MASTER

^{238}Pu FUEL-FORM PROCESSES QUARTERLY REPORT

APRIL - JUNE 1981

**E. I. du Pont de Nemours & Co.
Savannah River Laboratory
Aiken, SC 29808**

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An analytical program has been started to determine the cause of cracking in DOP-26 iridium alloy during welding of GPHS clad vent sets. Analyses revealed that (1) intergranular cracking in the interior weld bead occurs in the heat-affected zone adjacent to the arc quench taper and at weld edges, (2) grain surfaces exposed by cracking exhibit a characteristic ridge network topography, and (3) no elements that could cause hot shortness were detected in the ridge networks.

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FOREWORD

This report is one of a series to summarize progress in the Savannah River Laboratory ^{238}Pu Fuel Form Program. This program is supported primarily by the DOE Advanced Nuclear Systems and Projects Division (ANSPD).

Goals of the Savannah River Laboratory (SRL) program include providing technical support for the production of $^{238}\text{PuO}_2$ fuel forms in the Savannah River Plant's (SRP) Plutonium Fuel Form (PuFF) Facility. This part of the program includes:

Demonstration of processes and techniques developed by the Los Alamos National Laboratory (LANL) for production at SRP. Information from the demonstration will provide the technical data for technical standards and operating procedures.

Technical Support to assist plant startup and to ensure continuation of safe and efficient production of high-quality heat-source fuel.

Technical Assistance after startup to accommodate changes in product and product specifications, to assist user agencies in improving product performance, to assist SRP in making process improvements that increase efficiency and product reliability, and to adapt plant facilities for new products.

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GENERAL-PURPOSE HEAT SOURCE (GPHS) PROCESS SUPPORT

ANALYTICAL STUDIES OF WELD CRACKING IN DOP-26 IRIIDIUM ALLOY CLAD VENT SETS

An analytical program has been started to determine the cause of cracking in DOP-26 iridium alloy during welding of GPHS clad vent sets. Analyses revealed that (1) intergranular cracking in the interior weld bead occurs in the heat-affected zone adjacent to the arc quench taper and at edges of weld, (2) grain surfaces exposed by cracking exhibit a characteristic ridge network topography, and (3) no elements that could cause hot shortness were detected in the ridge network.

Introduction and Summary

In January 1981, quality control examinations of GPHS fueled clads made in the Plutonium Fuel Form (PuFF) Facility revealed cracks on interior surfaces in the girth welds on DOP-26 iridium alloy clad vent sets (CVS). In March, a GPHS Iridium Welding Team consisting of representatives from Savannah River Plant (SRP), Los Alamos National Laboratory (LANL), Mound Facility (MF), and Oak Ridge National Laboratory (ORNL) was formed to (1) study the weld cracking problem, (2) propose fixes with high probabilities of success, and (3) evaluate results of tests of the proposed fixes. Savannah River Laboratory (SRL) was asked to perform analyses to determine the cause of weld cracking. Because of ^{238}Pu contamination on CVS welds made in the PuFF Facility, analyses were limited to examinations with the contained scanning electron microscope (SEM). However, uncontaminated welds made by the Equipment Engineering Division (EED) of SRP showed grain-boundary features identical to those of PuFF Facility welds. EED welds were analyzed with the high-resolution SEM equipped with an x-ray energy spectrometer (XES), the scanning Auger microprobe (SAM), and the scanning electron microprobe quantometer (SEMQ). The purpose of these analyses was to (1) characterize the grain-boundary features in areas susceptible to cracking and (2) identify elements that might cause embrittlement.

Cracks in welded DOP-26 iridium alloy clad vent sets occur primarily along grain boundaries in single-pass-welded (girth welds) and unwelded (vent closure welds) alloy adjacent to the arc quench taper. Similar cracks also occur near the edges of the molten zone. Grain surfaces in cracks exhibit ridge networks which are not observed in other weld areas or in unwelded alloy.

While ridge network morphology suggests grain-boundary liquation (hot shortness), analyses of features in ridge networks have failed to detect any elements that could produce low-melting phases. Additional analyses to characterize grain-boundary phases in welded and unwelded DOP-26 alloy are being performed using the high-resolution SAM(SUPER SAM) at ORNL.

Discussion

CVS Welds

Table 1 lists the welds examined by SRL.

During development of procedures for making girth welds in CVS's in the PuFF Facility, the arc was struck with almost immediate full penetration, a complete revolution plus a short overlap was welded, and the arc was quenched by decreasing the current (and penetration) over a short distance. During destructive examinations performed for quality control, cracks were detected on interior surfaces of several CVS's, including CVS Nos. 44 and 67, in alloy welded on the first revolution (single-pass weld area) adjacent to the quench taper.

Fixes proposed by the Welding Team included a more-gradual (longer) quench to reduce thermal stresses, a vent hole for pressure relief, and a backing strip to refine weld grain structure. During examination of welds made to test the proposed fixes, interior cracks were detected in unwelded alloy adjacent to the quench taper for a vent hole closure weld on CVS No. 84 and in a girth weld near points where contact was made to a heat shield on CVS No. 85.

To provide uncontaminated specimens for analytical studies, EED welded CVS No. T2, using procedures similar to those used in the PuFF Facility development welding. Two extra-short overlap welds were made on the girth weld to provide additional specimens of quench regions. CVS No. T6 was welded using a pure tungsten electrode rather than with the thoriated tungsten normally used. CVS No. T10 included several short welds made to define proper welding parameters.

Analyses of PuFF Facility Welds

CVS No. 67

Cracks in CVS No. 67 (Figure 1) were about 1 mm long and extended from near the weld centerline out to one edge of the molten zone. High-magnification SEM examination (Figure 2) revealed ridge networks on grain boundaries exposed by cracking.

CVS No. 67 was intentionally fractured along the centerline in the area of the cracks (Figure 3) to reveal grain boundaries in various regions of the weld near the quench taper (Figures 4a through 4d). The quench taper characterized by columnar grains oriented perpendicular to the weld direction. Grains in the area of cracking in the single-pass weld adjacent to the quench taper (Figure 4a) had rougher surfaces than grains in the single-pass weld further away from the quench (Figure 4b), the quench region (Figure 4c), and the overlap region (Figure 4d). Networks of ridges were detected on the rough grain surfaces in the area of cracking (Figure 4a) but not on grain surfaces in other regions of the weld (Figures 4b through 4d).

CVS No. 44

Cracks in CVS No. 44 (Figure 5) were about 0.5 mm long and along grain boundaries near the weld centerline. Fracturing (Figure 6) revealed weld regions similar to those observed in CVS No. 67. Again, cracking occurred in the single-pass weld adjacent to the quench region. As observed for CVS No. 67, the grain boundaries in the cracked area on CVS No. 44 (Figure 7) were rougher than in those other regions of the weld and showed ridge networks not observed on grain surfaces in other regions of the weld.

CVS No. 84

Two intergranular cracks (Figure 8) were detected in unwelded alloy near the quench taper of a vent hole closure weld on CVS No. 84. One crack (Figure 9a) was about 0.2 mm long and located along the weld centerline at the tip of the quench taper. The second crack (Figure 9b) was about 0.4 mm long and was located ahead of the quench taper and off the weld centerline. Grain boundaries in the area of cracking appeared broad because of possible thermal etching or melting.

The vent hole closure weld was fractured (Figure 10) to reveal grain boundaries in areas near the weld. Grain boundaries (Figure 11a) in the area of the cracks were similar in appearance to unwelded grains (Figure 11b) except for the presence of ridge networks.

CVS No. 85

A crack about 0.8 mm long was detected in the girth weld on CVS No. 85 near spots where contact had been made with the weld shield (Figure 12). Ridge networks occurred on grain surfaces exposed by cracking.

Analyses of EED Welds

CVS No. T2 near first quench (Q1)

No cracks were detected in CVS No. T2 near the first quench (Q1). The weld was cut as shown in Figure 13 to provide specimens for SAM analyses. These specimens were subsequently analyzed with the SEM and SEMQ.

SAM Analyses of CVS No. T2. Specimens from four weld regions plus unwelded alloy from the CVS wall were fractured in the ultra-high vacuum (1×10^{-8} torr) in the SAM. The weld specimens fractured along the weld centerline, except for the single-pass specimen No. 1 which fractured at the edge of the molten zone (Figures 14a through 14d). SEM and SEMQ analyses showed that all these specimens fractured primarily intergranularly.

Auger spectra taken at nine different points on the fractured specimens from each weld region showed the presence of iridium, thorium, oxygen, and carbon (Figure 15). Oxygen and carbon were indicated by strong Auger peaks at 512 and 273 eV, respectively. These elements, minor constituents of the atmosphere of the Auger spectrometer bell jar, absorb on the specimens. This absorption was confirmed by noting the time-dependent increase in oxygen and carbon signals after mechanical fracturing of an unwelded specimen. The presence of iridium and thorium in specimens were indicated by the appearance of Auger peaks at 54 and 67 eV, respectively. The sensitivity factor for the Th/Ir ratio was determined to be 1.01, from measurements of standard spectra of pure iridium and thorium. This sensitivity factor was used to convert the relative peak heights of thorium and iridium to atom ratios. In this case, the ratios of the thorium (67 eV) and iridium (54 eV) peak heights were equivalent to their atom ratios.

Analysis of the fractured weld specimens showed that thorium is dispersed continuously over the grain surfaces. The Th/Ir atom ratios (shown in $\bigcirc$) in Figures 14a through 14d varied widely, even over the surface of a single specimen. The average Th/Ir atom ratios of all samples was 0.11 ± 0.04 (1 σ). Argon-ion sputtering indicated that the continuous thorium-bearing grain-boundary phase is in the form of a thin layer with approximately the same thickness in each weld region (Figure 16). Sputtering through these layers took about three minutes.

Surfaces of the weld specimens were reanalyzed after sputtering. No residual thorium was detected on the single-pass No. 3 and weld overlap specimens. On the quench and single-pass No. 1 specimens, discontinuous thorium-bearing areas were detected (Th/Ir atom ratios shown in Figures 14a and 14b). Thorium in these

areas remained even after an additional 25 minutes of sputtering. The average Th/Ir atom ratio (0.04) for these areas was smaller than the 0.11 measured on the surfaces before sputtering. The location of the thorium-bearing area on the quench specimen corresponds to the single-pass weld adjacent to the quench taper where cracks occur in PuFF Facility welds. As shown later, weld edges (where single-pass specimen No. 1 fractured) are also susceptible to cracking. Thus, these SAM results suggest that cracking may be related to the presence of a thick, discontinuous, thorium-bearing, grain-boundary phase.

SAM analyses of a fractured specimen of unwelded alloy also showed a continuous thorium-bearing grain-boundary phase with Th/Ir atom ratios similar to those measured on the weld specimens. However, sputtering showed that this continuous thorium-bearing layer is 4 to 8 times thicker than that on welded specimens (Figure 16). After sputtering, one area with residual thorium was detected.

SEMQ Analyses of CVS No. T2. Areas of interest on the fractured quench specimen, Single-Pass weld Specimen No. 1, and the weld overlap specimen of CVS T2 near the first quench (Q1) were examined with the SEMQ. Back-scattered electron imaging was used to record grain surface morphologies. Thorium distributions on the grain surfaces were recorded in corresponding thorium maps. The detection limit for thorium mapping varies with the thickness and thorium concentration of the grain-boundary features. The minimum detectable thorium-bearing area is equivalent to a feature about 0.5 μm thick with about 0.5 wt % thorium.

Figure 17a shows grain surfaces in the single-pass area adjacent to the quench taper on the quench specimen. Grain surfaces in this area exhibited the same rough textures and ridge networks observed in corresponding areas of PuFF Facility welds where cracking occurred (Figures 4a and 7). Mapping revealed discontinuous thorium-bearing areas, some covering over 100 μm^2 , on these grain surfaces. The thorium-bearing areas could not be correlated with any specific grain surface features but they do not occur in the ridge networks. In the quench taper and weld overlap areas of this same specimen, the grain surfaces were relatively smooth and had no ridge networks. Also, no thorium was detected on grain surfaces in the quench and weld overlap areas. The SEMQ results agree with the SAM analyses after sputtering in which thorium was only detected in the single-pass area adjacent the quench taper.

Grain surfaces on Single-Pass Specimen No. 1, which fractured at the edge of the molten zone, are shown in Figure 18a and 18b. No ridge networks were observed on these grain surfaces. Grains

near the inside were equiaxed like those of unwelded alloy and thorium was localized in small ($<2\text{-}\mu\text{m}$ -diameter) spots. Grains near the outside were elongated perpendicular to CVS surface (because they were at the edge of the molten zone) and thorium was localized in narrow ($<1\text{-}\mu\text{m}$ -wide) stringers which were also oriented perpendicular to the CVS surface. These are probably the same thorium-bearing areas that were detected by the SAM after sputtering. (See Figures 13 through 16).

Figure 19 shows grain surfaces on the fractured weld overlap specimen. No ridge networks were observed on these grain surfaces. No definite thorium-bearing areas were detected by mapping. SAM analyses of this specimen after sputtering also failed to detect any thorium.

CVS No. T2 Near Second Quench (Q2)

Specimens of quench, single-pass weld, weld overlap, and unwelded alloy specimens from CVS No. T2 near the second quench (Q2) were analyzed by spark source mass spectrometry. These analyses showed there were no significant differences in the concentrations of thorium or other elements in any of these specimens.

CVS No. T2 Near Third Quench (Q3)

Figure 20 shows several small cracks detected with the SEM at the edge of the molten zone on the inside surface of CVS No. T2 near the third quench (Q3). High-magnification examination (Figure 21) revealed a network of ridges on the grain surface in the crack. This result shows that edges of the molten zone are also susceptible to cracking.

A specimen was fractured across the weld near Quench Q3 (Figure 22). The specimen fractured mostly intergranularly except at the center of the weld where the thin grains fractured transgranularly. Grain surfaces at the edges of the molten zone (Figure 23) showed rough textures, ridge networks, and discontinuous thorium-bearing areas like those observed in the single-pass area near the quench Q1 (Figure 17a). These grain surfaces appear similar to those in areas where cracks occurred in PuFF Facility welds (Figures 4a and 7).

SEMQ point analyses for thirteen elements were performed on a grain surface at the edge of the molten zone in the area of a ridge network (Area A, Figure 24) and in an area with no ridge networks (Area B, Figure 25). Results are given in Table 2. Thorium values correspond to a minimum concentration because of the small size and

possible thinness of the surface features. SEMQ analyses revealed no differences between the ridges and areas between the ridges in the ridge network. Very little thorium (≤ 0.11 wt %) was measured in the ridge network. However, varying amounts of thorium (up to about 6 wt %) were measured at other points on the grain surface.

Figure 26 shows grain surfaces of unwelded alloy revealed by the fracture near Quench Q3. A stringer of submicron thorium-bearing particles was present on one grain surface. Although the measured thorium content was about 8 wt %, these small particles are presumably ThIr_5 (about 19 wt % Th). ThO_2 particles this size would have analyzed at >19 wt % Th. Very little thorium (<0.1 wt %) was measured on the intergranular fracture surfaces of unwelded alloy and transgranular fracture surfaces of grains near the weld centerline (Table 3).

CVS No. T10

A crack formed in unwelded alloy adjacent to the quench in a short weld in CVS No. T10 made by EED to establish welding parameters (Figure 27). Grain surfaces in this crack had ridge networks like those on cracks in welded alloy.

TABLE 1

DOP-26 Iridium alloy Weld Specimens Analyzed at SRL

<u>CVS Identification</u>	<u>Welding Conditions</u>	<u>Observations</u>
<u>Welded in PuFF Facility</u>		
44	Development weld	0.5-mm cracks in girth weld near quench
67	Development weld	About 1-mm cracks in girth weld near quench
84	Test of fix; Parameters set for minimum heat input	0.2 to 0.4-mm cracks in unwelded alloy near quench of vent closure weld
85	Test of fix; Parameters set for maximum heat input	About 0.8-mm crack in girth weld near contact point with heat shield
86	Test of fix; Centerline Parameters	No cracks
<u>Welded by EED</u>		
T2	Similar to development weld	0.2-mm cracks at edge of molten zone
T6	Similar to development weld; pure tungsten electrode	No cracks
T10	Short welds to set parameters	Cracks in unwelded alloy near quench

TABLE 2

Results* of SEMQ Analyses of DOP-26 Alloy, Ir-Standard, and Grain Surfaces at Edge of Molten Zone on CVS T2 Near Third Quench Q3

Element	Polished		Iridium Standard	Points in Ridge Network				
	DOP-26			Area Between Ridges			Ridges	
	Alloy			No. 2	No. 8	No. 11	No. 6	No. 7
Ir	99.64	99.45	99.81	99.57	99.64	99.71	99.58	99.68
W	0.30	0.30	0.00	0.31	0.25	0.18	0.23	0.14
Th	0.02	0.00	0.00	0.07	0.08	0.04	0.05	0.11
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Ni	0.01	0.00	0.01	0.04	0.00	0.03	0.01*	0.00
Cu	0.02	0.23	0.10	0.00	0.01	0.00	0.00	0.00
Si	0.01	0.01	0.01	0.01	0.01	0.02	0.04	0.02
P	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
S	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01
Mo	0.00	0.00	0.06	0.00	0.00	0.01	0.06	0.03
Ag	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00

	Points Adjacent to Ridge Network Area A					Points Away from Ridge Network Area B		
	No. 1	No. 3	No. 4	No. 5	No. 9	No. 12	No. 13	No. 14
Ir	93.60	99.34	99.64	99.66	98.77	99.69	99.56	97.93
W	0.16	0.34	0.25	0.19	0.23	0.25	0.33	0.06
Th	5.93	0.24	0.02	0.12	0.85	0.02	0.02	1.75
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.00	0.01	0.00	0.00	0.00	0.01*	0.00	0.01
Cu	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.15
Si	0.03	0.02	0.02	0.03	0.06	0.02	0.01	0.02
P	0.00	0.01*	0.00	0.00	0.00	0.00	0.00	0.01
S	0.00	0.01	0.01	0.00	0.00	0.02	0.00	0.00
Mo	0.00	0.02	0.06	0.00	0.06	0.00	0.07	0.00
Ag	0.24*	0.01	0.00	0.00	0.04*	0.00	0.01*	0.08*
Al	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00

* Elemental concentrations in weight percent normalized to 100%

** Interference from Thorium M α x-ray

TABLE 3

Results* of SEMQ Analyses of Grain Surfaces in Welded and Unwelded Alloy in CVS T2

Element	Transgranular Fracture Surfaces of Grains near Weld Centerline		Intergranular Fracture Surfaces of Unwelded Grains			Detection Limits wt % $\sigma = 100\%$
			Grain Surfaces		Particle in Stringer	
Ir	99.51	99.60	99.35	99.55	91.34	-----
W	0.42	0.31	0.57	0.38	0.19	0.020
Th	0.02	0.09	0.00	0.05	7.99	0.007
Cr	0.00	0.00	0.00	0.00	0.00	0.007
Fe	0.00	0.00	0.01	0.00	0.00	0.010
Ni	0.00	0.00	0.00	0.00	0.01	0.060
Cu	0.00	0.00	0.02	0.00	0.12	0.006
Si	0.01	0.00	0.00	0.00	0.00	0.006
P	0.00	0.00	0.00	0.00	0.00	0.030
S	0.01	0.00	0.01	0.01	0.00	0.004
Mo	0.03	0.00	0.05	0.00	0.01	0.023
Ag	0.00	0.00	0.00	0.00	0.30**	0.010
Al	†	†	†	†	†	0.003

* Elemental concentrations in weight percent normalized to 100%

** Interference from Thorium M α x-ray

† Not measured

FIGURE 1. Cracks on Interior of CVS No. 67 in Single-Pass Weld near Quench Taper

FIGURE 2. Magnified Crack in CVS No. 67 Showing Intergranular Separation and Ridges on Grain Surfaces in Crack

FIGURE 3. CVS No. 67 Fractured in Area of Cracks

a. Rough Grain Surfaces with Ridge Networks in Single-Pass Weld Below Quench Taper where Cracks Occurred

FIGURE 4. Grain Surfaces in and near Quench Taper of Fractured CVS Facility Weld No. 67

b. Grain Surfaces in Single-Pass Area Away from Quench Taper

FIGURE 4. (Continued)

c. Grain Surfaces in Quench Taper

FIGURE 4. (Continued)

d. Grain Surface in Overlap Area Near Quench Taper

FIGURE 4. (Continued)

FIGURE 5. Cracks on Interior of CVS No. 44 in Single-Pass Weld
Adjacent to Quench Taper

FIGURE 6. CVS No. 44 Fractured in Area of Cracks

FIGURE 7. Rough Grain Surfaces with Ridge Networks in Single-Pass Weld Below Quench Taper where Cracks Occurred in CVS No. 44

FIGURE 8. Cracks on Interior Surface of Vent Hole Closure Weld on CVS No. 84

a. Crack No. 1

b. Crack No. 2

FIGURE 9. Cracks in Vent Hole Closure Weld on CVS No. 84

FIGURE 10. Vent Hole Closure Weld on CVS No. 84 Fractured in Area of Cracks.

a. Rough Grain Boundaries
and Ridge Networks
in Area of Cracks

b. Grain Boundaries
in Unwelded Alloy

c. Grain Boundaries
in Quench Taper

FIGURE 11. Grain Boundaries in Areas near Vent Hole Closure Weld
on CVS No. 84.

Spots of Contact
with Weld Shield

Crack

Ridge Networks

FIGURE 12. Crack in CVS No. 85 Near Spots where Contact was Made with the Weld Shield. High Magnification Reveals Ridge Networks on Grain Surfaces in Crack.

FIGURE 13. Identification of Specimens from CVS No. T2 near First Quench

a. Quench Specimen Q1

b. Single-Pass Weld Specimen No. 1 (Fractured at Edge of Molten Zone)

FIGURE 14. Specimens of CVS T2, Fractured in the SAM, Showing Th/Ir Atom Ratios before (○) and after (□) Sputter Etching.

c. Weld Overlap Specimen

d. Single-Pass Weld Specimen No. 3

FIGURE 14. (Continued)

FIGURE 15. Typical Auger Electron Spectrum for a Fractured Weld Specimen from CVS No. T2.

FIGURE 16. SAM Th/Ir Profiles of DOP-26 Iridium Alloy from Specimens from CVS No. T2

Electron Image

Th Map

- a. Rough Textures, Ridge Networks, and Thick, Discontinuous Thorium-Bearing Areas on Grains Surface in Single-Pass Weld Adjacent to Quench Taper

FIGURE 17. Grain Surfaces Near Quench Taper on Fractured Quench Specimen Q1 of CVS No. T2. See Figure 14a.

Electron Image

Th Map

b. Grain Surfaces in Quench Taper

FIGURE 17. (Continued)

Electron Image

Th Map

c. Grain Surfaces in Weld Overlap Area

FIGURE 17. (Continued)

Thorium-bearing spots

Electron Image

Thorium-bearing spots

Th Map

a. Near Inside

FIGURE 18. Grain Surfaces on Single-Pass Specimen No. 1 of CVS No. T2 Fractured at Edge of Molten Zone.

Thorium-bearing Stringers

Electron Image

Thorium-bearing Stringers

Th Map

b. Near Outside

FIGURE 18. (Continued)

Possible Thorium-bearing Area

Electron Image

Possible Thorium-bearing Area

Th Map

FIGURE 19. Grain Surfaces in Fractured Weld Overlap Specimen of CVS No. T2 (See Figure 14c).

FIGURE 20. Cracks at Edge of Molten Zone on Inside Surface of CVS T2 Near Quench Q3

FIGURE 21. Ridge Network on Grain Surface in Crack 2.

FIGURE 22. CVS No. T2 Fractured Across Weld Near Quench Q3.

Electron Image

Th Map

**FIGURE 23. Grain Surfaces at Edge of Molten Zone in CVS No. T2
Fractured Across Weld**

Electron Image

Th Map

FIGURE 24. Analysis Points in Area A (See Figure 23).

Electron Image

Th Map

FIGURE 25. Analysis Points in Area B (See Figure 23).

Thorium-bearing Stringer

Electron Image

Thorium-bearing Stringer

Th Map

FIGURE 26. Intergranular Fracture in Unwelded Alloy near Quench Q3 in CVS No. T2.

Thorium-bearing Particles in Stringer

Electron Image (High Magnification)

Thorium-bearing Particles in Stringer

Th Map

FIGURE 26. (Continued)

FIGURE 27. Crack in Unwelded Alloy Adjacent to Quench Taper in a Short Weld in CVS No. T10. High Magnification Shows Ridge Networks on Grain Surfaces in Crack.