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General-Purpose Heat Source Development: Safety Test Program

Postimpact Evaluation, Design Iteration Test 3

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by

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ABSTRACT

The General-Purpose Heat Source (GPHS) provides power for space missions by transmitting the heat of $^{238}PuO_2$ 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. In the third test (DIT-3), a full GPHS module was impacted at 58 m/s and 930°C. The module impacted the target at an angle of 30° to the pole of the large faces. The four capsules used in DIT-3 survived impact with minimal deformation; no internal cracks other than in the regions indicated by Savannah River Plant (SRP) preimpact nondestructive testing were observed in any of the capsules. The 30° impact orientation used in DIT-3 was considerably less severe than the "flat-on" impact utilized in DIT-1 and DIT-2. The four capsules used in DIT-1 survived, while two of the capsules used in DIT-2 breached; a small quantity ($\approx$50 μg) of $^{238}PuO_2$ was released from the capsules breached in the DIT-2 impact. All of the capsules used in DIT-1 and DIT-2 were severely deformed and contained large internal cracks. Postimpact analyses of the DIT-3 test components are described, with emphasis on weld structure and the behavior of defects identified by SRP nondestructive testing.

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 $^{238}PuO_2$ alpha decay to generate power by means of a thermoelectric array. 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 test results described in this report are a portion of the ongoing impact program and will provide necessary design information.

Thé first Design Iteration Test (DIT-1) was c
out at a velocity of 57 m/s and 930°C, with th
module impacted flat-on against a hardened
target.[1] The test unit was a full GPHS module co
ing two graphite impact shells (GISs); each GIS
tained two heat source capsules filled with ^{238}PuO
fuel capsules were loaded and welded at Los Al
The four pellets provided a total thermal pow
250 W. The major concern in DIT-1 was the qualit
survivability of the welds. All of the capsules sur
impact, and none of the capsules breached. Postir
analysis revealed that the welds were of consist
good quality and behaved no differently from the
rounding material. Intergranular cracking was obs

on the capsule walls and in the welds; some 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. A full GPHS module was impacted flat-on against a hardened steel target at 58 m/s and 930°C.[2] The four capsules used in DIT-2 were fueled and welded at the Savannah River Plant (SRP). Two capsules were breached by the impact, and a small quantity (≈50 μg) of $^{238}PuO_2$ 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 also carried out at 58 m/s and 930°C. As before, the test unit was a full GPHS module. However, in DIT-3 the test module impacted the target at an inclination of 30° (Fig. 1) rather than flat-on as in DIT-1 and DIT-2. The 30° impact angle was selected because the GPHS module was believed to wobble ±30° about the pole of the large faces while in subsonic flight. In addition, the capsules used in DIT-3 were not flight quality; all of the DIT-3 capsules were identified by SRP nondestructive testing (NDT) as having crack indications in excess of 8.0.[3] The primary objectives of this test were to determine if capsules with SRP/NDT crack indications of up to 10.0 would be acceptable in flight quality applications and to evaluate the effect of a 30° impact angle.

II. PRETEST DATA

DIT-3 was added to the test series to evaluate the impact response of fuel clads containing internal weld defects of various sizes. The four capsules used in DIT-3 (SRP-127, SRP-140, SRP-251, and SRP-317) had SRP/NDT crack indications of 9.0, 11.5, 8.0, and 10.4, respectively. The iridium-alloy cups and fuel pellets used to assemble the individuals heat sources are identified in Table I, and data describing the fuel pellets are in Table II. As in DIT-1 and DIT-2, SRP produced the fuel pellets, Oak Ridge National Laboratory (ORNL) provided the iridium-alloy blanks and produced the graphite insulation [carbon-bonded carbon filament (CBCF)], the Mound Facility (MF) fabricated the iridium cups, and Los Alamos machined the aeroshell and impact shells from Fineweave-Pierced Fabric*(FWPF) graphite.

Each DIT-3 capsule was macroscopically examined for external weld defects. The macrostructures of the weld overlaps are shown in Fig. 2. All of the overlaps were uniform and contained no obvious defects. Each

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

TABLE I. Encapsulation Details for DIT-3 Fueled Clads

Capsule No.	SRP/NDT Crack Indication	Iridium Cup Vent	Iridium Cup Weld-Shield	Fuel Pellet
SRP-127	9.0	NR519-2	NR508-5	8106HF127
SRP-140	11.5	NR503-5	N515-4	8107HF140
SRP-251	8.0	PR722-4	PR722-3	8112HF251
SRP-317	10.4	Q816-1	Q816-2	8202HF317

TABLE II. Data for Sintered DIT-3 Fuel Pellets

Capsule No.	Fuel Form No.	Diameter (mm)	Length (mm)	Weight (g)
SRP-127	8106HF127	27.53	27.72	147.0
SRP-140	8107HF140	nonintegral	(3 pcs.)	148.9
SRP-251	8112HF251	27.50	27.45	151.2
SRP-317	8202HF317	nonintegral	(4 pcs.)	150.4

capsule had good wall alignment over the entire weld length.

After macroscopic examination, the fueled clads were radiographed and loaded into two graphite impact shells (GISs). The loaded GISs were then heat treated at 1312°C for 30 days to simulate the minimum expected service life. After heat treatment, the GISs were radiographed again. The radiographs (Figs. 3 and 4) show that all of the fuel pellets were severely cracked. (Note that SRP reported pellets 140 and 317 to be nonintegral at loading.)

III. TEST PROCEDURE

After heat treatment, the fueled GISs were loaded into the aeroshell as shown in Fig. 1. GIS-1 contained capsules SRP-140 and SRP-251, and GIS-2 held capsules SRP-127 and SRP-317 (the fuel labels are used throughout to identify the fuel/clad sets). The test module was impacted at 58 m/s and 930°C. DIT-3 differed from previous Design Iteration Tests in that the test unit impacted the target at a 30° inclination, whereas in DIT-1 and DIT-2 the test module was impacted flat-on. 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 applied in DIT-3 were the same as those used in DIT-1 and DIT-2.

IV. POSTIMPACT EXAMINATION

Previous experience with the DIT-1 and DIT-2 tests expedited postimpact disassembly. The catch tube was opened without difficulty, and only low levels (<2000 counts/min/cm^2) of $^{238}PuO_2$ contamination were encountered. The inner nickel can (a radiation shield assembly) was extracted with tongs, and the can/aeroshell/heat source assembly was placed on a bed of solid CO_2. The CO_2 cooled the assembly rapidly, and in a few seconds the temperature had dropped enough to eliminate the possibility of graphite combustion. The aeroshell was severely fractured. Postimpact photographs of the test module (Fig. 5) illustrate the extensive mechanical damage. Damage to the two GISs (Figs. 6 and 7) was significant but not unusual.

The fuel capsules were extracted from the GISs, photographed, and measured. Side and end views of each capsule are shown in Fig. 8. Macroscopic examination revealed that the DIT-3 capsules had not been deformed as severely as the capsules used in DIT-1 and DIT-2. As expected, the two leading capsules (SRP-251 and SRP-317) experienced significantly more deformation than the trailing capsules (SRP-127 and SRP-140). Capsule dimensions and the calculated gross strains are listed in Table III and IV. Although the magnitude of the strains observed in the DIT-3 capsules was not significantly different from that of DIT-1 and DIT-2 capsules, the strain distribution reflected the change in impact attitude.

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 reduced by minimizing the actual breakthrough of the capsule wall. The remaining iridium-alloy wall on capsules SRP-127, SRP-140, and SRP-251 was pried open with a small screwdriver, and the clads were defueled immediately after opening. To determine the quantity of respirable fuel particles produced by impact, capsule SRP-317 was selected for a particle-size determination. Before being opened, the capsule was transferred to a glove-box train used for fines analysis. The capsule was then opened under water to avoid the loss of any small particles.

The opened capsules were examined with a hand-held magnifier. No external cracks were visible on any of the closure welds but examination of the capsule interiors did reveal the presence of fine weld cracks. The cracked areas were removed for metallographic examination. No defects were observed on any of the capsule walls

A face-on weld sample was obtained from each capsule in accordance with SRP procedure DPSOL 235-F-PuFF-3129M.[4] The weld in each capsule was also sampled to provide specimens from the overlap and single-pass regions. The weld samples included a wall section sufficient to establish grain size and other microstructural features, as well as hardness of the weld-shield cup. Similarly, the vent cup sections included enough wall section to establish grain size and reveal other microstructural features. Samples of the two cups composing each capsule were submitted for spectrographic and Auger electron spectrographic analyses. The spectrographic samples were cut from the cup walls at about midheight.

The fuels extracted from SRP-127, SRP-140, and SRP-251 were sampled for ceramography by selecting two 1-g fragments from each pellet: one removed from the outer edge and one taken from the center. Two additional 1-g fragments were removed for chemical analysis: one for spectrographic analysis and one for a wet-chemistry phosphorus determination. The fuel in capsule SRP-317 was not sampled until a particle-size analysis had been completed. Results of the particle-size

TABLE III. Dimensions of DIT-3 Fueled Clads					
		Clad Number			
		SRP-127	SRP-140	SRP-251	SRP-317
Preimpact Dimensions					
Diameter					
vented cup		29.80mm	29.83mm	29.79mm	29.81mm
weld		30.00	29.97	29.97	29.97
nonvented cup		29.80	29.79	29.80	30.22
Length		30.21	30.20	30.23	30.22
Diagonal		37.55	37.55	39.56	37.56
Postimpact Dimensions					
Diameter					
vented cup	min	28.85	28.49	29.03	29.54
	max	30.48	30.48	30.48	31.04
weld	mix	29.51	29.21	29.54	28.80
	max	30.68	30.89	31.59	32.00
nonvented cup	min	29.54	29.72	29.97	27.94
	max	30.33	30.48	31.14	31.22
Length	min	30.07	30.10	30.48	29.85
	max	31.17	31.50	31.57	30.58
Diagonal	min	37.01	35.88	36.68	34.29
	max	37.67	37.77	38.05	38.20

TABLE IV. Postimpact Strains in DIT-3 Fueled Clads					
		Clad Number			
		SRP-127	SRP-140	SRP-251	SRP-317
		(%)	(%)	(%)	(%)
Diameter					
vented cup	min	−3.15	−4.56	−2.56	−0.90
	max	+2.30	+2.16	+2.30	+4.12
weld	min	−1.53	−2.54	−1.36	−3.90
	max	+1.02	+3.05	+1.78	+6.78
nonvented cup	min	−2.55	−0.26	+0.56	−6.22
	max	+0.05	+2.30	+4.48	+4.78
Length	min	−0.42	−0.34	−0.84	−1.22
	max	+3.20	+4.29	+4.45	+1.22
Diagonal	min	−1.45	−4.43	−2.35	−8.70
	max	+0.31	+0.58	+1.30	+1.72

analysis are presented in Table V. When the fuel samples had been repackaged for transfer, each lot was radioanalyzed to approximate the phosphorus content.

VI. METALLOGRAPHIC EXAMINATION

A. Weld Metallography

Because the main objectives of the DIT-3 test were to evaluate and compare the behavior of capsules containing centerline weld defects of varying magnitude, the weld samples were the first to be examined. The interior surfaces of the overlap welds were macroscopically examined for defects. Representative areas of the overlap welds, in which the submergence points of the weld pools are clearly visible, are shown in Fig. 9. After macroscopic examination, the equatorial weld of each capsule was sampled by removing 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 examination are given below.

1. SRP-127. Although no defects were observed on the surface of the overlap weld (Fig. 9a), SRP nondestructive testing reported a magnitude 9.0 defect. The "as-polished" overlap section (Fig. 10) contained one surface crack and a small amount of porosity; no large weld defects were observed. Figure 11 illustrates the overlap microstructure at the point of weld submergence. The microstructures of the single-pass and face-on specimens (Figs. 12 and 13) were typical, with no observed defects.

TABLE V. Sieve Analysis of Fuel Removed From Capsule SRP-317

Particle Size (μm)	Weight Fraction	Accumulated Weight Fraction
+6000	0.4671	0.4671
+2000	0.3371	0.8042
+ 841	0.1236	0.9278
+ 420	0.0483	0.9761
+ 177	0.0035	0.9795
+ 125	0.0044	0.9839
+ 74	0.0001	0.9840
+ 44	0.0049	0.9889
+ 30	0.0045	0.9934
+ 20	0.0034	0.9968
+ 10	0.0023	0.9991
− 10	0.0009	1.0000

2. SRP-140. Nondestructive testing completed at the Savannah River Plant indicated that capsule SRP-140 contained an internal weld defect of magnitude 11.5. Postimpact examination of the capsule did not reveal any large weld cracks. Several fine cracks were present at the surface of the overlap weld (Fig. 9b), and the metal appeared to be quite porous, but no large defects were observed. Metallographic examination of the overlap weld confirmed that the weld metal was unusually porous (Fig. 14a). Figure 14b reveals that except for porosity, the overlap microstructure was typical. The single-pass and face-on specimens (Figs. 15 and 16) were also typical and contained no observable defects.

3. SRP-251. The overlap weld section containing the point of weld submergence is shown in Fig. 9c. SRP/NDT indicated that this capsule contained a magnitude 8.0 defect. Although macroscopic examination did not reveal any large weld defects, metallographic examination of the overlap weld revealed the crack seen in Fig. 17a. This crack traversed more than 30% of the wall thickness. The overlap microstructure was typical and otherwise free of defects (Fig. 17b). The single-pass and face-on specimens were also typical and contained no observable defects (Figs. 18 and 19).

4. SRP-317. A large crack was observed in the overlap weld on capsule SRP-317 (Fig. 9d). SRP/NDT indicated that this capsule contained a magnitude 10.4 defect. Metallographic examination of the overlap section revealed that the crack penetrated over 15% of the wall thickness (Fig. 20a). The overlap weld microstructure was otherwise normal and free of defects (Fig. 20b). The single-pass and face-on microstructures were typical (Figs. 21 and 22).

B. Vent Metallography

All vents survived impact without significant harm. The vent cross sections are shown in Figs. 23 through 26. The vent structures were carefully examined to determine if the pretest heat treatment (30 days at 1312°C) had caused the transport of any fuel components and to further define the impact response of the vent assembly. No mechanical defects were observed in any of the vents; all of the frits were uniform and properly aligned, and no significant amounts of fuel impurities were detected in the vent cross sections. Apparently, the pretest heat treatment had little effect on the transport/deposition of fuel components into the vents, although a few fuel fragments and small amounts of glass (mixed oxides) were typically observed in the vent cross sections.

C. Iridium-Cup Wall Microstructures

Each of the eight iridium-alloy cups composing the DIT-3 capsules (SRP-127, SRP-140, SRP-251, and SRP-317) was sampled to provide a specimen for metallographic examination. Before testing, the capsules were given a heat treatment (30 days at 1312°C) to simulate the minimum expected service life. Because the heat sources were not exposed to temperatures in excess of the preimpact heat treatment, the postimpact grain size and microstructure were expected to be nearly identical to the preimpact condition (except in severely deformed areas). Microscopic examination revealed that the cup grain sizes ranged from 14 to 21 grains/0.025 in. wall thickness (Table VI). The cup microstructures may be seen in Figs. 27 through 34. The wall section removed from the SRP-127 vent cup contained several excessively large grains (Fig. 35); the orientation and appearance of the grains suggest that recrystallization has occurred. The postimpact hardnesses of the iridium-alloy cups are presented in Table VII. Except for the atypical area observed in the SRP-127 vent cup (no similar areas were observed in any other cup), the cup microstructures were normal.

VII. FUEL CERAMOGRAPHY

All four DIT-3 fuel pellets were cracked before testing; radiographic prints of the four pellets are shown in Figs. 3 and 4. Postimpact examination revealed that each fuel pellet responded to the impact stresses by fracturing in a completely brittle mode, and that all of the fuel pellets fractured in a similar manner. The general patterns of fuel breakup may be seen in Fig. 36. Although pellet 251 exhibited a well-defined cleavage surface (Fig. 36c) that matched a point of high local shear strain in the iridium clad, the fuel pellets usually fractured in a random manner.

Ceramographic specimens were obtained from the center and outer edge of each fuel pellet. The pellet microstructures are shown in Figs. 37 through 44. The photomicrographs reveal slight microstructural variations between pellets and from point to point within a given pellet. Because the mechanical responses of all four pellets were essentially the same, the slight microstructural differences apparently did not affect overall pellet performance.

VIII. CHEMICAL ANALYSES

A. Iridium-Alloy Chemistry

Samples were removed from each of the eight iridium cups used in DIT-3 for spectrographic and Auger electron spectroscopic examination. Spectrographic analysis was used to determine the bulk composition of each sample, and Auger electron spectroscopy was used to

TABLE VI. Grain Sizes of DIT-3 Capsules

[Average No. of grains/0.025 in. wall thickness]

Capsule No.	Cup	Grains/Thickness
SRP-127	Vent	21.5
	Weld-shield	18.1
SRP-140	Vent	17.7
	Weld-shield	16.2
SRP-251	Vent	16.4
	Weld-shield	17.4
SRP-317	Vent	14.8
	Weld-shield	17.8

TABLE VII. Postimpact Hardness of Iridium-Alloy Capsules Used in DIT-3

Capsule		DPHN (200-g load) @95% CL[a]	Range
SRP-127	vent cup	323 ± 11	289-349
	weld-shield cup	323 ± 9	290-340
	weld	334 ± 16	307-401
SRP-140	vent cup	282 ± 7	269-305
	weld-shield cup	339 ± 27	291-408
	weld	305 ± 7	294-323
SRP-251	vent cup	312 ± 10	288-338
	weld-shield cup	317 ± 7	299-335
	weld	315 ± 12	294-350
SRP-317	vent cup	325 ± 14	298-374
	weld-shield cup	266 ± 9	251-285
	weld	302 ± 11	276-329

[a]CL = confidence level.

determine the distribution of various elements on a fresh fracture surface. The results of the analyses are listed in Tables VIII and IX.

The spectrographic analyses (Table VIII) indicate that the iridium alloy was of good overall purity with little cup-to-cup variation in chemistry. The slight differences in composition that were observed would not be expected to have had any effect on the mechanical response. In addition, the chemical compositions of the DIT-3 cups were very similar to the compositions of cups used in DIT-1 and DIT-2.

The Auger results (Table IX) suggest that thorium segregated to the grain boundaries of both cast (weld bead) and recrystallized alloy. It also appears that carbon and oxygen were present in the grain boundaries but apparently had little effect on the mechanical response of the capsules. Similarly, neither the low quantities of sulfur nor the possible presence of boron and/or chlorine in the grain boundaries had any observable effect on capsule performance.

B. Fuel Chemistry

Samples for chemical analysis were removed from each of the DIT-3 fuel pellets. The results of spectrographic surveys, as well as the results of wet-chemistry and radioanalyses for phosphorus (Table X), indicate that the fuel pellets were chemically similar to one another and to the fuel pellets used in DIT-1 and DIT-2. Although the aluminum content of SRP-127 was unexpectedly high, it does not appear that this abnormality had any effect on the impact response (note, however, that SRP-127 and SRP-140 were trailing capsules and consequently were not exposed to severe impact stresses). The amount of phosphorus detected in each pellet was generally the same and was consistent with the levels of phosphous impurities observed in the DIT-1 and DIT-2 fuel pellets.

IX. LOCAL STRAINS

The 30° impact attitude produced little permanent deformation in the two trailing capsules (SRP-127 and SRP-140). The macrographs (Fig. 8) show small permanent strains in the leading capsules (SRP-251 and SRP-317) of the push-through (shear) type, rather than the large bends observed in the DIT-1 and DIT-2 capsules. The most severe local strains were found in capsule SRP-251, where a section through the largest wrinkle in the vent end experienced a local strain of approximately 9%. The magnitude of this strain was quite similar to the local strains observed in DIT-1 and DIT-2. Examination of the circumference on SRP-251 revealed a maximum local strain of 7%, again consistent with deformations observed in previous Design Iteration Tests. The maximum strains in capsule SRP-317 and capsule SRP-251 were qualitatively similar. Both maximum circumferential strain and local strain on the deformed end of the weld-shield cup were 5.5%.

TABLE VIII. Spectrochemical Analyses of the Iridium-Alloy Cups Used in DIT-3[a]

(all results are given in ppm by weight)

	SRP-127		SRP-140		SRP-251		SRP-317	
Element	V-cup[b]	W-cup[c]	V-cup	W-cup	V-Cup	W-Cup	V-cup	W-cup
Al	50	80	50	50	50	50	30	40
Ca	3	-	-	-	-	-	-	-
Cr	10	10	-	-	40	50	-	-
Cu	20	30	25	35	8	10	30	25
Fe	100	100	80	100	200	200	100	100
Mg	20	6	10	-	-	-	7	3
Ni	30	50	40	50	50	50	40	50
Pt	-	30	-	-	-	-	-	-
Si	20	15	10	-	10	10	20	10
W[d]								

[a]Elements are listed only if they exceed detectability limits in at least one fuel pellet.
[b]The cup containing the vent.
[c]The cup containing the weld shield.
[d]All of the clads had tungsten content between 10^3 and 10^4 ppm.

TABLE IX. Auger Intensity Ratios of Wall Samples Removed from DIT-3 Clads

Capsule	Sample	Location	Th_{65}/Ir_{54}	Th_{65}/Ir_{229}	C_{270}/Ir_{229}	O_{510}/Ir_{229}	Other
SRP-127	V-cup[a]	inside	0.045	0.476	-	-	-
		center	0.068	0.645	0.488	0.714	-
		outside	0.048	0.472	0.427	0.697	-
	W-cup[b]	inside	0.063	0.572	-	-	-
		center	0.072	0.810	-	-	-
		outside	0.052	0.590	-	-	-
	Weld	inside	0.061	0.590	-	-	-
		center	0.083	0.804	-	-	-
		outside	0.057	0.667	-	-	-
SRP-140	V-cup	inside	0.030	0.290	-	-	-
		center	0.045	0.432	-	-	-
		outside	0.041	0.354	-	-	-
	W-cup	inside	0.084	0.835	-	-	-
		center	0.067	0.627	-	-	-
		outside	0.051	0.468	-	-	0.05 B or Cl_{180}/Ir_{229}
	Weld	inside	0.058	0.550	-	0.813	0.092 B or Cl
		center	0.052	0.485	0.132	0.667	0.054 S_{150}/Ir_{229}
		outside	0.051	0.452	0.280	1.032	-
SRP-251	V-cup	inside	0.075	0.744	-	-	-
		center	0.093	1.000	-	-	-
		outside	0.076	0.727	-	-	0.068 S_{150}/Ir_{229}
	W-cup	inside	0.039	0.416	-	-	-
		center	0.076	0.763	-	-	-
		outside	0.060	0.564	-	-	0.090 S_{150}/Ir_{229}
	Weld	inside	0.045	0.463	-	-	-
		center	0.061	0.684	-	-	-
		outside	0.051	0.435	-	-	-
SRP-317	V-cup	inside	0.066	0.644	-	-	-
		center	0.096	0.876	-	-	-
		outside	0.068	0.625	-	0.417	-
	W-cup	inside	0.057	0.539	-	0.382	-
		center	0.072	0.773	-	-	-
		outside	0.058	0.565	-	0.544	-
	Weld	inside	0.046	0.435	-	-	-
		center	0.063	0.651	-	-	-
		outside	0.080	0.824	-	-	-

[a]The cup containing the vent.
[b]The cup containing the weld shield.

TABLE X. Chemical Analyses of the DIT-3 Fuel Pellets

Element[a]	SRP-127	SRP-140	SRP-251	SRP-317
Ag	4	5	15	20
Al	260	35	45	35
B	1	<1	<1	<1
Ba	4	2	2	2
Ca	80	80	80	80
Cr	5	20	20	4
Fe	85	140	135	65
Mg	<1	1	<1	1
Mn	1	1	1	<1
Na	20	3	4	3
Pb	5	5	4	8
Si	45	15	55	20
Ta	1000	500	100	100
Ti	50	50	50	25
P[b]	<20	<20	<20	<20
P[c]	15	10	13	20

[a]Elements are listed only if they exceed detectability limits in at least one fuel pellet.
[b]Determined by radioanalysis.
[c]Determined by wet chemistry.

X. DISCUSSION

The GPHS module impacted in DIT-3 behaved much like the modules tested in DIT-1 and DIT-2. In each test, postimpact examination revealed that the FWPF aeroshell and GISs were severely fractured. In DIT-1 and DIT-2, the fuel capsules were substantially deformed and contained large cracks. In DIT-2, two capsules breached. In DIT-3, however, the fuel capsules suffered little deformation. The two trailing capsules (SRP-127 and SRP-140) were relatively undamaged, and the leading capsules (SRP-251 and SRP-317) experienced only small permanent strains. Apparently, the 30° impact attitude used in DIT-3 was considerably less severe than the flat-on orientation used in previous DITs.

DIT-3 was intended to provide data on the detrimental effects of various-sized weld defects, but this objective was not fulfilled. No significant differences were observed between the mechanical responses of welds in the two leading capsules (SRP-251, NDT indication of a magnitude 8.0 defect; SRP-317, NDT indication of a magnitude 10.4 defect) or between the welds of the trailing capsules (SRP-127, NDT indication of a magnitude 9.0 defect; SRP-140, NDT indication of a magnitude 11.5 defect). Apparently, the "soft" impact produced by the 30° aeroshell tilt so reduced stress levels that shear stress across the capsule weld did not produce a significant load. The porosity and small cracks observed in the capsule welds were apparently preimpact artifacts that survived the test relatively unchanged.

The nondestructive testing completed at the Savannah River Plant (SRP) was not entirely accurate in predicting the size of internal weld defects. Metallographic examination revealed that all of the DIT-3 capsule welds contained a few hairline surface cracks. Large cracks were observed on the fuel side surfaces of the SRP-251 and SRP-317 welds. In addition, the weld on capsule SRP-140 was quite porous. None of the internal weld defects observed in the capsule welds could be correlated with SRP/NDT indications. It appears that the SRP/NDT was more effective in predicting the location of internal weld defects than in determining their size.

All of the microstructural and chemical results indicate that the iridium alloy was of good quality and reasonable reproducibility. The four capsules had similar chemistries, with all variations within the expected range for small-lot preparations. The microhardness tests indicate that the DIT-3 capsules were slightly softer than the capsules used in DIT-1 and DIT-2; the DIT-3 capsules ranged in hardness from 289 to 370 DPHN, while the DIT-1 and DIT-2 capsules ranged from 289 to 430 DPHN (Diamond pyramid hardness number). The minor deformations experienced by the DIT-3 capsules apparently prevented them from strain hardening to the levels observed in the DIT-2 capsules.

The fuel pellets used in DIT-3 were chemically and microstructurally similar both to one another and to the fuel pellets used in DIT-1 and DIT-2. The postimpact appearance of the fuel pellets and the results of the particle-size analysis performed on the fuel removed from SRP-317 indicate that the mechanical response of these fuel pellets was qualitatively similar to the behavior of fuel pellets used in DIT-1 and DIT-2.

XI. CONCLUSIONS

1. DIT-3 was intended to provide data on the detrimental effects of various-sized weld defects. In this the test was a failure; no significant differences existed between the mechanical responses of the welds on the two leading capsules (SRP-251 and SRP-317) and those of the trailing capsules (SRP-127 and SRP-140).

2. Nondestructive testing completed at the Savannah River Plant (SRP) was not accurate in predicting the size of internal weld defects. Postimpact examination of the capsule welds did not reveal any defects that could be directly correlated with the SRP/NDT crack indica-

tions. SRP/NDT was more effective in locating weld defects (small cracks, porosity, etc.) than in determining their size.

3. The 30° impact attitude used in DIT-3 was considerably less damaging than the flat-on orientation used in previous Design Iteration Tests. The absence of cracks (other than small weld cracks) in the DIT-3 capsules, as compared with the axial crack families observed in the DIT-1 and DIT-2 capsules, justifies this conclusion.

4. The results of DIT-3 demonstrate that the iridium alloy will perform adequately, provided the strains do not exceed the inherently limited ductility. A generalized deformation limit is inapplicable because the iridium alloy is sensitive to strain state as well as magnitude.

5. The microstructures and chemical analyses of the fuel pellets and iridium-alloy cups indicate that these components were similar to the components tested in DIT-1 and DIT-2. No structural or chemical anomalies were observed, so the impact behavior of these components must be considered typical.

6. The mechanical performance of the vents in all DIT-3 capsules was satisfactory. No defects were observed in any vent sections.

ACKNOWLEDGMENTS

We wish to thank J. Archuleta, L. Bergamo, and D. Pavone for their generous laboratory assistance.

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1. F. W. Schonfeld, "General-Purpose Heat Source Development: Safety Test Program, Postimpact Evaluation, Design Iteration Test 1," Los Alamos National Laboratory report LA-9680-SR (April 1984).

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3. "Ultrasonic Weld Examination, GPHS Fueled Clad," E. I. duPont de Nemours & Co., Savannah River Plant Operations Manual DPSOP-268, procedure DPSOL 235-F-PuFF-4620A.

4. "Iridium Weld Inspection Data Sheet (Metallography Lab)," E. I. duPont de Nemours & Co., Savannah River Plant Operations Manual DPSOP-268 procedure DPSOL-235-F-PuFF-3129M, Revision 1 (March 1981).

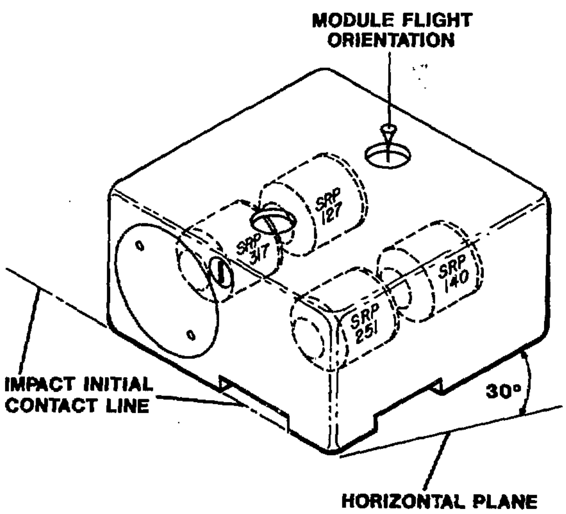


Fig. 1. DIT-3 GPHS and fueled clad test positions.

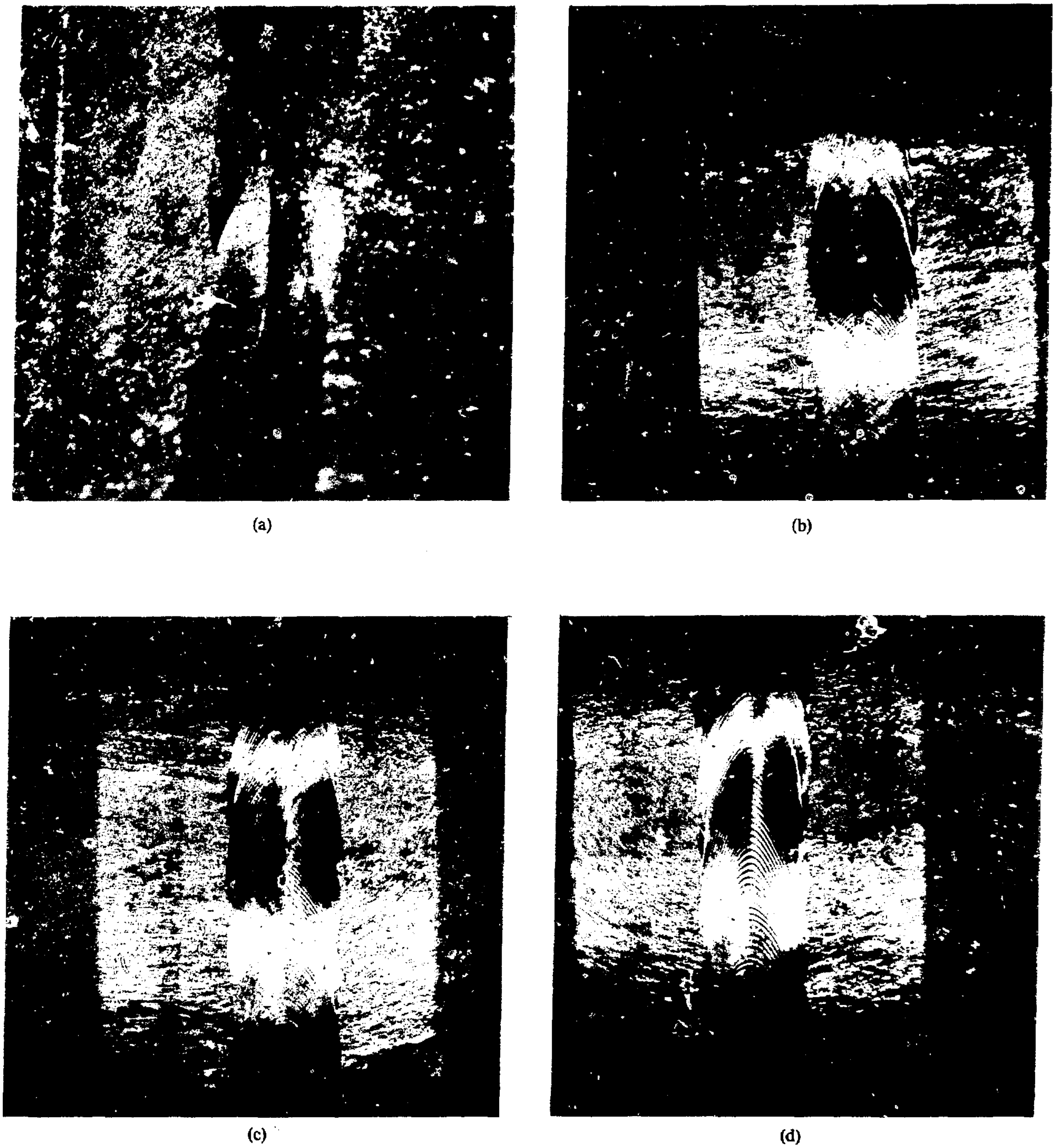


Fig. 2. Overlap welds of the DIT-3 capsules: (a) SRP-127, (b) SRP-140, (c) SRP-251, and (d) SRP-317. All at 7X.

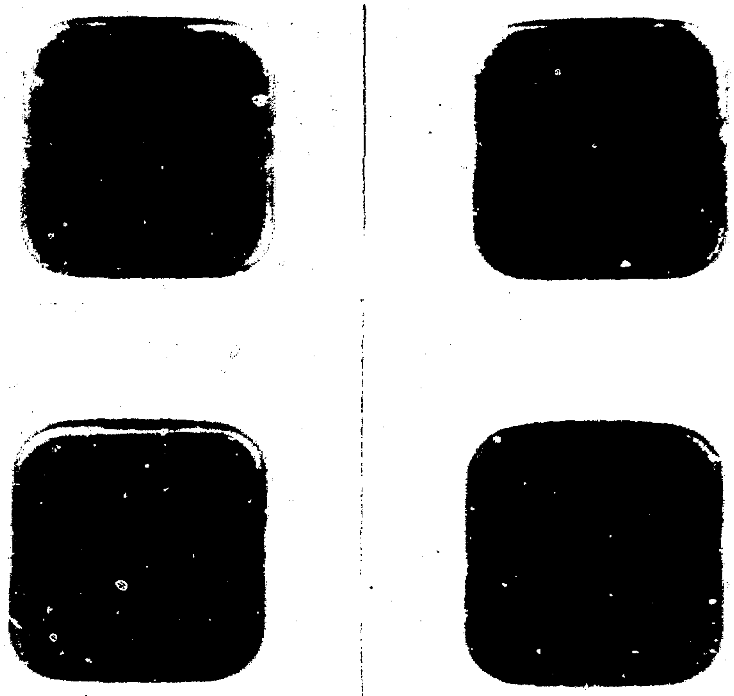


Fig. 3. Radiographic prints of the "as-received" fuel pellets, 1.15X.

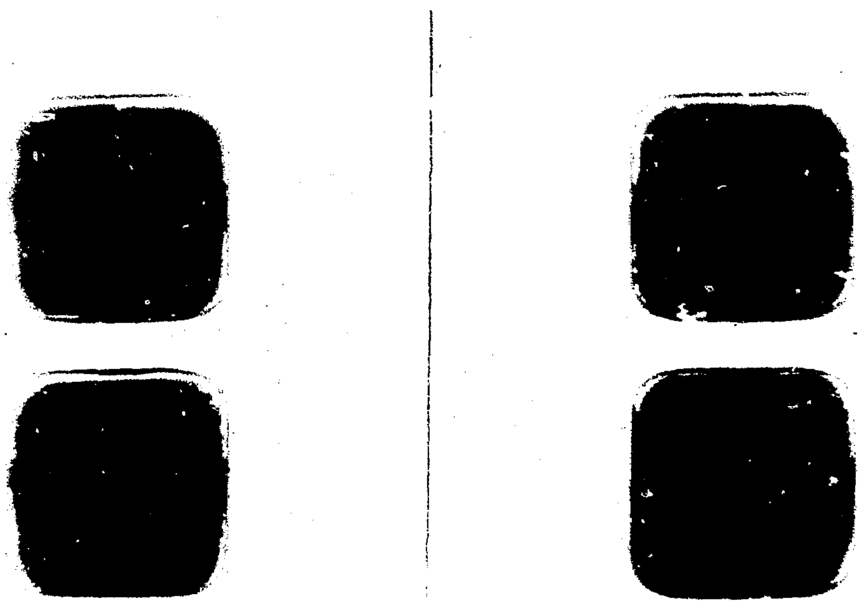
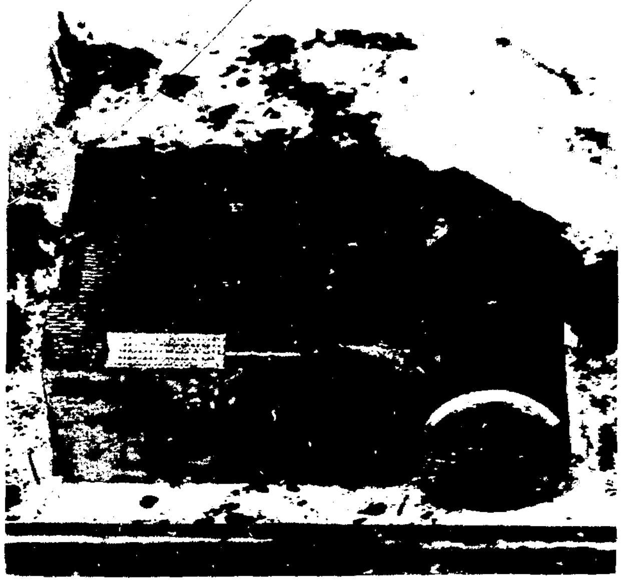


Fig. 4. Radiographic prints of the DIT-3 fuel pellets after heat treatment. (a) SRP-140 and SRP-251, held in GIS-1; and (b) SRP-127 and SRP-317, held in GIS-2. Both at 1X.

Fig. 5a.

(b)



(c)

Fig. 5. The re-entry shell used in the DIT-3 impact. (a) As extracted from the catch tube; (b) impact face of the module with the right vertical edge being the leading edge; and (c) impact face of the aeroshell, with the near upper edge as the trailing edge. All at 0.5X.

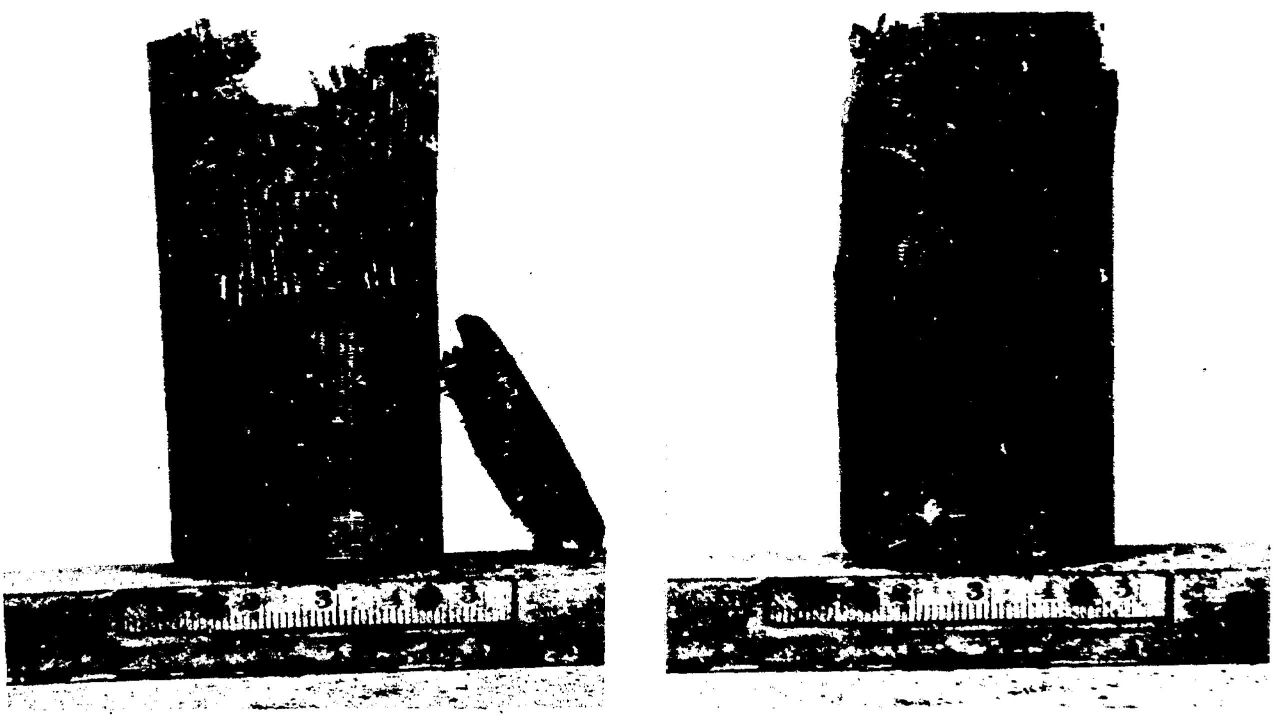
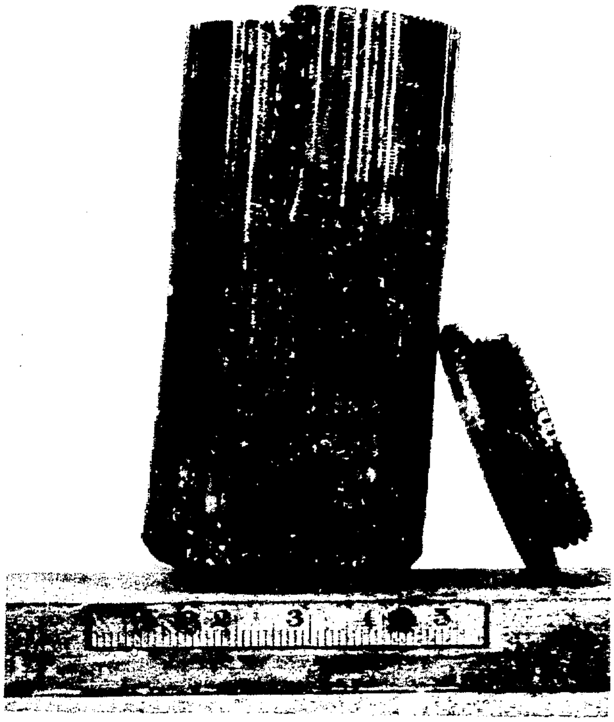
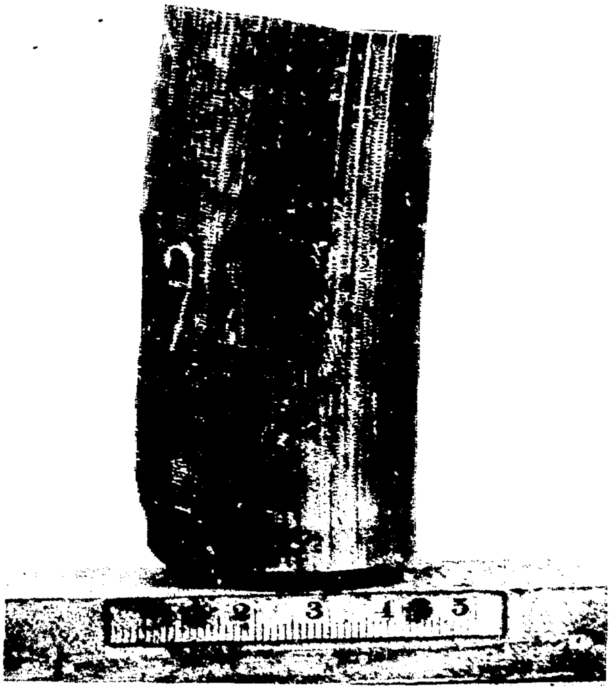


Fig. 6. GIS-1, containing fueled clads SRP-140 and SRP-251. (a) Impact face and (b) side view with impact face to the left. Both at 1X.



(a)



(b)

Fig. 7. GIS-2, containing fueled clads SRP-127 and SRP-317. (a) Impact face and (b) side view with impact face to the left. Both at 1X.

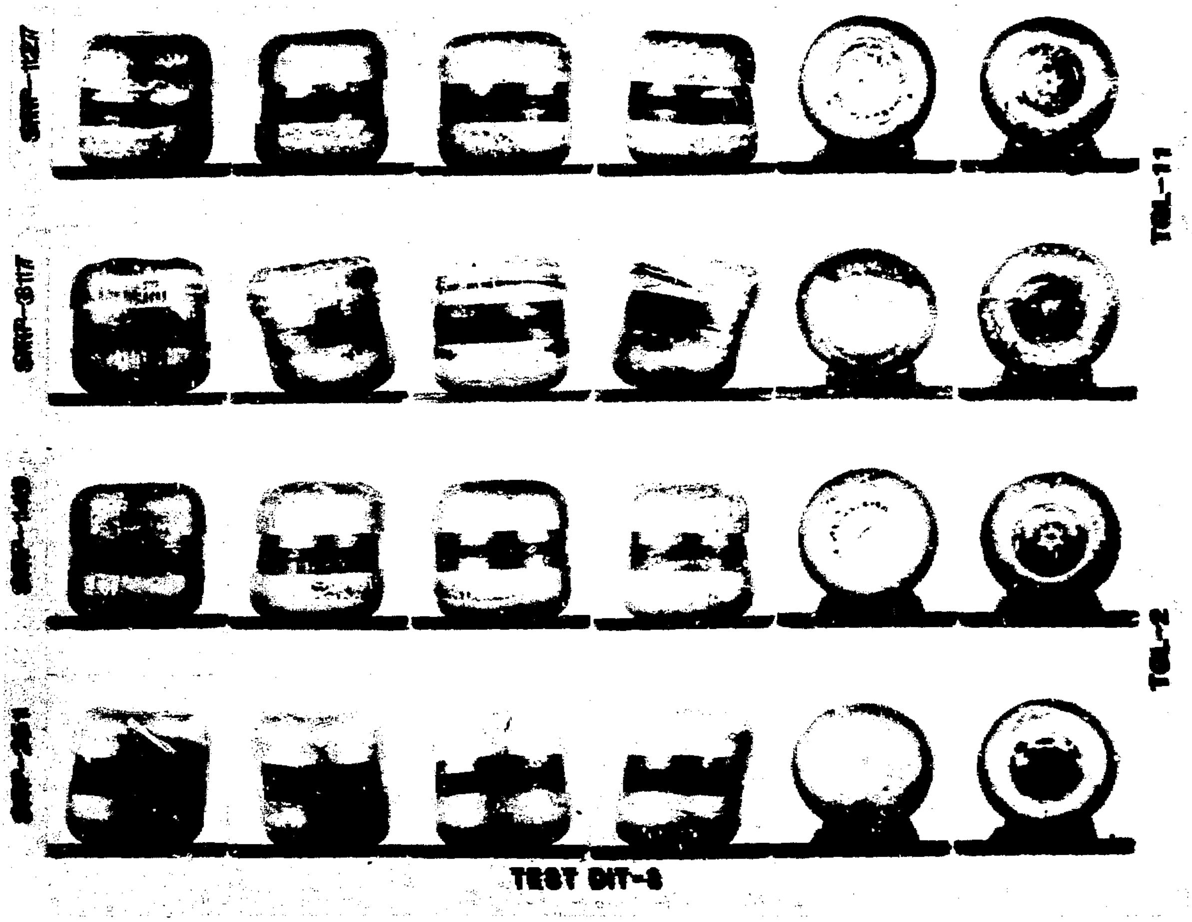
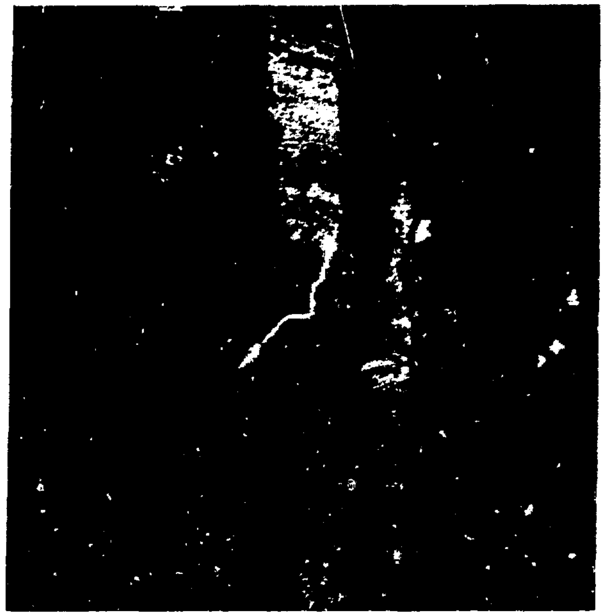


Fig. 8. Macrographs of the four impacted fuel capsules. The impact face of each capsule is shown in the left hand column; in each succeeding view the capsule is rotated 90°. The last two columns are end views. All at 1X.

(a)



(b)

(c)

(d)

Fig. 9. Internal overlap welds on the DIT-3 capsules. (a) SRP-127, (b) SRP-140, (c) SRP-251, and (d) SRP-317. All at 12X.

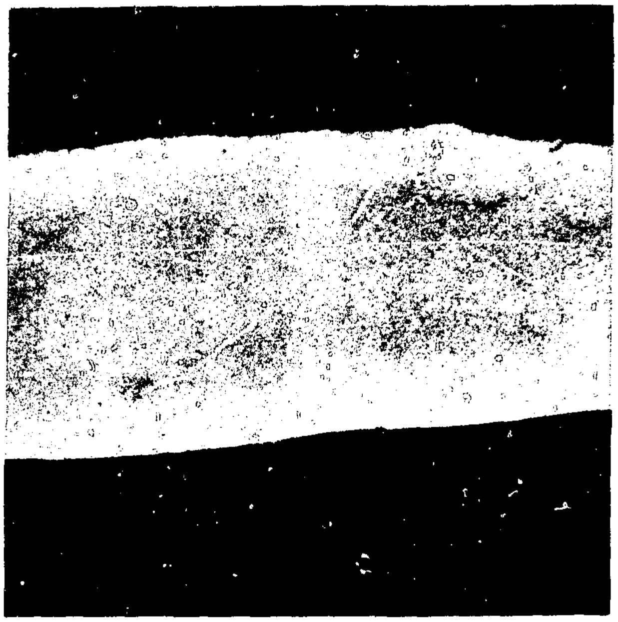


Fig. 10. Overlap section removed from capsule SRP-127, as polished; 50X.

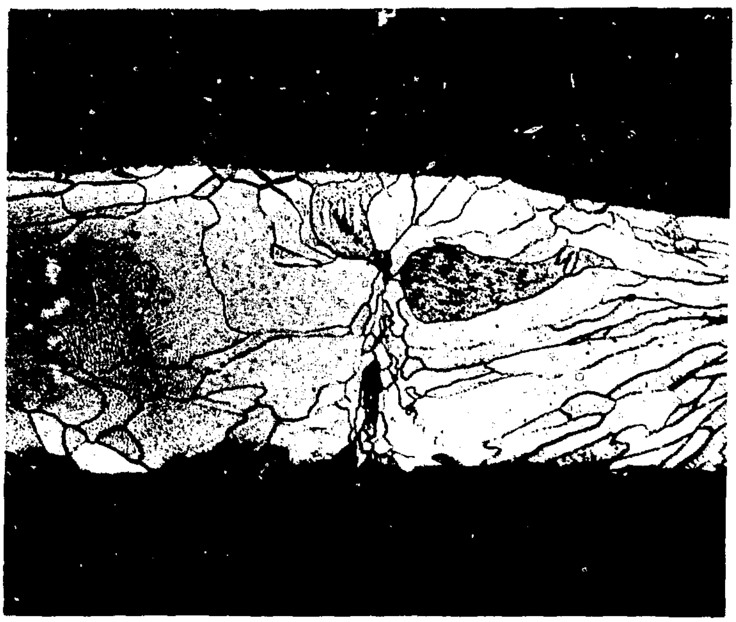


Fig. 11. Typical microstructure observed in the overlap section taken trom capsule SRP-127, as etched; 50X.

Fig. 12. Microstructure of the single-pass weld section taken from SRP-127, 50X.

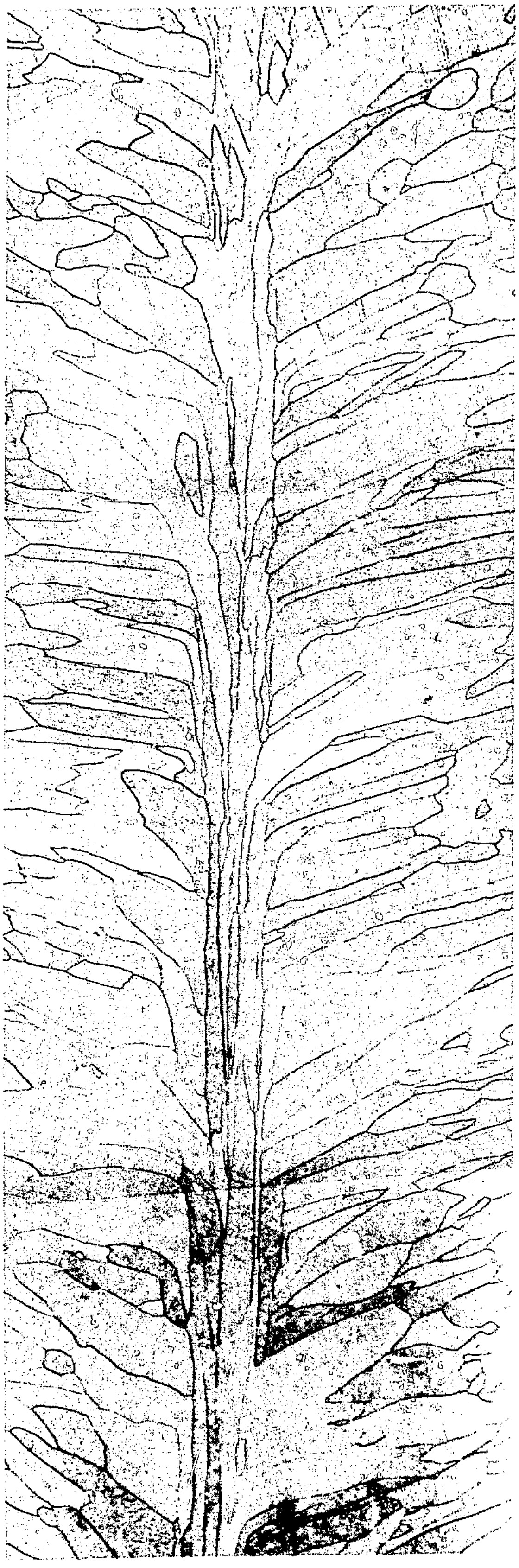
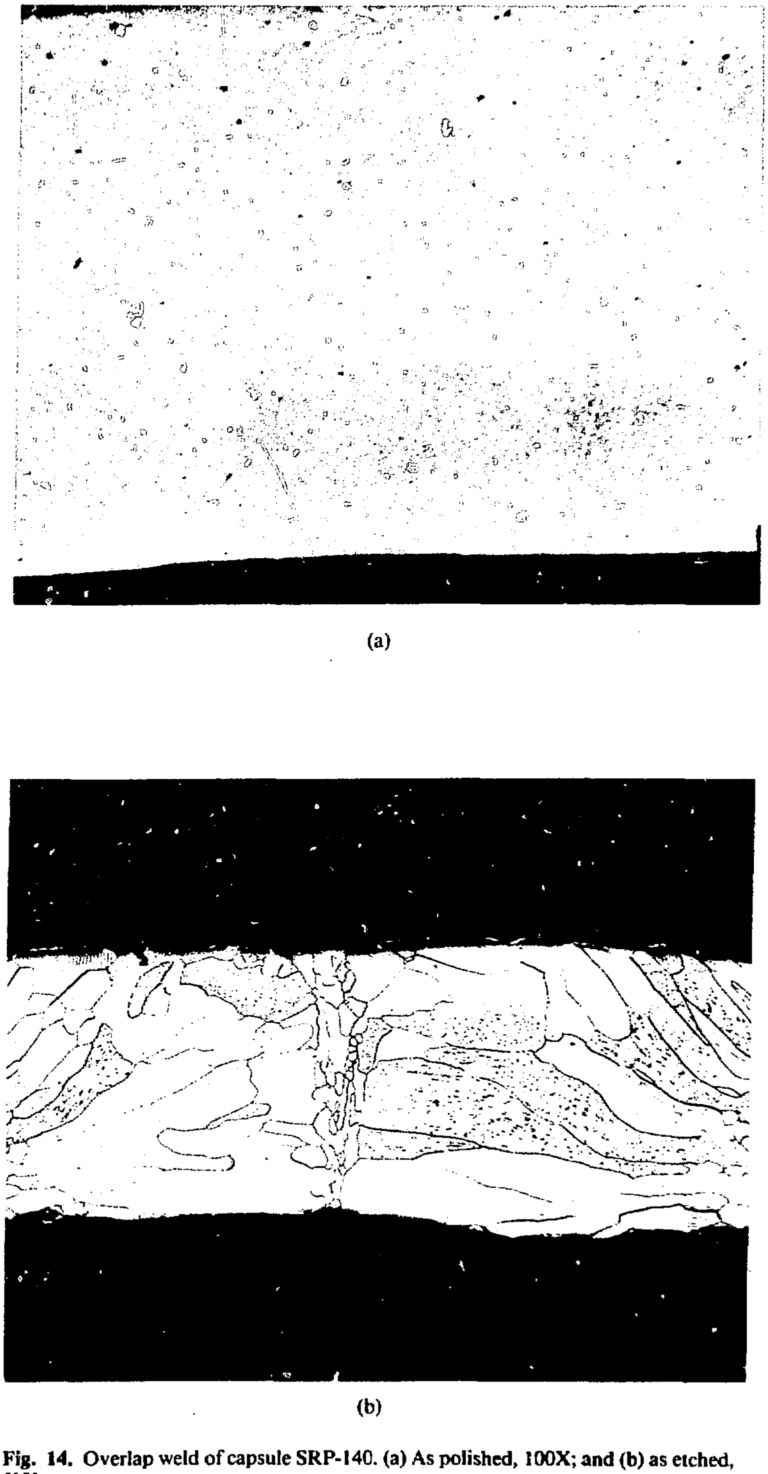


Fig. 13. Typical microstructure observed in the face-on weld section removed from capsule SRP-127, 50X.



(a)

(b)

Fig. 14. Overlap weld of capsule SRP-140. (a) As polished, 100X; and (b) as etched, 50X.

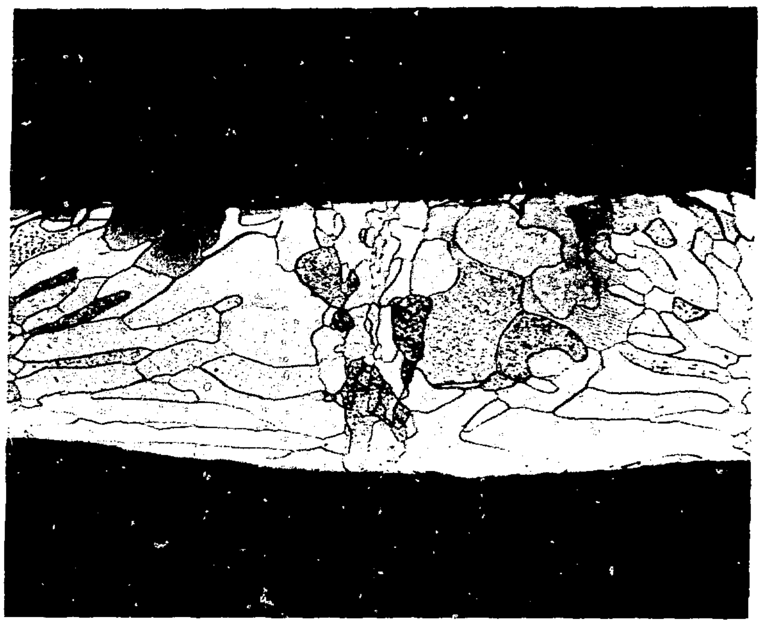


Fig. 15. Typical microstructure observed in the single-pass weld sample removed from capsule SRP-140, 50X.

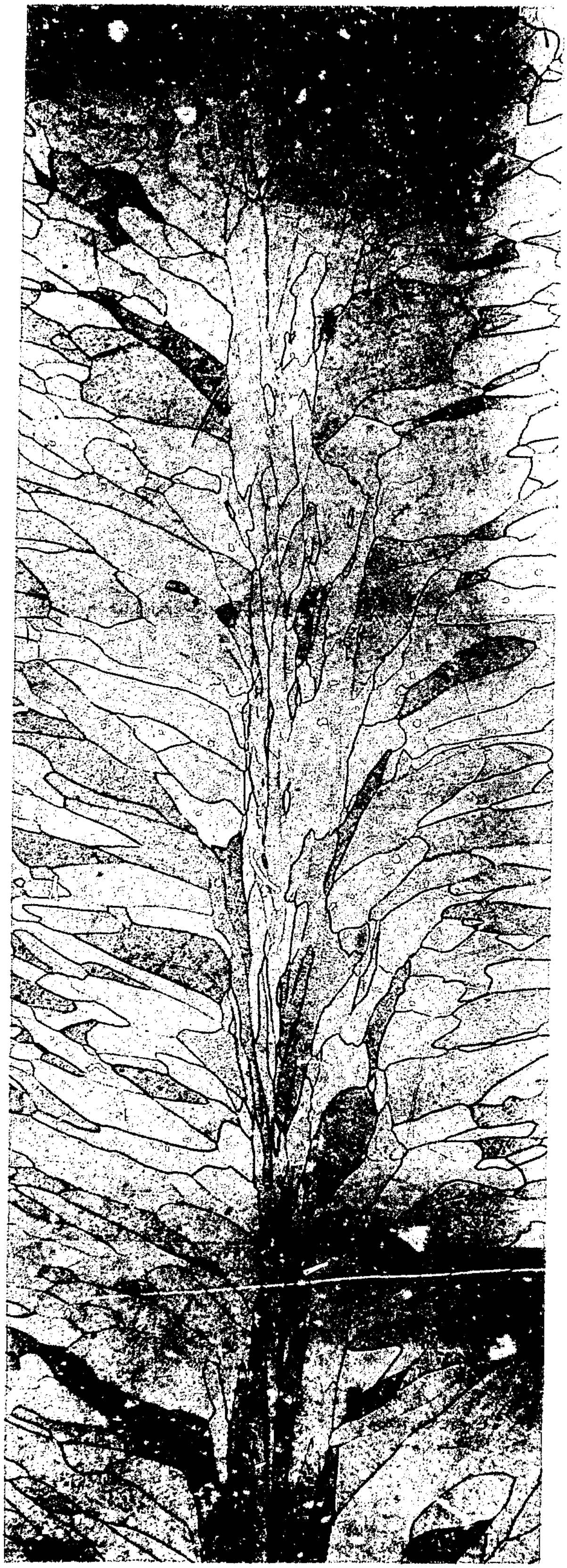
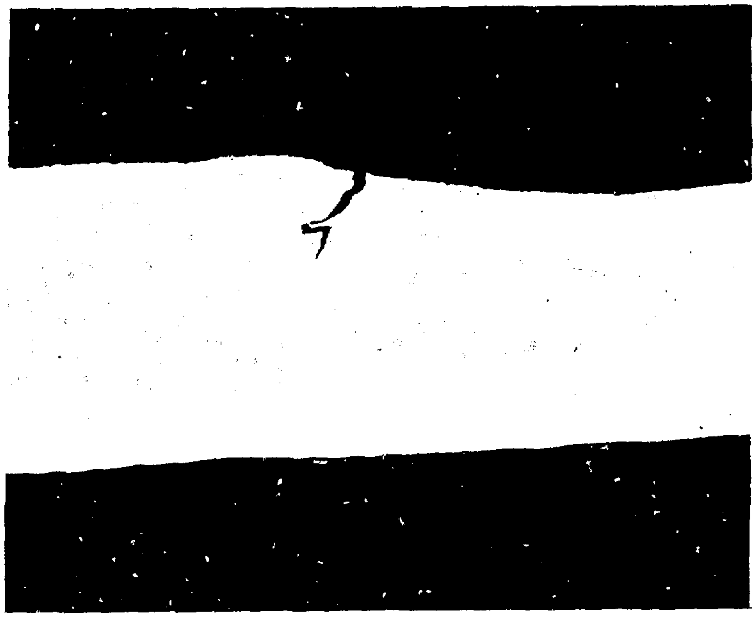


Fig. 16. The microstructure of the face-on weld specimen removed from SRP-140, 50X.



(a)

(b)

Fig. 17. A crack in the overlap weld on capsule SRP-251 penetrated over 30% of the wall thickness. (a) As polished and (b) as etched. Both at 50X.

Fig. 18. The single-pass weld specimen removed from capsule SRP-251 had a typical microstructure, 50X.

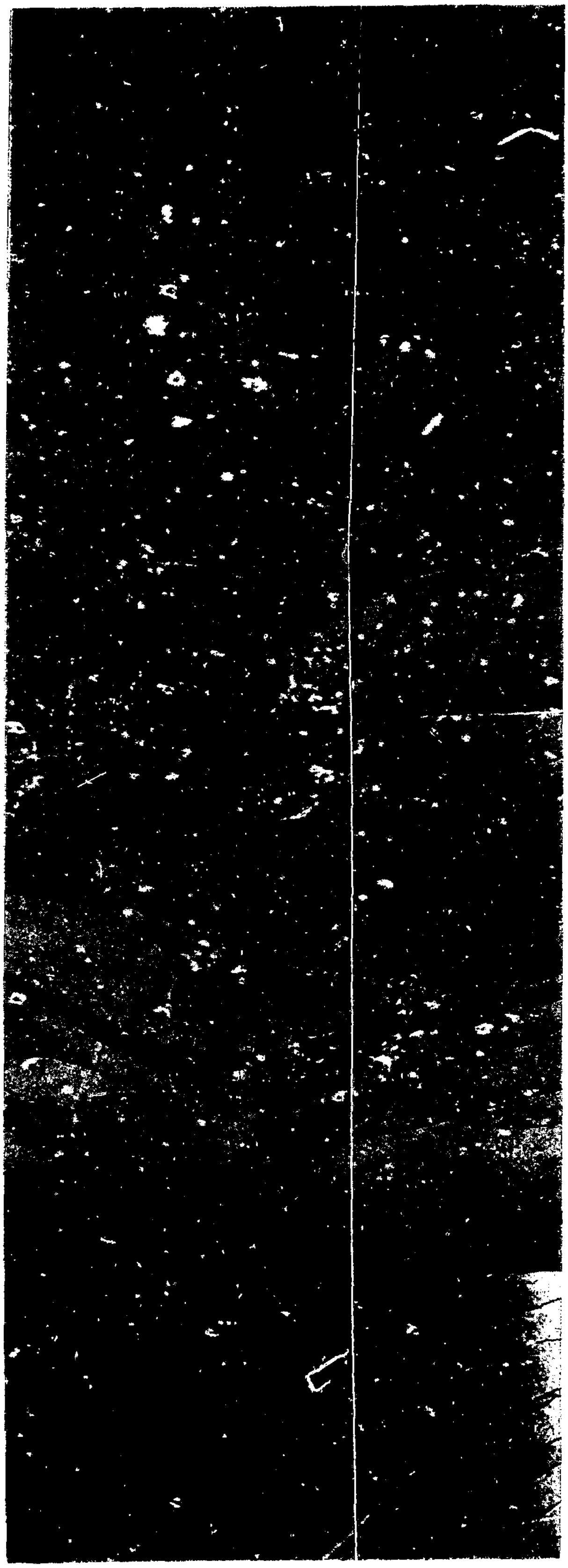


Fig. 19. The face-on weld section taken from SRP-251 was normal, 50X.

(a)

(b)

Fig. 20. A crack in the overlap weld of capsule SRP-317 penetrated over 15% of the wall thickness. (a) As polished and (b) as etched. Both at 50X.

Fig. 21. The single-pass weld section taken from SRP-317 had a typical microstructure, 50X.

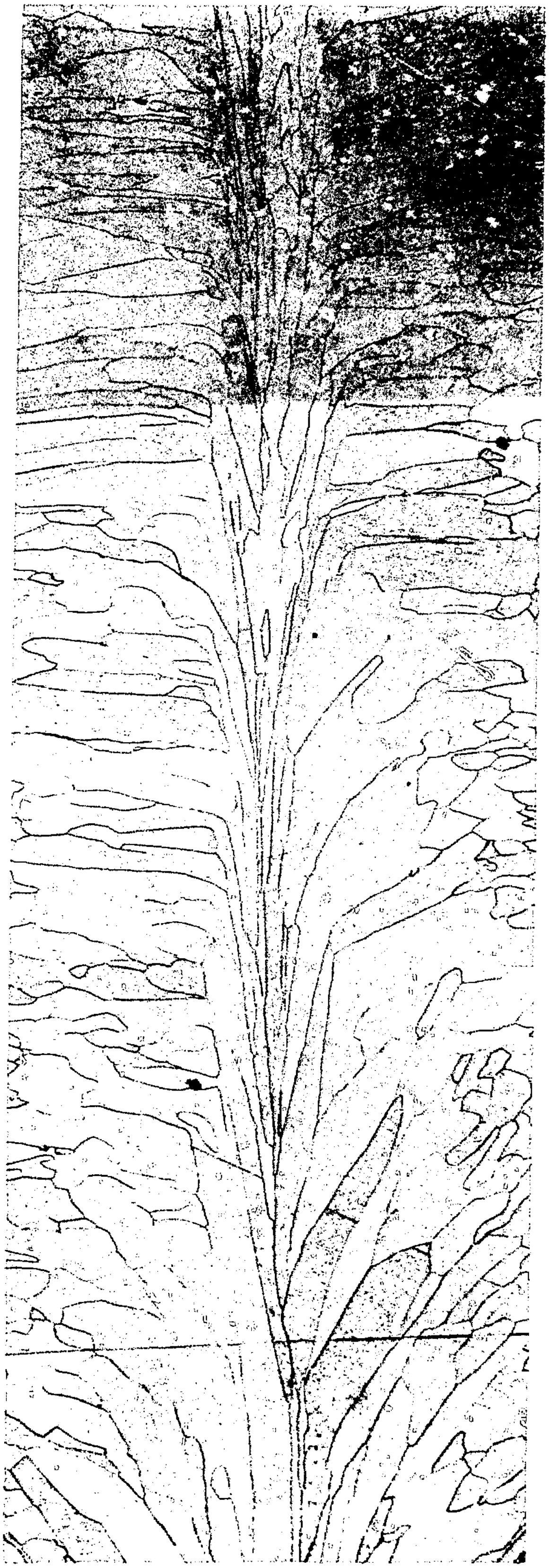


Fig. 22. The face-on weld specimen removed from capsule SI
was normal, 50X.

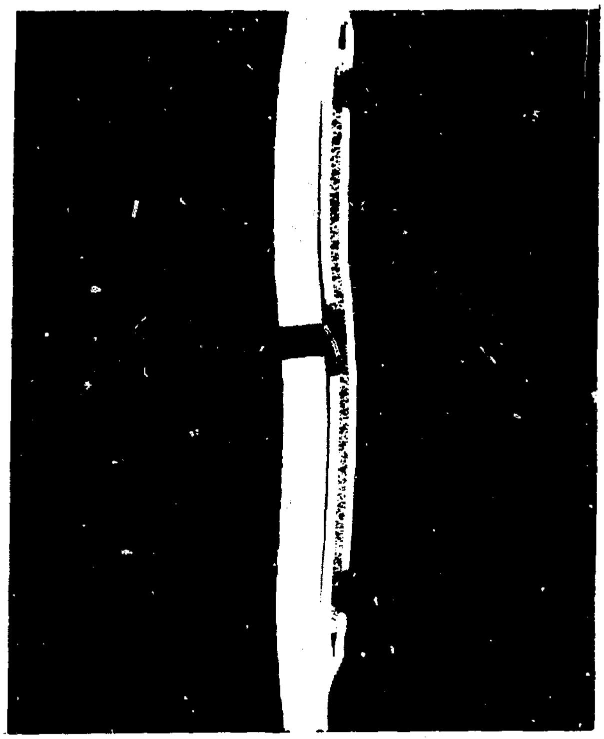


Fig. 23. A vertical section through the vent of capsule SRP-127, 10X.

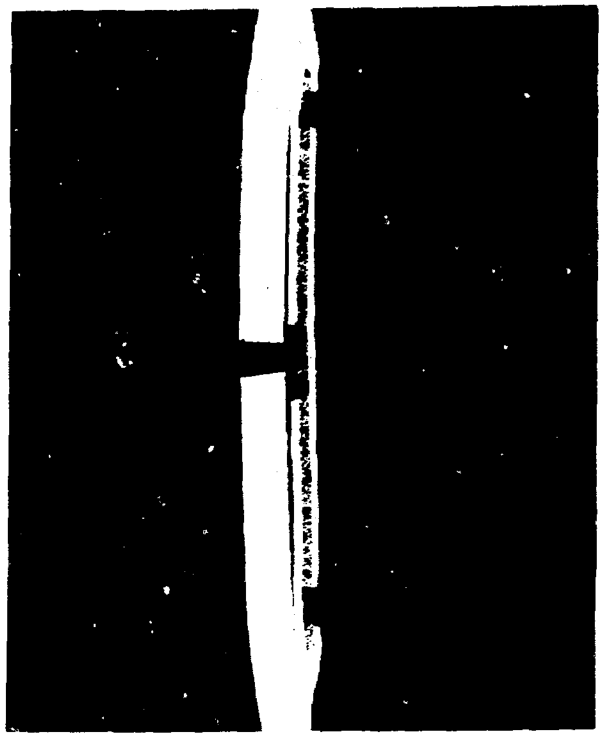


Fig. 24. The vent in capsule SRP-140 experienced little deformation, 10X.

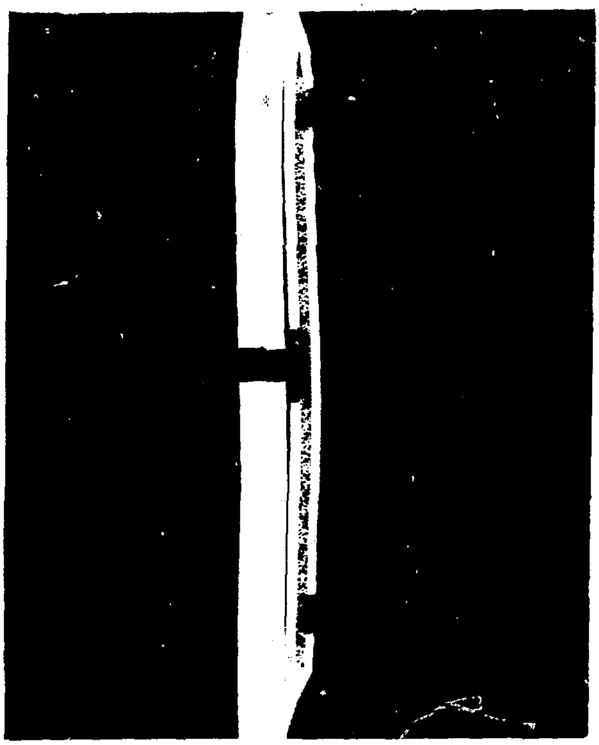


Fig. 25. A vertical section through the vent of capsule SRP-251, 10X.

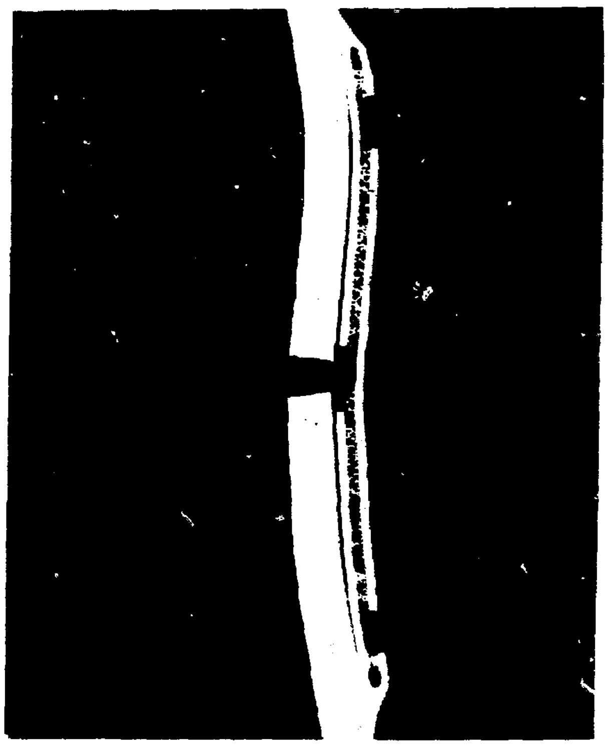


Fig. 26. Although the vent in capsule SRP-317 was deformed by the impact, no cracking occurred. 10X.

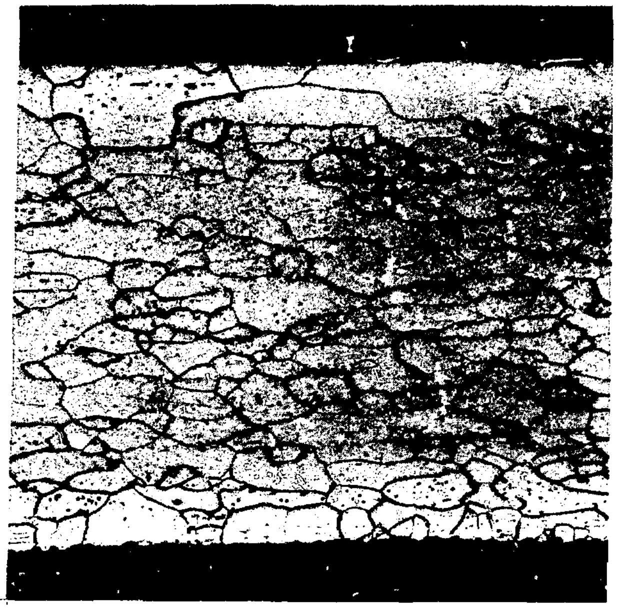


Fig. 27. Microstructure of a specimen removed from the vent cup of capsule SRP-127. As etched, 100X.

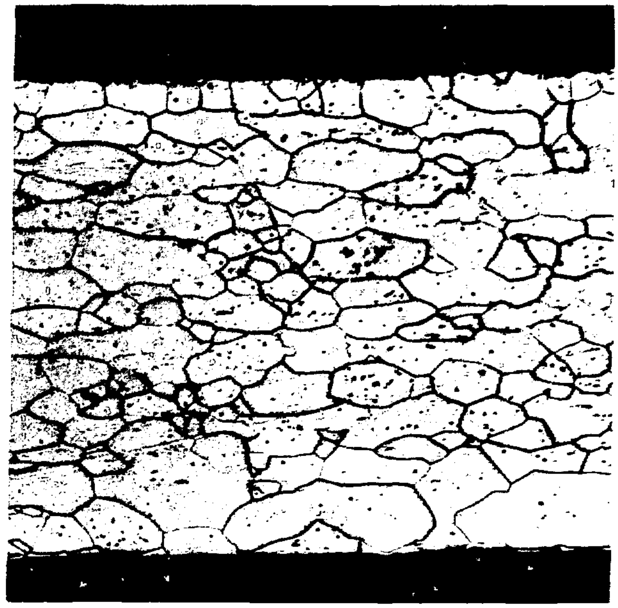


Fig. 28. Microstructure of a specimen removed from the weld-shield cup of capsule SRP-127, 100X.

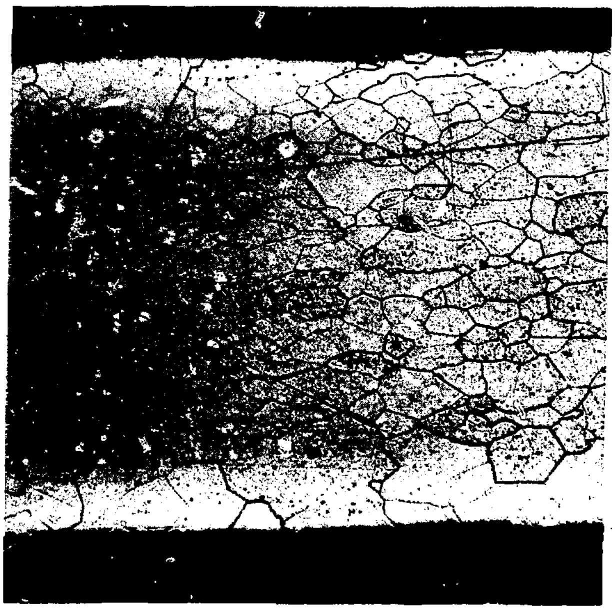


Fig. 29. Microstructure of a specimen removed from the vent cup of capsule SRP-140, 100X.

Fig. 30. Microstructure of a specimen removed from the weld-shield cup of capsule SRP-140, 100X.

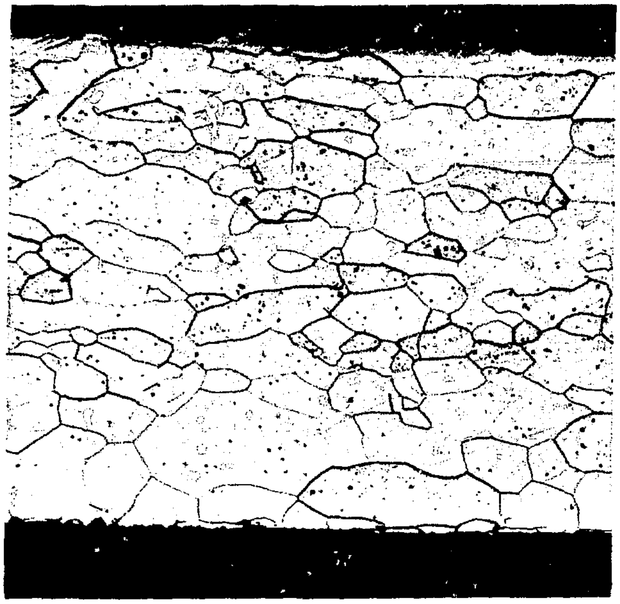


Fig. 31. *Microstructure* of a specimen removed from the vent cup of capsule SRP-251, 100X.

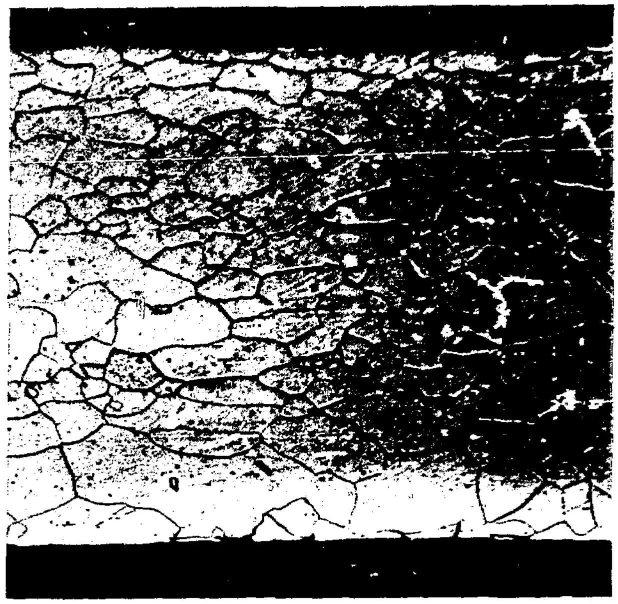


Fig. 32. Microstructure of a specimen removed from the weld-shield cup of capsule SRP-251, 100X.

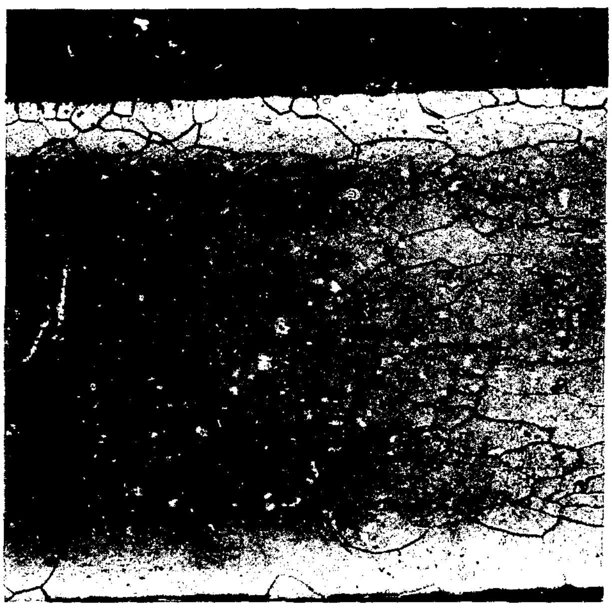


Fig. 33. Microstrucure of a specimen removed from the vent cup of capsule SRP-317, 100X.

Fig. 34. Microstructure of a specimen removed from the weld-shield cup of capsule SRP-317, 100X.

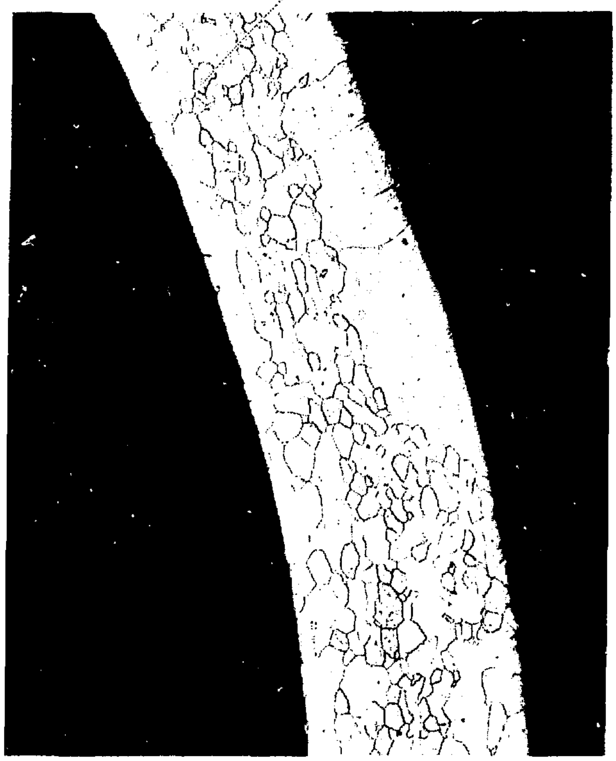
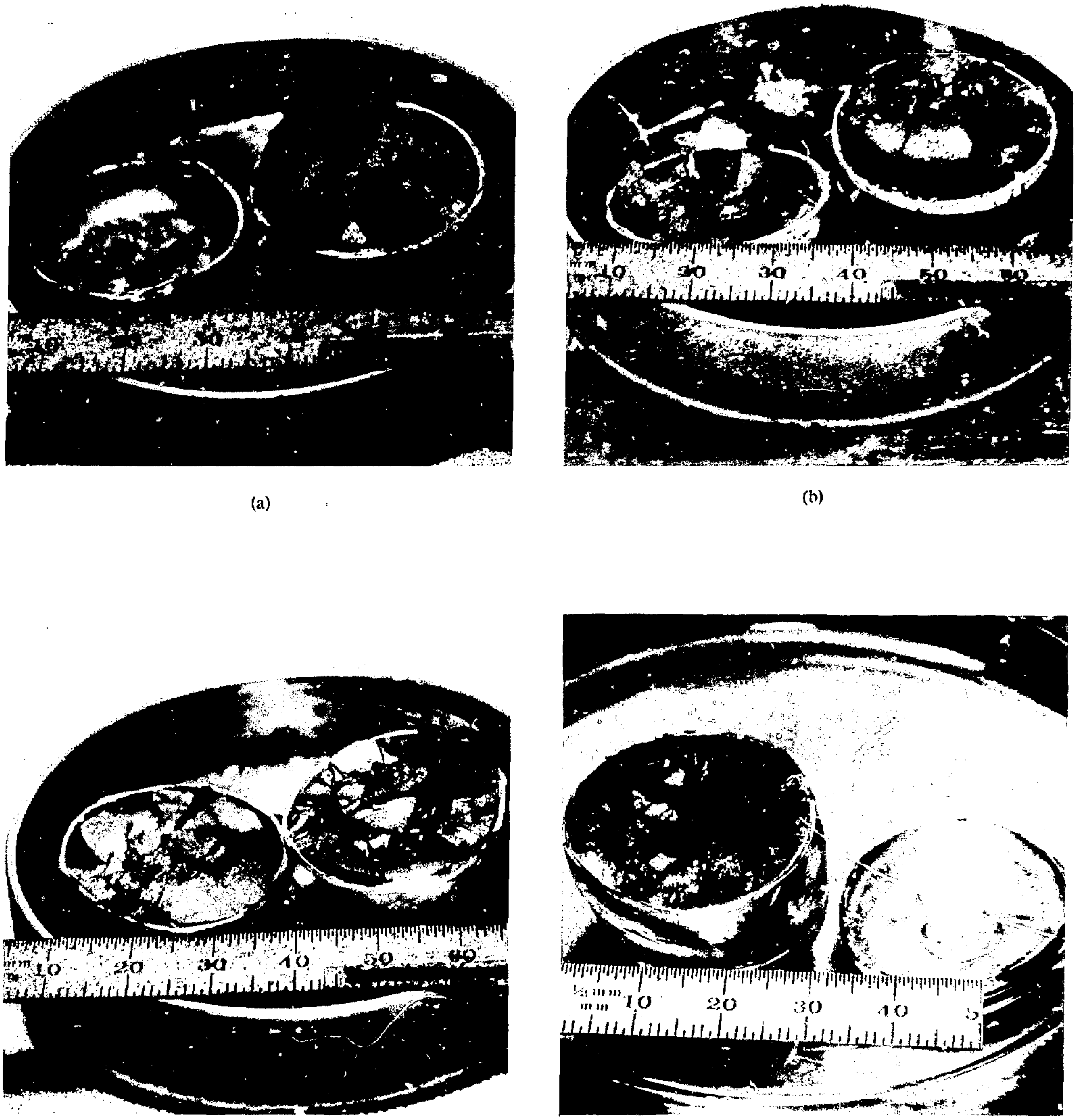


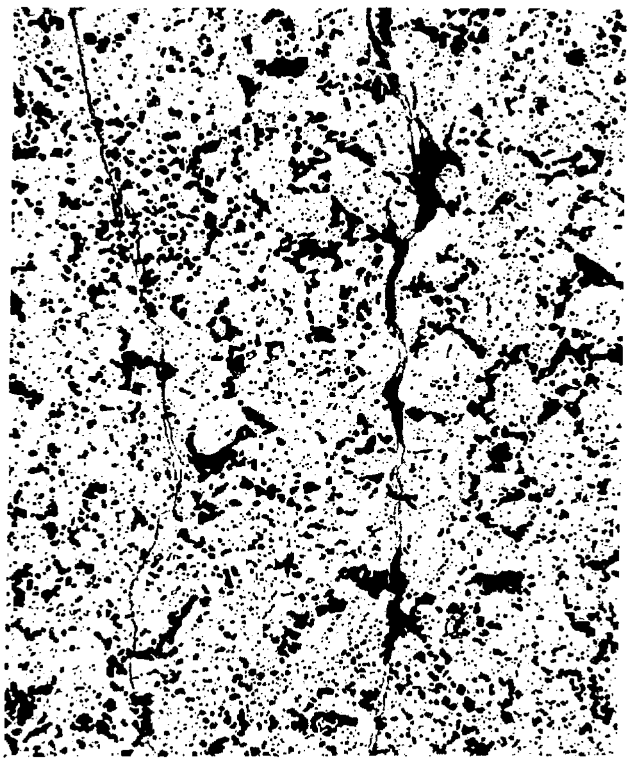
Fig. 35. Recrystallized area observed on the wall-to-end radius of the SRP-127 vent cup. As etched, 50X.



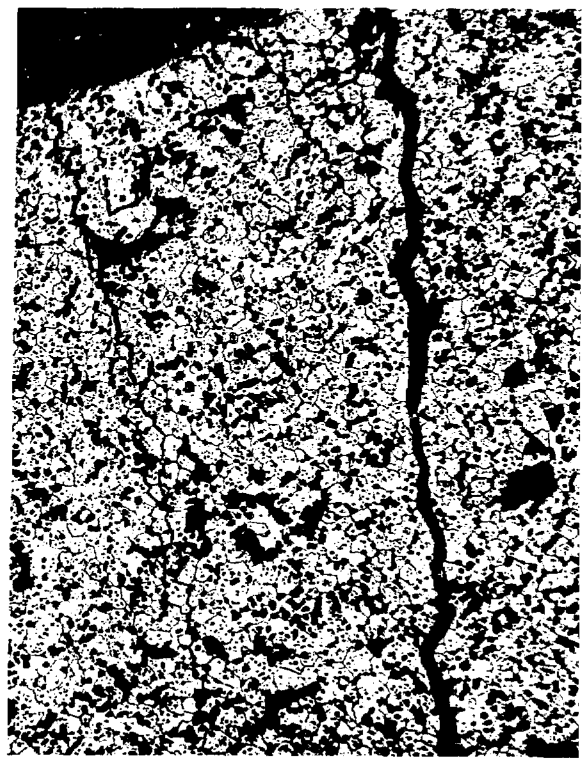
(a) (b) (c) (d)

Fig. 36. Macrographs of opened DIT-3 capsules, illustrating the patterns of fuel breakup. (a) SRP-127, (b) SRP-140, (c) SRP-251, and (d) SRP-317. All at 1.4X.

(a)

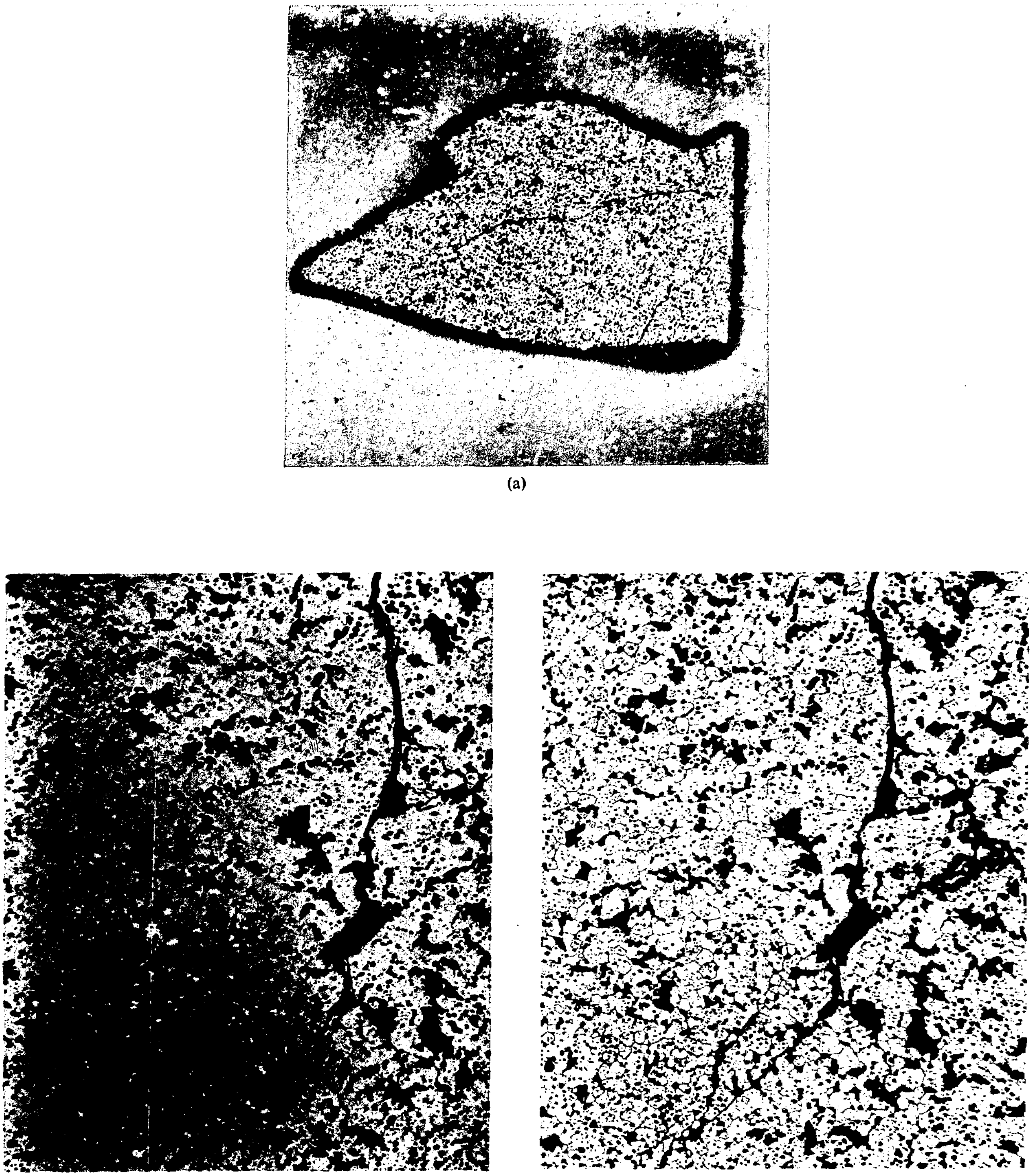


(b)



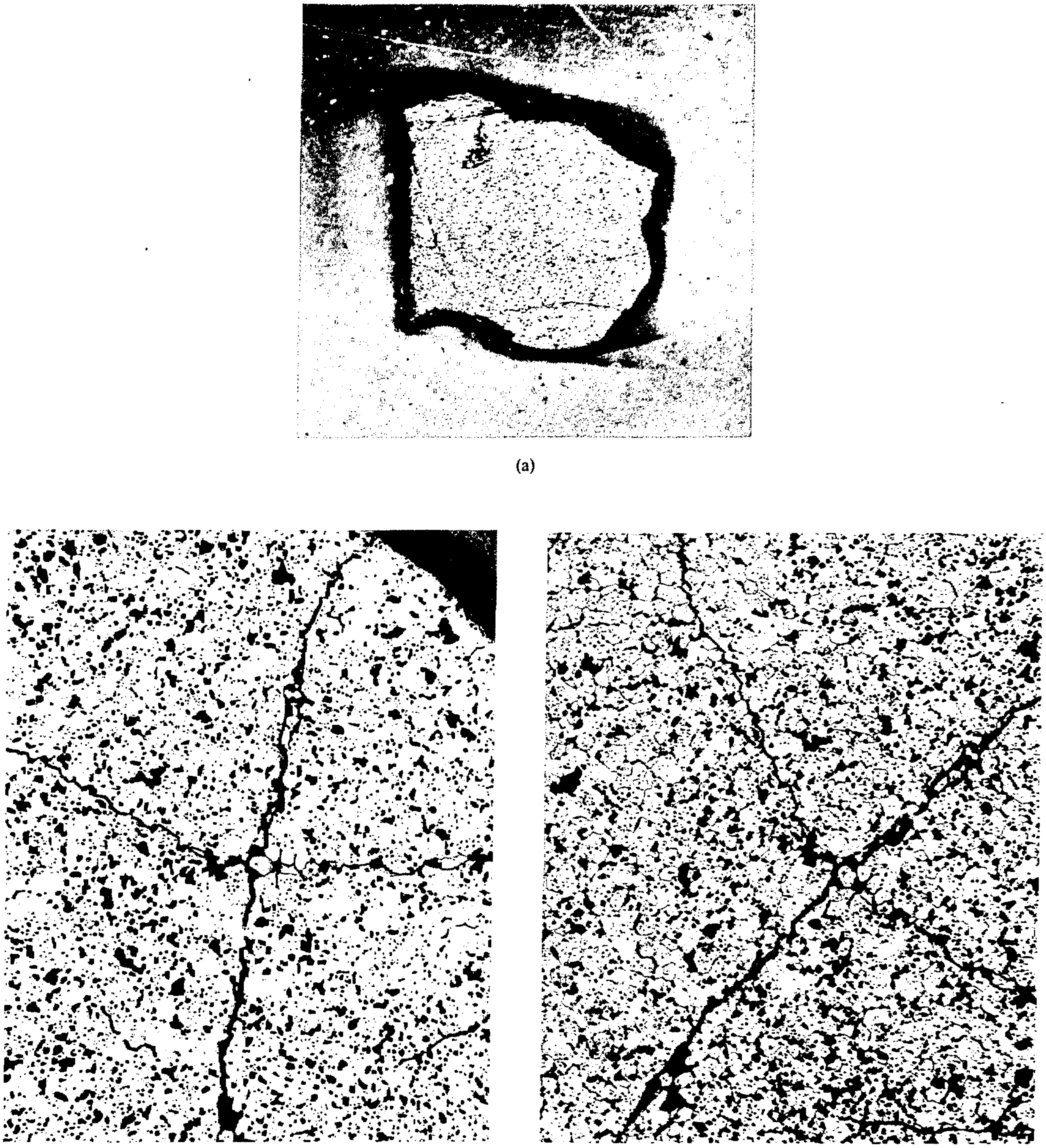
(c)

Fig. 37. Ceramographic specimen obtained from the central portion of fuel pellet SRP-127. (a) Macrograph, as polished, 10X; (b) micrograph, as polished, 100X; and (c) as etched, 100X.



(a) (b) (c)

Fig. 38. Ceramographic specimen obtained from the external portion of SRP-127. (a) Macrograph, as polished, 10X; (b) micrograph, as polished, 100X; and (c) as etched, 100X.

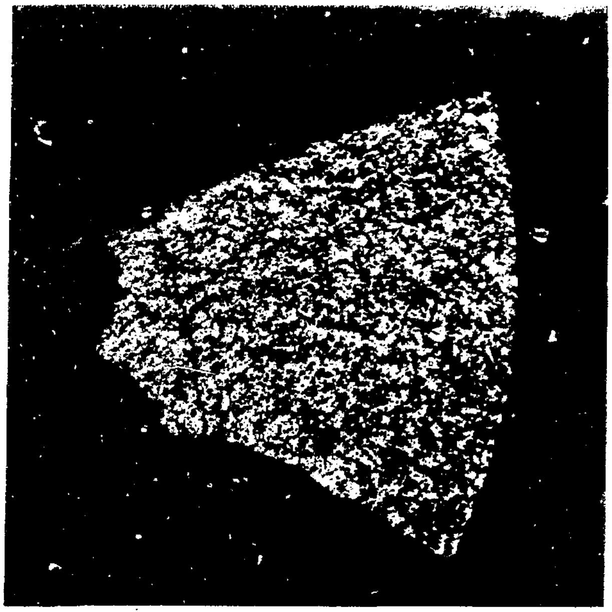


(a)

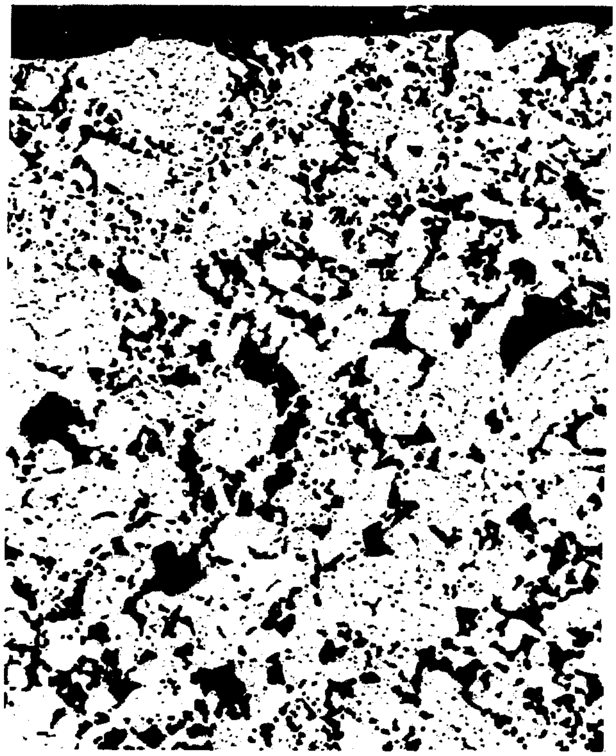
(b)

(c)

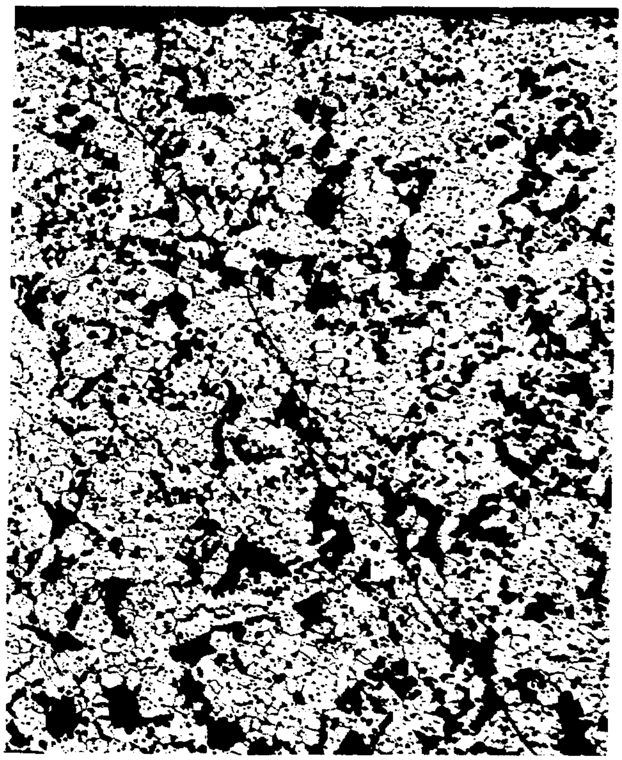
Fig. 39. Ceramographic specimen obtained from the central portion of fuel pellet SRP-140. (a) Macrograph, as polished, 10X; (b) micrograph, as polished, 100X; and (c) as etched, 100X.



(a)

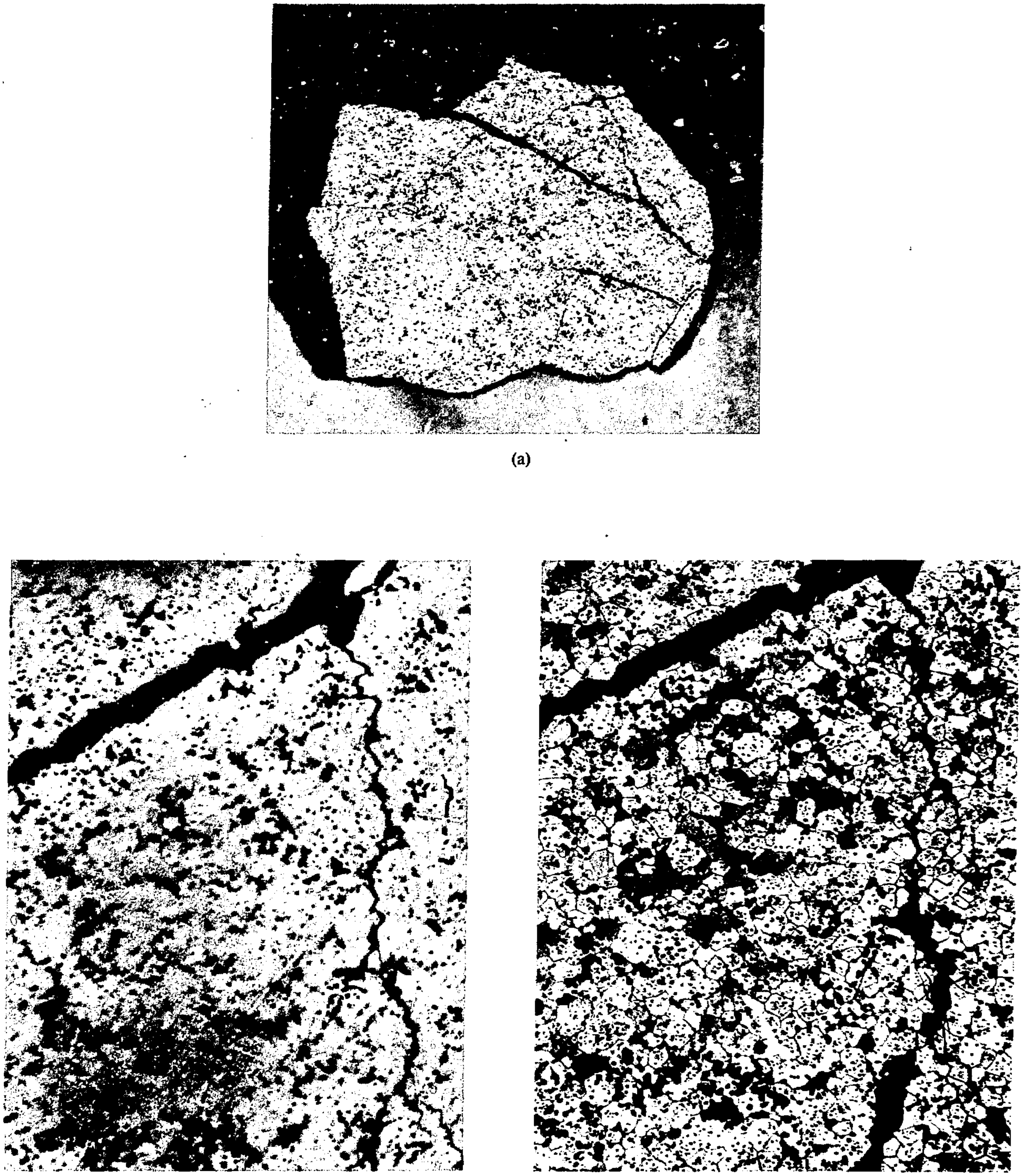


(b)



(c)

Fig. 40. Ceramographic specimen obtained from the external portion of SRP-140. (a) Macrograph, as polished, 10X; (b) micrograph, as polished, 100X; and (c) as etched, 100X.



(a)

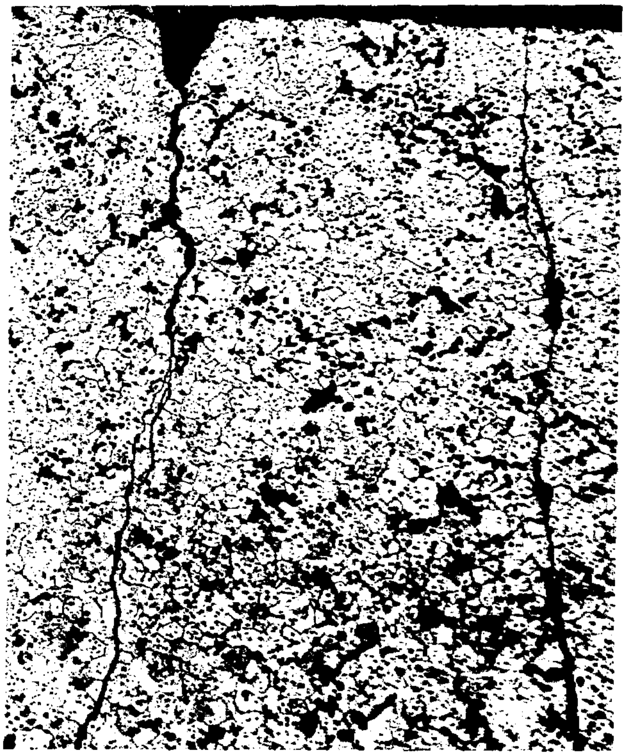
(b)

(c)

Fig. 41. Ceramographic specimen obtained from the central portion of fuel pellet SRP-251. (a) Macrograph, as polished, 10X; (b) micrograph, as polished, 100X; and (c) as etched, 100X.

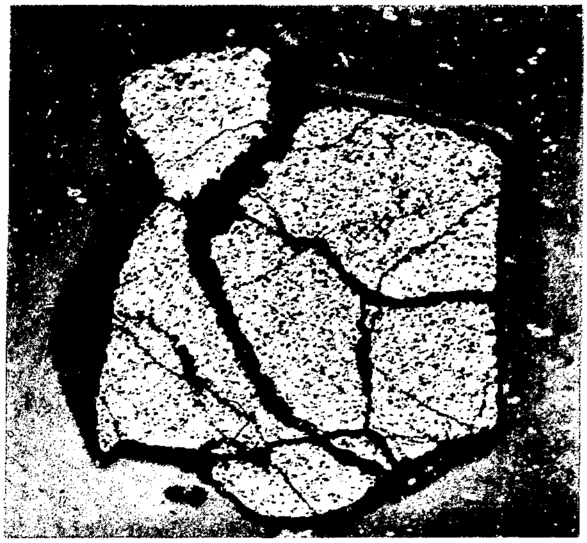
(a)

(b)

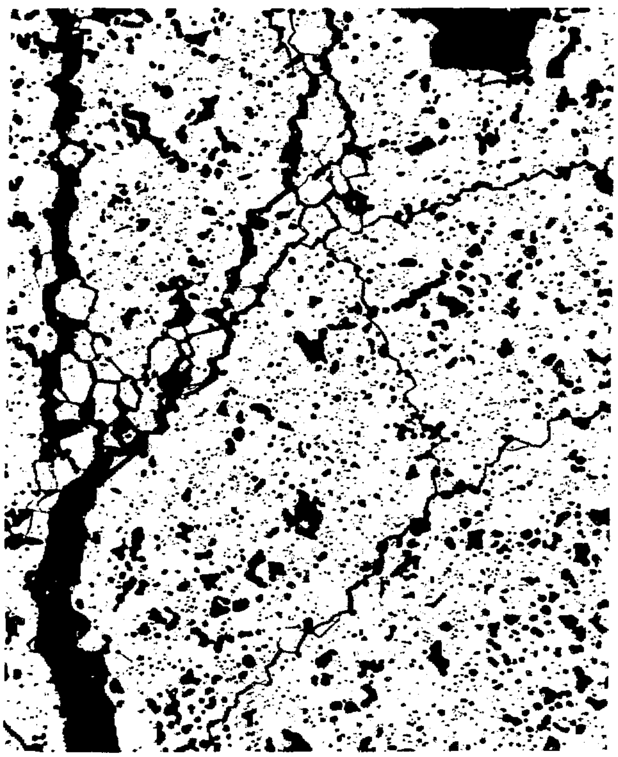


(c)

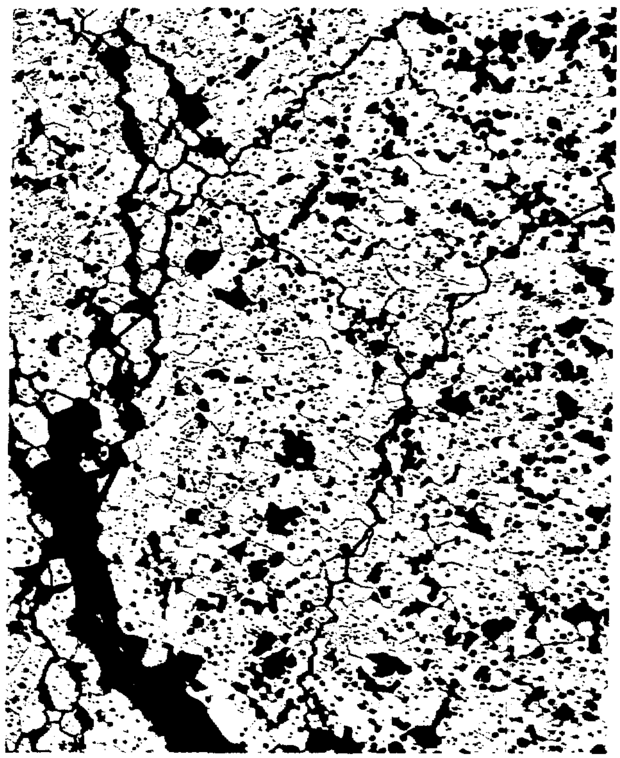
Fig. 42. Ceramographic specimen obtained from the external portion of SRP-251. (a) Macrograph, as polished, 10X; (b) micrograph, as polished, 100X; and (c) as etched, 100X.



(a)

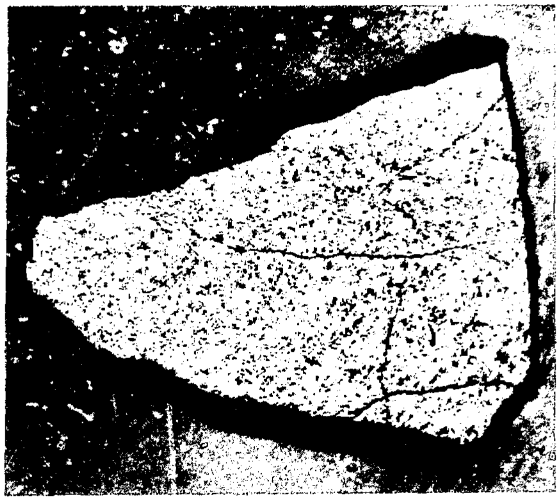


(b)

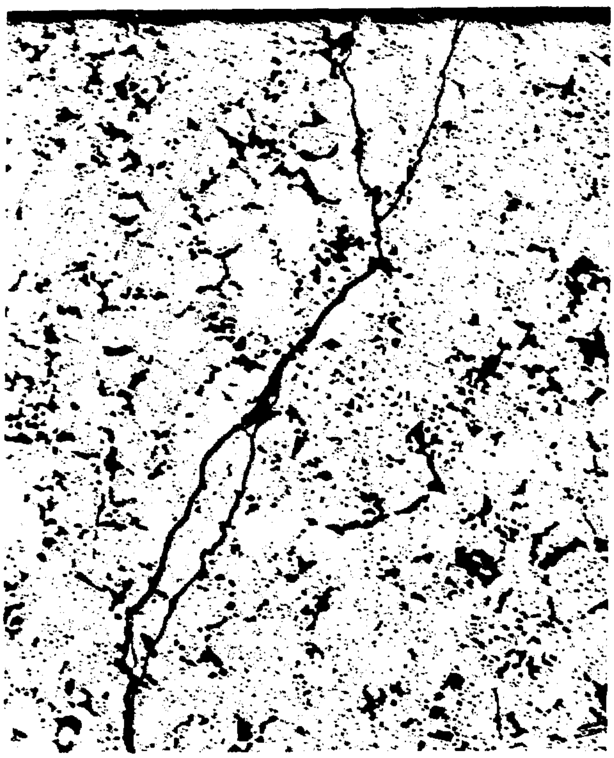


(c)

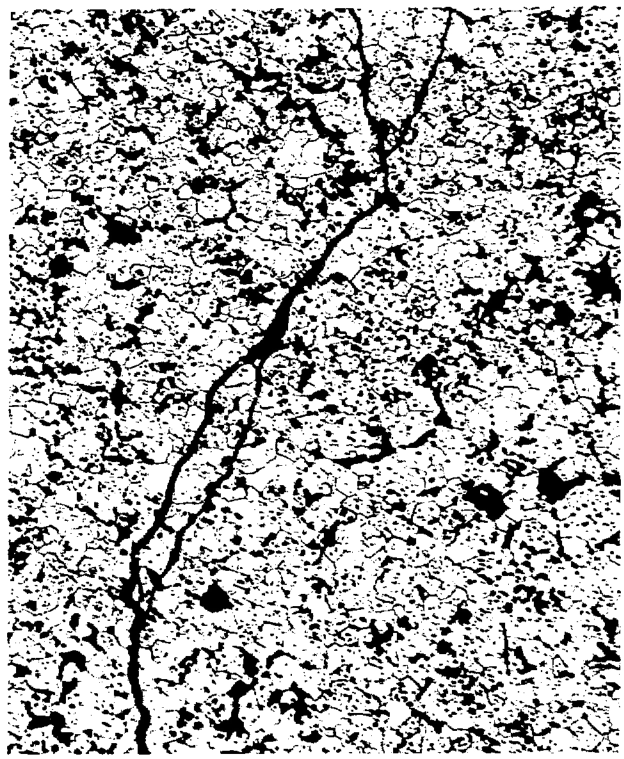
Fig. 43. Ceramographic specimen obtained from the central portion of fuel pellet SRP-317. (a) Macrograph, as polished, 10X; (b) micrograph, as polished, 100X; and (c) as etched, 100X.



(a)



(b)



(c)

Fig. 44. Ceramographic specimen obtained from the external portion of SRP-317. (a) Macrograph, as polished, 10X; (b) micrograph, as polished, 100X; and (c) as etched, 100X.

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