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*General-Purpose Heat Source Development:
Safety Test Program*

Postimpact Evaluation, Design Iteration Test 4

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T. G. George
F. W. Schonfeld

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GENERAL-PURPOSE HEAT SOURCE DEVELOPMENT: SAFETY TEST PROGRAM

Postimpact Evaluation, Design Iteration Test 4

by

T. G. George and F. W. Schonfeld

ABSTRACT

The General-Purpose Heat Source (GPHS) provides power for space missions by transmitting the heat of ^{238}Pu decay to thermoelectric elements. Because of the inevitable return of certain aborted missions, the heat source must be designed and constructed to survive both re-entry and Earth impact. The Design Iteration Test (DIT) series is part of an ongoing test program. The fourth test (DIT-4) was designed to evaluate the effect on impact behavior of changing the procedure used at the Mound Facility (MF) to remove surface defects from drawn cups. The change involved switching from a manual abrasion technique to a motorized, rubber-bonded abrasive wheel. In DIT-4 a partial GPHS module containing two fueled clads (one cleaned manually, and one cleaned with an abrasive wheel) was impacted at a velocity of 58 m/s and a temperature of 930°C. Both capsules were severely deformed by the impact and contained large internal cracks. Although the manually cleaned capsule breached, the breaching crack was only 2 μm wide and released negligible amounts of fuel. There did not appear to be any correlation between cleaning method and capsule performance. Postimpact analyses of the DIT-4 test components are described with emphasis on microstructure and impact response.

I. INTRODUCTION

The General-Purpose Heat Source (GPHS) will provide power for a number of space missions. The first two uses will be the 1986 Galileo and International Solar-Polar missions. The GPHS uses the heat of $^{238}\text{PuO}_2$ alpha decay to generate power by means of a thermoelectric array; a fully loaded GPHS (four capsules) provides a total thermal output of 250 W. In addition to the inevitable return of Near-Earth Missions, the probability of a launch failure can never be zero. Therefore, the GPHS module must be designed and constructed to survive both re-entry and earth impact. The results described in this report are a portion of an ongoing test program and will provide necessary design information.

The first Design Iteration Test (DIT-1) was carried out at a velocity of 57 m/s and 930°C; the test module

was impacted "flat on" against a hardened steel target.¹ The test unit was a full GPHS module that contained two graphite impact shells (GISs); each GIS in turn contained two heat source capsules filled with $^{238}\text{PuO}_2$. The fuel capsules were loaded and welded at Los Alamos. The major concern in DIT-1 was the quality and survivability of the welds. All of the capsules survived impact and none of the capsules breached. Postimpact analysis revealed that the welds were of consistently good quality and behaved no differently than the surrounding material. Intergranular cracking was observed on the capsule walls and in the welds; some of these cracks traversed more than 70% of the wall thickness.

The second Design Iteration Test (DIT-2) was carried out in much the same manner as DIT-1; the test module was impacted flat on against a hardened steel target at a velocity of 57 m/s and a temperature of 930°C.² The test unit was a full GPHS module. The capsules used in this

test were fueled and welded at the Savannah River Plant (SRP). Two of the capsules were breached by the impact, and a small quantity ($\approx 50 \mu\text{g}$) of $^{238}\text{PuO}_2$ was released. All of the capsules contained large internal cracks similar to the fractures observed in DIT-1.

The third Design Iteration Test (DIT-3) was carried out at a velocity of 58 m/s and a temperature of 930°C.³ The test unit was a full GPHS module. DIT-3 differed from previous Design Iteration Tests in that the test module impacted the target at an inclination of 30° rather than flat on as in DIT-1 and DIT-2. In addition, the capsules used in DIT-3 were not “flight quality”; all of the DIT-3 capsules had been identified by SRP nondestructive testing (NDT) as having crack indications in excess of 8.0.⁴ The primary objectives of DIT-3 were to evaluate the impact behavior of capsules with SRP/NDT crack indications of up to 10.0 and to determine the effect of a 30° impact angle. All of the DIT-3 capsules survived impact and none of the capsules breached. Capsule deformation was minor; the 30° impact attitude was apparently much less severe than the flat on orientation of previous tests. Microscopic examination of the capsules revealed that SRP/NDT had been effective only in locating internal weld defects; there was little correlation between the predicted and microstructurally observed size of internal weld defects.

The fourth Design Iteration Test (DIT-4) was designed to provide information about the possible effect on impact behavior of changing the procedure used at the Mound Facility (MF) to remove surface defects from drawn cups. The change involved switching from a strictly manual abrasion technique to a motorized, rubber-bonded abrasive wheel. In the test, fueled clads SRP-394 (manual abrasive cleaning) and SRP-398 (motor-driven abrasive cleaning) were loaded into a partial aeroshell and impacted at 58 m/s and 930°C in a flat on orientation. A schematic of the DIT-4 test configuration is shown in Fig. 1.

II. PRETEST DATA

DIT-4 was added to the Design Iteration Test series to provide information regarding the possible effect on impact behavior of changing the procedure used to remove surface defects from drawn iridium cups. Two fueled clads, SRP-394 (manual abrasive cleaning) and SRP-398 (motor-driven abrasive cleaning), were selected for testing. The iridium-alloy cups and fuel pellets used in the assembly of the heat sources are identified in Table I; data describing the fuel pellets are presented in Table II. As in previous Design Iteration Tests, the fuel pellets used in DIT-4 were produced by SRP; Oak Ridge National Laboratory (ORNL) provided the iridium-alloy blanks; the Mound Facility (MF) fabricated the iridium cups; ORNL produced the

TABLE I. Encapsulation Details for DIT-4 Fueled Clads

Capsule	Iridium cup	
	Vent	Weld-Shield
SRP-394	5023-6	S 020-1
SRP-398	RN 928-3	S 033-5

TABLE II. Data for Sintered DIT-4 Fuel Pellets

Capsule	Diameter (mm)	Length (mm)	Weight (g)
SRP-394	27.48	27.63	150.2
SRP-398	27.53	27.41	149.0

graphite insulation [carbon-bonded carbon filament (CBCF)]; and Los Alamos machined the aeroshell and impact shell from Fineweave-Pierced-Fabric* (FWPF) graphite.

Both of the DIT-4 capsules were macroscopically examined for external weld defects. The weld overlaps were uniform and contained no obvious defects. Both clads had good wall alignment over the entire weld length; no bulges were observed in either capsule.

After macroscopic examination, the fueled clads were radiographed and loaded into a graphite impact shell (GIS). The GIS was then aged at 1310°C for 30 days; the heat treatment was designed to simulate the minimum expected service life. Following heat treatment, the capsules were radiographed a second time. Radiographs of the fuel pellets, before and after heat treatment, are shown in Figs. 2 and 3. It should be noted that the radiographs are not directly comparable; the fuel capsules were loaded into the GIS in a geometric arrangement that differed from their relationship in the shipping container. The radiographs do indicate, however, that although small cracks were present in the as-received fuel pellets, the heat treatment caused little further degradation.

III. TEST PROCEDURE

After heat treatment, the fueled GIS was loaded into the partial module as shown in Fig. 1. Fueled clad

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

SRP-394 was located in the blind end of the impact shell and SRP-398 was in the closure end (to avoid unnecessary complication, the fuel labels are used throughout this report to identify the fuel/clad sets). The test module was impacted at a velocity of 58 m/s and a temperature of 930°C. After the test, a catch tube containing the impacted module was transferred to Wing 2 of the CMR Building (at Los Alamos) and opened in a hood. The postimpact procedures used in DIT-4 were in general the same as those applied in previous Design Iteration Tests.

IV. POSTIMPACT EXAMINATION

Experience with previous Design Iteration Tests enabled postimpact disassembly to proceed at a rapid pace. The catch tube was opened without difficulty and only low levels (<2000 counts/min/cm²) of ²³⁸PuO₂ contamination were encountered. The inner nickel can (a radiation shield) was extracted with tongs, and the can/aeroshell/heat source assembly was placed on a bed of solid CO₂. The CO₂ cooled the assembly rapidly, and in a few seconds the temperature had dropped far enough to eliminate the possibility of graphite combustion.

The aeroshell was found to be severely damaged (Fig. 4). The impact fractured the aeroshell along the axial contact lines of the GIS and removed the GIS closure, allowing the release of capsule SRP-398. Capsule SRP-394 remained in the blind end of the GIS. Damage to the impact shell was significant (Fig. 5); a crack on the impact face extended the length of the GIS. The impact shell exhibited the same bowed profile observed in the DIT-1 and DIT-2 impact shells.

The fuel capsules were extracted from the remains of the test module, photographed, and measured. Side and end views of each capsule are shown in Fig. 6. Deformation of the DIT-4 capsules was quite similar to the capsule deformations observed in DIT-1 and DIT-2. Capsule dimensions and calculated gross strains are listed in Tables III and IV.

V. CAPSULE OPENING AND FUEL SAMPLING

An abrasive slitting wheel was used to make a small circumferential cut 6-8 mm above the weld (vent side) on each capsule. Contact between the abrasive wheel and the fuel pellet was minimized by minimizing the actual breakthrough of the capsule wall. The remaining iridium-alloy wall on capsule SRP-394 was pried open with a small screwdriver; the clad was defueled immediately after opening. To determine the quantity of respirable fuel particles produced by the impact, capsule SRP-398 was selected for a particle-size determination.

TABLE III. Dimensions of DIT-4 Fueled Clads

Preimpact Dimensions (mm)		SRP-394	SRP-398
Diameter			
Vent cup		29.84	29.77
Weld		29.95	29.92
Blind cup		29.82	29.77
Length		30.10	30.17
Diagonal		37.52	37.47
Postimpact Dimensions (mm)			
Diameter			
Vent cup	min	27.10	26.31
	max	32.49	32.66
Weld	min	27.36	26.80
	max	33.66	33.63
Blind cup	min	26.85	27.94
	max	32.18	31.75
Length	min	30.96	31.19
	max	31.62	31.39
Diagonal	min	35.56	36.14
	max	38.53	38.53

Before it was opened, the capsule was transferred to a glovebox train used for fines analysis; the capsule was opened underwater to avoid the loss of any small particles.

The opened capsules were examined with the aid of a hand-held magnifier. No external cracks were visible on any of the closure welds. Examination of the clad interiors revealed the presence of small cracks in the capsule welds and walls. The cracked areas were removed for metallographic examination.

TABLE IV. Postimpact Strains in the DIT-4 Capsules

		SRP-394	SRP-398
Diameter			
Vent cup	min	-10.33%	-11.60%
	max	8.85	9.73
Weld	min	-9.47	-10.44
	max	12.38	12.39
Blind cup	min	-9.96	-6.14
	max	7.92	6.66
Length	min	-2.78	-3.37
	max	4.98	4.04
Diagonal	min	-5.21	-3.53
	max	2.71	2.85

A "face-on" weld sample was obtained from each capsule in accordance with SRP procedure DPSOL 235-F-PuFF-3129M.⁵ The weld in each capsule was also sampled to provide specimens from the overlap and single-pass regions. The weld samples were large enough to include a portion of wall sufficient to establish grain size, other microstructural features, and hardness of the weld-shield cup. Similarly, the vent cup sections were taken to include a wall section sufficient to establish grain size and reveal other microstructural features. Samples of the two cups making up each capsule were submitted for spectrographic and Auger electron spectrographic analyses. The spectrographic samples were cut from the cup walls at about mid-height.

The fuel extracted from SRP-394 was sampled for ceramography by the selection of two l-g fragments; one fragment was removed from the outer edge of the pellet, and one fragment was taken from the pellet center. Two additional l-g fragments were removed for chemical analysis: one fragment for spectrographic analysis and one for a wet-chemistry phosphorous determination. The fuel in capsule SRP-398 was not sampled until a particle-size analysis had been completed. Results of the particle-size analysis are presented in Table V. When the fuel samples had been repackaged for transfer, each lot was radioanalyzed to approximate the phosphorous content.

VI. METALLOGRAPHIC EXAMINATION

A. Weld Metallography

After the DIT-4 capsules had been opened and defueled, the interior weld surfaces were macroscopically

TABLE V. Sieve Analysis of Fuel Removed from SRP-398

Particle Size (μm)	Weight Fraction	Accumulated Weight Fraction
+6000	0.32691	0.32691
+2000	0.33905	0.66596
+ 841	0.18747	0.85343
+ 420	0.06388	0.91731
+ 177	0.03346	0.95077
+ 125	0.00714	0.95791
+ 74	0.00905	0.99696
+ 44	0.01028	0.97724
+ 30	0.00881	0.98606
+ 20	0.00678	0.99283
+ 10	0.00500	0.99784
- 10	0.00216	1.00000

examined for defects. Representative areas of the overlap welds are shown in Fig. 7. After macroscopic examination, the equatorial weld of each capsule was sampled by obtaining specimens from the overlap, single-pass, and face-on weld regions (in accordance with SRP procedure DPSOL 235-F-PuFF-3129M). Results of the metallographic examinations are given below.

1. SRP-394. The internal surface of the overlap weld is shown in Fig. 7a. A small centerline crack is visible just beyond the weld submergence. The microstructural features of a cross section containing that crack are shown in Fig. 8. Although the grain size and morphology are not unusual, the porosity and surface cracking are certainly undesirable. The single-pass weld specimen (Fig. 9) did not contain any cracks and was essentially free of porosity. The microstructure of the face-on weld specimen (Fig. 10) was typical.

2. SRP-398. A section of the overlap weld is shown in Fig. 7b. Small longitudinal cracks, formed in a region of reverse bending, are visible near the point of weld submergence. A cross section removed from the overlap weld (Fig. 11a) revealed an unusual amount of porosity; this specimen was considerably more porous than the SRP-394 overlap weld sample. The porosity in the SRP-398 overlap weld appeared to be concentrated away from the surface and was particularly prevalent along the overlap interface. Etching of the sample revealed that, apart from the unexpected porosity, the microstructure of the overlap weld was acceptable (Fig. 11b). The single-pass weld specimen also contained a significant amount of porosity (Fig. 12a), but the microstructure along the centerline of the weld was generally sound (Fig. 12b). However, a large pore with an apparent diameter of 45% of the wall thickness was observed on the outer edge of the single-pass specimen (Fig. 13). The face-on weld sample (Fig. 14) had a typical microstructure with no observable defects.

B. Iridium-Cup Wall Microstructure

Macroscopic examination of the DIT-4 clad interiors revealed the presence of numerous small cracks in the walls of both capsules. The majority of the cracks were observed in regions that had undergone reverse bending. An area on the interior of capsule SRP-394 that contained numerous cracks is seen in Fig. 15; this area was located in a region of reverse bending on the impact face. Metallographic examination of a cross section removed from this area revealed that all of the cracks were intergranular (Fig. 16) and that one crack traversed more than 80% of the wall thickness. The microstructure of the iridium alloy adjacent to the cracks was very

unusual; large grains were observed on both the inner and outer surfaces of the cup wall. The 930°C impact temperature was well below the normal recrystallization temperature of the DOP-26 iridium alloy, so the unusual grain growth must have occurred during the 30-day, 1310°C preimpact aging treatment.

During the examination of pieces removed from capsule SRP-394, a breaching crack was discovered in the radius of the nonvented iridium cup (Fig. 17a). The crack was approximately 2 μ m in width at the outer surface, but could have released only minimal amounts of fuel. The microstructure of the iridium alloy adjacent to the breaching crack was somewhat coarser than that observed in other areas of the cup (Fig. 17b).

The cracks observed in the reverse bend regions of capsule SRP-398 had the usual brittle, intergranular morphology (Fig. 18); the deepest crack penetrated more than 60% of the wall thickness. The microstructure of the reverse bend specimen was normal for the heat treatment.

Samples of undeformed wall material were obtained from each of the four iridium-alloy cups making up the DIT-4 capsules. These specimens were microscopically examined to determine the preimpact grain size. The cup grain sizes ranged from 16 to 26 grains/0.635-mm wall thickness; the grain size of each cup is listed in Table VI. The cup microstructures are shown in Figs. 19 through 22. The wall section removed from the nonvented cup of capsule SRP-398 contained several excessively large grains along the inner surface (Fig. 22); the range of grain sizes visible in this section is very unusual. Similar grain coarsening was observed on the inner surface of the SRP-394 vent cup (Fig. 19), but the range of grain sizes was much narrower. The results of microhardness tests conducted on the cup samples are listed in Table VII.

C. Vent Metallography

The vent structures were carefully examined to determine if the pretest heat treatment (30 days at 1310°C) had caused any transport of fuel components and to further define the impact response of the vent assembly.

TABLE VI. Grain Sizes of DIT-4 Capsules (average # of grains/0.635-mm wall thickness)

Capsule	Cup	Grains/ Thickness
SRP-394	Vent	19.6
	Weld shield	18.5
SRP-398	Vent	16.2
	Weld shield	25.5

TABLE VII. Postimpact Hardness of DIT-4 Capsules

Capsule	Section	DPHN (2000-g load) at 95% CL ^a	Range
SRP-394	Vent cup	318 $\pm$ 9	284 – 339
	Weld-shield cup	324 $\pm$ 9	303 – 342
	Weld	340 $\pm$ 11	319 – 369
SRP-398	Vent cup	326 $\pm$ 8	309 – 348
	Weld-shield cup	327 $\pm$ 8	306 – 346
	Weld	325 $\pm$ 12	300 – 350

^aCL = confidence level.

Macroscopic examination revealed that both vents survived impact without significant deformation. A cross section of the vent in capsule SRP-394 is shown in Fig. 23. No mechanical defects were observed in either vent; the frits in both vents were uniform and properly aligned. No significant amounts of fuel impurities could be detected in the vent cross sections; however, a few fuel fragments and small amounts of mixed oxides (glass) were visible in both vents. The central portion of the vent in capsule SRP-398 is shown in Fig. 24. The pretest aging treatment apparently had little effect on the transport/deposition of fuel components into the vents.

VII. FUEL CERAMOGRAPHY

Radiographic examination of the DIT-4 fuel pellets indicated that both pellets were cracked prior to testing (Figs. 2 and 3). Postimpact examination of the opened capsules revealed that each fuel pellet had fractured in a completely brittle manner; the breakup of each pellet may be seen in Figs. 25 and 26. Following macroscopic examination, ceramographic specimens were obtained from the edge and center of each fuel pellet. The pellet microstructures are shown in Figs. 27 through 30. The photomicrographs indicate that slight microstructural differences existed between pellets and from point to point within each pellet. Because both pellets fractured in essentially the same manner, it does not appear that the small microstructural variations had any effect on the impact responses.

VIII. CHEMICAL ANALYSES

A. Iridium Alloy Chemistry

Samples for chemical analyses were removed from each of the four iridium cups used in DIT-4. The

samples were submitted for spectrographic and Auger electron spectroscopic examination. Spectrographic analysis was utilized to determine the bulk composition of each sample, and Auger electron spectroscopy was used to determine the distribution of various elements on a fresh fracture surface. The results of the analyses are presented in Tables VIII and IX.

The spectrographic analyses (Table VIII) indicate that the iridium alloy was of good overall purity; there was little cup-to-cup variation in chemistry. The slight differences in chemistry that were observed would not be expected to affect the mechanical response. The chemical compositions of the DIT-4 cups were similar

TABLE VIII. Spectrochemical Analyses of Iridium-Alloy Cups Used in DIT-4^a (all results are given in ppm by weight)

Element	SRP-394		SRP-398	
	Vent Cup	Weld-Shield Cup	Vent Cup	Weld-Shield Cup
Al	40	50	30	25
Cr	10	10	10	15
Cu	7	10	3	3
Fe	130	100	70	80
Ni	40	30	25	20
Pt	10	10	30	30
W ^b				

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

^bAll cups had tungsten content of between 10³ and 10⁴ ppm.

TABLE IX. Auger Intensity Ratios of Wall Samples Removed from DIT-4 Clads

Capsule	Sample	Location	Th ₆₅ /Ir ₂₂₉	C ₂₇₀ /Ir ₂₂₉	O ₅₁₀ /Ir ₂₂₉	S ₁₅₀ /Ir ₂₂₉
SRP-394	V-cup ^a	inside	0.546	1.182	1.036	0.273
		center	0.208	0.916	0.900	---
		outside	0.581	1.116	0.930	---
	W cup ^b	inside	0.504	0.687	0.687	---
		center	0.571	0.629	0.829	---
		outside	0.542	0.830	0.906	---
	Weld	inside	0.769	---	---	---
		center	0.841	---	---	---
		outside	0.753	---	---	---
SRP-398	V cup	inside	0.491	0.622	0.982	---
		center	0.588	---	0.838	---
		outside	0.373	0.587	0.467	---
	W cup	inside	0.500	0.600	1.000	---
		center	0.400	0.600	0.580	---
		outside	0.483	0.864	0.818	0.159
	Weld	inside	0.675	---	---	0.063
		center	0.444	---	---	---
		outside	0.787	---	---	0.053

^aThe cup containing the vent.

^bThe unvented cup.

to the compositions of cups used in previous Design Iteration Tests.

The Auger results (Table IX) suggest that thorium in the weld beads had segregated to the grain boundaries. In addition, relatively large concentrations of carbon and oxygen were observed in the grain boundaries of the recrystallized alloy (capsule walls). The effect of the presence of these elements on mechanical behavior is unclear; notably, no detectable amounts of carbon or oxygen were observed in the weld samples.

B. Fuel Chemistry

Samples for chemical analysis were removed from each of the DIT-4 fuel pellets. The results of spectrographic surveys, as well as the results of wet and radioanalyses for phosphorous, are presented in Table X. The results indicate that the DIT-4 fuel pellets were chemically similar to one another and to the fuel pellets used in previous Design Iteration Tests. Although the calcium content of SRP-394 was extremely high, no significant differences were observed in the impact behavior of SRP-394 and SRP-398. In addition, no unusual amounts of glassy oxides or other impurities were observed in the SRP-394 vent. The amount of phosphorous detected in each pellet was generally the

same and was consistent with phosphorous levels observed in the DIT-1, DIT-2, and DIT-3 fuel pellets.

IX. DISCUSSION

The primary objective of the DIT-4 test was to determine the effect on impact behavior of changing the procedure used to remove surface defects from drawn iridium cups. Surface defects on the iridium-alloy cups used in capsule SRP-394 were removed by a manual abrasion technique; defects on the SRP-398 cups were removed with a motorized abrasive wheel. Although postimpact examination revealed numerous cracks in both clads, it did not appear that any of the cracks resulted from surface conditions produced by manual or motorized abrasion.

The mechanical response of the partial GPHS module impacted in DIT-4 was similar to that of the full modules tested in DIT-1, DIT-2, and DIT-3. In previous Design Iteration Tests the FWPF aeroshell and GISs were severely damaged by the impact. In DIT-4 the impact split the partial aeroshell and removed the impact shell's cap, allowing the release of capsule SRP-398; SRP-394 remained in the blind end of the GIS. Both of the DIT-4 capsules experienced substantial deformation; the macrographs seen in Fig. 6 illustrate

TABLE X. Chemical Analyses of the DIT-4 Fuel Pellets (all results are given in ppm by weight)

Element ^a	SRP-394	SRP-398
Ag	20	10
Al	160	35
B	8	<1
Ba	<2	3
Ca	5000	130
Cr	20	20
Fe	260	70
Mg	1	1
Mn	1	<1
Na	10	<2
Pb	<5	<5
Si	45	25
Ta	<100	<100
Ti	<5	<5
Zn	20	<5
P ^b	<20	<20
P ^c	7	8

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

^bPhosphorous content determined by radioanalysis.

^cPhosphorous content determined by wet chemistry.

the permanent strains induced in the DIT-4 clads. Measurement of the postimpact capsule dimensions revealed that the DIT-4 capsule strains (listed in Table IV) were consistent with those observed in DIT-1 and DIT-2 (in DIT-3 a full GPHS module was impacted at an angle of 30°, and capsule deformation was not significant).

Postimpact examination of the DIT-4 clads revealed numerous cracks in the welds and walls of both capsules. The majority of the cracks were observed in regions that had experienced reverse bending. Cracks in the weld beads were generally shallow (penetrating less than 15% of the wall thickness), whereas cracks in the capsule walls tended to run much deeper; the SRP-394 shield cup radius was breached by a narrow crack (Fig. 17), and the wall in capsule SRP-398 contained cracks that traversed more than 60% of the wall thickness (Fig. 18). Although numerous cracks were observed in regions of reverse bending on the impact faces, the deepest cracks were not always located in wall sections that experienced the maximum local strains; the capsule wall adjacent to the breaching crack in SRP-394 experienced little deformation. These observations support previous indications that the failure of DOP-26 iridium is determined as much by strain state as by strain magnitude.

Metallographic examination of cross sections removed from the DIT-4 capsule welds revealed numerous defects. The welds on both capsules were very porous (Figs. 8a and 11a); the single-pass weld specimen removed from capsule SRP-398 contained a large blowhole with an apparent diameter equivalent to 45% of the wall thickness (Fig. 13). In addition, numerous small cracks were observed on the inner surface of each weld bead. Although the DIT-4 capsule welds were not of good quality, it did not appear that any of the internal weld defects had acted as crack initiation sites.

Although the average grain sizes of the four iridium-alloy cups used in DIT-4 ranged from 16 to 26 grains/nominal 0.635-mm wall thickness, evidence of abnormal grain growth was observed in two cups. A section of undeformed wall material removed from the SRP-398 weld-shield cup contained several excessively large grains along the inner surface (Fig. 22). Similar grain coarsening was observed on the inner surface of the SRP-394 vent cup (Fig. 19). While the exact mechanism of abnormal grain growth in DOP-26 iridium is unclear, the presence of the coarse grains on the inner surfaces suggests some type of fuel interaction. It should be noted that Auger examination of wall specimens removed from each cup did not reveal any chemical anomalies that could be correlated with the abnormal grain growth. Auger intensity ratios of the DIT-4 wall samples are presented in Table IX.

The results of spectrographic and Auger electron spectroscopic examination indicate that the iridium alloy was of good quality and consistency. The cups

used in both capsules had similar chemistries; all variations were within the range expected for small-lot preparations. The results of microhardness tests indicate that the DIT-4 capsules were similar to capsules used in previous Design Iteration Tests.

The fuel pellets used in DIT-4 were chemically and microstructurally similar to one another, and to the fuel pellets used in DIT-1, DIT-2, and DIT-3. Although the calcium content of SRP-394 was unusually high, no significant differences were observed in the impact behavior of SRP-394 and SRP-398. The postimpact appearance of the fuel pellets and the results of the particle size analysis performed on fuel removed from SRP-398 (Table V) indicate that the mechanical response of these fuel pellets was qualitatively similar to the behavior of fuel pellets used in DIT-1, DIT-2, and DIT-3.

X. CONCLUSIONS

1. DIT-4 was included in the Design Iteration Test series to evaluate the effect on impact behavior of changing the procedure used to remove surface defects from drawn iridium cups. The test results indicate that there were no significant differences in the mechanical responses of capsule SRP-394 (defects removed by a manual abrasion technique) and capsule SRP-398 (defects removed by a motorized abrasive wheel).
2. Although capsule SRP-394 breached, the breaching crack was very narrow ($\approx 2\mu\text{m}$) and could have released negligible amounts of fuel. The breaching crack was not observed during macroscopic examination of the clad exterior but was revealed during metallographic examination of a wall cross section.
3. The deepest cracks in the DIT-4 clads were not confined to wall sections that experienced high local strains; the iridium alloy adjacent to the breaching crack in SRP-394 experienced little deformation. These observations provide further evidence that the failure of DOP-26 iridium is determined as much by strain state as by strain magnitude.
4. The DIT-4 capsule welds were not of good quality; both welds contained significant amounts of porosity. The single-pass weld specimen removed from capsule SRP-398 contained a large blowhole with an apparent diameter equivalent to 45% of the wall thickness.
5. Abnormal grain growth was observed in two of the four iridium-alloy cups used in DIT-4 (SRP-394 vent

cup and SRP-398 weld-shield cup). In both cups grain coarsening occurred along the inner surface.

6. The mechanical performance of the DIT-4 capsule vents was satisfactory; no defects were observed in either vent.
7. The results of chemical analyses and microscopic examination revealed that the DIT-4 fuel pellets were similar to the pellets used in DIT-1, DIT-2, and DIT-3.

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Fig. 1. The partial module used in DIT-4 contained a single impact assembly.

Fig. 2. Radiographic print of the “as received” fuel pellets. Top, SRP-398; bottom, SRP-394.

Fig. 3. Radiographic print of the DIT-4 fuel pellets after heat treatment. Top, SRP-398; bottom SRP-394.

Fig. 4. The impact severely damaged the aeroshell and allowed capsule SRP-398 to come out; SRP-394 remained in the blind end of the impact shell. 0.75X.

(a)

(b)

(c)

Fig. 5. The DIT-4 impact shell was cracked and bent by the impact. (a) Impact surface; (b) side view with thermocouple penetrations visible; and (c) end view into the impact shell. All at 1.0X.

Fig. 6. Deformations of the DIT-4 capsules were similar to those observed in the DIT-1 and DIT-2 impacts.

(a)

(b)

Fig. 7. Internal surfaces of the overlap welds on the DIT-4 capsules. (a) SRP-394, 12X; and (b) SRP-398, 7.5X.

(a)

(b)

Fig. 8. The overlap weld of capsule SRP-394 contained several small weld cracks and significant porosity. (a) As polished, 50X; and (b) as etched, 50X.

Fig. 9. The single-pass region of the SRP-394 closure weld had a typical microstructure; as etched, 50X.

Fig. 10. Microstructure of the face-on weld specimen removed from capsule SRP-394. As etched, 50X.

(a)

(b)

Fig. 11. As overlap weld specimen removed from capsule SRP-398 was quite porous. (a) As polished; and (b) etched. Both at 50X.

(a)

(b)

Fig. 12. The single-pass region of the SRP-398 closure weld was porous but had an acceptable microstructure. (a) As polished, and (b) etched. Both at 50X.

Fig. 13. A large blowhole was found in the single-pass weld specimen removed from capsule SRP-398. Etched, 50X.

Fig. 14. The face-on weld sample obtained from capsule SRP-398 had an acceptable microstructure. Etched, 50X.

Fig. 15. Capsule SRP-394 was cracked in several places in the reverse bend region on the impact face. 4.0X.

Fig. 16. Although the cracks in capsule SRP-394 had the expected intergranular morphology, there was evidence of abnormal grain growth. 50X.

(a)

(b)

Fig. 17. A small crack penetrated the nonvented cup in capsule SRP-394. (a) As polished, 10X; and (b) etched, 50X.

Fig. 18. The deepest crack on the impact face of capsule SRP-398 penetrated more than 60% of the wall thickness. 50X.

Fig. 19. Microstructure of a specimen removed from the vent cup of capsule SRP-394. 50X.

Fig. 20. Microstructure of a specimen removed from the weld-shield cup of capsule SRP-394. 50X.

Fig. 21. Microstructure of a specimen removed from the vent cup of capsule SRP-398. 50X.

Fig. 22. Microstructure of a specimen removed from the weld-shield cup of capsule SRP-398. 50X.

Fig. 23. The vent in capsule SRP-394 experienced little deformation. 10X.

Fig. 24. Central portion of the vent in capsule SRP-398. 40X.

Fig. 25. The fuel in capsule SRP-394 fractured in a completely brittle manner. 1.5X.

Fig. 26. Breakup of the fuel in capsule SRP-398 was extensive. 1.5X.

(a)

(b)

(c)

Fig. 27. Ceramographic specimen obtained from the central portion of fuel pellet SRP-394. (a) Macrograph, as polished, 10X; (b) micrograph, as polished, 100X; and (c) etched, 100X.

(a)

(b)

(c)

Fig. 28. Ceramographic specimen obtained from the exterior of fuel pellet SRP-394. (a) Macrograph, as polished, 10X; (b) micrograph, as polished, 100X; and (c) etched, 100X.

(a)

(b)

(c)

Fig. 29. Ceramographic specimen obtained from the central portion of fuel pellet SRP-398. (a) Macrograph, as polished, 10X; (b) micrograph, as polished, 100X; and (c) etched, 100X.

(a)

(b)

(c)

Fig. 30. Ceramographic specimen obtained from the exterior of fuel pellet SRP-398. (a) Macrograph, as polished, 10X; (b) micrograph, as polished, 100X; and (c) etched, 100X.