that had not occurred in five prior test runs.

When the catch box was tilted to empty its contents, the results were disappointing: the amount of iridium recovered from the catch box was no more than the equivalent of one fuel clad. However, a very large amount of iridium was recovered on or near the furnace base within a radius of about a meter. Some iridium was recovered upstream in the vicinity of the track rail. The 21 pieces recovered are shown in Figure 10. The amount of iridium recovered was 169.7 g, ~85% of the metal in the target module. The pieces of the aeroshell and impact shells recovered are shown in Figure 11. Some clinker-like material was recovered from the catch box. Since it is mildly radioactive, it is identified as depleted

UO₂ that was reacted with the vermiculite to form a glassy slag. This material is shown in Figure 12.

The apparent failure of one of the two linear charges to release the plate from both attachments casts a shadow on the test results. However, when these results are coupled with the results of the calibration run where four hot nickel cylinders were cleaved neatly, there can be no doubt that the edge-on fragment at 914.5 ms⁻¹ will open the GPHS iridium fuel clads. The solid nickel slugs were driven into the catch box, but the thin iridium clads apparently burst and were distributed radially.

II. LIGHT-WEIGHT RADIOISOTOPE HEATER UNIT (LWRHU) (R. Tate)

At the request of the Jet Propulsion Laboratory, a summary of probable weights of production heater units was supplied to them using weights of typical components measured by MST-11. The data are summarized in Table VIII. From these data, one can calculate that all units will weigh less than 40 g and that the maximum weight variation will be somewhat less than 1 g.

It should be noted that before shipment the weights of the fueled capsules will be reduced a very small amount by activating the vent (drilling a 0.652-mm hole in the vent end cap to expose the vent frit). After vent activation, the capsule will be inserted into the graphite components and the assembly completed by cementing the threaded cap in place and filling the spanner holes with a small amount of carbonaceous bonding agent. The small amount of cement will increase the unit weights very slightly.

III. HELIUM RELEASE (K. Axler)

A manifold assembly to be used in our helium release studies was completed, installed, and tested. The assembly, which will be used to calibrate the flow rate measurements, uses a series of Hastings flow meters in a progression of ranges that covers the expected levels of helium release.

IV. ENVIRONMENTAL SUPPORT (J. Archuleta)

A sample of debris collected on Johnson Island in 1977 was examined to determine its composition and to determine the character of the residual ²³⁹Pu associated with it. The sample, Johnson Island No. 3 (JI3) was a crumpled piece of thin metal (Fig. 13) that appeared to have been exposed to a fire. Although the sample bottle was labeled to indicate that the sample's contamination level was 250 000 counts/min, we were able to detect only 2500 counts/min by direct alpha counting.

A section of JI3 was removed, mounted at a 45° angle to enhance the possibility of detecting any surface layers, and prepared metallographically. No surface layers were detected other than the oxides visible in the upper left of Fig. 14. The prepared section was autoradiographed, and the developed film plate was examined through a microscope. Only very diffuse alpha tracks were present, suggesting that most of them originated, not from the sample, but from contaminated material from the polishing cloths forced into the fine crack between the sample and the mounting plastic during metallographic preparation.

The mounted section and the surface of the rest of the sample were examined in the scanning electron microscope and subjected to surface analysis. No plutonium was found. The metal was predominantly iron, chromium, and nickel (stainless steel). The cross section also contained aluminum and silicon, and the original surface contained these elements and calcium.

V. SAFETY TECHNOLOGY (T. George)

The first iridium disk, VR 227-6, was tested in biaxial tension at 45 ms⁻¹ at 1440°C. Its initial grain size was 25 μm. The disk deformed symmetrically and failed after local necking occurred at 50% strain ~9.5 mm from the cup lip (Fig. 15). The failure was very ductile (Fig. 16), with the separation occurring by necking to nearly a point.

Two planar defects were observed ~1.6 mm from the fracture (Fig. 17). Because of their location and orientation, it is unlikely that they contributed to the failure.

TABLE VIII. Summary of LWRHU Component Weights

Component	Average Wt. (g)	Standard Deviation	Minimum Wt. (g)	Maximum Wt. (g)
20 fueled capsules	8.257	± 0.048	8.134	8.340
10 graphite assemblies shipment 1	31.490	± 0.030	31.458	31.553
10 graphite assemblies shipment 2	31.040	± 0.044	30.958	31.091
10 graphite assemblies shipment 3	31.322	± 0.047	30.226	31.379

(a)

(b)

Fig. 1. The SVT-4 aeroshell failed in several places: (a) impact face; (b) back face ($\sim 0.6X$).

Fig. 2. Both of the SVT-4 impact assemblies were cracked and bowed. PGT-1015, the prime assembly, was cracked in several places: (a) impact face; (b) profile. PGT-1017, the secondary assembly, was cracked on the impact face and the back: (c) impact face; (d) profile; (e) back (IX).

(a)

(b)

(c)

(d)

Fig. 3. The fueled clads in the prime impact assembly of SVT-1 were both deformed and FC-348 was fractured: (a) FC-348's impact face had a longitudinal crack in the shield cup; (b) FC-348, side view; (c) FC-348, impact face; (d) FC-348, side view (1.5X).

(a)

(b)

(c)

(d)

Fig. 4. Both fueled clads in the secondary SVT-4 impact assembly were deformed, but neither failed: (a) FC-139, impact face; (b) FC-139, side view; (c) FC-162, impact face; (d) FC-162, side view (1.5X).

Fig. 5a.

(b)

(c)

(d)

Fig. 5. The impact fractured all the fuel pellets in SVT-4, but only HF-139 showed clear evidence of a columnar fracture pattern: (a) HF-348; (b) HF-354; (c) HF-139; (d) HF-162 (1.5X).

(a)

(b)

(c)

Fig. 6. The failure in the shield cup of FC-348 occurred in the reverse-bend region on the impact face: (a) the fracture region was deformed by a fuel fragment (7X); (b) the failure occurred without significant plastic deformation (50X); (c) a secondary crack opposite the fuel indentation started on the external surface and penetrated two thirds of the wall (50X).

(a)

(b)

Fig. 7. The reverse-bend region of the FC-348 vent cup was also cracked, but in the section exposed, the crack did not penetrate the wall: (a) 7X; (b) 50X.

(a)

(b)

(c)

(d)

Fig. 8. All of the cups in the prime clads used in SVT-4 had larger grains in their surfaces that had been next to the fuel: (a) FC-348 vent cup; (b) FC-348 shield cup; (c) FC-354 vent cup; (d) FC-354 shield cup (100X).

(a)

(b)

Fig. 9. The closure welds in both prime capsules used in SVT-4 were satisfactory: (a) FC-348; (b) FC-354 (50X).

Fig. 10. The iridium recovered after the edge-on fragment impact was severely deformed.

Fig. 11. Many aeroshell and impact shell fragments were recovered.

Fig. 12. Mildly radioactive slag was found in the catch box (~0.5X).

Fig. 13. Sample JI3 as received (7X).

Fig. 14. Only a small amount of surface oxide was detected on JJ3 (upper left) (50X).

Fig. 15. Biaxial disk VR 227-6 deformed symmetrically and necked at a principal strain of $\sim 50\%$ (1X).

Fig. 16. The failure of VR 227-6 was very ductile at 1440°C (50X).

Fig. 17. Two delaminations were present in VR 227-6 (50X).

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