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

Postimpact Evaluation, Design Iteration Test 1

MASTER

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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General-Purpose Heat Source Development: Safety Test Program

Postimpact Evaluation, Design Iteration Test 1

F. W. Schonfeld

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GENERAL-PURPOSE HEAT SOURCE DEVELOPMENT: SAFETY TEST PROGRAM

Postimpact Evaluation, Design Iteration Test 1

by

F. W. Schonfeld

ABSTRACT

The General Purpose Heat Source (GPHS) provides power for space missions by transmitting the heat of $^{238}\text{PuO}_2$ decay to thermoelectric elements. Because of the inevitable return of certain missions, the heat source must be designed and constructed to survive re-entry and Earth impact. The Design Iteration Test (DIT) series is part of an ongoing impact test program. The first DIT used a full GPHS module containing two graphite impact shells (GISs); each GIS contained two iridium (0.3 wt%) capsules filled with $^{238}\text{PuO}_2$. It was impacted at 57 m/s and 930°C. All four fuel capsules survived and none was breached. However, serious cracking of the iridium-alloy capsules was found; some cracks extended through ~70% of the wall thickness. Postimpact analyses of the unit are described with emphasis on weld structure and performance.

I. INTRODUCTION

The General-Purpose Heat Source (GPHS) provides power for a number of space missions. The heat of nuclear decay from the ^{238}Pu in the GPHS module is used to create a temperature differential across an array of thermoelectric elements to provide electrical power for the spacecraft. In addition to the inevitable return of near-Earth missions, the probability of a launch failure can never be zero for any mission attempt. Therefore, the GPHS must be designed and constructed to survive re-entry and Earth impact. The test results described in this report are a portion of the ongoing impact program and will provide necessary design information. The first design iteration test (DIT 1) was carried out at a velocity of 57 m/s at 930°C (as measured at the outer surface of the iridium alloy capsules). 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 four fuel pellets provided a total thermal power of 250 W. Our major concern during testing was the quality and survivability of the welds; therefore, this report emphasizes the weld structures and behaviors.

II. PRETEST DATA

A. Fuel Pellets and Iridium Alloy Cups

The iridium cups and fuel pellets used in the assembly of the individual heat sources are identified in Table I; data describing the fuel pellets are in Table II. The Savannah River Plant (SRP) produced the fuel pellets; Oak Ridge National Laboratory (ORNL) provided the iridium alloy blanks, the Mound Facility (MF) fabricated

TABLE I. Encapsulation Details for DIT-Fueled Clads

Capsule No.	Iridium Cup		Quality ^a	Fuel Pellet ^b	Use
	Vent	Shield			
IRG-105	L204-4	L260-5	EWO	GP-58	example weld
IRG-103	L307-1	L243-4	EUO	SRP-6	impact
IRG-104	LR308-2	L241-3	EUO	SRP-7	impact
IRG-101	LR302-8	LR269-3	FQ	SRP-27	impact
IRG-102	LR305-3	LR238-4	FQ	SRP-48	impact
IRG-106	L263-8	LR297-5	EWO	GP-58	example weld

^aEWO = example weld only; EUO = engineering use only; and FQ = flight quality.

^bGP = Los Alamos manufacture, and SRP = Savannah River Plant manufacture.

TABLE II. Data for Sintered SRP DIT-1 Fuel Pellets

Identification	Diam (mm)	Length (mm)	Weight (g)	Density (% TD)
SRP-6	27.61	27.66	149.32	83.6
SRP-7	27.61	27.69	149.54	83.6
SRP-27	27.61	27.74	149.74	83.1
SRP-48	27.71	27.84	149.07	82.3

the iridium cups; the Los Alamos National Laboratory did the assembly and iridium welding; ORNL produced the graphite insulation [carbon-bonded carbon filament (CBCF)]; and Los Alamos machined the aeroshell and impact shells from fine-weave-pierced-fabric* (FWPF) graphite. (Machining reduced the aeroshell thickness by 1.25 mm to simulate ablation losses.) Corners of the GISs were coated with 0.5 mm of pyrolytic graphite by Pfizer, Inc.** Photographs of the pellets made before assembly for welding are presented as Fig. 1. They effectively convey the extent and severity of the fuel pellet cracking.

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

**Pfizer, Inc., P. O. Box 548, Easton, PA 18042.

B. Weld Examinations

We placed two preconditions on the heat sources: (1) the weld exteriors had to be of good appearance and quality, and (2) weld sample microstructures of the preweld trial capsules (IRG-105 and IRG-90) had to be essentially the same.

We obtained optical macrographs (~10X) of external overlap and single-pass portions of the welds. Figures 2, 3, 4, and 5 illustrate the results. Also, we visually examined the individual capsules and estimated the extent of bulging and misalignment by comparing with a simple graphite sighting square (post and pedestal) in a hood. Rotating the capsules (counterclockwise from above, vent end up) provided primitive information on circumferential uniformity, and comparing them with a screw micrometer showed the magnitude of bulges, etc. We used a square notch in the graphite post at weld height so that wall distortions rather than weld protrusions could be estimated.

The four capsules, IRG-101, -102, -103, and -104, were all similar; all bulged slightly and irregularly, producing a tapered barrel shape (the original cups were all slightly tapered). IRG-101 displayed a uniform amount of bulging around its circumference; the gap between the graphite post and the upper and lower portions of the walls was ~0.25 mm. The bulge on IRG-102 was less regular than on IRG-101 with an

~0.25 mm offset of the two halves, ~90° from the overlap, and an ~0.37-mm bulge at ~120°. The bulge on IRG 103 was a relatively uniform 0.20 to 0.25 mm except for one 30° sector just ahead of the overlap that bulged by ~0.1 mm. IRG 104 bulged irregularly by 0 to 0.37 mm near the weld and to a lesser degree completely around the circumference.

The weld sections of IRG 105 and IRG 90 were taken, prepared, and examined according to SRP procedure DPSOL 235-F PuFF-3129M.¹ The microstructures of the sections are illustrated in Figs. 6 and 7, with the exception of IRG-90, which had no true overlap because of inadequate penetration. Inspection showed that the IRG 105 and IRG 90 weld structures were nearly identical morphologically, for this reason, we decided to proceed with the impact test. (During the same period, we examined the inside overlap weld area of IRG 106 and found a near centerline SRP type crack. IRG 106 was a postweld campaign demonstration capsule comprising two cups with a poor dimensional match, therefore, we gave it no weight in our decision to proceed with the test.)

III. POSTTEST EXAMINATIONS

The four capsules used in DIT 1, IRG 101 [flight quality (FQ)], IRG 102 (FQ), IRG 103 [engineering use only (EUO)], and IRG 104 (EUO), contained SRP fuel pellets 27, 48, 6, and 7, respectively. The capsules were arranged as shown in Fig. 8. Note that the closure weld overlap areas were oriented toward the trailing face of the module. The impact test conditions were 930°C and 57 m/s. After impact, the catch tube was transferred to Wing 2 of the CMR Building (at Los Alamos) and opened in a hood. A swab, inserted through the pump out plug of the catch tube, showed that no fuel had escaped from the inner nickel can (a radiation shield assembly), therefore, the catch tube end was removed as quickly as practicable. We could then observe the remnants of the nickel can and the GPHS unit, the two glowing GISs were visible through fractures in the impact face of the aeroshell. The estimated temperature of the GISs was ~700 to 750°C, somewhat lower (by 50 to 100°C) than was the equilibrium temperature while in the catch tube. Unfortunately when the can was removed from the catch tube and air became freely available, both GISs began to burn at their more exposed ends. Therefore, to meet the obligations set forth in document CMB 5 C 81 43, "Post Test Examinations of the DIT Samples," Part IV A², "the remains of the module will be removed from

the catch tube in a manner that minimizes the additional damage of the assembly, consistent with preserving the graphite from catastrophic oxidation," we decided that the two GISs must be separated at once to reduce their temperatures. To extract either GIS, a corner portion of the already damaged aeroshell had to be removed. With laboratory tongs, we broke off one corner of the impact face by completing an almost complete fracture. The instrumented GIS that contained IRG 101 and IRG 102 was removed from the aeroshell and transferred to a glove box. Because of the procedural uncertainties present in this first test of a live module (four capsules), we obtained no photograph of the as recovered aeroshell, but Fig. 9 shows the aeroshell after extraction of the GISs. The impact face of the aeroshell broke into uneven slabs, 6 to 13 mm wide and 25 to 50 mm long. Two corners (parallel to the axis of symmetry of the GIS) were almost broken off the aeroshell. Both aeroshell closures popped out from the impact but remained near their respective threaded receivers. The bodies and one set of ends of the GISs were plainly visible through the debris. (The "one set of ends" means only that the two ends were those adjacent to the end wall of the aeroshell. We assign no significance to this positioning because postimpact tumbling occurs and additional shifting of contents can take place during extraction from the gun and during transport.)

The two recovered GISs were similar in appearance. The impact side was battered and cracked for most of its length (IRG 101 and 102 GIS ~80%, 103 and 104 GIS ~70%). Crack patterns extended from the closure end, with the greatest mechanical damage occurring at 20 to 30% of the length from the closure end. Both GISs definitely bowed (~1 mm) toward the unsupported center, and both closures were displaced slightly and were loose in their sockets (Figs. 10 and 11).

The fuel capsules were extracted from the two GISs with little difficulty and were photographed and measured. In general appearance, the four capsules were amazingly similar in shape and size, and all four survived the test without failure. All were flattened on the impact side, and all showed protrusions at a position corresponding to the unsupported side of the GIS. When we consider the usual variable behavior of ²³⁸PuO₂ fuel pellets, these capsules show remarkably uniform responses to the test. General features of the four capsules are illustrated in Fig. 12. The engineering strains established by micrometer measurements are listed in Table III, and the capsule dimensions are in Table IV.

TABLE III. DIT-1 Engineering Strains in Percentages

	IRG-101		IRG 102		IRG-103		IRG-104	
Diametral								
Top cylinder	5.5	-4.8	5.6	-6.5	6.7	-8.0	6.3	-4.6
Weld	6.5	-4.2	7.3	-7.1	7.0	-5.7	6.3	-3.6
Bottom cylinder	4.8	-7.2	6.2	-7.8	5.5	-5.0	7.0	-4.1
Diagonal								
Wide face	1.1	1.3	0.9	1.4	0.95	1.6	1.5	1.6
Thickness	-2.7	-2.7	-4.0	-0.8	-4.7	-2.6	-3.5	-2.3
Length								
Maximum	2.9		5.7		3.0		5.0	
Minimum	2.4		5.0		2.0		3.9	

TABLE IV. Capsule Dimensions in Inches

	Diameter		Weld	Diagonal	Length
	Top	Bottom			
IRG 101-0 ^a	1.1755	1.1733	1.183	1.468	1.1735
F _{max} ^b	1.240	1.230	1.260	1.484, 1.487	1.217
F _{min}	1.119	1.089	1.133	1.429, 1.429	1.202
IRG-102-0	1.1738	1.1740	1.184	1.472	1.180
F _{max}	1.239	1.247	1.271	1.485, 1.493	1.247
F _{min}	1.098	1.083	1.100	1.413, 1.460	1.239
IRG-103 0	1.1768	1.1753	1.185	1.475	1.182
F _{max}	1.256	1.240	1.268	1.489, 1.498	1.217
F _{min}	1.083	1.117	1.117	1.406, 1.436	1.206
IRG-104 0	1.1767	1.1747	1.183	1.473	1.179
F _{max}	1.251	1.257	1.258	1.495, 1.497	1.238
F _{min}	1.123	1.127	1.141	1.421, 1.439	1.225

^a0 is original dimension.^bF is final dimension.

IV. CAPSULE OPENING AND CAPSULE AND FUEL SAMPLING

A. Cutting Procedure

Because the four impacted capsules were so similarly deformed, a uniform cutting procedure was adopted. A circumferential cut was made with a small abrasive slitting wheel 6 to 8 mm above (vent side) the weld (Fig.

13). All cuts minimized contact between the abrasive disk and the fuel pellet by minimizing actual breakthrough of the capsule wall. The remaining iridium-alloy wall on IRG-101, -103, and -104 was opened by prying with a small screwdriver, and the clads were immediately defueled. IRG-102 was transferred to the glove-box train used for fines analyses before opening (under H₂O to avoid the loss of any small particles).

B Weld and Wall Sampling

Because of the locations of the deformed areas and the similar conditions of all four capsules, weld area sampling in accord with SRP procedure DPSOL 235 F PuFF 3129M presented no problems and did not interfere with any other requirements. Therefore, the weld samples were the first to be cut from the capsules. Each weld cross section sample included enough capsule wall to test microstructure and hardness of the weld shield capsule without preparing separate samples. Figure 14 shows where these samples were cut from the capsules.

Next, Auger electron spectroscopy samples were cut from both lower (weld shield) and upper (vent) cups, and two across the weld samples were notched so that one would fracture across the weld and one along the centerline of the weld. The wall samples were cut at least 6 mm away from the fusion zone to ensure that the original cup material would be included, whereas the cross weld samples were immediately adjacent to the overlap weld sample. Approximate locations of these samples are shown in Fig. 15. Samples for spectrographic surveys of each capsule were cut from the walls at about mid height. Finally, we took cross sections of the vents, again in such a way that wall microstructures and hardnesses could be established without additional sampling. When the internal surfaces of the capsules could be examined, we found small cracks in all four capsules near the points of maximum bending strains. Additional samples were cut that encompassed these cracks.

C. Fuel Sampling

The fuels extracted from IRG 101, 103, and 104 were sampled for ceramography by selection of two fragments, each weighing 1 g, one from the outer edge of the fuel pellet and one from the central portion. For chemical analysis, two additional ~1 g fragments were selected, one for spectrography and one for a wet chemistry phosphorus determination. Fuel in IRG 102 was not sampled until the coarser particles had been separated and weighed in the particle size analyses, then samples were selected using the same criteria. When the fuel samples had been repackaged for transfer, each lot was radioanalyzed to quickly approximate phosphorus contents.

IV. WELD METALLOGRAPHY

Because no breach occurred in any of the four impacted DIT 1 capsules and because of the importance of the overlap weld crack problem to the production program, the weld samples were the first metallographic samples prepared and examined. According to the DPSOL 235 F PuFF 3129M procedures, each sample was labeled with a suffix 1, 2, or 3 to indicate that it was (1) the cross section through the overlap, (2) the cross section through the single pass portion, or (3) a section of the single pass weld to be examined face on (Fig. 14). The approximate dimensional characteristics of the overlap portion of the DIT 1 closure welds are given in Table V. The microstructures of the sections are illustrated by Figs. 16 through 19. As the figures show,* the four welds are reasonably uniform and of good quality. The minor microstructural differences observable do not seem to have produced any significant differences in behavior. The weld sections taken from IRG 105 and shown in Fig. 20 are morphologically identical to those from IRG 101, 102, 103, and 104. Figure 21 shows the pertinent areas of the IRG 105 and 106 overlap interior surfaces. The single pass and face on sections from IRG 106 (post campaign test weld capsule) (Fig. 22) are like those of the other capsules, but the first submerged region of the overlap/ramp down was cracked at the inside surface. Figure 22d shows a section through the single pass portion of the IRG 106 weld that was made near the

*Unless otherwise indicated, all microstructures were produced by the NaOH/NaCl electrolytic etch.

TABLE V Characteristic Dimensions of the Los Alamos Weld on the DIT 1 Impact Capsules

Capsule No	Dimensions (mm)		
	A Overrun	B Downramp	C Double Pass
IRG 101	7.1	3.6	10.2
IRG 102	3.4	5.3	9.1
IRG 103	7.1	3.8	9.6
IRG 104	7.4	3.8	
IRG 105	7.1	3.6	8.9
IRG 106	5.3	3.2	9.1

crack and that can be compared to the structure at the overlap (Fig. 22d). The ramp-down portion of the cracked weld is obviously quite different from the single-pass portion. Grain size at the weld center is much coarser, and the orientation relationships seem to be different; but we are not certain about the reasons for these differences. The larger average grain size and the relatively coarse microsegregation patterns in the grains near the crack suggest a lower cooling rate in the overlap melt. However, the tendency of the iridium weld pool to solidify by growth of unmelted grains, rather than by nucleation of additional grains, produces a larger grain size with each melt-solidification cycle and so makes this observation somewhat ambiguous. The single-pass section of the portion near the overlap (Fig. 23) was originally 5 mm from the section shown in Fig. 22. Examination of these sections supports the assumption that the microstructural differences are localized. If the rate of crystal growth during freezing is orientation dependent and the rolling/drawing/recrystallization texture of the cup is sharp, a critical orientation may exist that could produce two or four zones of unfavorable overlap location. Within such a zone, the orientation relationships favor extremely rapid growth of certain grains and thus produce a coarse structure; therefore, the resulting orientation may have an increased susceptibility to grain-boundary cracking. Certainly, a remelt (overlap) made within such a zone aggravates both these possibilities. Why a small portion of the circumference should have a cooling rate significantly different from the rest of the weld is difficult to explain; however, an increased growth rate by particular grains seems a reasonable hypothesis. Because the weld-start position is fixed by the previous placement of the vent notches, the welder has no choice of starting position and therefore no control of texture orientation. However, if the above speculations have any factual basis, one possible or partial remedy may be to make the overlap while rapidly increasing the rotational speed of the capsule rather than by ramping down the current. Additionally, the magnitude of the thermal stress, which is the actual crack producer, could be reduced by a preheat and a postweld stress-relief anneal applied (by laser?) ahead of and behind the weld arc.

VI. FUEL CERAMOGRAPHY

The four fuel pellets were sampled for structural pellet-to-pellet comparisons and edge-to-center comparisons.

Fuel breakup and movement on impact are important factors in overall capsule deformation, and the remarkable similarities among the four capsules suggest that the four fuel pellets (SRP-27 in IRG-101, SRP-48 in IRG-102, SRP-6 in IRG-103, and SRP-7 in IRG-104) must have been quite similar also. The appearance of the impacted fuels is shown in the Fig. 24 macrographs, and the microstructures are illustrated by Figs. 25 through 32.

Clearly, the microstructures of the four fuel pellets are similar but not identical. Differences exist in the degree of porosity, the grain size, and the number and size of cracks; yet the basic microstructural components are constant. Again, we are faced with the inevitable variability of small-lot production of an inherently difficult material. Experience suggests that pellet-to-pellet variations are not much different from the average point-to-point variation within a single pellet and that the edge-to-center differences usually are larger than the other differences. Microstructural differences are important because they influence the formation of macro- and microcracks, and impact behavior is largely determined by the propagation of pre-existing crack patterns. The low thermal conductivity and relatively high thermal expansion of PuO_2 , when coupled with the self-heat, produce severe thermal stressing during cool-down; the worst case may be cooling from the hot-pressing cycle.

If we assume that pre-existing cracks (including large numbers of microcracks) were the controlling factor in the breakup of the DIT-1 fuel pellets, then the similarities of fuel fragmentation and capsule deformation become understandable and perhaps predictable. The minimal damage to and fracture of sound UO_2 pellets impacted early in the test program support this postulate. Further, we would not expect small variations in chemistry or production procedures to greatly alter impact behavior because these factors seem to have no dramatic influence on cracking. The four crack patterns illustrated in Fig. 1 are largely radial and parallel to the pellet length. The large cracks are only a small portion of the total cracks, but the large cracks can permit movement of large chunks of fuel. The fine cracks, such as appear in Fig. 24, control the ultimate fracture into smaller pieces. Orientation of the fuel pellet at impact is also an important factor in crack propagation. Insofar as push-through failure is concerned, if the large cracks conform to the general pattern shown in Fig. 1, then side-on impact should be relatively benign and reproducible compared to a corner-on (45°) impact. The corner-on attitude provides a lesser constraint on fragment movement and a longer decelera-

tion time when movement can occur than does a side on impact. These factors may have contributed to the uniformity of deformation in the DIT 1 capsules. Certainly, the photographs of the fuel pellets (Fig. 1) strongly suggest that we should have expected little variation in the mechanical behavior of the four pellets.

Long term operation of the heat sources at operational temperatures leads to precipitation of helium gas bubbles in the grain boundaries, and a re entry heat spike produces more and larger grain boundary bubbles that further decrease the fracture strength of the fuel. An array of bubbles in a grain boundary affects fracture behavior in substantially the same way as does micro cracking, therefore, we can consider the high temperature aging (and re entry) a weakening process that will increase the number of fractures on impact and decrease the average fuel fragment size. The greater the degree of fragmentation, the less the danger of push through, but the greater the fragmentation, the greater the capacity of the fuel assembly for viscous flow and the more probable become such phenomena as the reverse bending and cracking seen in DIT 1.

In summary, the four fuel pellets used in DIT 1 were similar in macrostructure, microstructure, and impact behavior. We believe that these similarities are an important factor in the similar deformations in capsules IRG 101, 102, 103, and 104.

VII. VENT METALLOGRAPHY

The four vent structures were carefully examined to determine if the pretest heat treatment (100 h at 1300°C) produced any transport of fuel components into the vents as well as to define their mechanical responses. A thin film of PuO_2 blackened the interior surfaces of all four capsules, but no significant amounts of fuel impurities were detected in any of the four vent cross sections. No mechanical defects were found, all vents survived the test without significant harm. The macroscopic appearances before sectioning are in Fig. 33, and the macrosections are in Fig. 34. Selected microstructures are shown in Figs. 35, 36, 37, and 38. As the photographs suggest, the vent areas sustained only minor deformations during the test, apparently they were well protected, being held firmly between the fuel pellets and the FWPF graphite partitions.

VIII. LOCAL STRAINS

After the four test capsules were opened and defueled, cracks were found on the interior surfaces in the reverse bending areas that can be seen in Fig. 33. The cracks were found only in and near the weld beads, and Fig. 39 shows their macroscopic appearances. Microstructural details are illustrated by Figs. 40, 41, 42, and 43. Obviously, the operable safety margin in this test approached zero because crack propagation in a semibrittle material does not require large amounts of energy.

Other areas of significant local deformation, but without mechanical failure (cracking), were present in all four DIT 1 capsules. In a side on impact, the GIS deforms appreciably because it is supported only at the two ends, consequently, the central portion (containing the FWPF partitions and the vent ends of the two capsules) contacts the aeroshell wall slightly sooner than the remainder of the GIS. We assumed previously that these timing and geometry changes would produce a partition, wall, and fuel breakup pattern that would always yield greater corner deformations at the vent ends of both capsules and lesser deformations at the blind ends. The results of DIT 1 do not support this earlier assumption; they suggest that the corner deformation is actually controlled by the early stages of fuel fracture and the accompanying mechanical interactions with the leading edges of the FWPF end plugs and partitions, thus producing more or less random results. Apparently, corner deformations take place before the bulk volume of the fuel is increased and the volume of the capsules is decreased to the point that biaxial stressing reaches a high level. Further, the corner location is not subject to the same degree of frictional drag as is the center portion of the impact face. Because capsule deformation is controlled by two factors, the breakup and shape change of the fuel pellet and the degree of constraint (or lack thereof) immediately external to the capsule, reduction of the overall deformation can reduce the crack formation. If a sound fuel body and a GIS, both of infinite yield strength, hold the iridium capsule tightly between them, all deformation is elastic and permanent deformation does not occur. Closing all gaps and increasing the strength of the GIS/insulator combination are probably the best practicable approaches to that ideal situation. Such a course would exact a weight penalty but would dramatically increase the safety margin.

Measuring the radii of curvature and wall thicknesses on enlargements ($\sim 6X$) of the photographs in Fig. 44 established the deformation levels produced in each of the three high-strain areas of the four capsules. The results are listed in Table VI.

Note that most of the corner strains which produced no cracking are larger than most of the side-wall strains that did lead to cracking. Further, the side-wall strains in IRG-102 and -103 are only about half those of the corner strains. Thus, we have another indication that the state of strain is at least as important as the magnitude.

The microstructural features of the iridium-alloy specimen from the area subjected to the corner strains are illustrated by Fig. 45. Although the structure appears to be much like the preimpact structure and without strain markings despite the relatively low impact temperature (930°C), the very small grains at the inside of the bend show that the material can indeed recrystallize at this low temperature; perhaps the relatively high postimpact temperature produced by the presence of four fuel pellets had some influence.

IX. IRIIDIUM-ALLOY CHARACTERIZATION

A. Microstructure

Before loading, the capsules used in DIT-1 were given a heat treatment (20 h at 1500°C) to produce a grain size approximating that present after 6 months of service, as predicted by ORNL. A second heat treatment before impact testing (100 h at 1300°C) provided relief of the stresses produced by welding. The measured grain sizes and the expected grain sizes are listed in Table VII.

TABLE VI. Maximum Local Strain Levels Produced by DIT-1

Capsule	Vent-End		Blind-End
	Corner (%)	Side (%)	Corner (%)
IRG 101	8.4	7.3	5.5
IRG 102	8.1	4.1	7.2
IRG 103	8.1	4.0	3.7
IRG 104	4.5	6.7	8.8

TABLE VII. Grain Sizes of Iridium Alloy in DIT-1 IRGs
[Grains per 0.635 mm
(25 mil) wall thickness]

IRG	Vent Cup	Blind Cup	Anticipated
101	18-20	20-21	13-14
102	16-18	17-18	13-14
103	17-19	18-19	13-14
104	17-18	19-20	13-14
105	16-17	19-20	13-14
106	19-20	19-21	13-14

Included in the table are measured grain sizes of the weld-trial capsules IRG-105 and -106, which were not given the stress-relief treatment. Keep in mind that a grain size is not a single-valued number; point-to-point variations exist even in carefully processed brass, and in small-lot preparations such as these, variations are bound to be much larger. As a practical matter, grain sizes are usually given as averages of many grain counts or grain diameters. Obviously, when values are presented as grains per thickness, the numbers must be normalized to some common thickness for accurate intercomparison.

Table VII shows that prediction and result are different; the measured grain sizes are somewhat smaller than anticipated. In this instance, however, the discrepancy is not important because all experimental observations suggest that the finer grained iridium alloy must have had somewhat higher ductility than it would have had if the grains had reached the predicted size. Thus, cracking would have been more extensive if the grain size had conformed to prediction, and the already low safety margin would have been even lower. Whether coarser grained capsules would have breached is indeterminable, but the possible performance differential would represent only a difference in degree and none in kind.

Representative microstructures from the walls of the 12 cups that made up the 6 DIT 1 capsules are illustrated in Figs. 46 through 51. These photomicrographs show only the usual and normal structural features, as did all the metallographic samples examined. All our microstructural results indicate that the iridium alloy was of good quality and reasonable reproducibility.

B. Hardness

Hardness tests were carried out on both deformed and undeformed portions of the walls and the welds. A Leitz* microhardness tester applied a 200 g load on a standard, square pyramidal diamond indenter. Diamond pyramid hardness (DPH) numbers are given in Table VIII. All listed numbers are the averages of 3, 5, 6, 9, or 12 individual tests, and except when only five or fewer numbers are available, the probable ranges are calculated at the 95% confidence level. The experimentally observed ranges of hardness levels are also shown.

The hardness survey indicates that the deformation temperature (930°C) is sufficiently low to produce considerable strain hardening during impact. Because of the slow postimpact cool-down resulting from the mass of the test array and the continuous generation of heat by the fuel pellets, the instantaneous strain hardening is probably somewhat greater than the hardness measurements indicate, as some stress relief is inevitable. In fact, the microstructure shown in Fig. 45 suggests that recrystallization may be possible at highly strained points. However, if modest softening and recrystallization are postimpact events, they are not relevant to capsule impact performance and can be disregarded in that context. The observations may be useful in our

attempts to understand some of the rather unusual properties of the alloy.

C. Chemistry

Samples of each cup of the four impacted capsules and the two trial weld capsules were submitted for spectrographic analyses, and four samples of each capsule (two from cup walls, one perpendicular to and crossing the weld centerline, and one parallel to and including the weld centerline) were prepared for Auger analyses. The results of these analyses are summarized in Tables IX and X. The six capsules had similar chemistries with all variations well within the range expected from small lot preparations. The Auger results are always variable and provide no new information that increases our understanding of iridium alloy behavior.

X. FUEL CHARACTERIZATION

Figures 25 through 32 show the microstructures of the four impacted fuel pellets, and Fig. 24 shows the general appearance of the recovered fuel. The four pellets are similar in structure and performance. Evidence that the fuels were also chemically similar is presented in Table XI, which lists the results of spectrographic surveys and

*E. Leitz, Inc., Rockleigh, NJ 07647

TABLE VIII. Hardness of the Iridium Alloy Capsules Used in the DIT 1 Impact

Capsule	Vent Cup		Shield Cup		Weld		
	Undeformed	Deformed	Undeformed	Deformed	Vent	Center	Shield
IRG 101	289	315	315	393	293	308	304
	263 305	283 374	308 325	355 435	292 299	300 314	303 305
IRG 102	319	353	314	393	313	335	316
	309 339	322 391	278 334	351 408	288 332	397 374	301 334
IRG 103	310	379	318		315	313	300
	294 333	355 412	299 339		290 349	249 349	250 317
IRG 104	335	397	320	390	337	336	323
	313 383	362 441	265 339	364 423	312 407	303 438	301 351
IRG 105	282		279		278	291	273
	279 297		272 285		272 283	281 301	267 281
IRG 106	270		276		266	272	269
	260 284		262 290		246 282	255 311	254 325

TABLE IX. Spectrographic Analyses of GPHS Clads Used in DIT-1

Element	IRG 101		IRG 102		IRG 103		IRG 104		IRG-105		iRG 106			
	V-Cup ^a	B-Cup ^b	V Cup	B Cup	V Cup	B-Cup	V Cup	B Cup	V-Cup	B-Cup	V-Cup	B-Cup	V-Cup	B-Cup
Li	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100
Be	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3
B	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
Na	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300
Mg	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3
Al	50	50	50	50	40	40	30	50	40	80	60	60	60	60
Si	10	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
P	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300
K	<3000	<3000	<3000	<3000	<3000	<3000	<3000	<3000	<3000	<3000	<3000	<3000	<3000	<3000
Ca	3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3
Ti	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
V	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
Cr	10	<10	<10	<10	<10	20	<10	10	20	<10	<10	<10	<10	<10
Mn	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Fe	100	20	20	20	20	30	<10	10	10	<10	<10	<10	40	40
Co	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Ni	50	20	40	30	<10	<10	<20	<20	<20	<20	<20	<20	<20	<20
Cu	20	15	15	15	20	30	5	30	10	10	7	15	15	15
Zn	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50
Ga	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
Ge	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
Sr	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3
Zr	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300
Nb	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300
Mo	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300
Ru	<30	<30	<30	<30		---	<30	<30	<30	<30	<30	<30	<30	<30
Rh	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
Pd	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Ag	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Cd	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100
In	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
Sm	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50
Sb	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300	<300
Ba	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3
Hf	<500	<500	<500	<500	<500	<500	<500	<500	<500	<500	<500	<500	<500	<500
Ta	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000	<1000
W	0.1 - 1%	0.1 1%	0.1 - 1%	0.1 1%	0.1 - 1%	0.1 - 1%	0.1 - 1%	0.1 - 1%	0.1 - 1%	0.1 1%	0.1 1%	0.1 1%	0.1 1%	0.1 1%
Pt	<30	<30	<30	<10	<10	<10	<30	<30	<30	<30	<30	<30	<30	<30
Au	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Tl	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
Pb	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
Bi	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30

^aThe cup containing the vent.^bB Cup is Blind Cup.

TABLE X. Results of Auger Analyses of the Four Iridium Alloy Capsules Impacted in DIT 1

Capsule		Th _{6s} /Ir _{4d}			Th _{6s} /Ir ₂₂₉			P ₁₂₀ /Ir ₂₂₉			S ₁₅₀ /Ir ₂₂₉			B ₁₈₀ /Ir ₂₂₉		
		Inside	Center	Outside	Inside	Center	Outside	Inside	Center	Outside	Inside	Center	Outside	Inside	Center	Outside
IRG-101	A1 ^a	0.043	0.062	0.051	0.275	0.443	0.324	-	-	-	-	-	0.043	-	-	-
	A2	Trace	0.036	0.006	Trace	0.231	0.041	-	-	-	-	-	-	-	-	-
	A3	0.050	0.106	0.050	0.355	0.907	0.370	-	-	-	-	-	-	0.150	-	-
	sputtered A3	0.034	---	---	0.268	---	---	-	-	-	0.206	-	-	-	-	-
IRG 102	A4	0.070	0.083	0.044	0.511	0.784	0.330	-	-	0.070?	-	-	-	-	-	-
	A1	0.040	0.104	0.045	0.279	0.800	0.307	-	-	-	-	-	-	-	-	-
	A2	(Specimen too short)														
	-A3	0.056	0.040	0.029	0.333	0.294	0.195	-	-	---	-	-	-	-	-	-
IRG 103	sputtered A3	---	-	Trace	---	Trace	---	-	-	---	0.085	-	-	-	-	-
	A4	0.038	0.026	0.007	0.300	0.200	0.055	-	0.073	-	-	-	-	-	-	-
	sputtered -A4	-	Trace	---	---	Trace	---	-	-	---	-	-	-	-	-	-
	A1	0.073	0.069	---	0.559	0.513	---	-	-	-	-	-	-	-	-	-
IRG 104	A2	0.018	0.081	0.029	0.172	0.583	0.0236	-	-	-	-	-	-	-	-	-
	-A3	0.074	0.076	0.014	0.555	0.638	0.103	-	---	-	-	-	-	-	-	-
	A4	0.031	Trace	0.044	0.273	Trace	0.362	-	---	-	-	-	-	-	-	-
	A1	0.005	0.071	0.020	0.038	0.528	0.137	-	-	-	-	-	-	-	-	-
IRG 104	A2	0.057	0.106	0.042	0.460	0.860	0.321	-	-	---	-	-	-	-	-	-
	-A3	0.056	0.043	0.057	0.415	0.327	0.460	-	---	-	-	-	-	-	-	-
	-A4	0.063	0.074	0.057	0.521	0.640	0.431	-	---	-	-	-	-	-	-	-
	-A4	0.063	0.074	0.057	0.521	0.640	0.431	-	---	-	-	-	-	-	-	-

^aA1 = -; A2 = | welds; A3 = wall, vent end; and A4 = wall, closed end.

both wet and radioanalyses for phosphorus. Magnesium, silicon, calcium, titanium, and tantalum impurities vary widely in the fuel pellets. (The first three exceed the specified impurity limits as shown in the table.) The effects of these elements are not clear, but we think that they should not greatly affect the mechanical performance of the fuel. The chromium, iron, and nickel impurity levels may represent pickup from stainless steel tools or enclosures.

We analyzed the IRG-102 fuel by size to determine the extent of breakup and to provide data for source-term calculations. The results of these analyses are shown in Table XII. Comparison with other GPHS size analyses shows that the impact behavior was qualitatively similar to that of other impact tests, but behavior did vary somewhat in detail, which is usual in tests of this kind. The DIT-1 results do suggest that the SRP fuel may fracture more completely on impact than does the Los Alamos fuel.

XI. SUMMARY

The strikingly similar responses of the two GISs and the four capsules (when impacted flat-side-on at ~930°C and ~57 m/s against a hardened and ground steel plate) provide a solid basis for predicting the behavior of similar assemblies. Intergranular cracking in both welds and walls in areas subjected to reverse bending and the unusually high observed deformations of the original radii at the impact line suggest that the capsules might have been breached had the impact conditions been slightly different.

Even though no capsules were breached, cracks traversed more than 70% of the wall thickness; and because iridium behaves as a semibrittle material, the margin between no breach and breach is small. The modest ductility of iridium is inversely proportional to grain size, and grain size increases with service time at elevated temperatures; therefore, the margin of safety will

TABLE XI. Results of Spectrographic Analysis and Phosphorus Analysis of DIT-1 Fuel Pellets

Element	SRP-27 (IRG-101)	SRP-48 (IRG-102)	SRP-6 (IRG-103)	SRP-7 (IRG-104)
Li	<1	<1	<1	<1
Be	<1	<1	<1	<1
B	<1	5 ^a	5 ^a	5 ^a
Na	<2	<2	<2	<2
Mg	20	300 ^a	250 ^a	300 ^a
Al	15	60	25	30
Si	85	370 ^a	150	180
K	<5	<5	<5	<5
Ca	50	2000 ^a	3000 ^a	2000 ^a
Ti	15	140	400	160
V	<3	<3	<3	<3
Cr	55	60	65	60
Mn	4	5	5	5
Fe	260	260	340	280
Co	<3	<3	<3	<3
Ni	45	45	50	35
Cu	<1	<1	<1	<1
Zn	5	25	20	25
Rb	<10	<10	<10	<10
Sr	<5	<5	<5	<5
Y	<25	<25	<25	<25
Zr	<100	<100	<100	<100
Nb	<10	<10	<10	<10
Mo	4	30	3	10
Ag	<1	8	5	10
Cd	<10	<10	<10	<10
Sn	<5	<5	<5	<5
Ba	<2	<3	<2	<3
La	<25	<25	<25	<25
Hf	<25	<25	<25	<25
Ta	100	500	100	500
W	<10	<10	<10	<10
Re	<25	<25	<25	<25
Pb	<5	<5	<5	<5
Bi	<1	<1	<1	<1
P (wet)	20	20	20	15
P (radioanalytic)	<20	<20	<20	<20

^aValues exceed the impurity limits for sintered shards (DPSP-79-1076).

TABLE XII. Sieve Analysis of the Fuel from Capsule IRG-102 after Impact at 58 m/s and 930°C

Particle Size (μm)	Weight Fraction	Accumulated Weight Fraction
+6000	0.3702	0.3702
+2000	0.3713	0.7415
+ 841	0.1596	0.9011
+ 420	0.0426	0.9437
+ 177	0.0173	0.9610
+ 125	0.0036	0.9646
+ 74	0.0062	0.9708
+ 44	0.0073	0.9781
+ 30	0.0095	0.9876
+ 20	0.0033	0.9909
+ 10	0.0069	0.9978
- 10	0.0022	1.0000
≤ 4	0.0002	

also decrease with service time. All in all, the opinion of this investigator is that the heat source is underdesigned for impact survival.

XII. CONCLUSIONS

1. The DIT-1 impact results suggest that the various components of the GPHS are reasonably reproducible in impact responses, thus indicating that the manufacturing processes are also reasonably reproducible. Because of the necessarily small lot sizes and poor understanding of the physical and chemical characteristics of the materials, it seems likely that neither the production methods nor the properties of the materials have been optimized. Nonetheless, they seem equal to the task at hand.

2. Deformation of the GPHS clad is largely controlled by two factors: the fracture strength of the fuel and the amount of external support provided to the fuel/clad

combination. If the strength of the fuel could be increased, then deformation should be decreased, but cracking by thermal stresses and weakening because of helium bubble precipitation in grain boundaries at elevated temperatures are major obstacles to that remedy. Thus, we must conclude that the only practicable method of limiting deformation (and therefore cracking) is to increase the degree of support external to the fuel clad.

3. The weak links in the chain of mechanical performance are the CBCF insulation and the open window between GISs. Their use provides a necessary thermal barrier, but they simultaneously degrade impact performance because significant loads cannot be transmitted during the early part of deceleration.

4. The three-dimensional FWPF graphite parts continue to perform in acceptable fashion.

5. This investigation indicates that the fuel pellets and the DOP-26 iridium alloy, at their present stages of development, provide a marginally acceptable impact performance in a DIT-1 situation; however, safety could be greatly improved by a modest increase in the support provided to the fueled clad.

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Fig. 1a.

(b)

(c)

(d)

Fig. 1. Photographs of the four DIT-1 fuel pellets, showing that all four contained large and more-or-less radial cracks, with the largest such cracks in pellet 27 and the smallest in pellet 7. Additionally, the radii of pellet 27 were rougher than those of the other pellets. (a) Pellet SRP 6, 1.5X; (b) pellet SRP 7, 1.5X; (c) pellet SRP 27, 1.6X; and (d) pellet SRP 48, 1.7X.

(a)

(b)

Fig. 2. External views of the IRG-101 closure weld. (a) Overlap and (b) weld ripples on single-pass portion. Both 10X.

(a)

(b)

Fig. 3. External views of the IRG-102 closure weld. (a) Overlap and (b) weld ripples on single-pass portion. Both 10X.

(a)

(b)

Fig. 4. External views of the IRG-103 closure weld. (a) Overlap and (b) weld ripples on single-pass portion. Both 10X.

(a)

(b)

Fig. 5. External views of the IRG-104 closure weld. (a) Overlap and (b) weld ripples on single-pass portion. Both 10X.

Fig. 6a.

(b)

(c)

Fig. 6. Microstructures of vertical sections of the IRG-90 closure weld (single pass). (a) Cross section, 50X; (b) cross section, 100X; and (c) face-on view at $\cong 250 \mu\text{m}$ depth, 50X.

Fig. 7a.

(b)

(c)

(d)

(e)

Fig. 7. Microstructures of vertical sections of the IRG-105 closure weld. (a) Cross section at overlap, 50X; (b) cross section at overlap, 100X; (c) cross section of single-pass portion, 50X; (d) cross section of single-pass portion, 100X; and (e) face on section at $\approx 250 \mu\text{m}$ depth, 50X.

Fig. 8. Schematic layout of geometric arrangement of the DIT-1 module. Not indicated is the end-to-end arrangement of the fuel clads with all vents toward the centerline.

Fig. 9. Aeroshell breakup produced by the impact.

Fig. 10a.

(b)

(c)

(d)

(e)

(f)

Fig. 10. The unopened GIS that contained IRG-101 and IRG-102. (a) Impacted side, (b) rotated 90° clockwise from top, (c) rotated 180°, (d) rotated 270°, (e) closure end, and (f) blind end. All 1X.

Fig. 11a.

(b)

(c)

(d)

(e)

(f)

Fig. 11. The unopened GIS that contained IRG-103 and IRG-104. (a) Impacted side, (b) rotated 90° clockwise from top, (c) rotated 180°, (d) rotated 270°, (e) closure end, and (f) blind end. All 1X.

Fig. 12. Macrographs in profile of the four DIT-1 fuel capsules. The layout is intended to facilitate comparison.

Fig. 13. Postimpact macrograph of IRG-101. Because the four impacted capsules are markedly similar, one photograph is adequate to illustrate the locations of all four opening cuts. Each circumferential cut was made in the vent cup at the lower boundary of the abraded zone, as indicated by the arrows. 1.3X.

Fig. 14. Schematic diagram showing locations of weld samples for microstructural determinations. Sample 1 provides a cross section of the overlap area; sample 2 is of the single-pass zone; and sample 3 shows the weld structure when viewed side-on (face-on). (Illustration from SRP procedure DPSOL 235-F-PuFF-3129M.)

Fig. 15. Postimpact macrograph of the trailing side of IRG-101, showing the locations of the four Auger samples cut from each capsule. Sample A-1 was taken from the weld near the overlap and was notched to fracture perpendicular to the weld direction and through the weld; sample A-2 also was of the weld but was notched to fracture parallel to the weld direction and along its centerline; sample A-3 was taken from the vent-side wall; and sample A-4 was taken from the blind-side wall. All 1.3X.

Fig. 16a.

(b)

(c)

(d)

(e)

Fig. 16. Microstructures of IRG-101 weld samples. (a) Sample 101-1, overlap zone, 50X; (b) sample 101-1, overlap zone, 100X; (c) sample 101-2, single-pass zone, 50X; (d) sample 101-2, single-pass zone, 100X; and (e) sample 101-3, face-on, 40X.

Fig. 17a.

(b)

(c)

(d)

(e)

Fig. 17. Microstructures of IRG-102 weld samples. (a) Sample 102-1, overlap zone, 50X; (b) sample 102-1, overlap zone, 100X; (c) sample 102-2, single-pass zone, 50X; (d) sample 102-2, single-pass zone, 100X; and (e) sample 102-3, face-on, 40X.

Fig. 18a.

(b)

(c)

(d)

(e)

Fig. 18. Microstructures of IRG-103 weld samples. (a) Sample 103-1, overlap zone, 50X; (b) sample 103-1, overlap zone, 100X; (c) sample 103-2, single-pass zone, 50X; (d) sample 103-2, single-pass zone, 100X; and (e) sample 103-3, face-on, 40X.

Fig. 19a.

(b)

(c)

(d)

(e)

Fig. 19. Microstructures of IRG-104 weld samples. (a) Sample 104-1, overlap zone, 50X; (b) sample 104-1, overlap zone, 100X; (c) sample 104-2, single-pass zone, 50X; (d) sample 104-2, single-pass zone, 100X; and (e) sample 104-3, face-on, 40X.

Fig. 20a.

(b)

(c)

(d)

(e)

(f)

(g)

Fig. 20. Microstructures of IRG-105 weld samples. (a) Sample 105-1, overlap zone, 50X; (b) sample 105-1, overlap zone, 100X; (c) sample 105-2, single pass zone, 50X; (d) sample 105-2, single-pass zone, 100X; (e) sample 105-2, single-pass zone, etched with HCl/NaCl solution, 50X; (f) sample 105-2, single-pass zone, etched with HCl/NaCl solution, 100X; and (g) sample 105-3, face-on, 40X.

(a)

(b)

Fig. 21. SEM photographs of the interior surfaces of overlap zones of (a) IRG-105 and (b) IRG-106. Both $\sim 35\times$.

Fig. 22a.

(b)

(c)

(d)

(e)

Fig. 22. Microstructures of IRG-106 weld samples. (a) Sample 106-1, overlap zone, 50X; (b) sample 106-1, overlap zone, 100X; (c) sample 106-2, single-pass zone, 50X; (d) sample 106-2, single-pass zone, 100X; and (e) sample 106-3, face-on, 40X.

(a)

(b)

Fig. 23. Microstructure of single-pass portion of IRG-106 weld at a section ~5 mm from the overlap shown in Fig. 22. (a) 50X and (b) 100X.

Fig. 24a.

(b)

(c)

(d)

Fig. 24. Macrographs (1.5X) of the four DIT-1 fuels after impact that illustrate the extent of pellet breakup. Although fragment sizes differ, the differences are not of sufficient magnitude to suggest that the mechanical responses varied widely. (a) SRP-27 fuel pellet in IRG-101, (b) SRP-48 fuel pellet in IRG-102, (c) SRP-6 fuel pellet in IRG-103, and (d) SRP-7 fuel pellet in IRG-104.

(a)

(b)

(c)

(d)

Fig. 25. Macro- and microstructures of the edge sample taken from impacted fuel pellet SRP-27 (IRG-101). (a) Macrograph of mounted and polished sample, 10X; (b) as-polished, 100X; (c) as-polished, 250X; and (d) etched, 250X.

(a)

(b)

(c)

(d)

Fig. 26. Macro- and microstructures of the internal sample taken from impacted fuel pellet SRP-21 (IRG-101). (a) Macrograph of mounted and polished sample, 10X; (b) as-polished, 100X; (c) as-polished, 250X; and (d) etched, 250X.

(a)

(b)

(c)

(d)

Fig. 27. Macro- and microstructures of the edge sample taken from impacted fuel pellet SRP-48 (IRG-102). (a) Macrograph of mounted and polished sample, 10X; (b) as-polished, 100X; (c) as-polished, 250X; and (d) etched, 250X.

(a)

(b)

(c)

(d)

Fig. 28. Macro- and microstructures of the internal sample taken from impacted fuel pellet SRP-48 (IRG-102). (a) Macrograph of mounted and polished sample, 10X; (b) as-polished, 100X; (c) as-polished, 250X; and (d) etched, 250X.

(a)

(b)

(c)

(d)

Fig. 29. Macro- and microstructures of the near-edge sample taken from impacted fuel pellet SRP-6 (IRG-103). (a) Macrograph of mounted and polished sample, 10X; (b) as-polished, 100X; (c) as-polished, 250X; and (d) etched, 250X.

(a)

(b)

(c)

(d)

Fig. 30. Macro- and microstructures of the interior sample taken from impacted fuel pellet SRP-6 (IRG-103). (a) Macrograph of mounted and polished sample, 10X; (b) as-polished, 100X; (c) as-polished, 250X; and (d) etched, 250X.

(a)

(b)

(c)

(d)

Fig. 31. Macro- and microstructures of the near-edge sample taken from impacted fuel pellet SRP-7 (IRG-104). (a) Macrograph of mounted and polished sample, 10X; (b) as-polished, 100X; (c) as-polished, 250X; and (d) etched, 250X.

(a)

(b)

(c)

(d)

Fig. 32. Macro- and microstructures of the interior sample taken from impacted fuel pellet SRP-7 (IRG-104). (a) Macrograph of mounted and polished sample, 10X; (b) as-polished, 100X; (c) as-polished, 250X; and (d) etched, 250X.

(a)

(b)

(c)

(d)

Fig. 33. Macrographs of cross sections of impacted capsules. (a) IRG-101, (b) IRG-102, (c) IRG-103, and (d) IRG-104. All 1.5X.

(a)

(b)

(c)

(d)

Fig. 34. Macrographs of cross sections of the vents from (a) IRG-101, (b) IRG-102, (c) IRG-103, and (d) IRG-104. All 10X.

(a)

(b)

(c)

(d)

Fig. 35. Representative microstructures of the vent cross section from IRG-101. (a) At the location of the inlet slots at one end of the section, 40X; (b) at the location of the inlet slot at the other end of the section, 40X; (c) at the exit hole at the center of the section, 40X; and (d) at $\sim 1/2$ radius to illustrate the frit, 100X.

(a)

(b)

(c)

(d)

Fig. 36. Representative microstructures of the vent cross section from IRG-102. (a) At the location of the inlet slots at one end of the section, 40X; (b) at the location of the inlet slot at the other end of the section, 40X; (c) at the exit hole at the center of the section, 40X; and (d) at $\sim 1/2$ radius to illustrate the frit, 100X.

(a)

(b)

(c)

(d)

Fig. 37. Representative microstructures of the vent cross section from IRG-103. (a) At the location of the inlet slots at one end of the section, 40X; (b) at the location of the inlet slot at the other end of the section, 40X; (c) at the exit hole at the center of the section, 40X; and (d) at $\sim 1/2$ radius to illustrate the frit, 100X.

(a)

(b)

(c)

(d)

Fig. 38. Representative microstructures of the vent cross section from IRG-104. (a) At the location of the inlet slots at one end of the section, 40X; (b) at the location of the inlet slot at the other end of the section, 40X; (c) at the exit hole at the center of the section, 40X; and (d) at $\sim 1/2$ radius to illustrate the frit, 100X.

(a)

(b)

(c)

(d)

Fig. 39. Macrographs of interior surfaces at regions of reverse bending, showing varying degrees of cracking. (a) IRG-101, (b) IRG-102, (c) IRG-103, and (d) IRG-104. All 8X.

(a)

(b)

(c)

Fig. 40. Microstructures of cracked area in IRG-101 cross section. (a) As-polished, 50X; (b) etched, 50X; and (c) etched, 100X.

(a)

(b)

(c)

Fig. 41. Microstructures of cracked area in IRG-102 cross section. (a) As-polished, 50X; (b) etched, 50X; and (c) etched, 100X.

(a)

(b)

(c)

(d)

Fig. 42. Microstructures of cracked area in IRG-103 cross section. (a) Weld crack, as-polished, 50X; (b) weld crack, etched, 50X; (c) wall crack, as-polished, 50X; and (d) wall crack, etched, 50X.

(a)

(b)

(c)

(d)

Fig. 43. Microstructures of cracked area in IRG-104 cross section. (a) Weld cracks, as-polished, 40X; (b) weld cracks, etched, 40X; (c) wall cracks, as-polished, 50X; and (d) wall cracks, etched, 50X. (The dark spots near the crack are hardness impressions.)

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

Fig. 44. Macrographs illustrating the corner strains in the impacted capsules. (a) IRG-101, vent end; (b) IRG-101, weld-shield end; (c) IRG-102, vent end; (d) IRG-102, weld-shield end; (e) IRG-103, vent end; (f) IRG-103, weld-shield end; (g) IRG-104, vent end; and (h) IRG-104, weld-shield end. All $\sim 2\times$.

(a)

(b)

Fig. 45. Microstructure of strained corner section of IRG-101. (a) 50X and (b) 100X. A few small grains at the inner surface (compressed) suggest that impact deformation was sufficient to support recrystallization.

(a)

(b)

Fig. 46. Typical microstructures of wall sections from capsule IRG-101. (a) Vent cup and (b) weld-shield cup. Both 100X.

(a)

(b)

Fig. 47. Typical microstructures of wall sections from capsule IRG-102. (a) Vent cup and (b) weld-shield cup. Both 100X.

(a)

(b)

Fig. 48. Typical microstructures of wall sections from capsule IRG-103. (a) Vent cup and (b) weld-shield cup. Both 100X.

(a)

(b)

Fig. 49. Typical microstructures of wall sections from capsule IRG-104. (a) Vent cup and (b) weld-shield cup. (The presence of the crack does not prevent an accurate microstructural comparison.)

(a)

(b)

Fig. 50. Typical microstructures of wall sections from capsule IRG-105. (a) Vent cup and (b) weld-shield cup. Both 100X.

(a)

(b)

Fig. 51. Typical microstructures of wall sections from capsule IRG-106. (a) Vent cup and (b) weld-shield cup. Both 100X.

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