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Progress Report

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Space Nuclear Safety Program

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Compiled by
T. G. George

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SPACE NUCLEAR SAFETY PROGRAM

August 1984

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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 are ongoing; the results and conclusions described may change as the work progresses.

I. GENERAL-PURPOSE HEAT SOURCE (GPHS)/SAFETY VERIFICATION TEST (SVT) SERIES

A. SVT-8 Postmortem Examination (T. George)

Details of the test conditions, module disassembly, and preliminary results were given in previous monthly reports. In this month we received the results of additional analyses and concluded metallographic examination of all test components.

1. Iridium Chemistry. Specimens for spectrographic analysis were removed from each of the primary clads (FC-436 and FC-437) and from the breached secondary clad (FC-391). Results of the spectrographic analyses are given in Table I. The results of Auger electron spectroscopic (AES) analyses conducted on specimens removed from the primary clads are presented in Table II.

The spectrographic results indicate that all of the iridium cups had similar chemistries. The minor variations that were observed would not have affected the impact responses.

Results of the AES analyses indicate that the interior surfaces of the FC-436 vent cup and both FC-437 cups were low in thorium. Electron imaging of the specimens did not reveal any abnormal grain growth that could be correlated with the reduced thorium contents.

2. Weld Metallography. The closure welds on the primary clads were generally of good quality and had typical microstructures. However, the FC-391 weld (trailing clad that opened along the closure weld) contained a significant amount of porosity (Fig. 1). Although the weld microstructure was acceptable (Fig. 2), the vent and weld shield cups were not properly aligned (Fig. 3). In addition, two large voids were present at the edge of the fusion zone (Fig. 4) on the shield cup side of the weld. The presence of such significant defects (the largest void was approximately 0.33 mm in diameter) in a weld with an SRP/NDE* rating of 9.8 is disturbing; 8.0 is the minimum value for flight-quality capsule welds.

3. Iridium Microstructure. Specimens for metallographic examination were removed from capsules FC-391, FC-436, and FC-437. The cup microstructures were fine grained and were consistent with the grain sizes observed in previous SVT clads. The cup grain sizes are listed in Table III. Details of the metallographic examinations are given below.

Examination of an FC-391 shield cup section revealed that the large axial crack on the trailing face (Fig. 5) occurred in a relatively fine grained region (Fig. 6). The crack had the same brittle intergranular appearance observed in previous clad failures, with no indication that the crack resulted from anything other than the significant deformation produced by the weld

*Savannah River Plant nondestructive evaluation.

TABLE I. Spectrographic Analyses (ppm) of the SVT-8 Primary and Breached Secondary Clads

Element ^a	FC-391		FC-436		FC-437	
	Vent Cup	Blind Cup	Vent Cup	Blind Cup	Vent Cup	Blind Cup
Fe	300	300	400	500	400	400
Al	50	50	50	70	50	50
Ca	3	<3	5	10	3	3
Ni	50	50	100	150	100	60
Cr	70	70	100	80	50	50
Cu	20	20	20	20	20	10
Si	20	<10	10	15	<10	<10
Mg	<3	<3	<3	3	<3	<3
W	0.1-1.0%	0.1-1.0%	0.1-1.0%	0.1-1.0%	0.1-1.0%	0.1-1.0%

^aElements are listed only if they exceed detectability limits in at least one sample.

failure. Examination of an FC-391 vent cup section revealed a typical microstructure, with no evidence of coarsening along the vent cup radius.

The FC-436 vent and weld shield cups had typical microstructures (Figs. 7 and 8). The cup radii were somewhat coarser grained than the average microstructures (Fig. 9), but preferential grain growth on the interior surfaces was not evident. Sections of the FC-436 vent cup showed an unexpected amount of ductility (Figs. 10 and 11). A transverse section containing a deep bend on the impact face (Fig. 10) was particularly interesting because of the apparent grain elongation.

The FC-437 vent and shield cup microstructures were also fine grained (Figs. 12 and 13). However, a small region of abnormal grain growth occurred on the interior of one vent cup section (Fig. 14). Slight grain coarsening also occurred at the interiors of the vent and shield cup radii (Figs. 15 and 16). As in FC-436, a vent cup section containing a reverse bend on the impact face showed an unexpected amount of ductility (Fig. 17).

4. Vent Metallography. Metallographic examination of the FC-436 and FC-437 capsule vents did not reveal any mechanical defects. The vent frits were uniform and properly aligned. No large inclusions or glassy oxides were observed in either frit.

Although macroscopic examination did not reveal vent effusates (Figs. 18 and 19), glassy deposits were observed on the vent exteriors and in the center holes (Fig. 20). A thin layer of glassy material was also present at an interior opening of the FC-436 vent (Fig. 21). The small deposit on the exterior of the FC-436 vent reacted with the iridium (Fig. 22) and began to form an intergranular network. The deposits on both vents promoted excessive iridium grain growth (Figs. 23 and 24). Although the composition of these deposits is currently unknown, we plan to submit specimens for microprobe analysis.

In addition to grain growth near the vent center holes, large grains were visible in wall sections adjacent to the FC-437 vent cover weld (Fig. 25). This phenomenon was observed on the vents of clads used in previous SVT impacts.

5. Fuel Ceramography. Ceramographic examination of specimens removed from each of the SVT-8 fuel pellets did not reveal any unusual features. All of the fuel samples had typical microstructures.

B. SVT-9 Postmortem Examination (D. Pavone)

The SVT-9 test assembly was subjected to aging heat treatments to simulate orbital-decay reentry and was impacted against a steel target at a module orientation of $\alpha = 30^\circ$, $\beta = \gamma = 0^\circ$. During the 90-day preimpact aging treatment, continuous monitoring of helium release indicated that no vent plugging occurred. Because of an error in loading the aeroshell, the secondary impact assembly was placed in the lead (primary) position. For the purposes of this examination we treated FC-473 and FC-501, the fueled clads of the original secondary graphite impact shell (GIS), as "primary" fueled clads. Components of the entire test assembly are listed in Table IV.

The recovered aeroshell is shown in Fig. 26. Aero-shell damage was greater than that in $\alpha = 0^\circ$ or the $\alpha = 15^\circ$ orientations. Two pieces were broken from the leading broad face of the aeroshell; the remainder of the body was severed into two pieces by fractures along the narrow closure faces and by a crack on the trailing broad face, roughly parallel to the axis of the secondary impact assembly. Both impact shells had axial, irregular cracks on the impact face center; however, the overall distortion of the leading impact shell was greater than that of the trailing impact shell.

TABLE II. Results of AES Examinations

Specimen	Th₆₅/Ir₂₂₉	C₂₇₀/Ir₂₂₉	O₅₁₀/Ir₂₂₉	S₁₅₀/Ir₂₂₉	Cl₁₈₀/Ir₂₂₉
FC-436 Vent Cup					
Impact face					
inside	0.138	---	0.276	0.034	---
center	0.666	0.033	0.316	---	---
outside	0.393	0.032	0.951	0.033	---
Trailing face					
inside	0.178	0.071	0.696	---	0.143
center	0.385	0.154	1.135	0.038	0.038
outside	0.459	0.032	0.918	0.098	0.295
FC-436 Blind Cup					
Impact face					
inside	0.313	0.031	1.266	0.063	0.156
center	0.431	0.039	1.647	0.039	0.078
outside	0.444	0.074	1.055	0.037	0.185
Trailing face					
inside	0.385	0.038	0.115	---	0.038
center	0.923	---	0.269	---	---
outside	0.596	0.070	0.386	0.018	---
FC-437 Vent Cup					
Impact face					
inside	0.392	---	---	---	---
center	0.823	---	---	---	---
outside	0.772	---	---	---	---
Trailing face					
inside	0.151	0.038	0.452	---	---
center	0.500	0.038	0.615	---	---
outside	0.593	0.074	0.555	---	---
FC-437 Blind Cup					
Impact face					
inside	0.208	---	0.042	---	---
center	0.961	---	---	---	---
outside	0.622	---	0.333	---	---
Trailing face					
inside	0.109	0.036	0.473	---	---
center	0.400	0.060	0.880	---	---
outside	0.326	0.082	0.694	---	---

TABLE III. SVT-8 Clad Grain Size (Average No. of Grains/0.635-mm Nominal Wall Thickness)

Capsule	Cup	Section	Average Grains/Thickness
FC-391	Vent	Axial	13.2
		Transverse	not determined
	Blind	Axial	not determined
		Transverse	15.0
FC-436	Vent	Axial	12.1
		Transverse	13.9
	Blind	Axial	13.2
		Transverse	12.9
FC-437	Vent	Axial	13.4
		Transverse	14.1
	Blind	Axial	13.0
		Transverse	13.4

TABLE IV. Components of the SVT-9 Test Assembly

Aeroshell	PAL-034
Prime impact assembly	
Insulation cylinder	C-43-6
Insulation disks	P-12-2-53:P-12-1-8
Impact shell	PGL-098
Fueled clad (open end)	FC-591
Fuel pellet	HF-591
Vent cup	S38-2
Shield cup	S37-2
Fueled clad (blind end)	FC-592
Fuel pellet	HF-592
Vent cup	SR-65-3
Shield cup	SR-65-6
Secondary impact assembly	
Insulation cylinder	C-39-5
Insulation disks	P-8-1-19:P-12-1-9
Impact shell	PGL-091
Fueled clad (open end)	FC-473
Fuel pellet	HF-473
Vent cup	S39-4
Shield cup	S14-2
Fueled clad (blind end)	FC-501
Fuel pellet	HF-501
Vent cup	SR-52-1
Shield cup	SR-51-6

No failures occurred in any of the fueled clads. Overall capsule deformation was generally symmetric, and localized iridium deformation was mild. The impacted fueled clads are shown in Fig. 27. Details of the test parameters and capsule strains are given in Table V.

The as-opened fueled clads are shown in Fig. 28. These photographs illustrate the symmetrical deformation of the fueled clads and the generally similar plutonia fragmentation. Fragment sizes of pellets HF-591 and HF-501 were slightly greater than those of HF-473 and HF-592.

The microstructures of the FC-473 and FC-501 iridium shells exhibited grain coarsening on the interior 20-25% of the wall thickness. In addition, sections with large grains on the wall exterior occurred in the vent cups of both fueled clads. In isolated locations, the microstructure showed unusual mixed grain sizes

TABLE V. Summary of SVT-9, Orbital Decay Reentry at 30° Impact Orientation^a

Fueled Clad	NDE Value	Gross Deformation (%)		
		Diam	Height	Axial
FC-592	3.0	+6.0	-6.1	+2.4
FC-591	1.6	+7.1	-8.9	+3.7
FC-501	11.4	+6.7	-5.7	+4.3
FC-473	10.3	+6.0	-5.1	+2.0

^aAged 90 Days at 1287°C. Impact at 54 m/s and 975°C.

(Fig. 29). Typical cup microstructures are shown in (Fig. 30); the average grain sizes are tabulated in Table VI.

The FC-473 and FC-501 vent orifices were free of vapor-transported deposits; only modest amounts of plutonia were deposited at the filter element entrances. The vent assembly and decontamination cover welds were sound, but abnormal iridium grain growth was associated with these welds (Fig. 31).

Cross sections of the FC-473 and FC-501 closure welds are shown in Fig. 32. Although both welds were free of porosity and had acceptable microstructures, the bead width of the FC-473 weld was significantly less than that of the FC-501 weld. In addition, grain coarsening occurred on the interior of capsule FC-473 within the heat-affected zone of the weld.

Results of the AES analysis of the iridium grain boundary chemistry are tabulated in Table VII. Thorium depletion at the interior was moderate in most samples and severe in a few. Low levels of phosphorus were observed in samples from both fueled clads. Sulfur was also detected in small amounts in three FC-473 samples and in one sample of each FC-501 cup. The other samples, however, showed low to moderate sulfur concentrations. Moderate levels of chlorine were found in a vent cup sample of FC-501, and low concentrations were indicated at some locations in four other samples.

Emission spectrographic analysis (Table VIII) revealed lower concentrations of iron than in previous clad samples subjected to identical thermal treatment. The aluminum contents (30 ppm) were also lower.

The microstructures of the HF-473 and HF-501 fuel pellets were typical of SRP-produced fuel. Table IX presents the results of chemical analysis of the four plutonia pellets. The calcium contents (750 ppm) were higher than those of previous SVT pellets. One pellet, HF-473, also had a high aluminum content. The high calcium contents suggest that the samples may have been contaminated during the handling and analytical

procedures. We were not able to confirm the calcium analyses by γ -scan techniques.

The total quantity of plutonium present in the graphite components was 0.0024 g. Because there were no failures, this amount represents material that effused through the vents; the particle size of this material is considered to be less than 10 μm .

C. Bullet/Fragment Tests (T. George and R. Tate)

The third and fourth SVT bullet/fragment tests were conducted at a remote Los Alamos test site. In both tests, a .50-caliber, 18-g, aluminum-alloy bullet (Fig. 33) was fired into a simulated module stack. The target assembly consisted of four parts: a Fineweave-Pierced Fabric* (FWPF) half-module containing a FWPF GIS and two simulant-fueled (UO_2) clads, a bulk graphite backing block, and two bulk graphite blocks of GPHS configuration on either side of the target module. The backing block and adjoining blocks were weighted with tantalum rods to match the masses of the components being simulated. All FWPF components were made from flight-quality material machined to flight configurations. The iridium-alloy containment shells were provided by the Mound Facility and were also flight-quality material. Los Alamos provided the UO_2 fuel simulant pellets, welded the capsules, and assembled the target components.

Results and conditions of the third and fourth bullet/fragment tests are summarized in Table X. Preliminary results of the test postmortems are given below.

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

TABLE VI. Average Grain Size of the SVT-13 Primary Clads

Clad No.	Cup No.	Grains per Nom. 640 μm		Comments
		Transverse	Axial	
FC-473	S39-4	13	15	Large interior grains, 25% of thickness, and isolated large exterior grains.
	S14-2	16	17	Large interior grains, 25% of thickness, and isolated areas of mixed grain size.
FC-501	SR52-1	14	14	Large interior grains, 25% of thickness, and isolated large exterior grains.
	SR51-6	15	18	Large interior grains, 20-30% of thickness, and isolated areas of mixed grain size.

TABLE VII. AES Analyses of SVT-9 Iridium Clads

Specimen	Location	Th ₆₅ /Ir ₂₂₉	P ₁₂₀ /Ir ₂₂₉	C ₂₇₀ /Ir ₂₂₉	O ₅₁₀ /Ir ₂₂₉	S ₁₅₀ /Ir ₂₂₉	Cl ₁₈₀ /Ir ₂₂₉
FC-473							
Vent cup 1	Int. Edge	0.08	nd ^a	0.43	0.70	0.07	0.10
	Center	0.48	0.10	0.43	0.92	nd	0.04
	Ext. Edge	0.54	nd	0.84	1.36	0.10	0.14
	Average	0.37	0.03	0.57	0.99	0.06	0.09
Vent cup 2	Int. Edge	0.38	nd	1.08	1.21	0.22	nd
	Center	0.45	nd	0.66	1.28	0.04	nd
	Ext. Edge	0.42	nd	0.68	0.90	0.11	nd
	Average	0.42	nd	0.81	1.13	0.12	nd
Shield cup 1	Int. Edge	0.05	nd	0.43	0.54	nd	nd
	Center	0.51	0.07	0.30	0.83	nd	nd
	Ext. Edge	0.37	0.14	0.46	0.96	nd	0.09
	Average	0.31	0.07	0.40	0.78	nd	0.03
Shield cup 2	Int. Edge	0.23	nd	0.36	0.82	nd	nd
	Center	0.63	0.08	0.38	0.93	0.03	nd
	Ext. Edge	0.51	0.16	0.65	0.97	0.08	nd
	Average	0.46	0.08	0.46	0.91	0.04	nd
FC-501							
Vent cup 1	Int. Edge	0.09	nd	0.82	1.08	vs ^b	nd
	Center	0.24	nd	0.55	1.74	vs	nd
	Ext. Edge	0.15	nd	0.94	1.14	vs	0.08
	Average	0.16	nd	0.77	1.32	vs	0.03
Vent cup 2	Int. Edge	0.24	nd	1.51	0.73	0.16	0.29
	Center	0.38	nd	1.10	0.93	0.06	0.18
	Ext. Edge	0.59	0.07	1.28	0.98	0.33	0.37
	Average	0.40	0.02	1.30	0.88	0.18	0.28
Shield cup 1	Int. Edge	0.41	0.06	0.90	1.00	nd	nd
	Center	0.37	nd	0.80	0.94	0.10	0.06
	Ext. Edge	0.62	0.10	0.95	0.86	0.02	0.02
	Average	0.47	0.05	0.88	0.93	0.04	0.04
Shield cup 2	Int. Edge	0.31	nd	0.89	0.73	vs	nd
	Center	0.50	nd	0.57	1.18	vs	nd
	Ext. Edge	0.56	nd	0.76	1.10	vs	nd
	Average	0.46	nd	0.74	1.04	vs	nd

^aNot detected.^bVery strong.

TABLE VIII. Emission Spectrographic Analysis of SVT-9 Iridium Clads (ppm)

Clad No.	Cup No.	Cu	Mg	Ca	Al	Si	Cr	Fe	Ni	Pt
473	S39-4	5	nd	nd	30	nd	10	100	20	nd
	S14-2	20	nd	nd	30	nd	30	100	70	nd
501	SR52-1	5	nd	nd	30	nd	10	100	20	nd
	SR51-6	5	nd	nd	30	nd	10	70	10	nd

TABLE IX. Chemical Analyses of the SVT-9 Fuel Pellets

Pellet No.	Selected Elements (ppm)								
	P	Mg	Ca	Al	Si	Fe	Cr	Ni	Ti
HF-473	16	5	750	770	40	35	10	nd ^a	35
HF-501	14	5	750	145	40	7	7	nd	35
HF-591	20	3	750	nd	15	nd	10	nd	35
HF-592	4	2	750	85	15	20	8	nd	35

^aNot detected.

1. **Bullet/Fragment Test 3.** Bullet Test 3 was completed on August 23, 1984. In the test, a .50-caliber aluminum 2219/T87 bullet was fired into a partial GPHS module at 458 m/s. Clad temperature at impact was 1080°C.

The bullet penetrated the aeroshell (Fig. 34) and struck the top clad approximately 4 mm above the weld centerline (weld shield cup). The bullet remained in place but melted from the heat of the test assembly.

Disassembly of the test module revealed that the molten aluminum had reacted with the iridium, possibly along cracks opened by the impact. Two large holes and a number of spatter marks were evident on the impact face of the clad (Fig. 35). The hole at the center of the bullet contact area was a rough oval, with approximate dimensions of 6.5 mm × 3.4 mm. This hole was originally plugged by an intermetallic mass attached to the solidified bullet (Fig. 36). The second hole, less obvious in a straight-on view, was on the grit blast line of the vent cup (Fig. 37). This hole was approximately 10 mm long and 3.5 mm across at the widest point. A centerline weld crack, 22 mm long, was also observed on the trailing face of the clad (Fig. 38).

Macroscopic examination of the holes and spatter marks on the impact face revealed several unusual features. The hole at the center of the bullet contact area was ringed by a shiny intermetallic compound (Fig. 39). The compound was apparently brittle and fractured in a conchoidal pattern when the bullet was removed. Examination of a shiny deposit (spatter mark) just below the center hole revealed a similar surface morphology

(Fig. 40). Interestingly, the interior wall section corresponding to this deposit was cracked (Fig. 41). The same phenomena was observed on the interior of a vent cup section with a large external deposit (Fig. 42).

The intermetallic compound(s) that forms from the Ir/Al reaction apparently is considerably less dense than the parent iridium. Consequently, the compound formation is accompanied by a large volumetric expansion. This increase in volume at the clad surface appears to produce strains sufficient to crack the clad interior.

The clad and aluminum bullet will be sectioned to provide specimens for optical metallography, SEM examination, x-ray diffraction, and microprobe analysis. In September, these samples will be analyzed and we will conduct several thermodynamic experiments to increase our understanding of the Ir/Al reaction and its implications.

2. **Bullet/Fragment Test 4.** In the fourth bullet test, the projectile velocity was 460 m/s and the clad temperature at impact was 1060°C. The bullet struck the half-module 6 mm to the right of the module centerline (Fig. 43). In contrast to the third test, the module tipped forward onto the impact face, allowing the molten bullet to drain out. In two small areas, the aluminum reacted with the iridium, but the clad was not breached. The bullet apparently struck the GIS off center, and when it reached the fuel clad it was deflected upward and to the right. The deformed capsule is shown in Fig. 44. No breach was observed on the clad exterior.

TABLE X. Summary of the SVT Bullet/Fragment Tests

Test	Temperature (°C)	Velocity (m/s)	Clad	Bullet Contact Area (mm²)	Remarks
1	1091	319	IRG-113	93	Bullet struck the clad ≈3.5 above the weld centerline and did not fully penetrate the impact shell; no breach.
2	1030	415	IRG-119	288	Bullet struck the clad tangentially along the weld centerline; weld unzipped over 330°. Breaching crack measured 2.5 mm at widest point. Three small areas of apparent Ir/Al reaction observed on clad surface.
3	1080	458	IRG-130	342	Bullet impacted ≈4.0 mm above the weld centerline, remained in place, and melted. Brittle intermetallic formed at Ir/Al interface. Large hole (10 mm × 3.5 mm) observed on vent cup impact face.
4	1060	460	IRG-111	266	Bullet struck the clad ≈6.0 mm above the weld centerline; no breach. Two small areas of Ir/Al reaction observed on clad surface.

II. SAFETY TECHNOLOGY PROGRAM

A. Investigation of Ir/Th/P Ternary Compounds (K. Axler)

We continued our studies of ternary phases of thorium phosphides and carbides. In one experiment, we arc-melted a mixture of thorium and iridium having a Th:Ir atomic ratio of 1:5. Subsequent x-ray diffraction confirmed the formation of ThIr_5 , a thorium compound present in the DOP-26 iridium heat source cladding. The arc-melted compound was ground, pressed, combined with phosphorus, placed in an alumina crucible, and sealed in an evacuated quartz tube. The sample was then heated to 900°C for 24 h. Unfortunately, the heat treatment led to the formation of a pyrophoric phase that reacted when the quartz tube was opened. X-ray diffraction of the crucible contents identified only IrP_2 , Ir_2P , ThIr_5 , and unreacted iridium.

We also began a second experiment in which we are attempting to grow a phosphide single crystal in a molten copper flux. As before, we arc-melted a Th/Ir mixture and combined the resulting product with phosphorus. This mixture was then placed in an alumina crucible containing copper powder. The crucible was sealed in an evacuated quartz tube and was heated to 1240°C. A computer-controlled furnace is slowly cooling the mixture from this temperature.

B. Characterization of the Al/Ir Binary System (K. Axler)

Because of the vigorous iridium/aluminum reaction observed in the SVT bullet/fragment tests, we are now trying to characterize the Al/Ir system. Mixtures with atomic ratios corresponding to AlIr and Al_2Ir_3 were arc-melted and submitted for x-ray diffraction. Preliminary

results indicate that AlIr was formed from the first mixture.

C. Iridium Biaxial Testing (T. George)

In this month, we analyzed the results of previous impacts and determined the direction of future testing. Our current results indicate the following:

Test Conditions (+, 0 strain state)	Approximate Strain (%) at Failure
1440°C, 45 m/s, 25 grains/thickness	110
1440°C, 45 m/s, 5 grains/thickness	20
800°C, 45 m/s, 25 grains/thickness	20
600°C, 45 m/s, 25 grains/thickness	15

These values are approximate because the scatter of the data does not permit the determination of precise failure limits. We will need additional information on the alloy behavior in other strain states (specifically the +, - state) to accurately determine strain at failure in the +, 0 strain state.

We expect that 12 tensile specimens being circle-gridded will be returned shortly. After these samples have been tested, we will have a better understanding of the failure limits. We also plan to test disks at the following conditions:

- 1000°C, 45 m/s, 25 grains/thickness
- 1440°C, 45 m/s, 15 grains/thickness
- 1000°C, 45 m/s, 15 grains/thickness

(a)

(b)

Fig. 1. The FC-391 closure weld contained a significant amount of porosity. (a) Weld-shield side of centerline weld crack and (b) vent cup side; both at 50X.

Fig. 2. The microstructure of the FC-391 weld was acceptable; etched, 50X.

Fig. 3. The FC-391 vent and weld shield cup were slightly misaligned; as polished, 50X.

(a)

Fig. 4. A face-on section of the FC-391 weld contained two large voids; the terminus of the breaching crack is also visible. (a) As polished, 7X, and (b) etched, 50X.

(b)

Fig. 5. A large axial crack was present on the trailing face of the FC-391 shield cup; 2X.

(a)

(b)

Fig. 6. The crack on the trailing face of the FC-391 shield cup penetrated a relatively fine grained section. (a) Left side of crack and (b) right side; both at 50X.

Fig. 7. The FC-436 vent cup had an acceptable microstructure; etched, 50X.

Fig. 8. The FC-436 shield cup also had a typical microstructure; etched, 50X.

(a)

(b)

Fig. 9. A minor amount of grain coarsening was observed on the radii of the FC-436 iridium cups. (a) Vent cup radius and (b) shield cup radius; both at 50X.

Fig. 10. An unexpected amount of ductility was observed in a transverse section removed from the impact face of the FC-436 vent cup; 50X.

Fig. 11 An axial section of the FC-436 vent cup also contained a deep bend; 50X.

Fig. 12. The FC-437 vent cup had a generally fine grained microstructure; 50X.

Fig. 13. The FC-437 shield cup was also relatively fine grained; 50X.

Fig. 14. A small section of the FC-437 vent cup was coarse grained; 50X.

Fig. 15. There was also evidence of grain growth at the FC-437 vent cup radius; 50X.

Fig. 16. Large grains were observed on the radius of the FC-437 shield cup; 50X.

Fig. 17. A reverse bend on the impact face of the FC-437 vent cup contained evidence of ductile deformation; 50X.

Fig. 18. No effusate was visible on the exterior of the FC-436 vent; 1.5X.

Fig. 19. The exterior of the FC-437 vent was also free of visible deposits; 1.5X.

Fig. 20. Glassy deposits were visible within and around the center hole of the FC-436 vent; 50X.

Fig. 21. A similar deposit was observed at an interior opening of the FC-436 vent; 50X.

Fig. 22. The glassy deposits reacted with the iridium and began to form an intergranular network; as polished, 100%.

Fig. 23. The deposits on the FC-436 vent apparently promoted abnormal grain growth; 50%.

Fig. 24. The FC-437 vent also contained evidence of excessive grain growth; 50X.

(a)

(b)

Fig. 25. Excessive grain growth was also observed in wall sections adjacent to the FC-437 vent cover weld. (a) Impact face side and (b) opposite face; both at 50X.

Fig. 26. The aeroshell in SVT-9 incurred greater damage than those impacted in the $\alpha = 15^\circ$, $\beta = 0^\circ$ orientations.

SVT-9 : Leading GIS

SVT-9 : Trailing GIS

Fig. 27. There were no failures of the fueled clads in SVT-9. Left to right: Impact face, side view, back side, and vent end view, (a) FC-473, (b) FC-501, (c) FC-591, and (d) FC-592.

(a)

(b)

(c)

(d)

Fig. 28. All of the SVT-9 fuel pellets fractured in a random manner; the fragment sizes in HF-501 and HF-591 were generally larger than in the other pellets. (a) HF-373, (b) HF-501, (c) HF-591, and (d) HF-592; all at 1.5%.

(a)

(b)

Fig. 29. Abnormal microstructures consisting of mixed grain sizes were observed at isolated locations in the shield cups of (a) FC-473 and (b) FC-501; both 50X.

Fig. 30. Typical microstructures of the FC-473 and FC-501 iridium cups. (a) FC-473 vent cup, (b) FC-473 shield cup, (c) FC-501 vent cup, and (d) FC-501 shield cup; 50X.

(a)

(b)

Fig. 31. Abnormal grain growth occurred adjacent to the FC-473 and FC-501 vent cover and assembly welds. (a) FC-473 vent and (b) FC-501 vent; both at 50X.

(a)

(b)

Fig. 32. The microstructures of the FC-473 and FC-501 closure welds were acceptable. (a) FC-473 weld and (b) FC-501 weld; both at 50X.

Fig. 33. Schematic of the bullet/fragment test projectile.

Fig. 34. In the third SVT bullet test, the Al 2219 bullet penetrated the aeroshell and struck the top capsule, SC-130, approximately 4 mm above the weld centerline.

Fig. 35. Two large cracks and numerous spatter marks were evident on the impact face of capsule SC-130; 1.5X.

Fig. 36. A small intermetallic mass attached to the solidified bullet originally plugged the hole at the center of the SC-130 impact face; 1.5X.

Fig. 37. A second hole was visible on the grit blast line of the SC-130 vent cup; 1.2X.

(a)

(b)

Fig. 38. A centerline weld crack was observed on the trailing face of SC-130; (a) 1.5X and (b) 5X.

Fig. 39. The hole at the center of the SC-130 impact face was ringed by an intermetallic compound; 10.5X.

Fig. 40. A spatter mark below the center hole appeared to be composed of the same intermetallic compound; 10.5X.

Fig. 41. The interior of the wall section seen in Fig. 36 was cracked; 6.7X.

(a)

(b)

Fig. 42. The same intermetallic compound and corresponding fracture on the interior wall were observed in the SC-130 vent cup. (a) External deposit and (b) crack on inner surface; both at 10.5X.

Fig. 43. GPHS half-module after fourth bullet test at 460 m/s.

Fig. 44. The simulant-fueled clad used in bullet/fragment test 4 was significantly deformed but did not breach.

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