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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 Tests

1. Post-Mortem of SVT-1 (D. Pavone). The results of emission spectrographic chemical analysis of the iridium cups used to make the fueled clads for the SVT-1 heat source module are listed in Table I. Although iron appears as the principal impurity in each cup, even its maximum concentration of 150 ppm is at the low end of the range observed in Multihundred-Watt iridium. Silicon is higher in both cups of FC-410 than in the other six cups, but it was not found segregated in the grain boundaries by Auger electron spectroscopy and probably is not the cause of the failure.

2. Post-Mortem of SVT-2 (D. Pavone). The impact assemblies were aged for 200 h at 1287°C in a vacuum, subjected to a simulation of a 1580°C reentry pulse, and impacted in the face-on (0°) orientation at $54.96 \pm 0.18 \text{ ms}^{-1}$ and 917°C to simulate a minimum-gamma earth-return accident. Table II lists the components of the module used for this test.

A preimpact radiographic inspection revealed that all of the fuel pellets were cracked severely. Pellet HF-273 in the secondary impact shell had a major axial fracture over half its length.

When SVT-2 was recovered from the impact catch tube, it was found to be cracked but intact (Fig. 1). The impact face contained two cracks roughly parallel to the axes of the impact assemblies. These cracks extended

around the ends of the aeroshell. Both side faces were cracked longitudinally, and the back face was cracked diagonally.

Both impact shells were cracked on the impacted side along 80% of their lengths (Fig. 2). The crack in the prime assembly, PGL-054, was off center and somewhat less severe than that in the secondary assembly. Both impact shells had slightly bowed profiles, as is usual for this impact orientation.

Neither fueled clad in the prime impact assembly failed. The clads were only modestly deformed (Fig. 3). Fueled clad FC-273, which was in the blind end of the secondary impact assembly, was also intact after the impact (Fig. 4). In contrast, FC-449, the other fueled clad in the secondary impact assembly, failed in three places (Fig. 5). None of the fractures occurred on the impact face (Fig. 5a). One crack was in the weld, about 90° from the center of the impact face (Fig. 5b). It was not associated with the weld overlap, which was diametrically opposite the crack site. Another crack was a longitudinal failure on the back of the capsule (Fig. 5c). It extended across the weld into both cups. The third crack occurred on the radius of the vent cup on the back of the capsule (Fig. 5d). The overall fueled clad deformations caused by the impact are listed in Table III along with a failure summary. No external deposit of vent effusate was visible on any capsule.

The fracture patterns of the fuel pellets are visible in Fig. 6. The radial columnar fragments in HF-273 (Fig. 6a) and the generally equiaxed fragments in HF-449 (Fig. 6b) are similar to the patterns usually seen in

impacted PuO_2 pellets. The large, blocky fragments present in HF-355 have not been seen before (Fig. 6c). Similarly, the small randomly oriented fragments in HF-369 (Fig. 6d) are unique in our experience. These two patterns probably represent the least and most desirable of the fuel fracture modes. The former, with its larger fuel blocks, should be more likely to cause local push-through clad failures, whereas the latter should tend to produce more evenly distributed hydrostatic-like forces.

Sections through each of the failures in FC-449 are shown in Fig. 7. All of the failures were intergranular with insignificant local thickness reductions. The relative displacements of the sides of the cracks were caused by the forces generated by the movement of fuel fragments, which is referred to as the push-through failure mode. The fine grains, the absence of fuel push through, and the location in a relatively low-stress region all make the occurrence of the crack on the cup radius (Fig. 7d) extremely puzzling.

Sections were taken through the welds in the primary capsules (FC-355 and FC-369) and prepared metallographically. They showed both welds were fully penetrated and free of porosity (Fig. 8). The section from FC-355 was taken fortuitously through the weld overlap and intersected a typical closure-weld crack. This section was on the side of the capsule in a low-stress region; it is highly unlikely that the crack could have been caused by the impact stresses.

Typical microstructures of the iridium cups that make up the prime fueled clads in SVT-2 are shown in Fig. 9. The microstructures are quite uniform and free of large grains. The grain sizes (Table IV) are in the same range as those in the SVT-1 clads, which were subjected to the same thermal environment.

The results of the emission spectrographic analysis of the prime clads, FC-355 and FC-369, and the failed secondary clad, FC-449, are listed in Table I, where they may be compared with the results on the clads in SVT-1 and SVT-3. The impurity concentrations in the SVT-2 clads are similar to those in the clads examined previously. There appears to be nothing unusual about the iridium chemistry in HF-449 that would account for its failures.

The grain-boundary chemistry of the same three clads (FC-355, FC-369, and FC-449), as determined by Auger electron spectroscopy, are listed in Table V. Both cups from each clad were examined; the weld metal at the site of the weld crack in FC-449 was also examined. The thorium levels were in the expected range, except for the shield-cup weld sample in FC-449, which had a very low thorium content. Low concentrations of phosphorus were found in all four cups of FC-355 and FC-369, but

none were detected in FC-449. Both oxygen and carbon were found in all of the samples.

The chemical analyses of the plutonia pellets are listed in Table VI. The concentrations of all the impurity elements are well within the guideline limits, and the level of calcium is significantly less than that found in the plutonia of SVT-1 and SVT-3.

The total plutonium released by the failures in FC-449 was determined by analysis of the recovered graphitic components, including the catch-tube debris. Details of the results are in Table VII. One sample, the $<10\text{-}\mu\text{m}$ fraction of the aeroshell and insulation ash, was lost because of failure of the quartz tube during the dissolution step. An estimated value for this sample is listed in the table. A total of 28.9 mg was found, with 4.1 mg in the $<10\text{-m}$ particle-size fraction.

3. Post-Mortem of SVT-3 (D. Pavone). The results of the emission spectrographic analysis of the SVT-3 clads, FC-343 and FC-350, are listed in Table I. Again, iron was the principal impurity element. Its concentration in both FC-350 cups was the highest yet seen in the SVT samples. The iron contents of the fuel pellets in these assemblies were 20 and 35 ppm, respectively.

4. Impact of SVT-4 (C. Frantz). The fourth module in the SVT series was subjected to an orbital-decay thermal pulse and impacted in the face-on orientation at 54 ms^{-1} and 975°C .

5. Fragment Test (R. Tate). The final calibration run of the rocket-propelled fragment impact test of the GPHS module was completed successfully. The first actual test will be conducted in January.

The objective of this experiment was to conduct a dress rehearsal for the real test. The target module contained cylindrical nickel mass simulants instead of iridium-clad uranium pellets; otherwise, the setup was identical to that intended for the actual test. The target was heated slowly to 1118°C and allowed to soak there for 20 min. At $T = 60\text{ s}$, the furnace was retracted; at $T = 30\text{ s}$, the catch box was positioned 25 mm from the back of the module; and at $T = 0$, the rocket sled propelled the 203- by 203- by 3-mm aluminum alloy sheet into the target at 975 ms^{-1} . The edge-on fragment was released 50 mm from the target by linear explosive charges.

All four fueled-clad simulants were found in the catch box. Each was cleaved into halves by the edge-on plate (Fig. 10). The temperature of the target module dropped to 1064°C between the furnace removal and the impact. In the real test, the furnace will be withdrawn at $T = 30\text{ s}$ to reduce the temperature drop.

II. LIGHT-WEIGHT RADIOISOTOPE HEAT SOURCE

The final shipment of clad components was received. The fueling and assembly operation will be resumed in January.

III. SAFETY TECHNOLOGY (D. Peterson)

The computer codes that analyze helium release data to obtain diffusion constants and activation energies

were revised so that they operate in the HP-87 Microprocessor to enable on-line analysis of helium release rates during an experiment.

The computer was also programmed and interfaced through a multiplexer to an automatic optical pyrometer and a power supply in order to control and measure the furnace temperature.

(a)

(b)

Fig. 1. The impacted module of GPHS test SVT-2 was cracked but intact: (a) impact face (0.6X); (b) back side (0.65X).

(a)

(b)

(c)

(d)

Fig. 2. Both impact assemblies in SVT-2 were cracked by the force of the impact: (a) PGL-054 impact face; (b) PGL-054 side view; (c) PGL-018 impact face; (d) PGL-018 side view (1X).

(a)

(b)

(c)

(d)

Fig. 3. Neither fueled clad in the prime impact assembly in SVT-2 failed in the impact: (a) FC-355 impact face; (b) FC-355 side view; (c) FC-369 impact face; (d) FC-369 side view (1.5X).

Fig. 4. Fueled clad FC-273 did not fail in the SVT-2 impact test: (a) impact face; (b) side view (1.5X).

TABLE I. Results of Spectrographic Analysis of GPHS Iridium

Test No.	Clad No.	Cup No.	Selected Elements ^a (ppm)								
			Cu	Mg	Ca	Al	Si	Cr	Fe	Ni	Pt
SVT-1	FC-232	LR313-1	3	nd ^b	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
SVT-2	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
SVT-3	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

^a Elements present in excess of the detection limit.

^b nd—not detected.

(a)

(b)

(c)

(d)

Fig. 5. Fueled clad FC-449 sustained three failures when impacted as part of the SVT-2 assembly: (a) impact face; (b) side view showing the weld crack; (c) back view showing the longitudinal crack (1.5X); (d) quarter view showing the radius crack (2X).

(a)

(b)

(c)

(d)

Fig. 6. The fracture patterns of the plutonia pellets in SVT-2 varied considerably: (a) HF-273; (b) HF-449; (c) HF-355; (d) HF-369 ($\sim 1.5X$).

(a)

(b)

(c)

(d)

Fig. 7. Sections through the impact failures in FC-449 showed them to be brittle and intergranular: (a) longitudinal crack in vent cup; (b) longitudinal crack in shield cup; (c) weld crack; (d) radius crack in vent cup (50X).

(a)

(b)

Fig. 8. The closure welds in the prime SVT-2 clads were fully penetrated and free of porosity: (a) FC-355 showing a typical weld crack in the overlap region; (b) FC-369 (50X).

TABLE II. SVT-2 Components

Component	Serial No.
Aeroshell	PAL-015
Prime impact assembly	
Impact shell	PGL-054
Fueled clads	FC-355, FC-369
Fuel pellets	HF-355, HF-369
Insulation sleeve	C40-5
Insulation disks	P8-2-44, P12-1-17
Secondary impact assembly	
Impact shell	PGL-018
Fueled clads	FC-273, HF-449
Fuel pellets	HF-273, HF-449
Insulation sleeve	C33-9
Insulation disks	P11-1-10, P11-1-11

(a)

(b)

(c)

(d)

Fig. 9. The microstructures of the cups that made up the prime SVT-2 clads were quite uniform: (a) FC-355 vent cup; (b) FC-355 shield cup; (c) FC-369 vent cup; (d) FC-369 shield cup (100X).

Fig. 10. The nickel mass simulants used in the final calibration run for the GPHS fragment test were cleaved by the edge-on sheet fragment (0.4X).

TABLE III. Impact Summary, GPHS SVT Series

Test No.	Clad No.	Deformation (%)		Failures ^a	
		Diametral	Axial	Number	Area (mm ²)
SVT-1	FC-232(P) ^b	+13.5, -11.1	+5.8	0	25.4
	FC-238(P)	+9.6, -7.3	+3.8	0	
	FC-261(S)	+11.7, -11.1	+5.6	2	
	FC-410(S)	+9.8, -9.6	+1.4	1	
SVT-2	FC-355(P)	+10.0, -10.4	+4.1	0	8.4
	FC-369(P)	+9.1, -9.3	+4.1	0	
	FC-449(S)	+12.5, -10.3	+5.6	3	
	FC-273(S)	+10.3, -10.5	+4.4	0	
SVT-3	FC-343(P)	+12.3, -9.0	+5.7	0	0.4
	FC-350(P)	+10.0, -8.5	+2.6	0	
	FC-457(S)	+10.8, -7.2	+5.6	0	
	FC-454(S)	+9.5, -6.4	+2.9	1	

^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.

^b(P)—prime assembly; (S)—secondary assembly.

TABLE IV. Iridium Grain Size, GPHS SVT Series

Test No.	Clad No.	Cup No.	Intercept Diam ^a (μm)	Nominal ^b	Comments
SVT-1	FC-232	LR313-1(v) ^c	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

^a Intercept size is average diameter measured by the boundary intercept method.^b Nominal size is the number of grains across a 640- μm thickness.^c (v)—vent cup; (s)—shield cup.

TABLE V. Results of Auger Electron Spectroscopy Analysis of the Iridium Clads of GPHS Test SVT-2

Specimen	Location	Th ₆₅	P ₁₂₉	C ₂₇₀	O ₅₁₀
		Ir ₂₂₉	Ir ₂₂₉	Ir ₂₂₉	Ir ₂₂₉
FC-449 Vent cup-1	Int. edge	0.60	nd ^a	0.12	0.42
	Center	0.69	nd	0.14	0.39
	Ext. edge	0.64	nd	0.22	0.60
	Average	0.61	nd	0.16	0.47
FC-449 Vent cup-2	Int. edge	0.82	nd	nd	nd
	Center	0.97	nd	nd	nd
	Ext. edge	0.66	nd	0.27	0.25
	Average	0.82	nd	0.09	0.08
FC-449 Shield cup-1	Int. edge	0.43	nd	0.72	0.96
	Center	0.32	nd	0.45	0.97
	Ext. edge	0.43	nd	0.61	1.09
	Average	0.39	nd	0.59	1.01
FC-449 Shield cup-2	Int. edge	0.45	nd	0.30	0.66
	Center	0.68	nd	0.32	0.43
	Ext. edge	0.65	nd	0.35	0.61
	Average	0.59	nd	0.32	0.57
FC-449 Weld	Vent cup side	0.62	nd	0.19	0.49
	Shield cup side	0.23	nd	0.92	0.88
FC-369 Vent cup-1	Int. edge	0.48	nd	0.29	0.74
	Center	0.63	nd	0.40	1.01
	Ext. edge	0.40	0.10	0.22	0.46
	Average	0.50	0.03	0.31	0.74
FC-369 Vent cup-2	Int. edge	0.46	nd	0.47	0.74
	Center	0.53	0.05	0.33	0.90
	Ext. edge	0.46	0.11	0.37	0.62
	Average	0.48	0.05	0.39	0.79
FC-355 Vent cup-1	Int. edge	0.82	nd	0.14	0.29
	Center	0.93	nd	nd	0.27
	Ext. edge	0.76	0.16	0.16	0.37
	Average	0.84	0.05	0.10	0.31
FC-355 Shield cup-1	Int. edge	0.65	0.15	nd	0.25
	Center	0.85	0.08	0.16	nd
	Ext. edge	0.63	nd	0.17	0.32
	Average	0.71	0.08	0.11	0.19
FC-355 Shield cup-1	Int. edge	0.55	nd	0.14	0.52
	Center	0.86	nd	0.09	0.21
	Ext. edge	0.56	0.15	0.13	0.34
	Average	0.66	0.05	0.12	0.36
FC-355 Shield cup-2	Int. edge	0.37	nd	0.43	0.77
	Center	0.53	0.06	0.19	0.49
	Ext. edge	0.54	0.07	0.13	0.37
	Average	0.48	0.04	0.24	0.54

^and—not detected.

TABLE VI. Plutonia Analyses, GPHS SVT Series

Test No.	Pellet No.	Selected Elements (ppm)							
		P ^a	Mg	Ca	Al	Si	Fe	Cr	Ti
SVT-1	HF-232	5	1	130	20	15	60	15	nd ^b
	HF-238	5	1	200	25	70	70	15	5
	HF-261	5	nd	200	20	25	85	40	nd
	HF-410	2	3	400	25	45	110	35	5
SVT-2	HF-355	4	2	40	25	30	65	30	nd
	HF-369	3	2	30	15	15	45	10	nd
	HF-273	3	2	40	25	70	55	25	7
	HF-449	2	2	40	35	50	80	30	nd
SVT-3	HF-350	3	nd	200	35	20	35	10	nd
	HF-343	5	10	100	35	30	20	10	nd
	HF-454	2	nd	200	60	50	70	60	nd
	HF-457	3	nd	150	35	10	20	15	nd

^aColorimetric analysis.^bnd—not detected.

TABLE VII. GPHS-SVT Fuel Release

Module No.	Component ^c	Pu Content (g)		
		10 μ m	>10 μ m	Total
SVT-1	GIS, intact ^b	0.0010	0.0034	0.0044
	GIS, failed	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

^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.

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