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General-Purpose Heat Source Development: Safety Verification Test Program

Titanium Bullet/Fragment Test Series

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GENERAL-PURPOSE HEAT SOURCE DEVELOPMENT: SAFETY VERIFICATION TEST PROGRAM

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by

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ABSTRACT

The radioisotope thermoelectric generator (RTG) that will provide power for the Galileo and Ulysses space missions contains 18 General-Purpose Heat Source (GPHS) modules. Each module contains four $^{238}\text{PuO}_2$ -fueled clads and generates 250 W(t). Because the possibility of a launch-pad or postlaunch explosion exists and because any explosion would generate a field of high-energy fragments, the fueled clads within each GPHS module must be able to survive fragment impact. In this test series we investigated the responses of bare, simulant-fueled (UO_2) clads to the impact of high-energy titanium alloy fragments. We determined that 425 m/s is the threshold impact velocity of a 3.25-g titanium bullet that will cause direct mechanical failure of a bare fueled clad.

1. INTRODUCTION

The General-Purpose Heat Source (GPHS) is a modular component of the radioisotope thermoelectric generator (RTG) that will provide power for a number of space missions. The first two flights will be the NASA Galileo and ESA Ulysses (formerly International Solar-Polar) missions. The RTG generates electrical power by using the heat of ^{238}Pu α -decay to create a temperature differential across a thermoelectric array. The Galileo mission will require two RTGs, and Ulysses will use a single RTG. Each RTG contains 18 GPHS modules.

Each GPHS module contains four $^{238}\text{PuO}_2$ -fueled clads and provides a total thermal output of 250 W(t). Each fueled clad consists of a $^{238}\text{PuO}_2$ fuel pellet encapsulated within an iridium alloy (DOP-26) shell. Two fueled clads are held within a Fineweave-Pierced Fabric* (FWPF) graphite impact shell (GIS), and two GISs are contained within a FWPF aeroshell (Fig. 1). Because a launch accident is always possible, the GPHS module has been designed and constructed to maximize containment of the plutonia in any accident environment.

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

In the Galileo and Ulysses missions, a fueled Centaur rocket will be transported within the space shuttle cargo bay. Any explosion of the shuttle and/or the Centaur would expose the RTG and GPHS modules to an explosive overpressure and to a field of high-energy fragments. The response of clads contained within a GPHS module to the impact of high-energy aluminum fragments was investigated in the original bullet/fragment test series.¹ The results of these tests indicated that a fragment velocity of approximately 555 m/s is required for direct mechanical failure of a clad contained within an undamaged GPHS module when impacted by an 18-g aluminum alloy bullet.

The titanium bullet/fragment (TiB) tests were added to the Safety Verification Test (SVT) plan² to provide information on the response of a bare fueled clad to impact by a high-energy titanium fragment (representing a titanium bolt used in the spacecraft mounting ring). Accident analysis has shown that this type of impact has a high relative probability in the event of a launch vehicle or Centaur explosion.³ Presumably, the explosive overpressure necessary to generate a field of high-energy fragments would also strip the protective graphite from the fueled clads. Although a large number of aluminum fragments would also be generated by such

Fig. 1. The GPHS module.

an explosion, the impact of a high-energy titanium fragment has the greater potential for damage because of the higher density and strength of titanium. Module and clad responses to the impacts of various-sized aluminum fragments are addressed in other sections of the SVT test plan.

II. THE TEST PROGRAM

The titanium bullet/fragment tests were designed to simulate the impact of a dense, high-energy fragment against a bare, $^{238}\text{PuO}_2$ -fueled capsule. This type of impact is considered possible in the event of a launch vehicle/Centaur explosion. Because of the toxicity of plutonia and the lack of a completely contained test facility, we tested capsules fueled with sintered uranium dioxide prepared from depleted uranium. The density and dimensions of the UO_2 pellets were tailored to match the mass and configuration of an average plutonia pellet. However, we chose not to simulate the fragmentation normally present in launch-ready plutonia. This fragmentation, the extent of which is quite variable, results from thermal stresses induced during encapsulation, degradation caused by helium buildup, and stresses developed in transport. Although the UO_2 pellets did not accurately simulate the usual plutonia breakup, they were somewhat fragmented as a result of the encapsulation welding.

Before testing the simulant-fueled clads, we conducted a series of fragment tests to determine the at-

tenuating effects of the FWPF graphite elements that normally encase the capsules. In a previous series of bullet/fragment tests, we used a single layer of 4.86-mm FWPF graphite, corresponding to the thinnest section of the GPHS aeroshell sidewall, and an 18-g aluminum alloy bullet; the results of this test series indicated that the stopping power of the FWPF graphite was inversely related to fragment velocity. However, these tests provided no information as to the attenuating effects of the multiple FWPF layers that are present in a module. Consequently, in the follow-up tests the target consisted of two FWPF plates (4.86 and 4.23 mm thick, equivalent to the minimum aeroshell and GHS thicknesses), spaced 1.78 mm apart (a standoff equivalent to the thickness of the carbon-bonded, carbon filament insulation that surrounds each GHS). The FWPF plates were held in place within an aluminum frame (Fig. 2) and were positioned in front of a .50-caliber gun configured to fire an 18-g aluminum alloy bullet (Fig. 3). A schematic of the test setup may be seen in Fig. 4. The results of three tests conducted at bullet velocities of 357, 600, and 960 m/s are summarized in Table I, and the bullet deformation in each test is listed in Table II. The tested plates are shown in Fig 5. The results suggest that the attenuating effect of two FWPF layers on fragment kinetic energy decreases with increasing fragment velocity; the kinetic energy decrement attributable to the FWPF layers ranged from 47% at 357 m/s to only 18% at 960 m/s. Bullet deformation, in contrast, was directly proportional to fragment velocity, ranging from 2% at the lowest velocity to 36% at the highest.

Fig. 2. The graphite plates used for the FWPF stopping power tests were held in position by an aluminum frame.

Fig. 3. Dimensions of the .50-caliber aluminum alloy bullet used in the FWPF stopping power tests.

Fig. 4. Schematic of the FWPF test setup.

Table I. Results of the SVT FWPF Graphite Stopping Power Tests
(all velocities are given in m/s)

Bullet Velocity		Velocity Drop Caused by Graphite ($\Delta V - \Delta V_e$)		
Initial	Final	ΔV^a	ΔV_e^b	
960	832	128	35	93
660	501	99	23	76
357	258	99	3	96

^a $\Delta V = V_{\text{initial}} - V_{\text{final}}$.

^b ΔV_e = Velocity drop (without target in place) of a projectile traveling the 17 ft between velocity screens.

Table II. Bullet Deformation in the SVI FWPF Graphite Stopping Power Tests

Bullet Velocity (m/s)	Orig. Diam.	Bullet Deformation ^a	
		Max. Final Diam.	% Change
960	0.500	0.680	36.0
600	0.500	0.560	12.0
357	0.500	0.510	2.0

^aBullet dimensions are given in inches.

A. Test Components

Simulant-fueled clads were used as targets in all of the TiB impacts. However, in the TiB-Eng test, the target was an engineering use only (EUO) capsule composed of a simulant fuel pellet and two inverted iridium cups (one cup was drilled with a small hole to vent the capsule). In TiB-1 and TiB-2, capsules recovered from converter segment test 6 (CST-6) were used as targets. These capsules had experienced an explosive over-pressure estimated to be above 500 psi. Because live fueled clads would be exposed to a field of high-energy fragments only in the aftermath of a launch ve-

hicle Centaur explosion, the CST-6 clads were considered ideal targets for the TiB test series.

Each of the simulant-fueled capsules used in the TiB test series consisted of a uranium dioxide (depleted uranium) fuel pellet encapsulated within an iridium alloy containment shell. All of the simulant fuel pellets were fabricated at the Los Alamos National Laboratory. The iridium alloy containment shells were flight-quality units provided by the Mound Facility. The simulant fuel pellets were welded into the iridium shells by the Savannah River Laboratory (SRL). Data describing the iridium and UO_2 test components are presented in Table III.

B. Procedures

To simulate the impact of a dense, high-energy fragment, we fired a .30-caliber titanium alloy bullet, which weighed 3.25 g and had a nonballistic configuration (Fig. 6), against a bare, simulant-fueled clad. The bullet was fabricated from a Ti-6Al-4V titanium alloy, the same material used for spacecraft mount ring bolts on the Centaur.

All of the TiB tests were conducted at an outdoor Los Alamos test range. The gun used to fire the projectiles was a thick-walled, .30-caliber barrel mounted on a heavy pedestal. Bullet velocity was adjusted by varying the amount of powder loaded into the cartridge case and filling the remaining case volume with wheat bran. The gun was aimed by means of a telescopic bore sight and was triggered remotely from a bunker. The test setup used for the TiB impacts may be seen in Fig. 7.

In each test, the target clad was heated in a wire-wound furnace to a nominal test temperature of 1091°C—the average temperature of the iridium clad in an on-pad RTG. The target capsule was positioned in the furnace by means of a two-piece graphite jig (Fig. 8). Two thermocouples monitored the furnace and clad temperature; one thermocouple was in contact with the clad surface, and the other was suspended in the furnace, approximately 1 in. from the capsule. An inert atmosphere (argon) was maintained in the furnace throughout each test. To maintain the inert atmosphere, a refractory plug covered the furnace mouth during the

Fig. 5. Postimpact condition of graphite plates used in the FWPF stopping power tests.

Table III. Components Used in the TiB Test Series

Test	Target Clad	Vent Cup No.	Blind Cup No.	UO ₂ Peller ^a	Fueled Capsule Weight (g)
TiB-Eng	M-25	0556	0073	85-18	206.928
TiB-1	M-26	0172	0185	85-17	207.359
TiB-2	M-15	2361	5544	85-14	203.262

^aDepleted ²³⁸U.

Fig. 6. Dimensions of the .30-caliber titanium alloy bullet used in the TiB test series.

heat-up and cool-down periods and was removed only to fire the projectile.

Before each test, the target assembly, consisting of the simulant-fueled clad and graphite jig, was positioned in the center of the furnace, and one thermocouple was placed in contact with the clad. The gun was sighted on the capsule, the furnace mouth was plugged, and a flow of inert gas was introduced. The furnace was slowly

heated to 1160°C, a starting temperature determined by previous tests to compensate for the temperature drop anticipated between furnace shutdown and bullet impact. When the clad temperature reached 1160°C, power to the furnace was cut, the furnace mouth was unplugged, and the gun was fired. The bullet velocity in each test was determined by flash x ray. After each impact, the furnace was resealed and allowed to cool.

Fig. 7. Schematic of the TiB test setup

III. RESULTS

The results and conditions of each TiB impact are summarized in Table IV. After each test, the target capsule was transported to the metallographic laboratory, examined, and photographed. The capsule was then opened and sectioned to provide specimens for metallography. The average cup grain sizes are listed in Table V; representative cup microstructures may be seen in Figs. 9-14. Details of the individual tests and postmortem examinations are given below.

A. TiB-Eng

The target clad was impacted at 446 m/s and 1095°C. The bullet struck the capsule approximately 6.0 mm above the weld centerline (vented cup) and produced several small breaching cracks (Fig. 15). The total crack area was approximately 25.25 mm². Capsule deformation was negligible outside the bullet contact area. The iridium within the bullet contact area had an unusual appearance (Fig. 15a), and a portion of the titanium bullet apparently had fused to the clad.

Fig. 8. The capsule was positioned in the furnace by means of a two-piece graphite jig.

Table IV. Results of the Titanium Bullet/Fragment Impact Tests

Test	Target	Temp. (°C)	Bullet Velocity (m/s)	Results
TiB-Eng	Virgin EUO ^a Clad	1095	446	Bullet struck the clad approximately 6.0 mm above the weld centerline (vented cup). The impact produced several small, breaching cracks (total crack area = 25.25 mm ²).
TiB-1	CST-6 Clad ^b	1085	423	Bullet struck the clad approximately 6.0 mm below weld centerline (blind cup). The impact produced several small cracks within the bullet contact area, two of which breached the clad (total crack area = 1.3 mm ²). After impact the bullet was deflected away from the clad.
TiB-2	CST-6 Clad ^b	1110	684	Bullet struck the clad approximately 7.0 mm above the weld centerline (vent cup) and was deflected. The clad breached, with the vent cup radius of the impact face opened (total crack area = 215 mm ²); 86.5% of the uranium fuel simulant remained within the clad.

^aThe EUO clad used in TiB-Eng was fabricated from two blind cups and was vented at Los Alamos by drilling a 1/16-in. hole through one cup.

^bBoth clads were recovered bare, after the CST-6 test.

Microscopic examination of the bullet contact area revealed numerous cracks (Fig. 16) and what appeared to be an intermetallic deposit (Fig. 17). However, subsequent analysis of the deposit revealed that it was composed only of titanium metal and TiO₂, with no evidence of any Ti/Ir compounds.

The breaching crack at the edge of the bullet contact area (Fig. 18) had an extremely ductile appearance; wall sections on both sides of the breach had necked down to knife edges (Fig. 19). The wide breaching crack, in contrast, was intergranular (Fig. 20). A deep crack adjacent to the main breach also had a brittle intergranular appearance (Fig. 21).

Examination of cracks on the vented cup radius (Fig. 22) revealed exclusively intergranular fractures with evidence of slight grain elongation (Fig. 23). The side of one fracture apparently thickened in response to a complex strain state (Fig. 24).

Although one of the cracks in the bullet contact area propagated into and ran approximately 4.0 mm along the centerline of the capsule weld, the weld had an acceptable microstructure (Fig. 25).

Both iridium cups were consistently fine grained. The vented cup contained an average of 28.7 grains/0.635-mm nominal wall thickness, and the weld shield cup averaged 24.8 grains/thickness.

Table V. Grain Sizes of Iridium Cups Used in the TiB Test Series

Capsule	Cup	Average No. of Grains/ 0.635-mm Nominal Wall Thickness
TiB-Eng	vent	28.7
	blind	24.8
TiB-1	vent	21.5
	blind	21.7
TiB-2	vent	30.0
	blind	22.2

B. TiB-1

In TiB-1, the target clad was impacted at 423 m/s and 1085°C. The titanium bullet struck the clad approximately 6.0 mm below the weld centerline (blind cup) and was deflected. The impact produced several cracks (Fig. 26), two of which breached the clad (total crack area = 1.3 mm²).

Apart from areas immediately adjacent to the bullet contact area, capsule deformation was minor (note that the capsule had been moderately deformed in the CST-6 overpressure test).

After macroscopic examination, the capsule was defueled and sectioned for metallography. Results of a particle size analysis of the capsule fuel are presented in Table VI.

Microscopic examination of the bullet contact area (Fig. 27) revealed the breaching cracks and a network of smaller cracks adjacent to the main breach; no titanium-iridium reaction was evident. Both breaching cracks were exclusively intergranular (Fig. 28 and 29) and occurred after moderate plastic deformation. The network of deep cracks adjacent to the main breach (Fig. 30) also occurred after appreciable plastic deformation. The iridium at the edge of the bullet contact area was quite deformed (Fig. 31), but there was no evidence of recrystallization or cracking. The degree of deformation visible in this section demonstrates the importance of strain state in iridium deformation; the impact apparently produced a localized strain state that favored grain elongation over fracture.

Examination of the capsule weld showed it to be sound and of typical microstructure. Both iridium cups were consistently fine grained. The vent cup contained an average of 21.5 grains/0.635-mm nominal wall thickness, and the blind cup averaged 21.7 grains/thickness.

Although the capsule vent was undeformed (Fig. 32a), one side of the vent assembly fractured (Fig. 32b). The

vent was free of any other defects. No grain growth was observed on the vent assembly or decontamination cover welds.

C. TiB-2

The TiB-2 target clad was impacted at 684 m/s and 1110°C. The bullet struck the clad approximately 7.0 mm above the weld centerline (vent cup) and was deflected upward. The impact opened the capsule at the vent end radius (Fig. 33), and a portion of the breach extended to the capsule weld, where it propagated for 2.0 mm along the weld centerline. The total crack area was approximately 215 mm²; 13.5% of the fuel simulant was released.

Microscopic examination of the remains of the bullet contact area (Fig. 34) revealed the main breach, an area of substantial iridium deformation, and a deep crack on the interior capsule wall. The breaching crack was exclusively intergranular and occurred with minimal plastic deformation (Fig. 35). The crack on the interior surface also had a brittle appearance (Fig. 36) and penetrated more than 50% of the wall thickness. In contrast to the fractures, the capsule wall at the edge of the bullet contact area was remarkably deformed (Fig. 37). The iridium in this area had been reduced by approximately 60%.

Examination of the capsule weld (single pass region) revealed an acceptable microstructure and no observable defects (Fig. 38a). The overlap region of the weld, however, was very coarse grained (Fig. 38b). This undesirable microstructure of the overlap appears to have weakened the weld and permitted the vent cup breach to propagate along the weld centerline.

The vent cup was extremely fine grained, averaging 30 grains/0.635-mm nominal wall thickness. The weld shield cup was also uniformly fine grained, containing an average of 22.2 grains/thickness. Examination of the vent remnants (Fig. 39) revealed that the central portion of the vent assembly had remained intact, even though it was no longer attached to the capsule wall. The vent cover and assembly welds were unusually fine grained (Fig. 40).

IV. DISCUSSION

The results of the three TiBs indicate that 425 m/s is the approximate threshold velocity that causes direct mechanical failure of a simulant-fueled clad struck by a 3.25-g (.30-caliber) titanium bullet. This conclusion, however, is based only on the results of impacts normal to the clad sides; the fragment velocity threshold for capsule end impact could be considerably different.

Table VI. Particle Size Analysis of the Fuel in Capsule M-26 (TiB-1)

Particle Size Range (μm)	Weight Fraction
+6000	0.6578
+2000 to 6000	0.1687
+841 to 2000	0.1028
+420 to 841	0.0370
+177 to 420	0.0196
+125 to 177	0.0037
+74 to 125	0.0037
+44 to 74	0.0018
+30 to 44	0.0013
+20 to 30	0.0007
+10 to 20	0.0008
+9 to 10	0.0002
+8 to 9	0.0091
+7 to 8	0.0002
+6 to 7	0.0001
+5 to 6	0.0001
+4 to 5	0.0003
+3 to 4	0.0004
+2 to 3	0.0004
+1 to 2	0.0002
0 to 1	0.0001
Weight Fraction < 10 μm =	0.0021

Although we did not run enough tests to develop a good statistical base, the results of the three impacts unexpectedly suggested that bullet contact area does not necessarily increase with bullet velocity. Apparently, as bullet velocity increases (at least in the range of 400 to 700 m/s), the likelihood of obtaining a clean hit decreases, and even when a clean hit occurs, the size of the bullet contact area does not increase with increasing velocity. Interestingly, this relation loses validity as the point of impact approaches the capsule ends, the breach that occurred in TiB-2 being a prime example.

One aspect of capsule response evident in all three TiB impacts is the strain state sensitivity of iridium. All of the target clads contained areas of remarkable grain elongation at the edges of the bullet contact areas (Figs. 18, 31, and 37), often near breaching cracks that occurred with minimal deformation.

Another aspect of capsule response revealed in this test series was the damage tolerance of the vent structure. In the TiB-2 impact, although wall sections adjacent to the capsule vent were peeled away and a small crack propagated from the main breach into the outer layer of the vent assembly (Fig. 33c), the central portion of the vent remained integral (Fig. 39). However, conclusions regarding vent survivability in a direct impact should not be drawn from the TiB-2 vent response: the vent deformation occurred as a result of a side-on fragment impact, and the vent assembly and decontamination cover welds were unusually fine grained. Nevertheless, the vent assembly apparently is much more rugged than had previously been believed.

All of the capsules used in the TiB test series were very fine grained; the average cup grain sizes ranged from 21.5 to 30 grains/0.635-mm nominal wall thickness.

The undesirable microstructure of the TiB-2 capsule weld significantly weakened the weld, which permitted a portion of the main breach to propagate along the weld centerline. The closure welds in the other two capsules had acceptable microstructures.

No evidence was observed to indicate that a Ti/Ir reaction is possible, or that Ti/Ir compounds can be formed by titanium fragment impacts.

V. CONCLUSIONS

- (1) The velocity threshold for direct mechanical failure of a simulant-fueled clad impacted by a .30-caliber, 3.25-g titanium alloy bullet is approximately 425 m/s.
- (2) The DOP-26 iridium alloy that encapsulates the fuel is sensitive to strain state, but can under some conditions be reduced in thickness by at least 60% without failure.
- (3) The vent structure is resistant to deformation and apparently has a high damage tolerance.
- (4) None of the TiB impacts show evidence of a Ti/Ir reaction.
- (5) All of the capsules used in the TiB impacts were very fine grained (average grain sizes ranged from 21.5 to 30 grains/0.635-mm nominal wall thickness).

VI. RECOMMENDATION

The capsule response to the end-on impact of compact fragments should be investigated in additional fragment tests.

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Fig. 9. The vented cup of the TiB-Eng capsule was consistently fine grained; 50X.

Fig. 10. The vented cup of the TiB-Eng clad also had a fine-grained microstructure; 50X.

Fig. 11. The vent cup of the TiB-1 capsule contained an average of 21.5 grains/0.635-mm nominal wall thickness; 50X.

Fig. 12. The shield cup of the TiB-1 capsule averaged 21.7 grains/ thickness; 50X.

Fig. 13. The vent cup of the TiB-2 clad was consistently fine grained 50X.

Fig. 14. The shield cup of the TiB-2 clad was also consistently fine grained; 50X.

(a)

(b)

(c)

(d)

Fig. 15. The TiB-Eng clad was breached by several small cracks. (a) Impact face, (b) profile, (c) vented end, and (d) blind end; all at 1.5X.

Fig. 16. Several cracks were visible in a cross section of the bullet contact area; 6.5X.

Fig. 17(a)

(b)

Fig. 17. It appeared that an intermetallic compound formed at the bullet/clad interface. (a) As polished, 100X, and (b) as polished, 250X.

Fig. 18. The crack at the edge of the bullet contact area had a ductile appearance; as polished, 50X.

(a)

(b)

Fig. 19. Wall sections on both sides of the crack necked to knife edges; (a) and (b) both at 100X.

(a)

(b)

Fig. 20. The wide breaching crack in the TiB-Eng capsule was exclusively intergranular; (a) and (b) both at 50X.

Fig. 21. A deep crack adjacent to the main breach also had a brittle appearance; 50X.

(a)

(b)

Fig. 22. Numerous cracks were observed along the vent end radius of the TiB-Eng capsule; (a) and (b), both as polished and at 6.5X.

Fig. 23. The fractures on the vent end radius were exclusively intergranular; 50X.

Fig. 24. One wall section thickened in response to a complex strain state; 50X.

Fig. 25. The microstructure of the TiB-Eng capsule weld was acceptable; 50X.

(a)

(b)

(c)

(d)

Fig. 26. The T:B-1 target clad was impacted at 423 m/s and 1085°C. (a) Impact face, (b) profile (c) vent end, and (d) blind end; all at 1.5X.

Fig. 27. Microscopic examination of the bullet contact area revealed multiple cracks; 6.5X.

(a)

(b)

Fig. 28. The main breach was exclusively intergranular, but apparently occurred after moderate plastic deformation. Both at 50X.

Fig. 29. The other breaching crack also had an intergranular appearance; 50X.

Fig. 30. The deep cracks adjacent to the main breach formed after appreciable deformation; 50X.

Fig. 31. The material at the edge of the bullet contact area was severely deformed; 50X.

(a)

(b)

Fig. 32. Although the TiB-1 capsule vent was relatively undeformed, one side of the vent assembly fractured. (a) As polished, 7X, and (b) as polished, 50X.

(a)

(b)

(c)

(d)

Fig. 33. The bullet impact opened the vent end radius of the TiB-2 target clad. (a) Impact face, (b) profile, (c) vent end, and (d) blind end; all at 1.5X.

Fig. 34. Only a portion of the bullet contact area could be prepared for metallographic examination; 7X.

Fig. 35. The main breach was exclusively intergranular; 50X.

Fig. 36. A deep crack on the interior of the capsule wall also had a brittle appearance; 50X.

Fig. 37. The wall material at the edge of the bullet contact area was markedly deformed; 50X.

(a)

(b)

Fig. 38. Although the single pass region of the capsule weld was acceptable, the overlap portion was coarse grained. (a) Single pass region and (b) overlap; both at 50X.

Fig. 39. Although the vent end of the TiB-2 target clad was badly damaged, the central portion of the capsule vent remained intact; 7X.

Fig. 40. The TiB-2 vent cover and assembly welds were unusually fine grained; 50X.