SG-SGDA-04-1 Rev. 1

STEAM GENERATOR PULLED TUBE EXAMINATION

Watts Bar Unit 1 – Cycle 5 RFO

FINAL REPORT

March 2004

Prepared by

Westinghouse Electric Company LLC

A. R. Vaia
W. R. Junker
C. Deflitch
J. M. Conermann

Prepared for

Tennessee Valley Authority

CONTENTS

SECTION 1

INTRODUCTION

Watts Bar Unit 1 is a four loop Westinghouse designed pressurized water reactor owned and operated by the Tennessee Valley Authority (TVA). The plant, which has a nominal rating of 1210 MWe, commenced commercial operation in February 1996 and has accumulated 6.62 EFPY of operation through October 2003. The steam generators are Model D3 with mill annealed Alloy 600 tubing, full depth mechanical (hardroll) expanded tube to tubesheet joints, and carbon steel tube support plates (TSP's) with drilled tube holes and flow holes. The mill annealed Alloy 600 steam generator tubes are 0.750 inch in outer diameter and have a nominal wall thickness of 43 mils.

Upon completion of Cycle 4 of operation, axial outside diameter stress corrosion cracking (ODSCC) was confirmed within the TSP regions of the Watts Bar steam generators. To reduce the number of tubes that needed to be plugged due to the presence of detectable ODSCC, Watts Bar implemented an alternate repair criteria (ARC) defined in NRC Generic Letter 95-05 (GL95-05) during the Cycle 4 inspection effort. As required by GL95-05, TVA selected two steam generator tubes from Watts Bar Unit 1 for removal and laboratory non-destructive and destructive examinations to support the implementation of the ARC. The tube selection and laboratory examinations were in compliance with ARC requirements that were established in GL95-05. The two tubes removed following the completion of Cycle 5 operation were from Steam Generator 2 (SG2). The removal of the tubes required elimination of the tube-to-tubesheet weld and TIG relaxation of the hard roll expansion region, after which the tubes were pulled though the tubesheet. The pulled tubes were from row 10 column 39 hot leg (R10C39 HL) and row 11 column 41 hot leg (R11C41 HL) and were cut approximately 6 inches below the H04 tube support plate. Watts Bar eddy current protocol designates the flow distribution baffle plate as H01 and subsequent tube support plates as H02, H03, etc. The section lengths and pull forces for each tube are provided in Table 1-1. Each tube removed contained a top of tubesheet intersection, a flow distribution baffle intersection, and two support plate intersections.

Following the removal from the steam generators, the pulled tube segments were transported to the Westinghouse Remote Metallographic Laboratory for destructive and nondestructive examinations. The evaluation effort consisted of the following activities:

- Verification of section identification – All pulled sections were measured for length and visually surveyed for landmark features (e.g. TSP intersections) for comparison with tube pull records.
- Visual characterization of pulled tube sections – The purpose of this effort was to identify and characterize any tube degradation, characterize the appearance of any secondary side deposits, and identify any damage from the tube pulling process.

- Eddy current inspection – Full length bobbin examination and +Pt confirmation of all bobbin signals was performed on each pulled section. This information served to precisely locate all indications and to determine any differences from the pre-pull inspection.
- OD profile of tube sections at TSP intersections.
- Leak testing at elevated temperature of sections containing apparent through wall defects.
- Burst and tensile testing.
- Material chemistry verification.
- Characterization of tubing material by microhardness, residual stress, grain size, carbide distribution and Huey testing.
- SEM characterization of burst fracture face including length versus depth profiles.
- Metallography to confirm morphology of stress corrosion cracks.
- Limited chemical characterization of deposits and oxide films (EDS of OD deposits and fracture face oxides).

The results of the various evaluations are summarized in the following sections. All examinations and testing presented in this report were treated as safety-related and were performed in accordance with the Westinghouse Quality Assurance program, which satisfies the requirements of 10CFR50 Appendix B.

Table 1-1

Piece Lengths and Areas of Interest of the Pulled Tubes

R10C39 HL Piece Number	**Pull Force (lbs)**	**Length of Piece (Inches)**	**Area of Interest**
Piece 1	300	13.875	Below TTS
Piece 2	480	27.875	TTS and H01 (FDB) Note 1
Piece 3	95	25.250	H02 (2nd TSP)
Piece 4	95	23.50	H03 (3rd TSP)
Piece 5	0	21.0	Freespan above H03 and below H04 (4th TSP)
		Total Length: 111.50	

R11C41 HL Piece Number	**Pull Force (lbs)**	**Length of Piece (Inches)**	**Area of Interest**
Piece 1	1150	14.0	Below TTS
Piece 2	430	25.0	TTS and H01 (FDB) Note 1
Piece 3	100	25.75	H02 (2nd TSP)
Piece 4	100	24.625	H03 (3rd TSP)
Piece 5	0	22.25	Freespan above H03 and below H04 (4th TSP)
		Total Length: 112.625	

Note 1: Based on Watts Bar designation, the flow distribution baffle is identified as H01 and is considered the 1st tube support plate. The nominal diameter of the tube hole in the FDB is 0.828 inch.

SECTION 1

INTRODUCTION

Watts Bar Unit 1 is a four loop Westinghouse designed pressurized water reactor owned and operated by the Tennessee Valley Authority (TVA). The plant, which has a nominal rating of 1210 MWe, commenced commercial operation in February 1996 and has accumulated 6.62 EFPY of operation through October 2003. The steam generators are Model D3 with mill annealed Alloy 600 tubing, full depth mechanical (hardroll) expanded tube to tubesheet joints, and carbon steel tube support plates (TSP's) with drilled tube holes and flow holes. The mill annealed Alloy 600 steam generator tubes are 0.750 inch in outer diameter and have a nominal wall thickness of 43 mils.

Upon completion of Cycle 4 of operation, axial outside diameter stress corrosion cracking (ODSCC) was confirmed within the TSP regions of the Watts Bar steam generators. To reduce the number of tubes that needed to be plugged due to the presence of detectable ODSCC, Watts Bar implemented an alternate repair criteria (ARC) defined in NRC Generic Letter 95-05 (GL95-05) during the Cycle 4 inspection effort. As required by GL95-05, TVA selected two steam generator tubes from Watts Bar Unit 1 for removal and laboratory non-destructive and destructive examinations to support the implementation of the ARC. The tube selection and laboratory examinations were in compliance with ARC requirements that were established in GL95-05. The two tubes removed following the completion of Cycle 5 operation were from Steam Generator 2 (SG2). The removal of the tubes required elimination of the tube-to-tubesheet weld and TIG relaxation of the hard roll expansion region, after which the tubes were pulled though the tubesheet. The pulled tubes were from row 10 column 39 hot leg (R10C39 HL) and row 11 column 41 hot leg (R11C41 HL) and were cut approximately 6 inches below the H04 tube support plate. Watts Bar eddy current protocol designates the flow distribution baffle plate as H01 and subsequent tube support plates as H02, H03, etc. The section lengths and pull forces for each tube are provided in Table 1-1. Each tube removed contained a top of tubesheet intersection, a flow distribution baffle intersection, and two support plate intersections.

Following the removal from the steam generators, the pulled tube segments were transported to the Westinghouse Remote Metallographic Laboratory for destructive and nondestructive examinations. The evaluation effort consisted of the following activities:

- Verification of section identification – All pulled sections were measured for length and visually surveyed for landmark features (e.g. TSP intersections) for comparison with tube pull records.
- Visual characterization of pulled tube sections – The purpose of this effort was to identify and characterize any tube degradation, characterize the appearance of any secondary side deposits, and identify any damage from the tube pulling process.

- Eddy current inspection – Full length bobbin examination and +Pt confirmation of all bobbin signals was performed on each pulled section. This information served to precisely locate all indications and to determine any differences from the pre-pull inspection.
- OD profile of tube sections at TSP intersections.
- Leak testing at elevated temperature of sections containing apparent through wall defects.
- Burst and tensile testing.
- Material chemistry verification.
- Characterization of tubing material by microhardness, residual stress, grain size, carbide distribution and Huey testing.
- SEM characterization of burst fracture face including length versus depth profiles.
- Metallography to confirm morphology of stress corrosion cracks.
- Limited chemical characterization of deposits and oxide films (EDS of OD deposits and fracture face oxides).

The results of the various evaluations are summarized in the following sections. All examinations and testing presented in this report were treated as safety-related and were performed in accordance with the Westinghouse Quality Assurance program, which satisfies the requirements of 10CFR50 Appendix B.

Table 1-1
Piece Lengths and Areas of Interest of the Pulled Tubes

R10C39 HL Piece Number	Pull Force (lbs)	Length of Piece (Inches)	Area of Interest
Piece 1	300	13.875	Below TTS
Piece 2	480	27.875	TTS and H01 (FDB) [Note 1]
Piece 3	95	25.250	H02 (2nd TSP)
Piece 4	95	23.50	H03 (3rd TSP)
Piece 5	0	21.0	Freespan above H03 and below H04 (4th TSP)
		Total Length: 111.50	

R11C41 HL Piece Number	Pull Force (lbs)	Length of Piece (Inches)	Area of Interest
Piece 1	1150	14.0	Below TTS
Piece 2	430	25.0	TTS and H01 (FDB) [Note 1]
Piece 3	100	25.75	H02 (2nd TSP)
Piece 4	100	24.625	H03 (3rd TSP)
Piece 5	0	22.25	Freespan above H03 and below H04 (4th TSP)
		Total Length: 112.625	

Note 1: Based on Watts Bar designation, the flow distribution baffle is identified as H01 and is considered the 1st tube support plate. The nominal diameter of the tube hole in the FDB is 0.828 inch.

SECTION 2

RECEIPT INSPECTION

The various sections of the Watt Bar Unit 1 Steam Generator 2 tubes as they were received at the Westinghouse Remote Metallographic Facility are described in this section. The information presented includes the lengths and locations of the tube sections, along with the general visual observations of the as-received condition.

2.1 Description of Tube Sections Received

Row 10 Column 39 tube (hereafter referred to as R10C39 HL) and Row 11 Column 41 (hereafter referred to as R11C41 HL) were cut at a distance of 114 inches from the tube end and were cut into five sections each for shipment. Each pulled tube section received from Watts Bar Unit 1 was measured for length to compare with site length data to verify tube piece identity and to provide data to aid in identifying the position of tube support plates. Each tube piece was visually inspected and surface features documented per the discussion provided below. Based on Watts Bar eddy current protocol, the flow distribution baffle plate is considered the 1st tube support plate and is designated as H01. Subsequent hot leg tube support plates are designated as H02, H03, etc. For a Model D-3 design, the flow distribution plate is designed with a nominal tube hole diameter of 0.828 inch, while the nominal tube hole diameter for the tube support plates is 0.766 inch.

2.2 Visual Observations

In addition to visual examination of the tube sections, low magnification photographs of the areas of interest were taken. The areas of interest included those areas identified in the field as having eddy current indications, as well as those areas with OD surface anomalies or support structures, i.e., top of tubesheet, flow distribution baffle, and tube support plates.

2.2.1 R10C39 HL and R11C41 HL - Freespan Areas - General Observations

All tube pieces were categorized as having relatively uniform gray deposit. The gray deposits were the typical surface oxide formed during steam generator operation. Minimal evidence of deposit buildup or scale formation was seen on these sections. Fresh axial scratches, randomly distributed around and along the tubes, were noted on a majority of the sections. The scratches occasionally were down to bare metal, and appeared to have occurred during the tube removal process. Belt polishing marks were observed in small areas where the deposit had been displaced during handling.

In the following descriptions, scratches and grooves are shallow, axial visual indications on the tube OD surface. The distinction between scratches and grooves in this examination is simply the width of the indication. Scratches are basically singular, narrow indications while grooves have a greater width and at times may consist of multiple scratches. As noted throughout the following discussion, reference is made to the fact that the scratch or groove was likely produced during the tube pulling operation. Scratches and grooves produced during the tube removal normally are characterized as being "shiny" (non-oxidized) and exhibiting a "ragged" surface appearance with evidence of "upset" material.

2.2.2 Tube R10C39 HL

Piece 1:

Piece 1 is the segment cut from the lower portion of the tubesheet expansion region. This segment was TIG-relaxed to facilitate the tube removal process. This piece has a dark gray oxide and circumferential scratch marks. No photographs were taken.

Piece 2:

Piece 2 contains the top of the tubesheet expansion transition (TTS) and the flow distribution baffle intersection (H01). Based on Watts Bar eddy current protocol the flow distribution baffle plate is referred to as the 1st TSP. Longitudinal scratches, as well as light circumferential markings, were seen along the length of Piece 2. The deepest scratches were noted on the lower end of the piece. The lower portion, corresponding to the tube length expanded into the tubesheet, was "clean and shiny". A dark gray-colored deposit was observed at the TTS region. Fresh scratches were noted around the tube above the TTS expansion region. Circumferential scratches from the tube removal were visible near the TTS expansion. The oxide below the TTS was light gray. Circumferential scratch marks were visible. Above the TTS the oxide was dark gray in appearance and thicker. The oxide had spalled off in places due to the tube removal, revealing a shiny tube surface. Evidence of belt polishing marks was observed in small areas where the deposit had been displaced during handling. Shiny, longitudinal scratch marks were also visible. A scribe mark showing the divider plate orientation was evident on Piece 2. Photographs documenting the tube OD at the top of tubesheet and the OD deposit seen at the H01 intersection are presented in Figures 2-1 and 2-2, respectively.

Piece 3:

Piece 3 contains the H02 tube support plate. The H02 area is visible, with slightly less oxide than the rest of the tube piece and has a rougher appearance. Some of the oxide may have flaked off during the removal process. The oxide on the remaining tube was dark gray in appearance and thick. The oxide had spalled off in large areas due to the tube removal process. A large area, approximately ¼" in width, shiny and devoid of oxide, was present intermittently down the side of the tube. Shiny scratches were also visible in oxidized areas.

Intermittent longitudinal scratches, as well as light circumferential markings, were seen along the length of Piece 3. Evidence of belt polishing marks was observed in small areas where the deposit had been displaced during handling. The oxide deposit was relatively light over the entire length of the tube. A scribe mark showing the divider plate orientation was evident on Piece 3. Photographs documenting the deposit seen on the tube OD at the H02 tube support plate intersection are presented in Figure 2-3.

Piece 4:
Piece 4 contains the H03 tube support plate. A thick dark gray oxide was present on most of the tube. The H03 area was visible and had a non-uniform oxide which appeared to be thinner than the oxide on the rest of the tube. The tube oxide had spalled in large areas during the removal process, revealing a shiny surface below. The spalled areas collectively comprised ~30% of the tube surface. A scribe mark showing the divider plate orientation was evident on Piece 4. Photographs documenting the OD surface deposit are presented in Figure 2-4.

Piece 5:
No scribe mark was evident on Piece 5. This piece was the freespan region between the H03 and H04 tube support plates. The surface of the tube had a thick dark gray oxide which was fairly uniform. Large, intermittent shiny areas where the oxide had spalled due to the tube removal process comprised ~30% of the tube surface. No photo-documentation of the as received condition was done since this section of tubing was not associated with any support structure.

2.2.4 Tube R11C41HL

Piece 1:
Piece 1 is the segment cut from the lower portion of the tubesheet expansion region. This segment was TIG-relaxed to facilitate the tube removal process. This piece had a dark gray oxide and circumferential scratch marks. Photographs were not taken.

Piece 2:
Piece 2 contains the top of the tubesheet expansion transition (TTS) and the H01 flow distribution baffle. Based on Watts Bar eddy current protocol the flow distribution baffle plate is referred to as the 1st TSP. The TTS expansion transition was visible and relatively clean with some sporadic oxide on the surface. The lower portion, corresponding to the tube length expanded into the tubesheet, was "clean and shiny". A dark gray-colored oxide was observed at the TTS region and above. The amount of OD deposit seen on the tube at and above the tubesheet expansion transition was minimal. The deposit was more typical of the oxide developed from operation rather than deposit buildup from corrosion product transport. Evidence of belt polishing marks was observed in small areas where the oxide had been

displaced during handling. The oxide below the TTS was light gray in coloration. Circumferential scratch marks were visible. Above the TTS the oxide was dark gray in appearance and thicker. Shiny, longitudinal tube removal scratches were visible. No unusual surface features were noted in the area identified by eddy current to contain a single circumferential indication (SCI). A scribe mark showing the divider plate orientation was evident on Piece 2. Photographs documenting the tube OD at the top of tubesheet and the OD deposit seen at the H01 intersection are presented in Figures 2-5 and 2-6, respectively.

Piece 3:

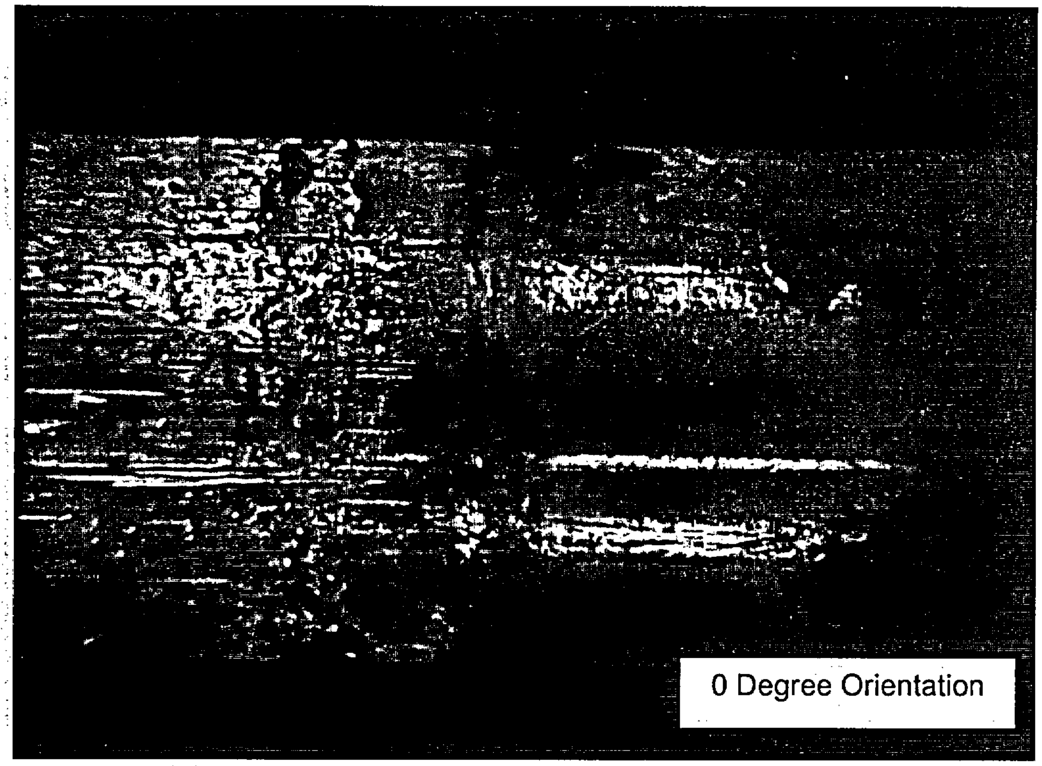
Piece 3 contains the H02 tube support plate. The H02 area was visible and had an irregular oxide. Some of the H02 oxide may have spalled off during the tube removal process. The remaining tube had a thick dark gray oxide which appeared fairly uniform. Shiny scratches due to tube removal were visible. A few light longitudinal, circumferential marks, and a number of "shiny" areas were seen along the length of this section. Evidence of belt polishing marks was observed in small areas where the oxide had been displaced during handling. The oxide deposit was relatively light over the entire length of the tube. A scribe mark showing the divider plate orientation was evident. Photographs documenting the deposit seen on the tube OD at the H02 intersection are presented in Figure 2-7.

Piece 4:

Piece 4 contains the H03 tube support plate. The H03 area was visible and had a lighter oxide than the rest of the tube. The remaining tube had a thick dark gray oxide. Shiny scratches from removal were visible, along with small shiny areas where the oxide was removed. A scribe mark showing the divider plate orientation was evident. Photographs documenting the deposit seen on the tube OD are presented in Figure 2-8.

Piece 5:

No scribe mark was evident on Piece 5. This piece was the freespan region between the H03 and H04 tube support plates. The surface of the tube had a thick dark gray oxide which was fairly uniform. Light longitudinal and circumferential markings were seen along the length of Piece 8 associated with the tube pull process. The oxide deposit was relatively light over the entire length of the tube. The OD surface exhibited a few longitudinal and circumferential scratches due to the tube pull process. Shiny scratches from the tube removal were visible, along with small shiny areas where the oxide had been removed. No photo- documentation of the as-received condition was done since this section was not associated with any support structure.



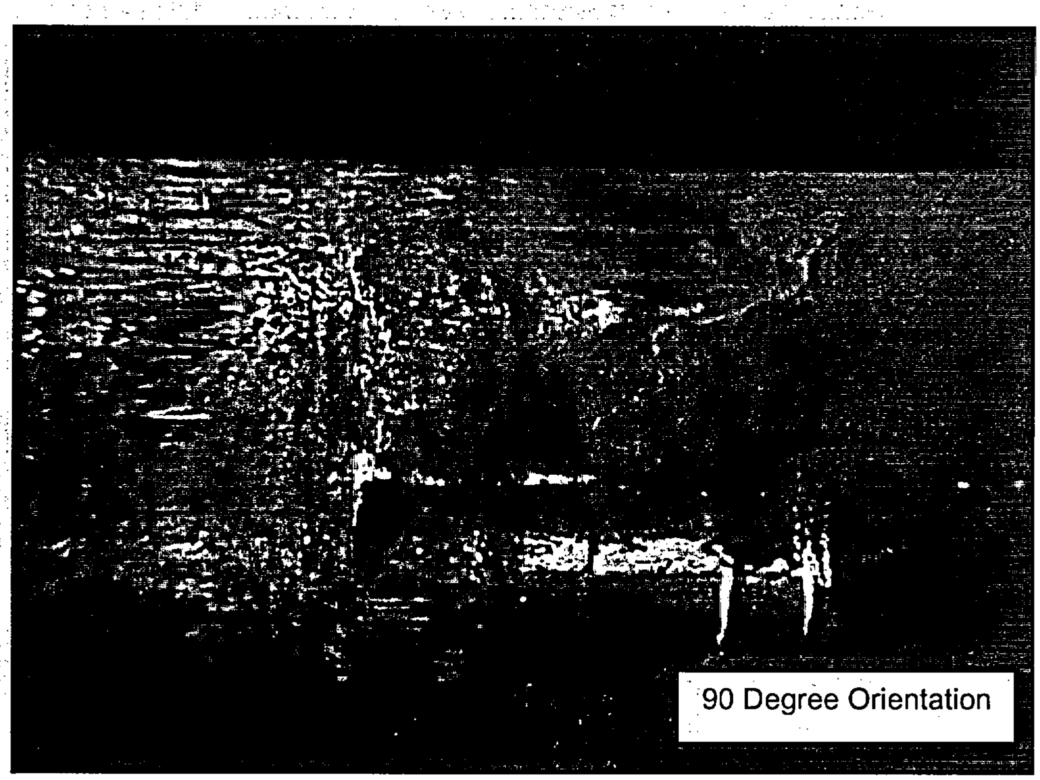


Figure 2-1
OD Appearance of R10C39 HL, Piece 2 at Top of Tubesheet

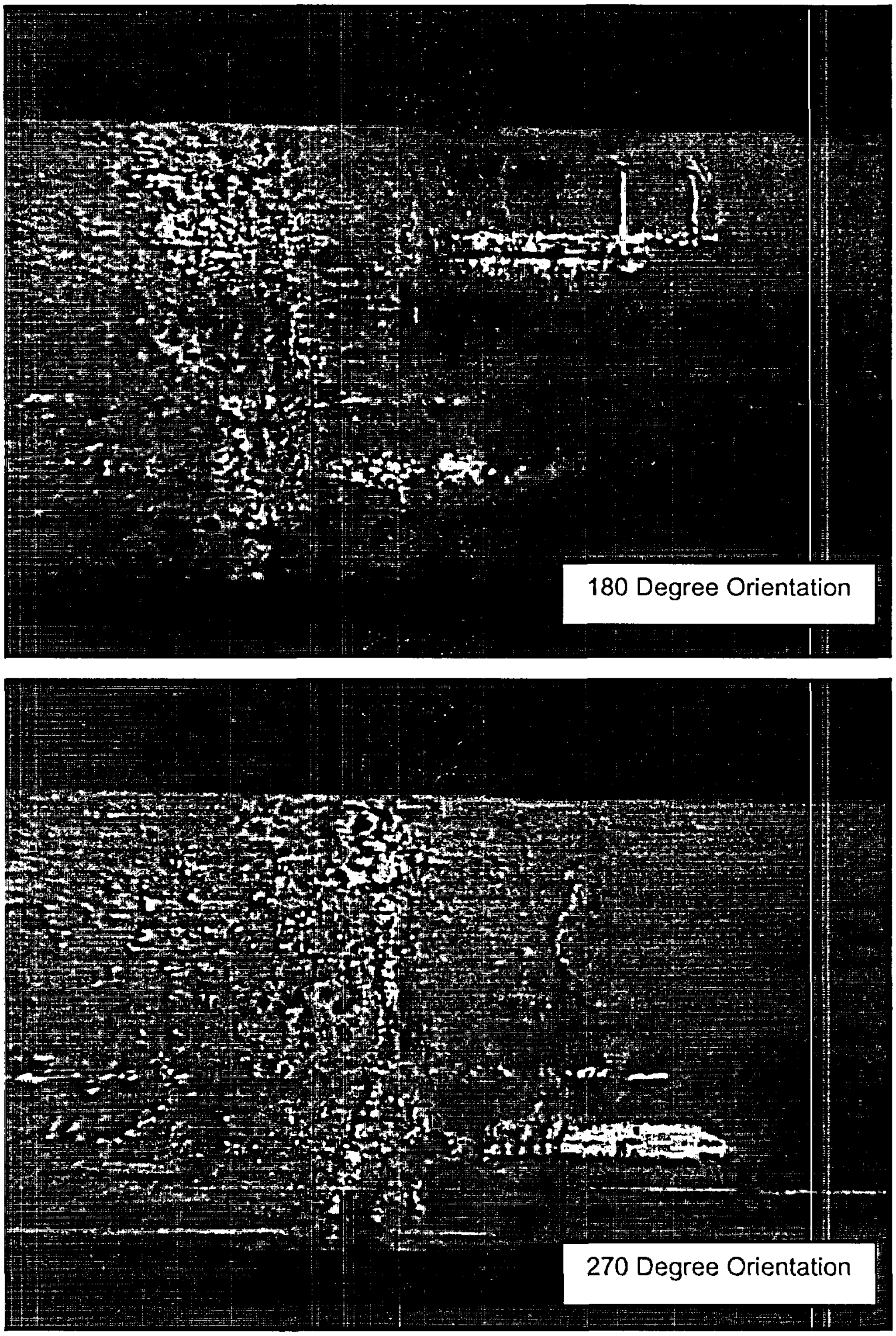
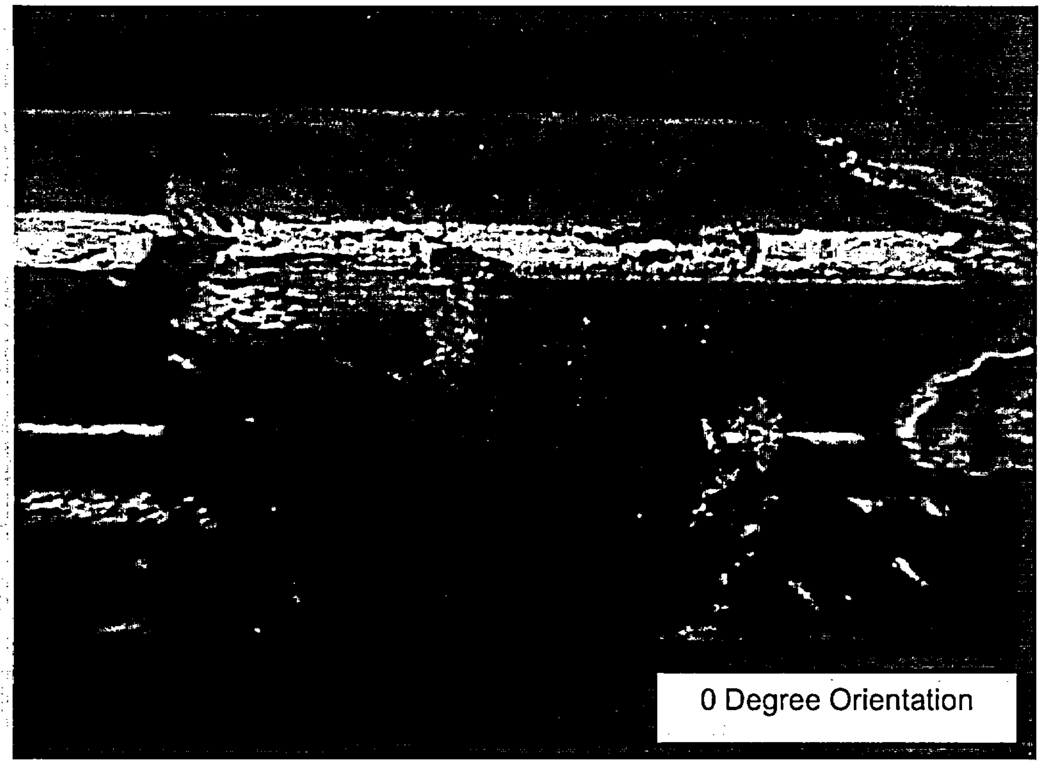


Figure 2-1 (Cont'd)
OD Appearance of R10C39 HL, Piece 2 at Top of Tubesheet



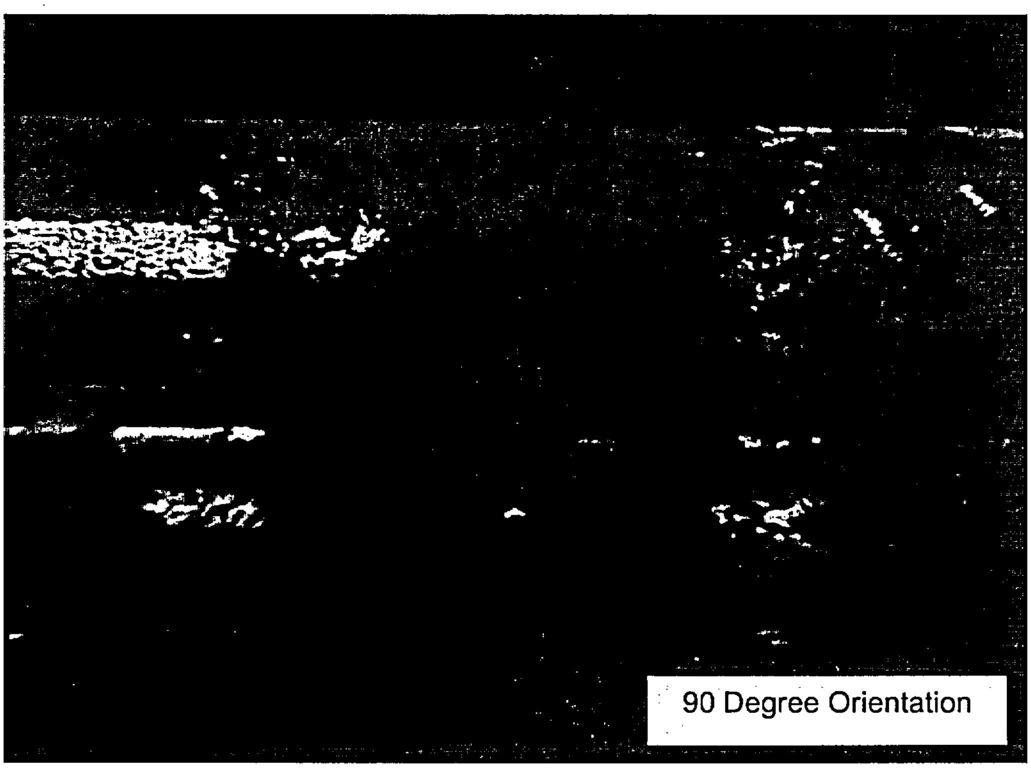
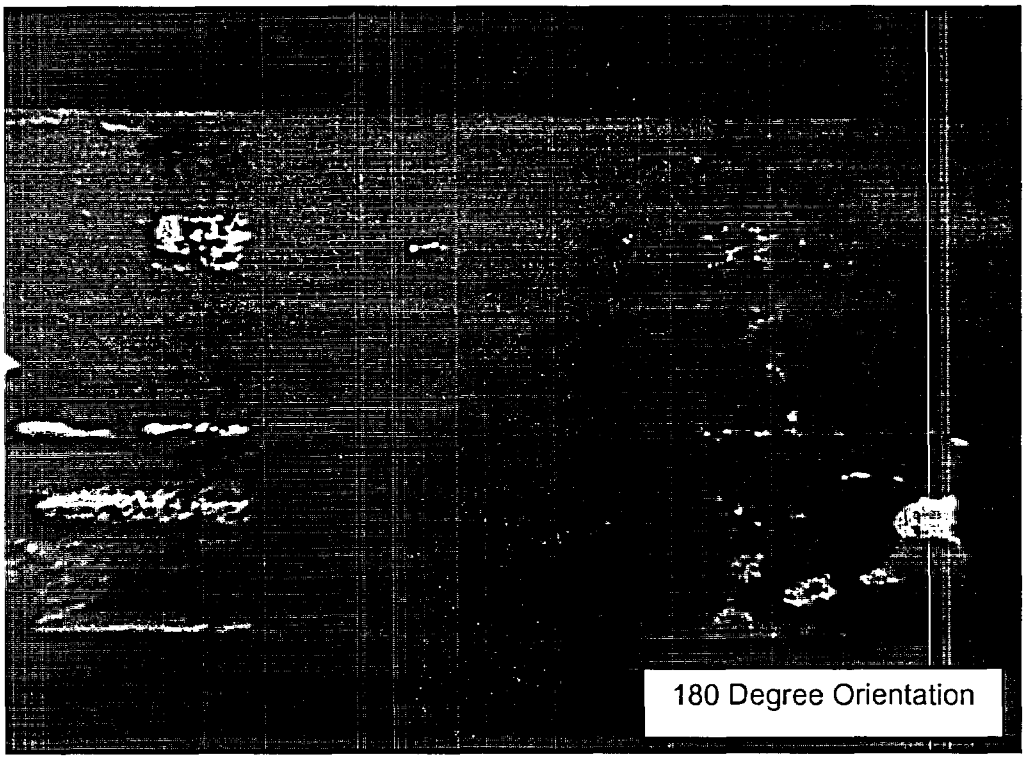


Figure 2-2
OD Appearance of R10C39 HL, Piece 2 at H01 (Flow Distribution Baffle)



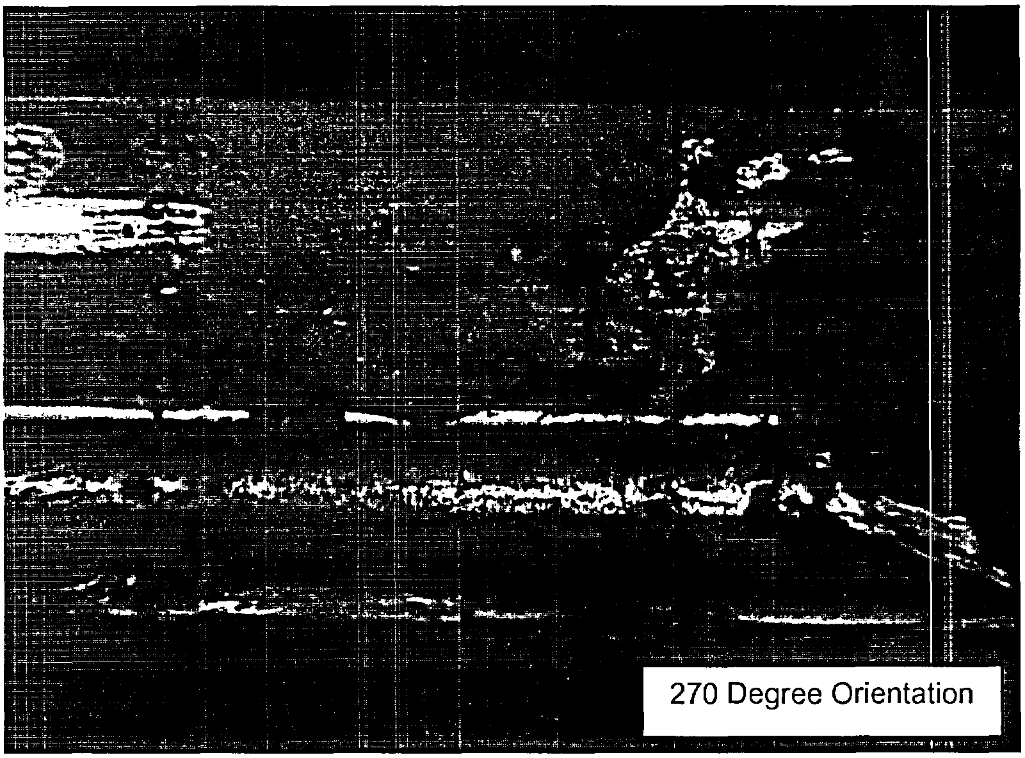
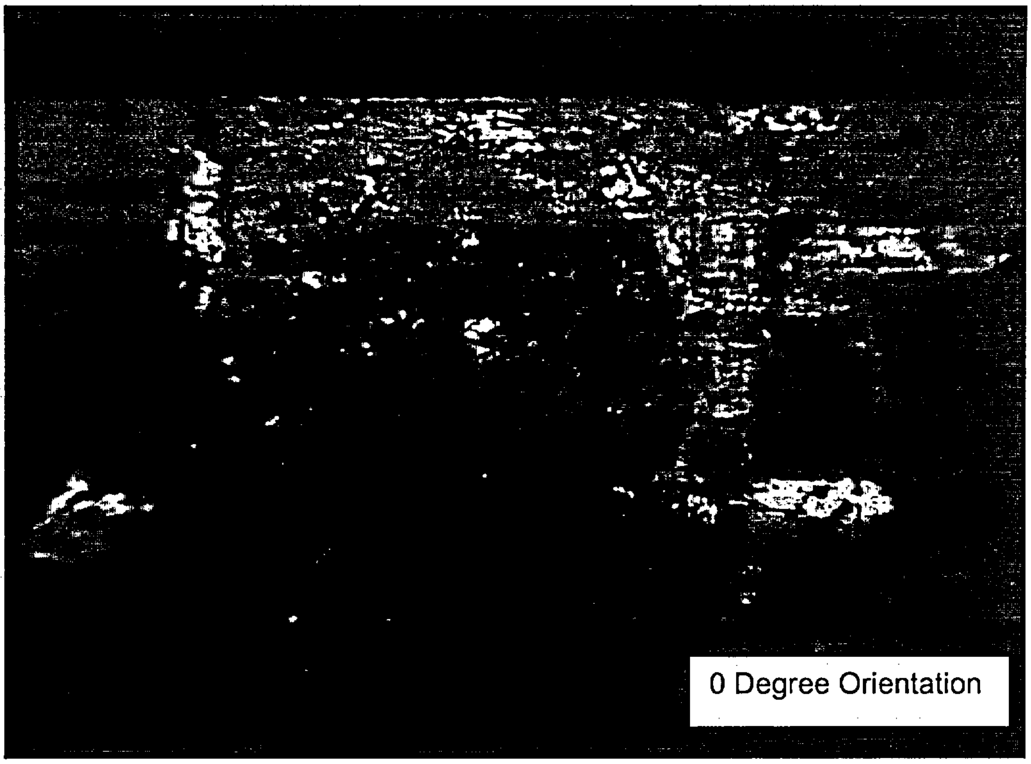


Figure 2-2 (Cont'd)
OD Appearance of R10C39 HL, Piece 2 at H01 (Flow Distribution Baffle)



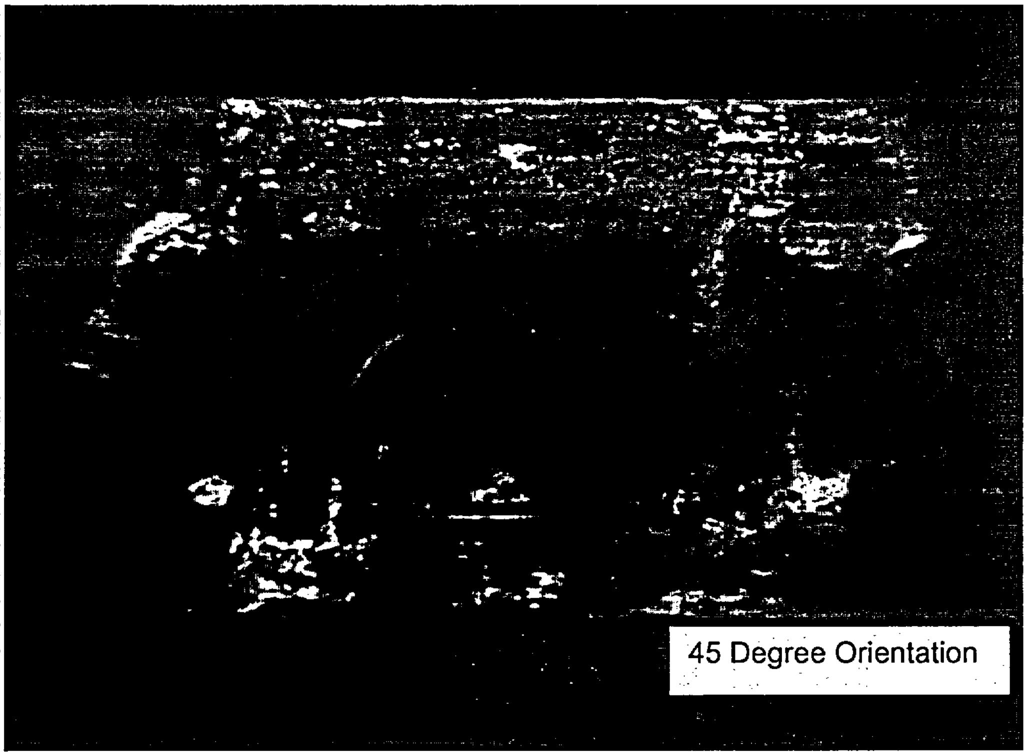
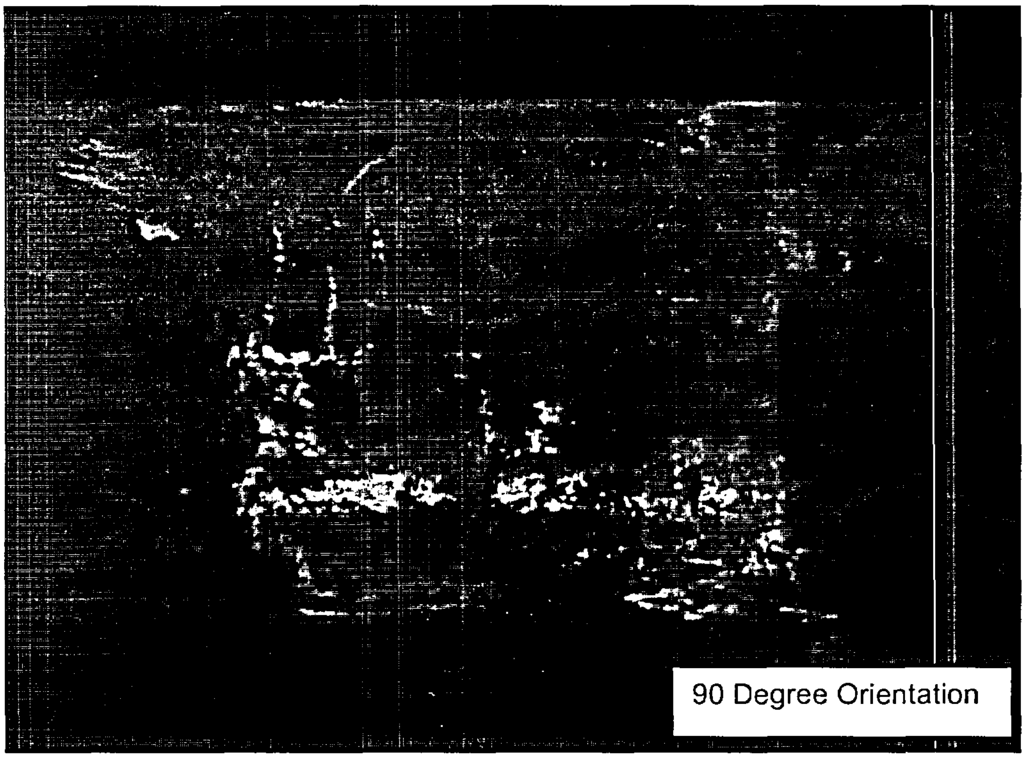


Figure 2-3
OD Appearance of R10C39 HL, Piece 3 at H02 Tube Support Plate



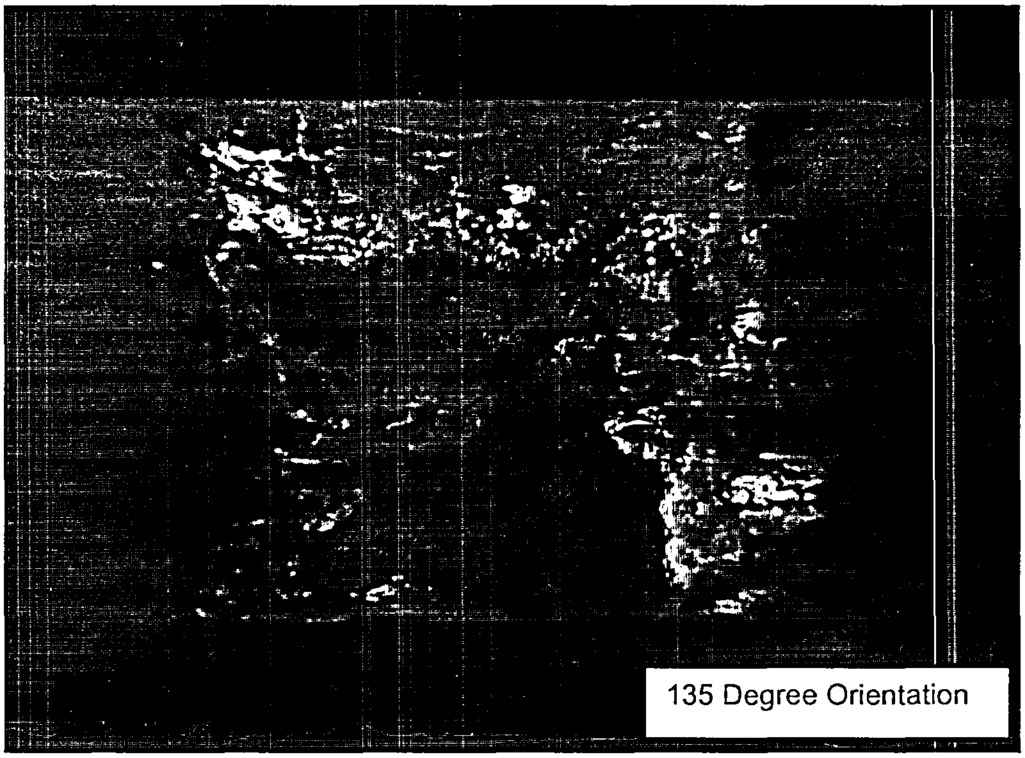
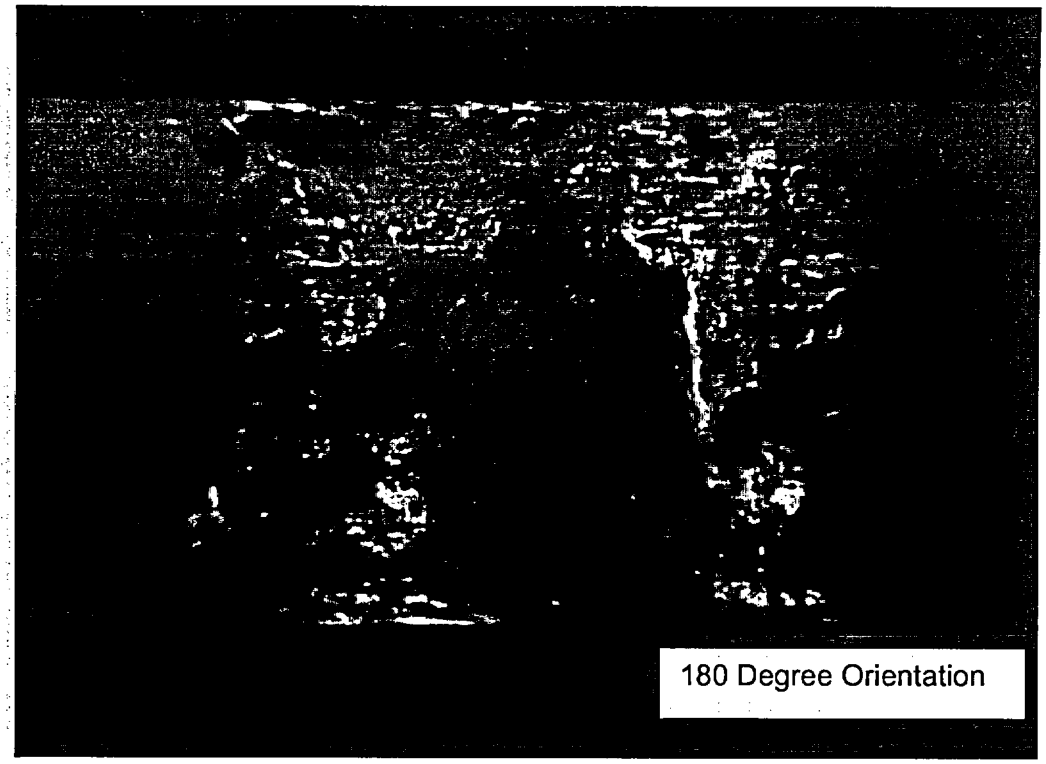


Figure 2-3 (Cont'd)
OD Appearance of R10C39 HL, Piece 3 at H02 Tube Support Plate



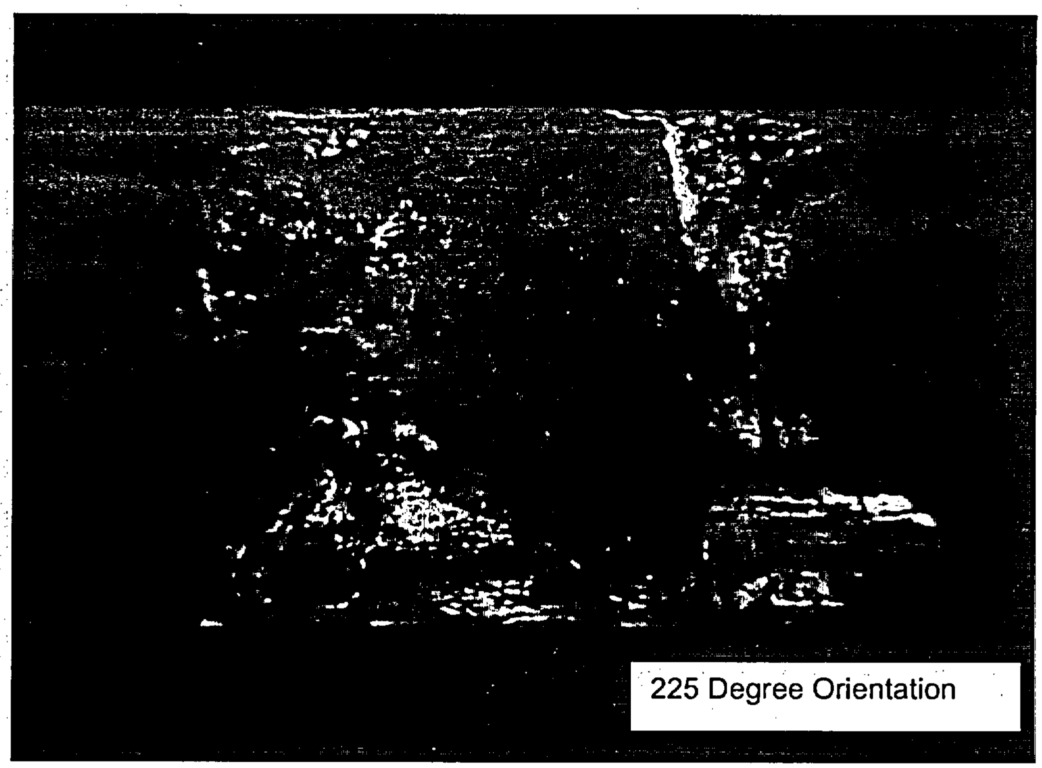
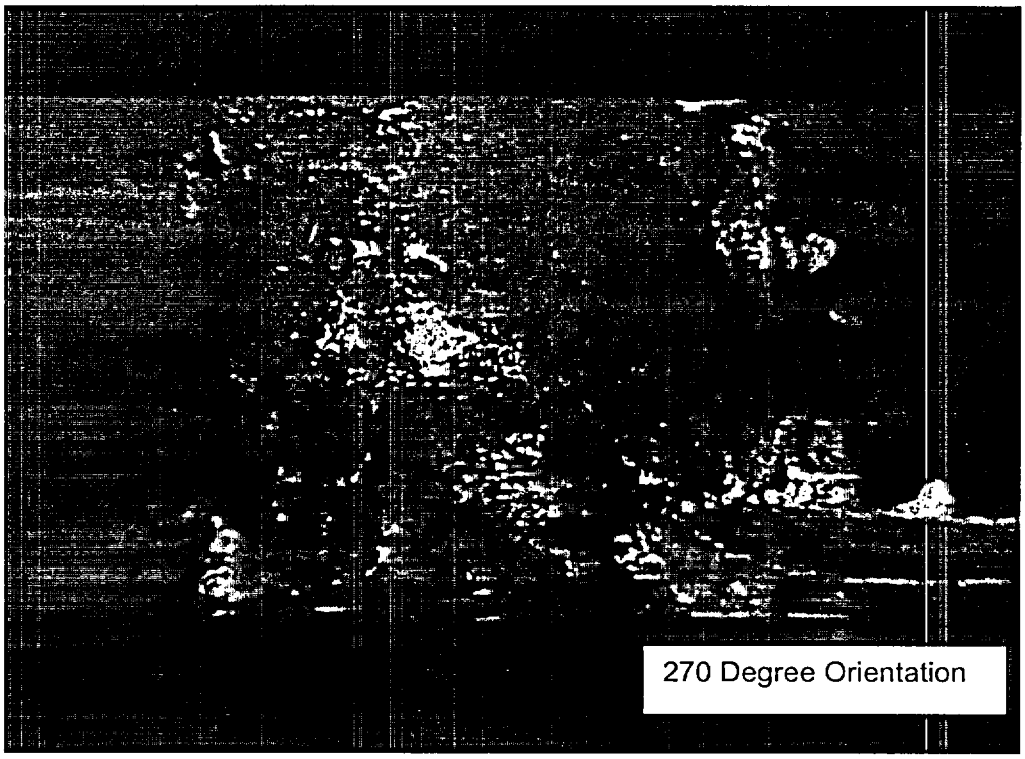


Figure 2-3 (Cont'd)
OD Appearance of R10C39 HL, Piece 3 at H02 Tube Support Plate



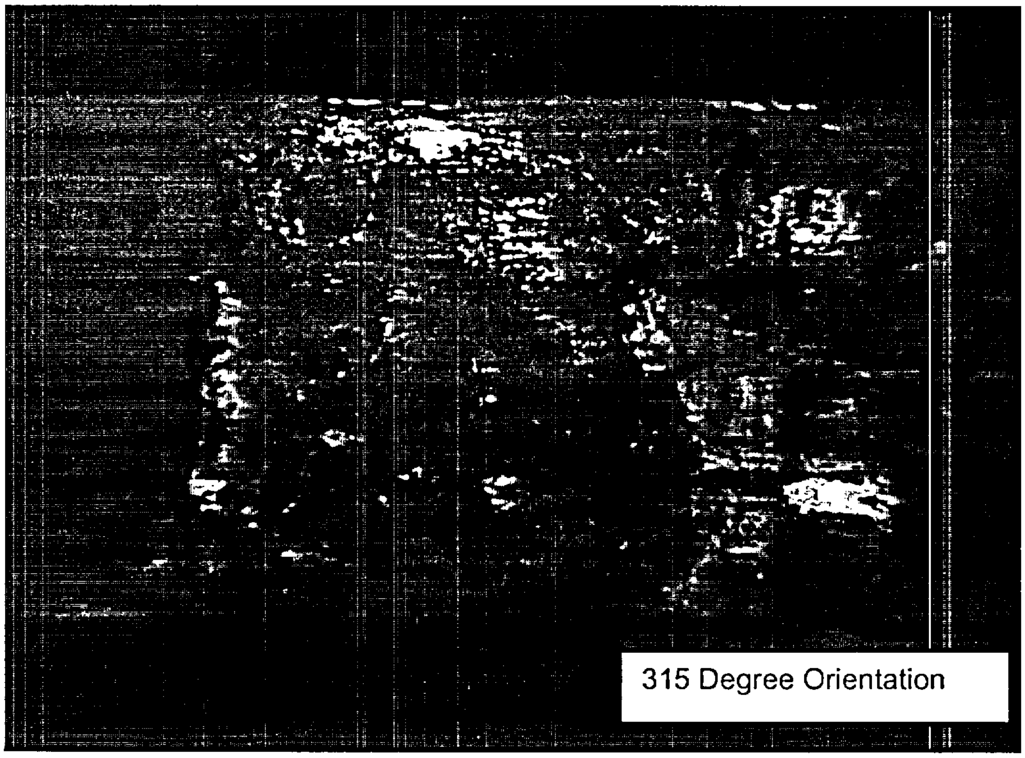
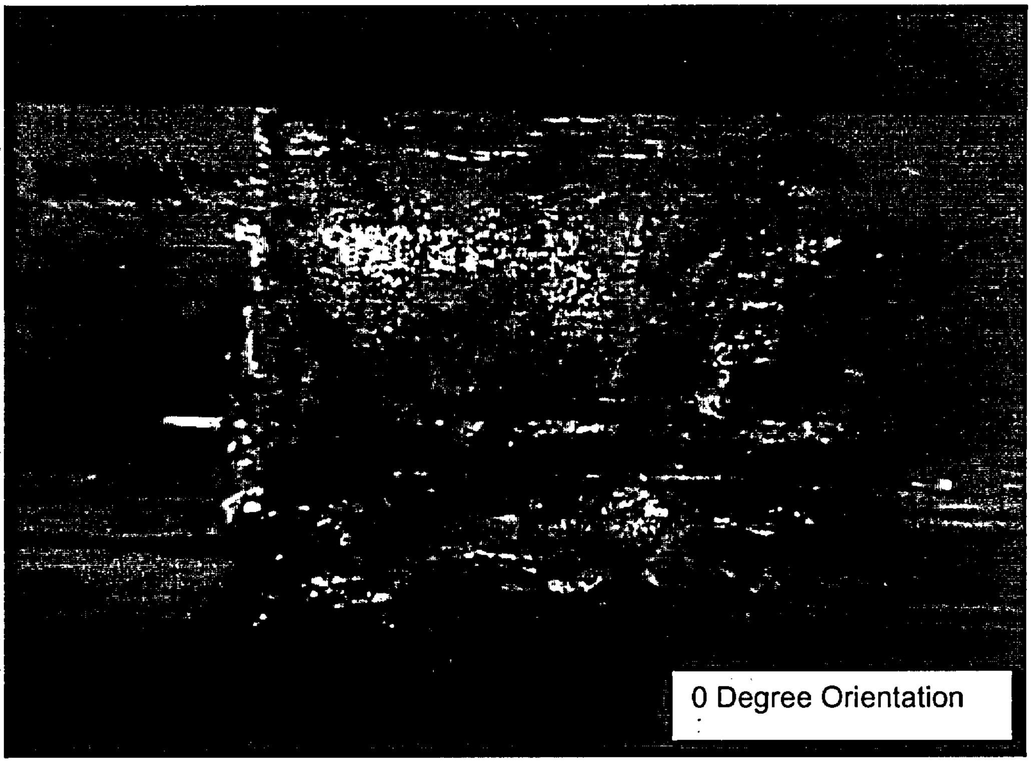


Figure 2-3 (Cont'd)
OD Appearance of R10C39 HL, Piece 3 at H02 Tube Support Plate



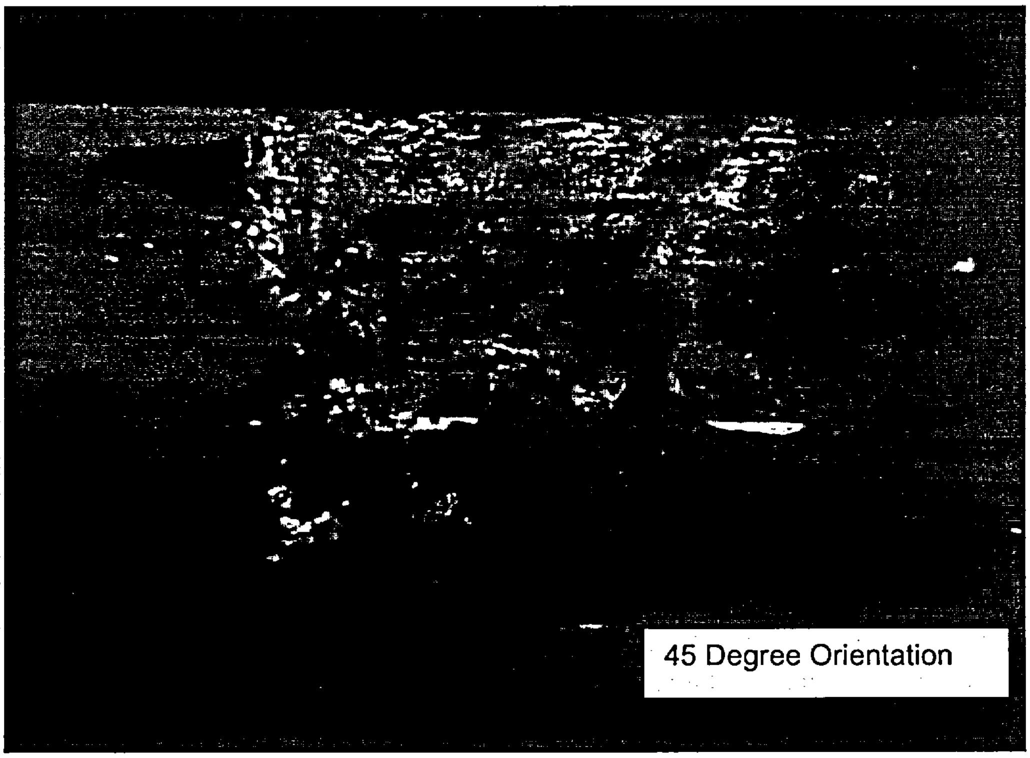
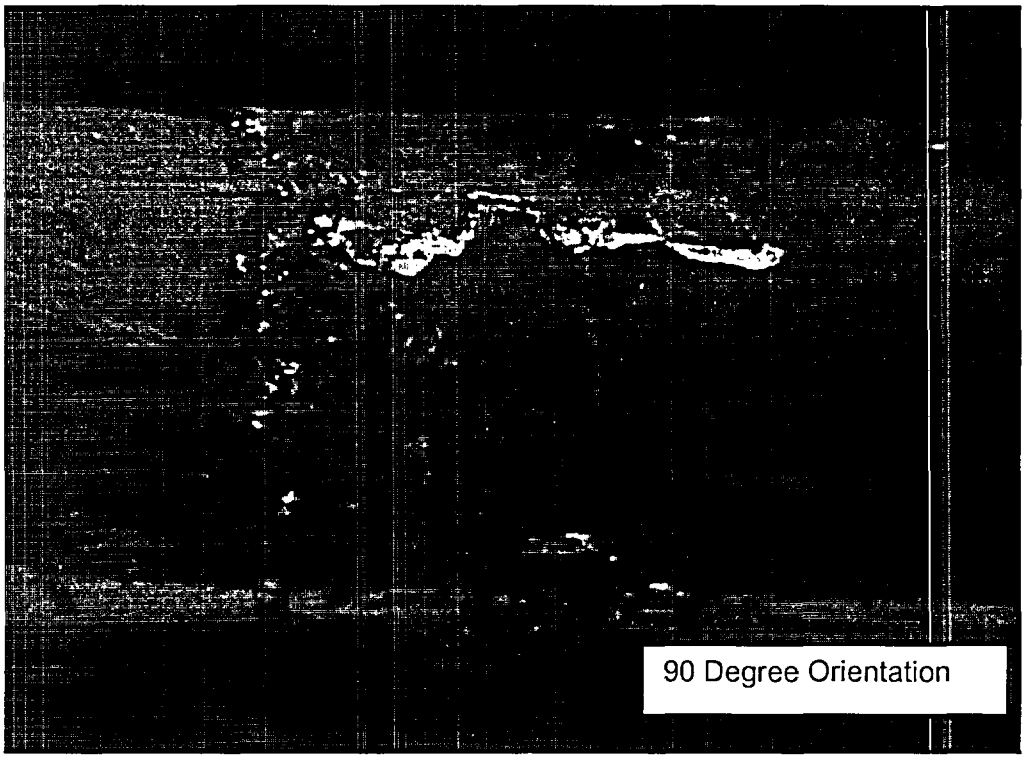


Figure 2-4
OD Appearance of R10C39 HL, Piece 4 at H03 Tube Support Plate



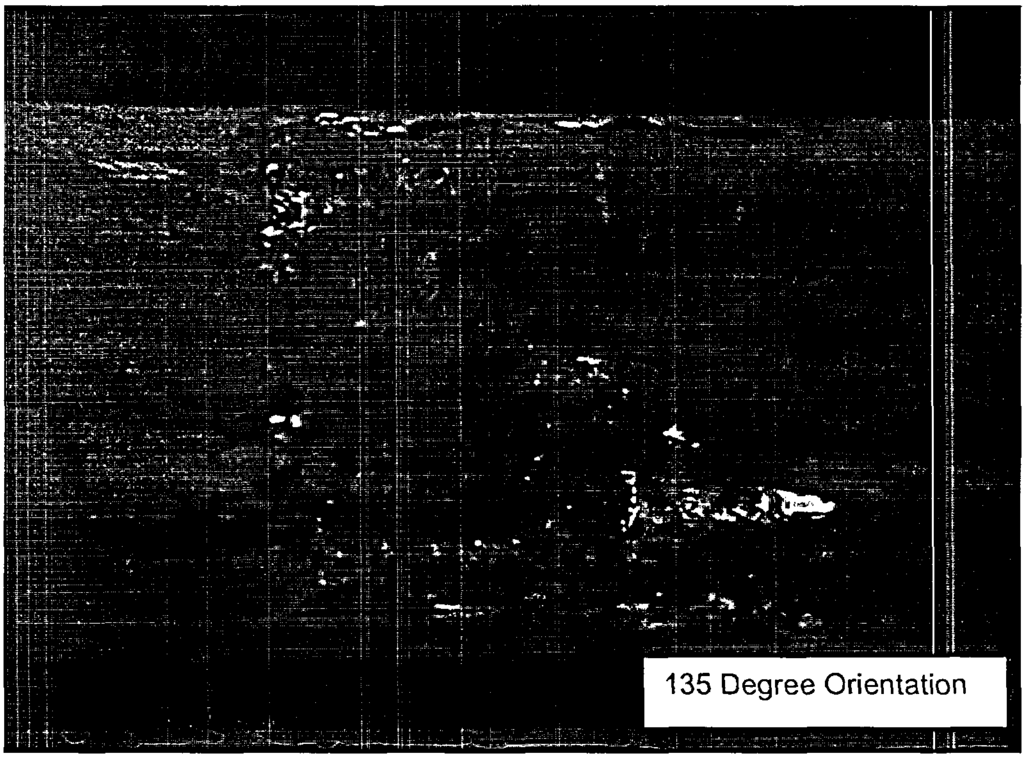
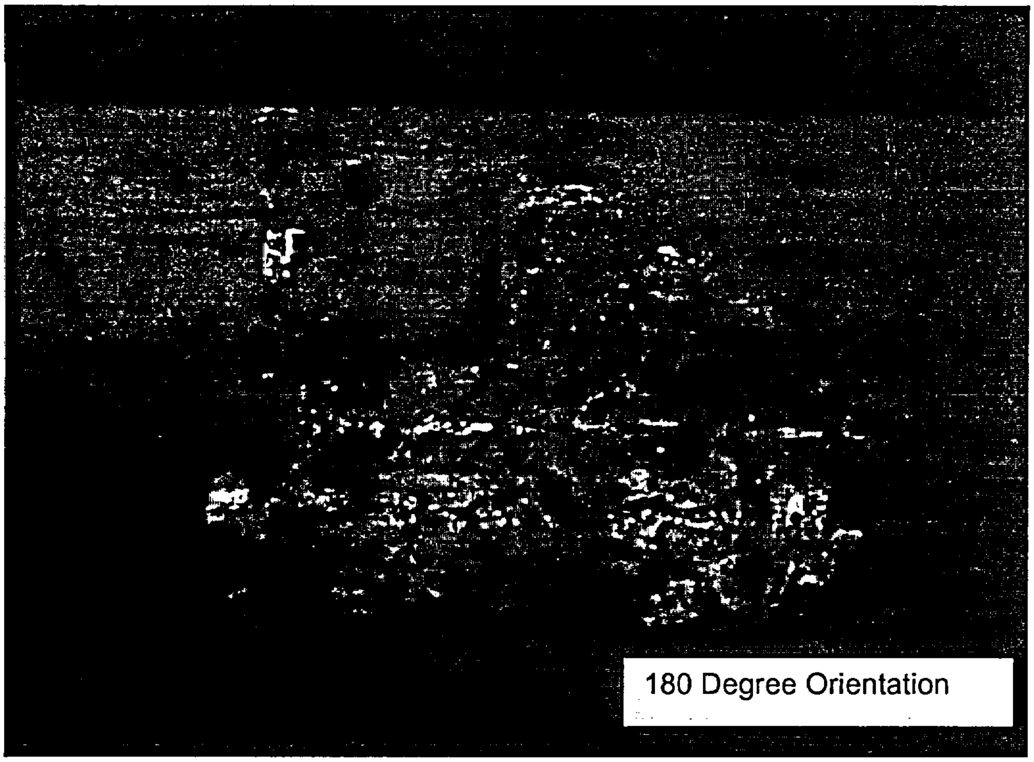


Figure 2-4 (Cont'd)
OD Appearance of R10C39 HL, Piece 4 at H03 Tube Support Plate



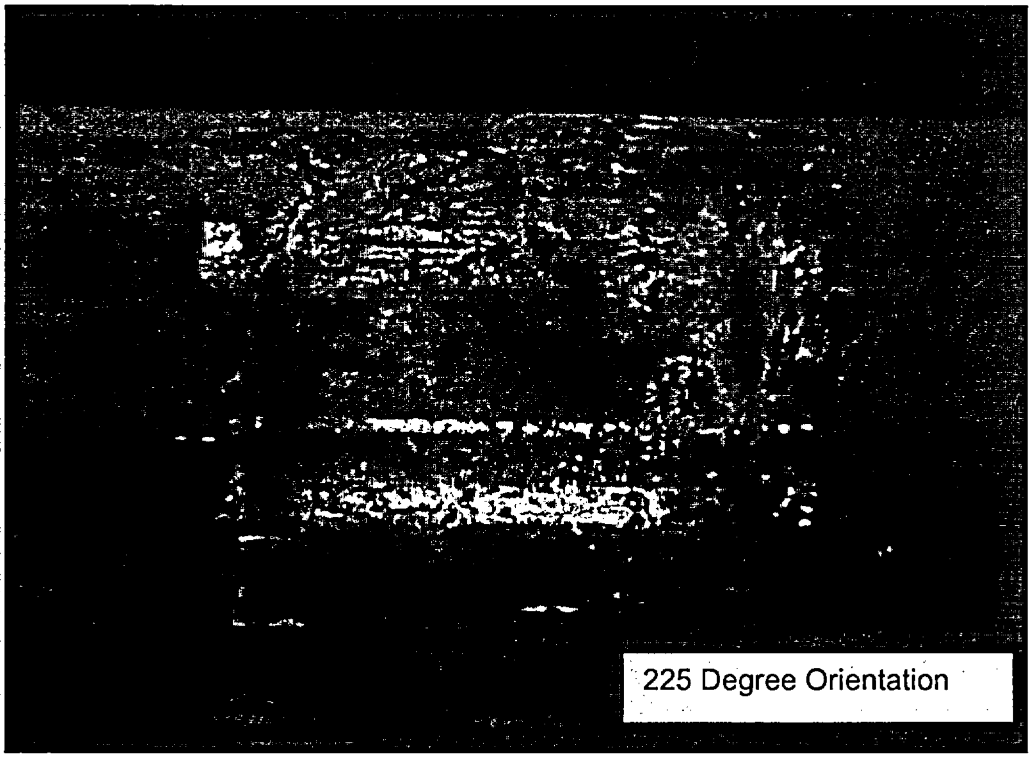
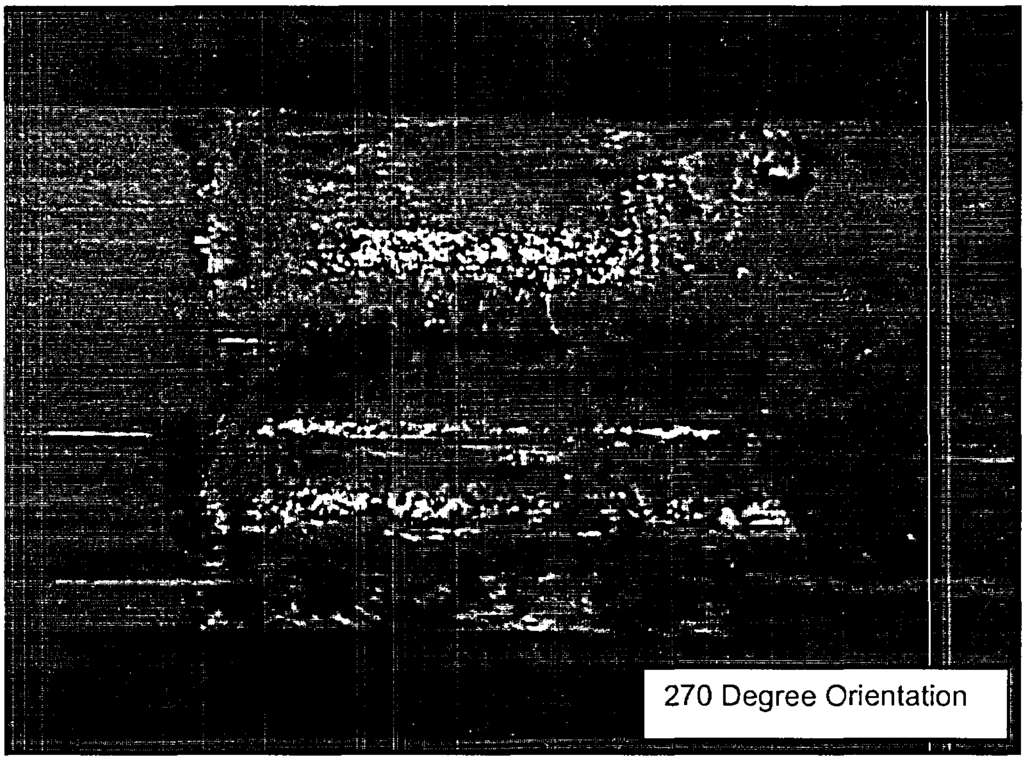


Figure 2-4 (Cont'd)
OD Appearance of R10C39 HL, Piece 4 at H03 Tube Support Plate



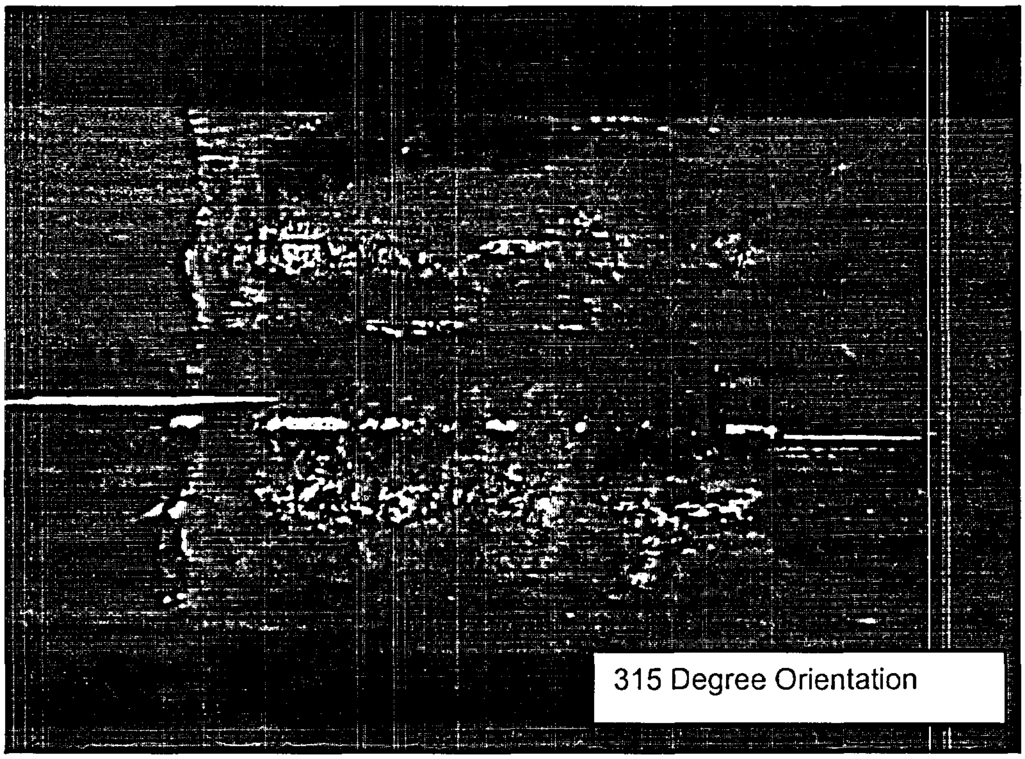


Figure 2-4 (Cont'd)
OD Appearance of R10C39 HL, Piece 4 at H03 Tube Support Plate

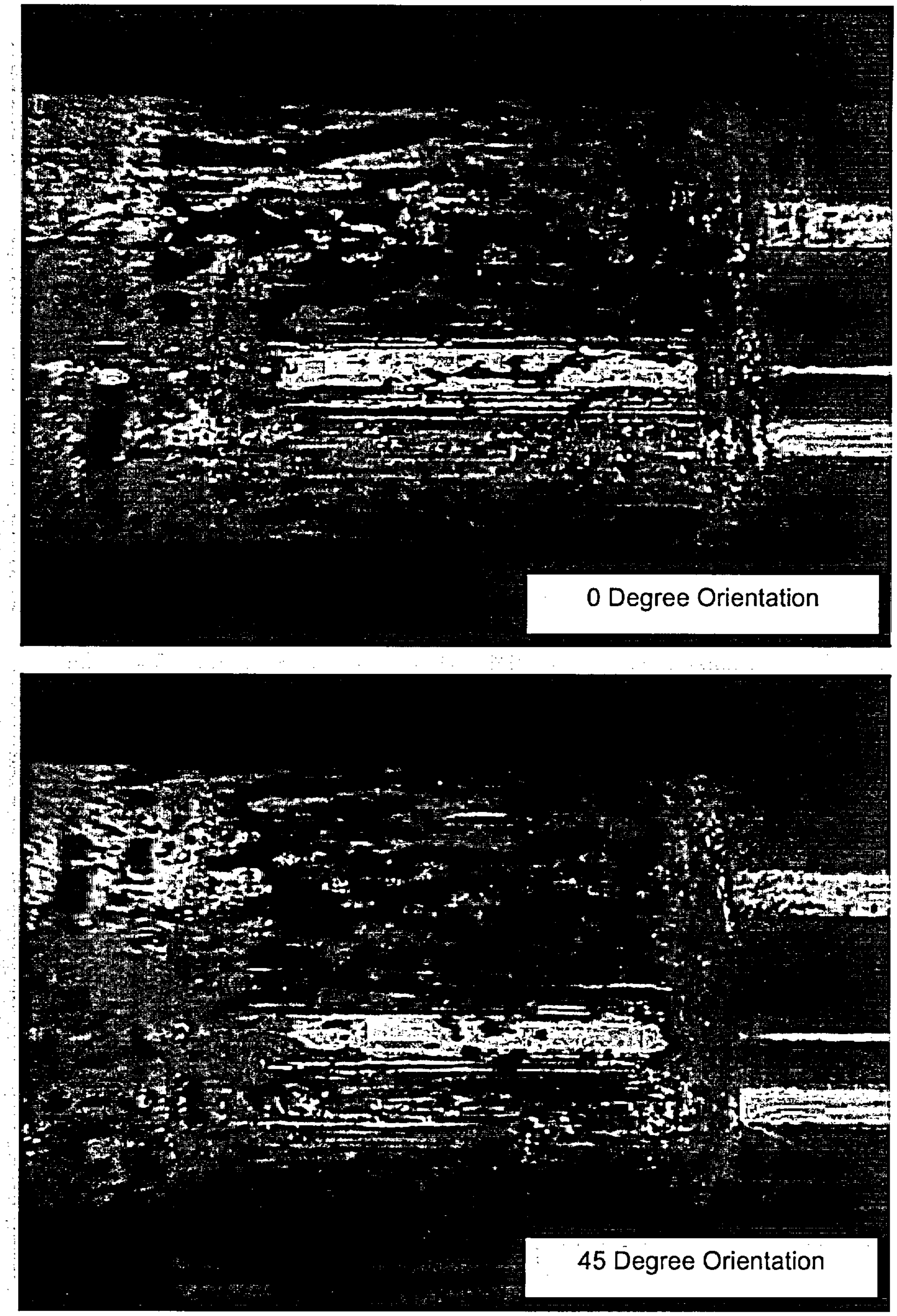


Figure 2-5
OD Appearance of R11C41 HL, Piece 2 at Top of Tubesheet

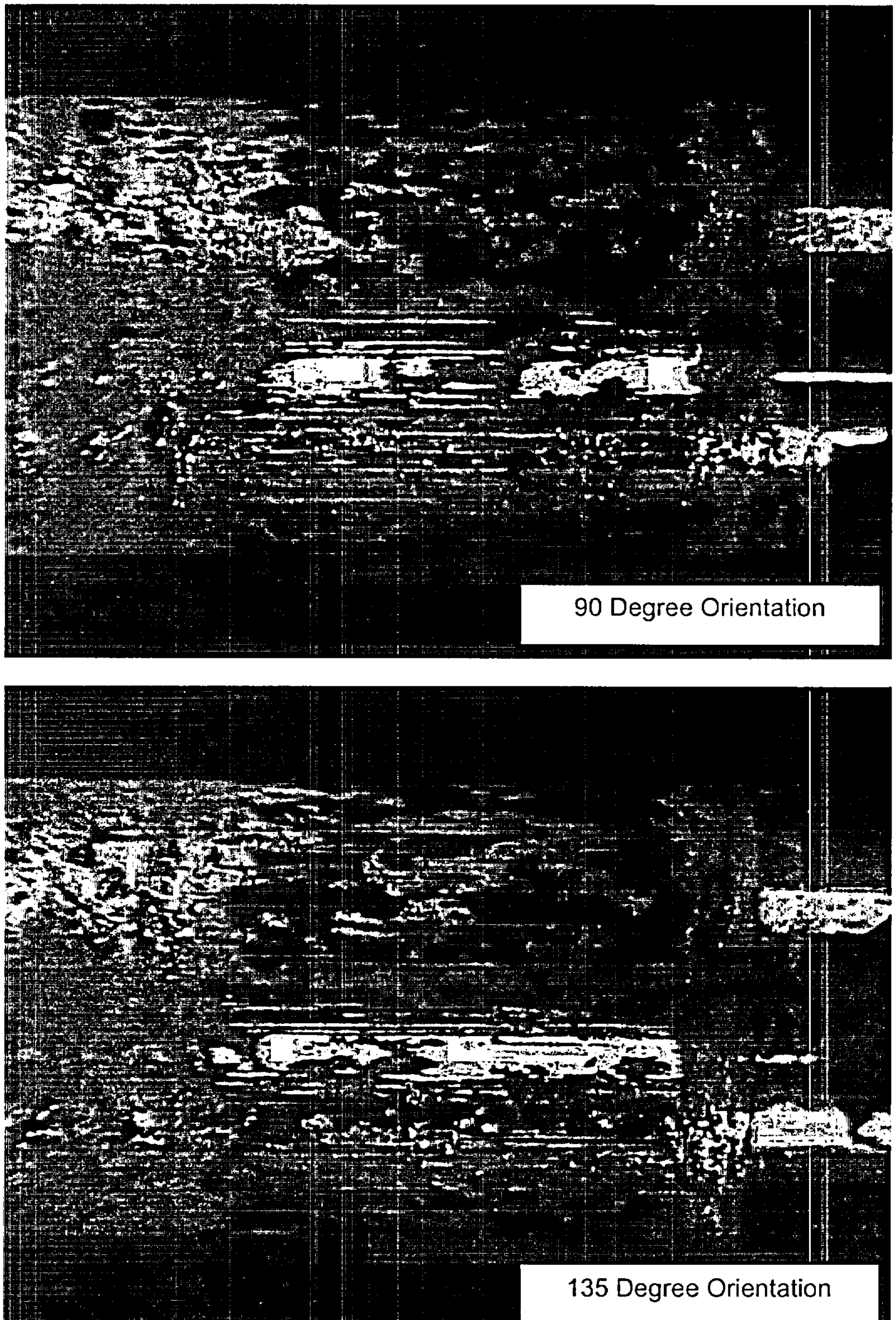
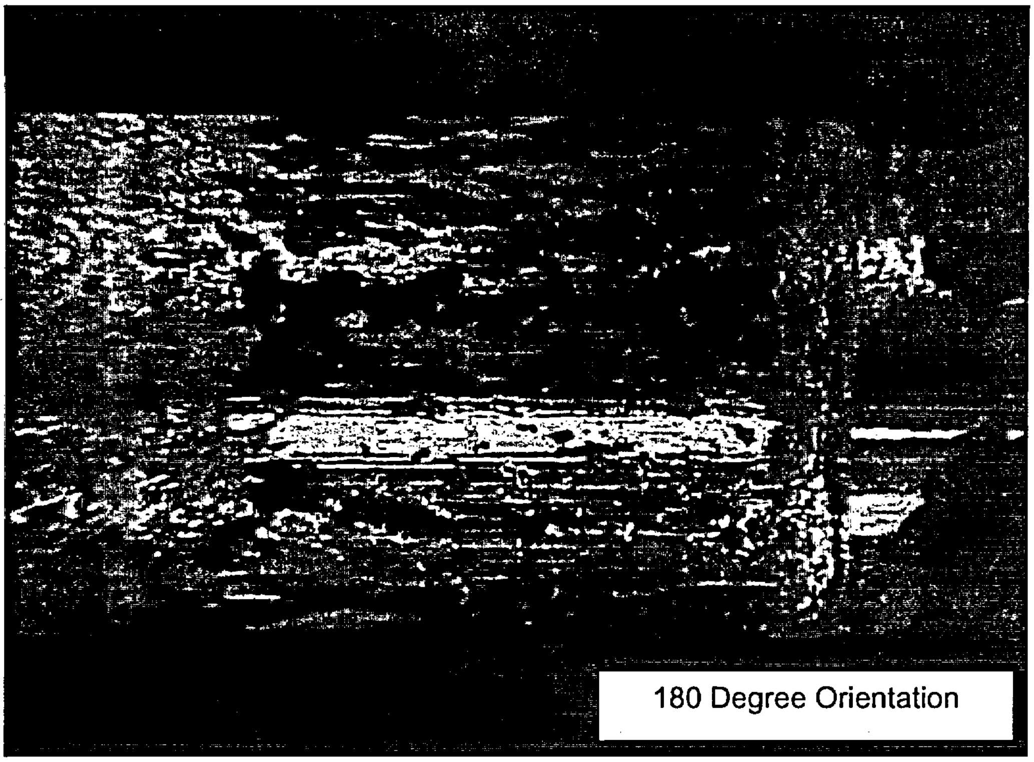


Figure 2-5 (Cont'd)
OD Appearance of R11C41 HL, Piece 2 at Top of Tubesheet



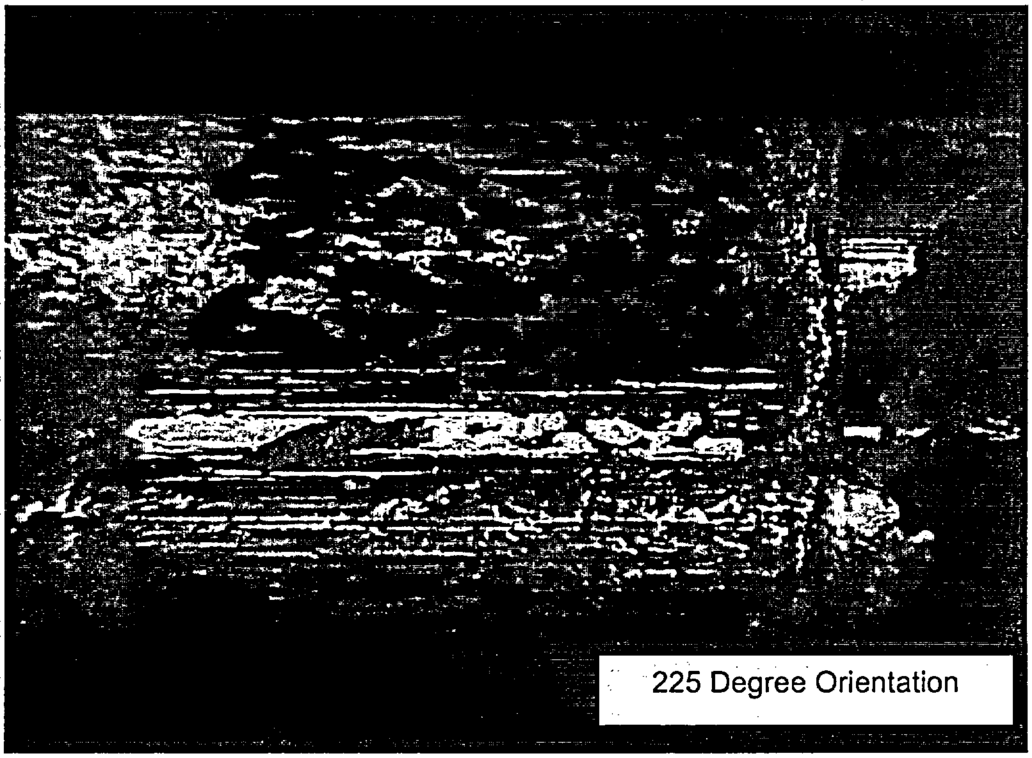
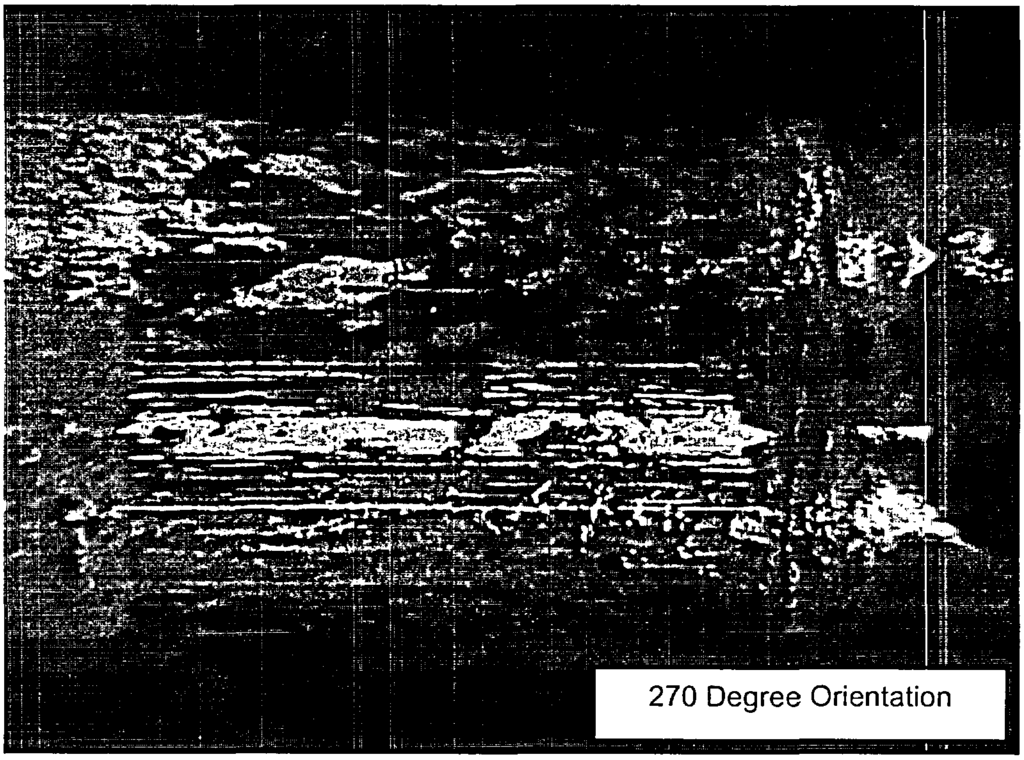


Figure 2-5 (Cont'd)
OD Appearance of R11C41 HL, Piece 2 at Top of Tubesheet



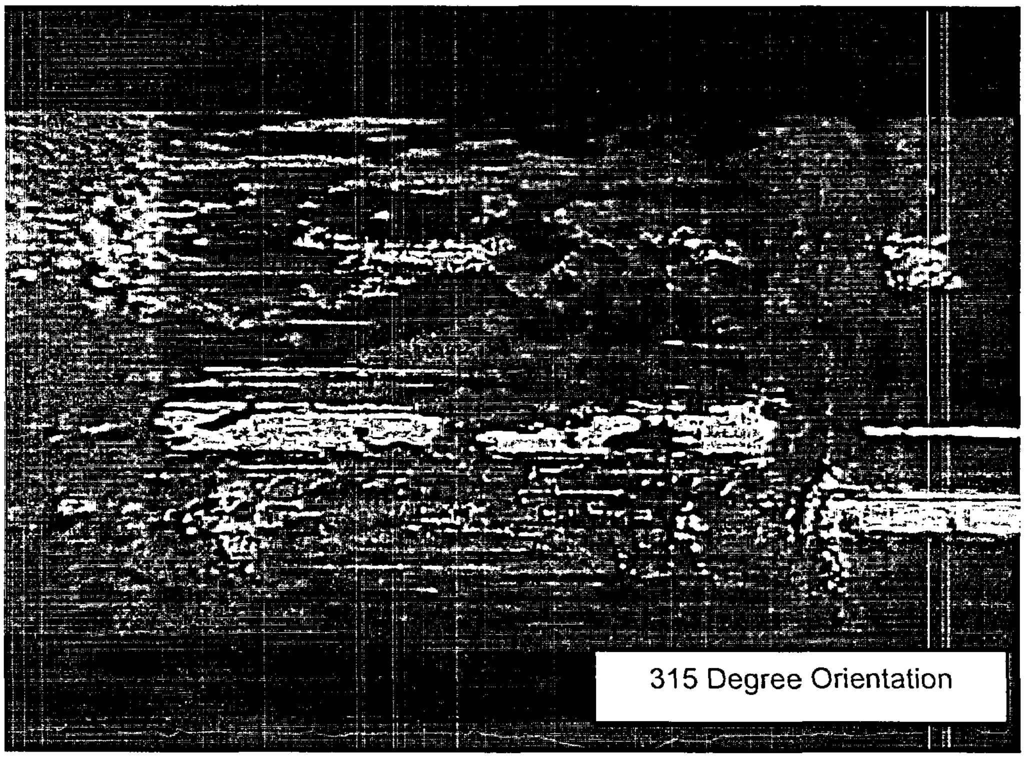


Figure 2-5 (Cont'd)
OD Appearance of R11C41 HL, Piece 2 at Top of Tubesheet

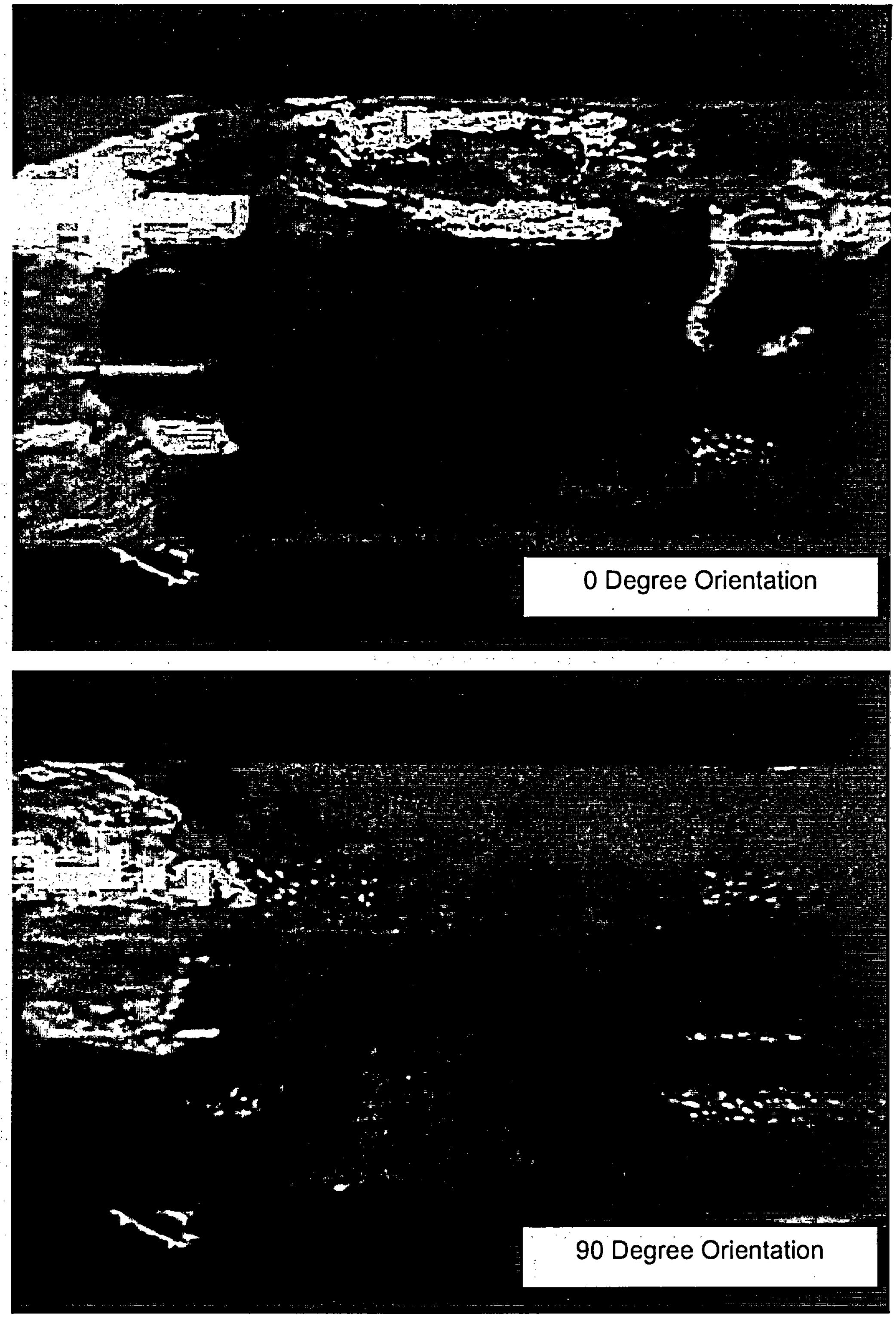
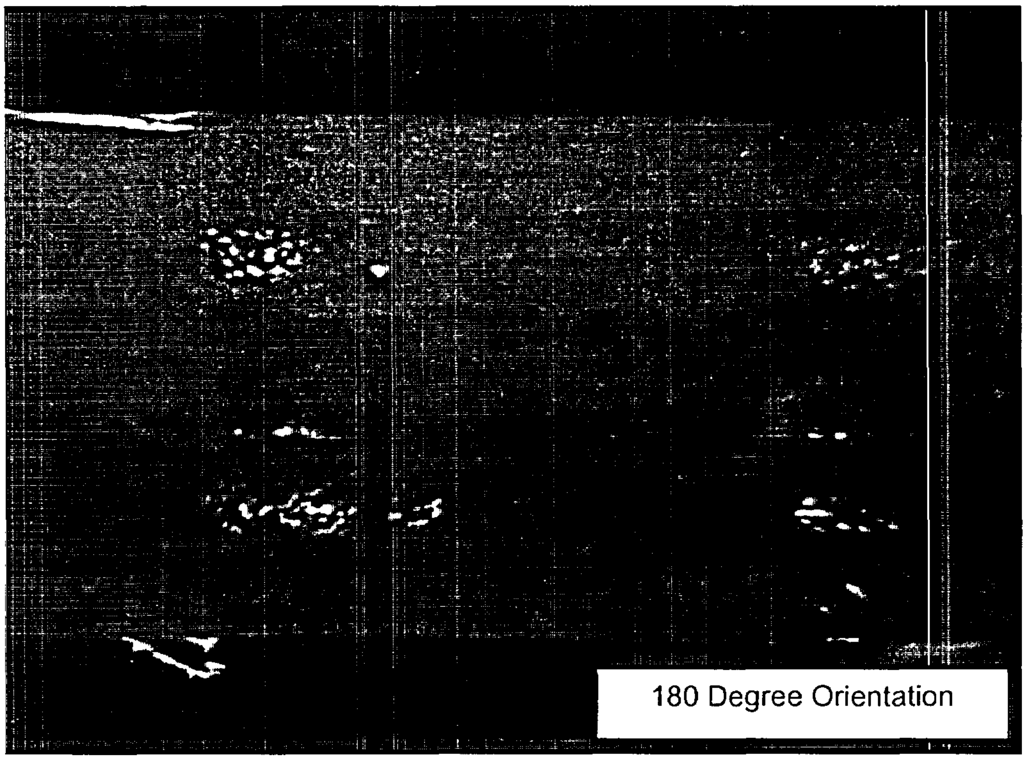


Figure 2-6
OD Appearance of R11C41 HL, Piece 2 at H01 (Flow Distribution Baffle)



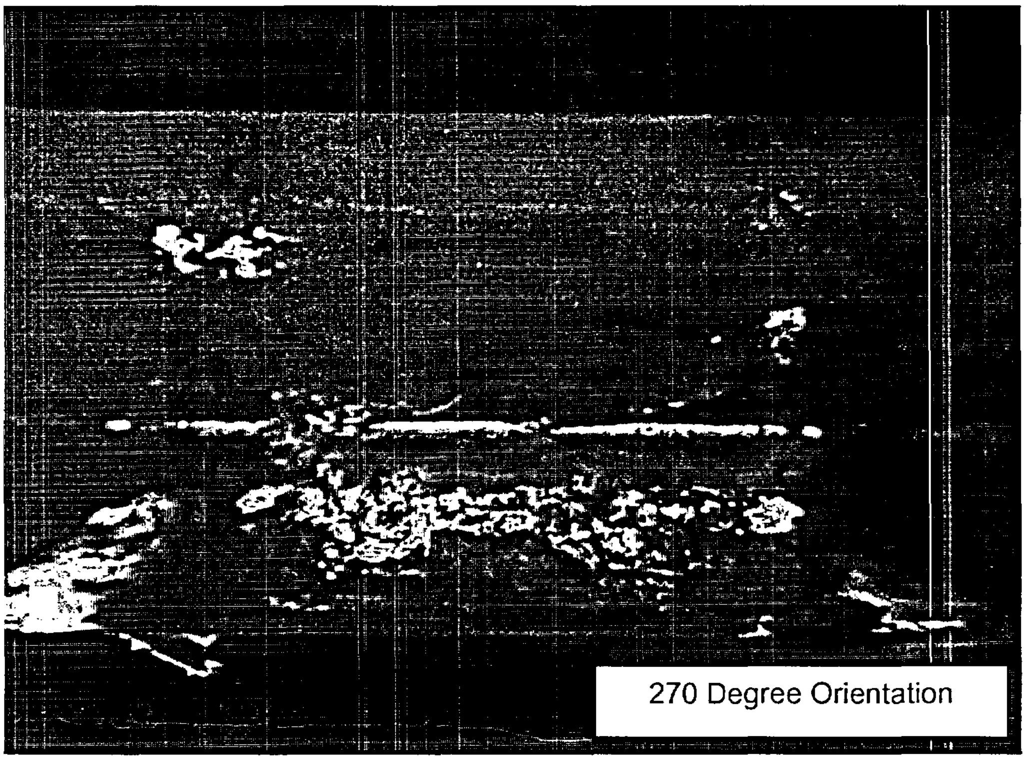
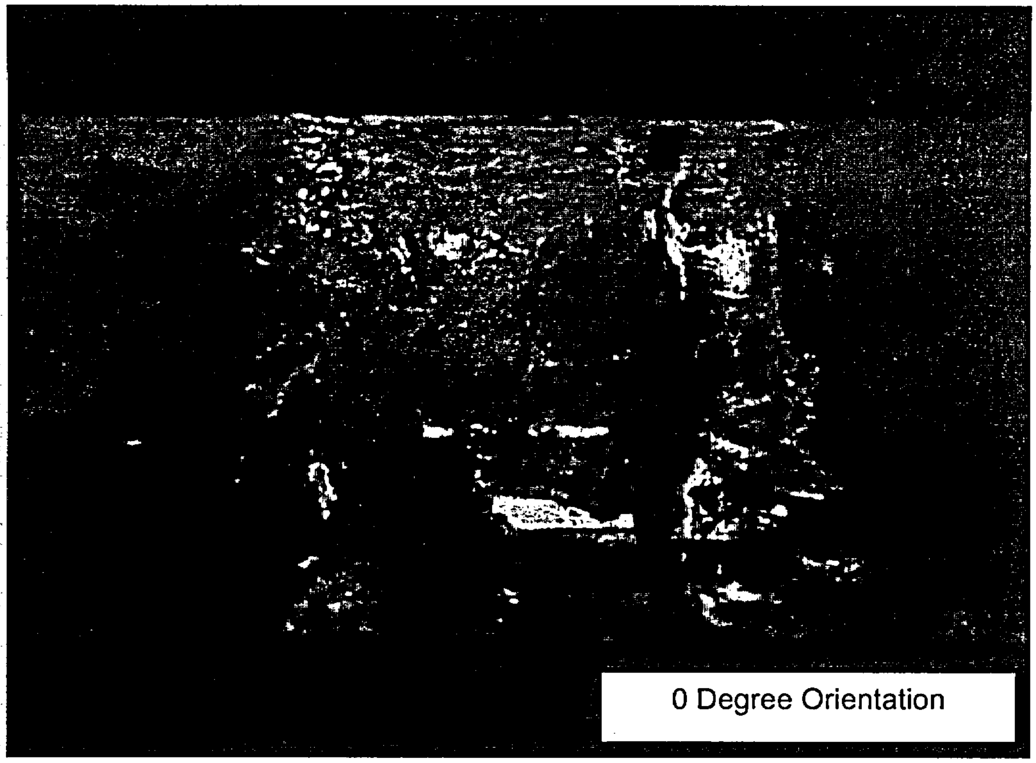


Figure 2-6 (Cont'd)
OD Appearance of R11C41 HL, Piece 2 at H01 (Flow Distribution Baffle)



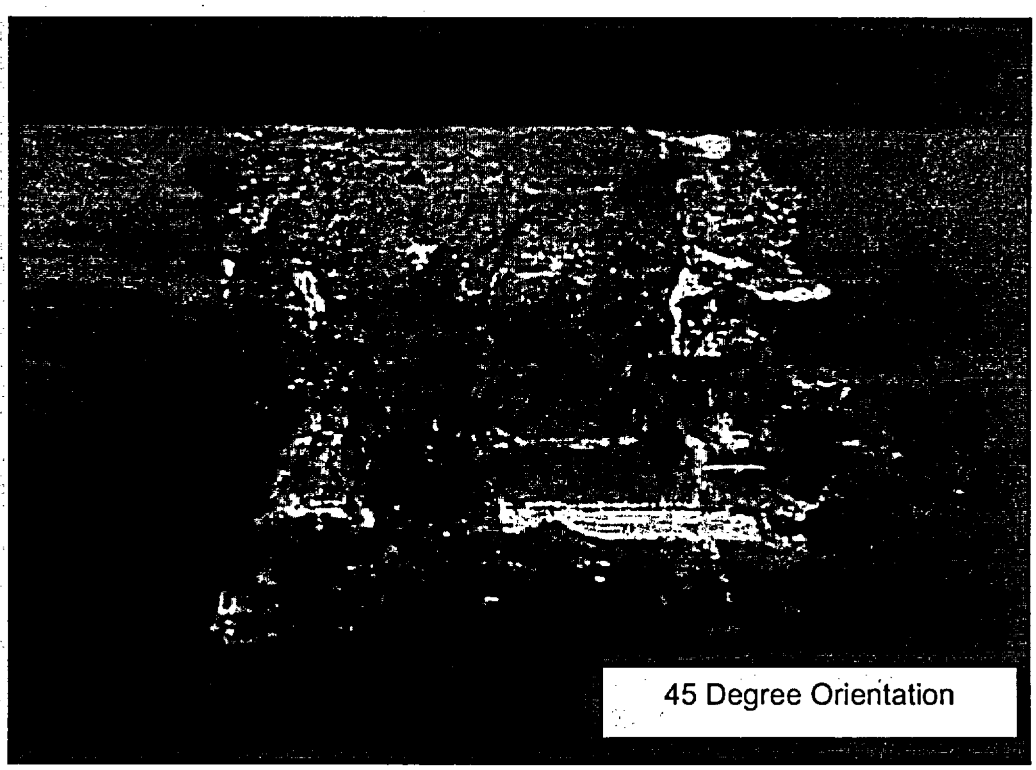
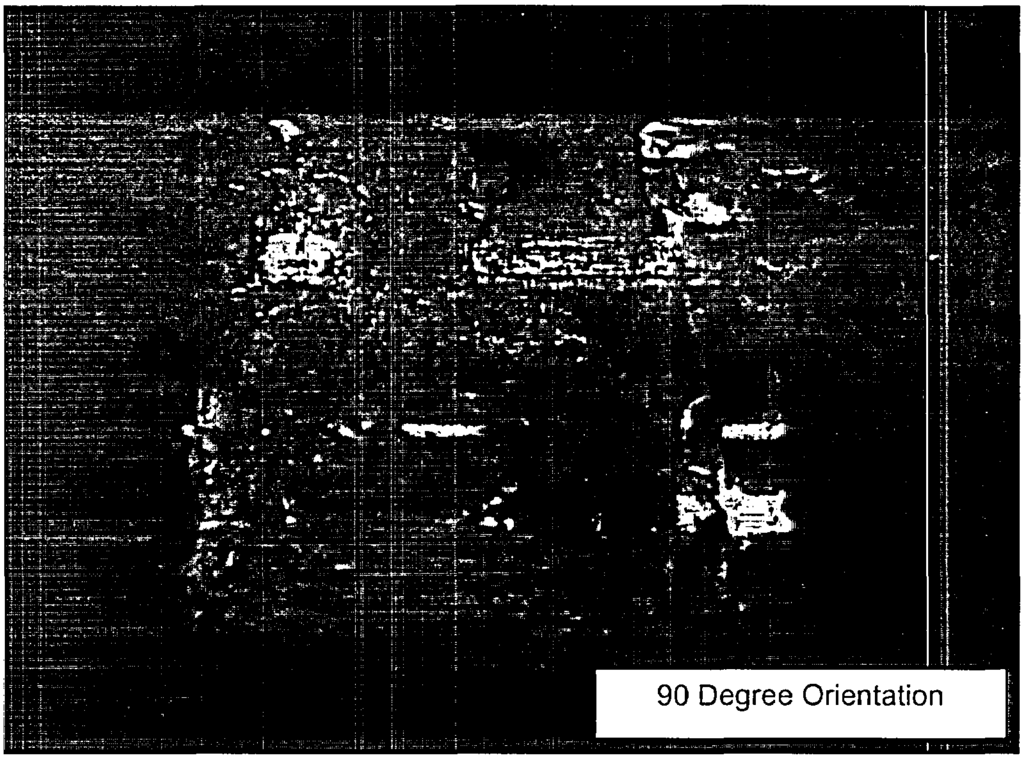


Figure 2-7
OD Appearance of R11C41 HL, Piece 3 at H02 Tube Support Plate



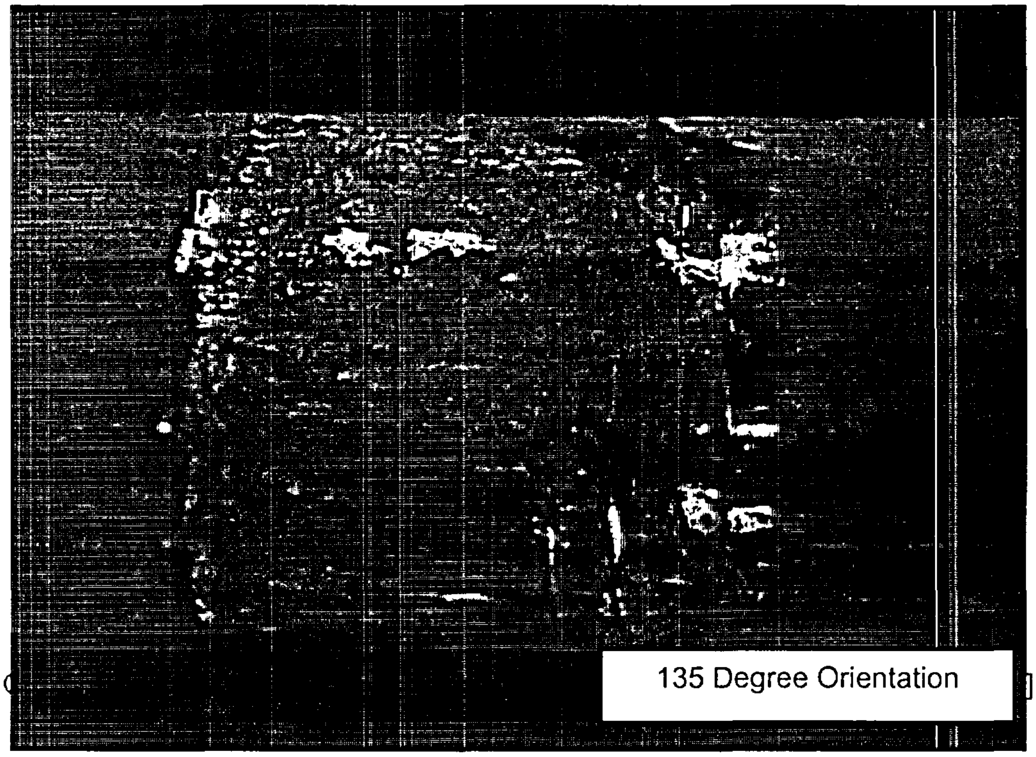
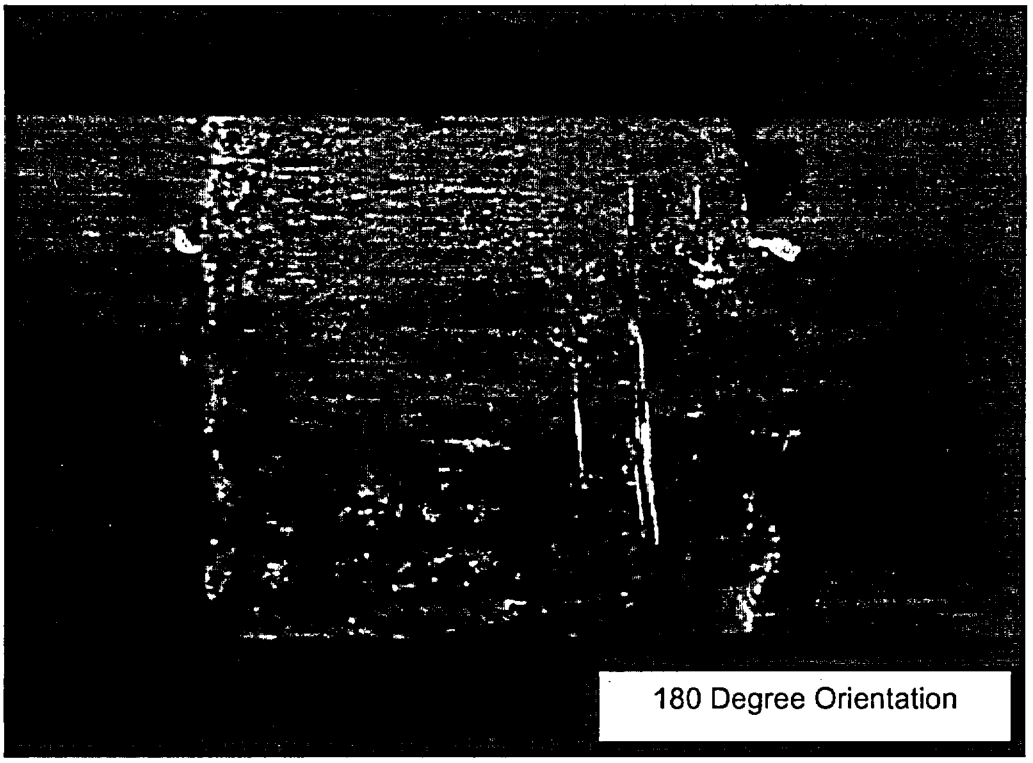


Figure 2-7 (Cont'd)
OD Appearance of R11C41 HL, Piece 3 at H02 Tube Support Plate



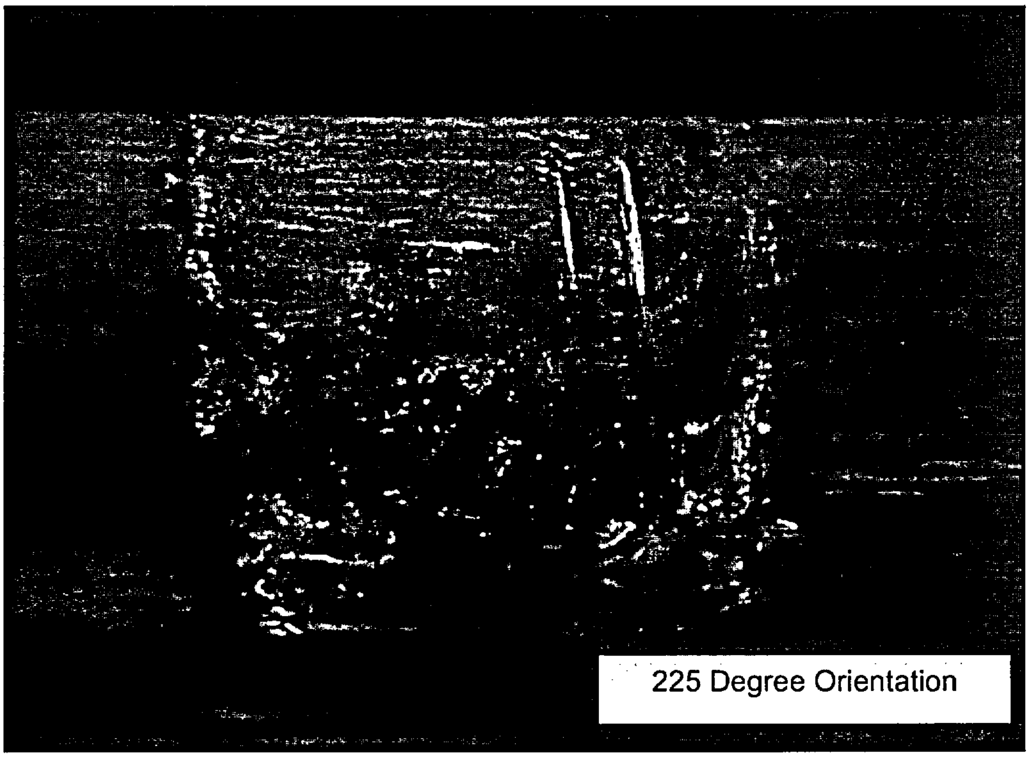
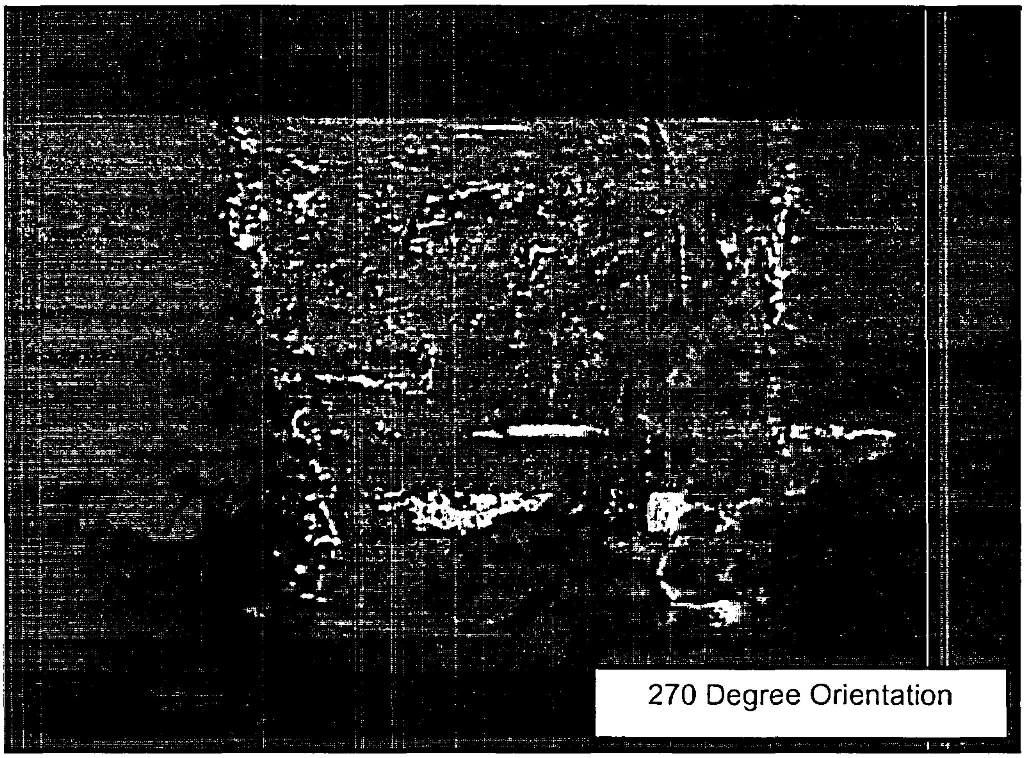


Figure 2-7 (Cont'd)
OD Appearance of R11C41 HL, Piece 3 at H02 Tube Support Plate



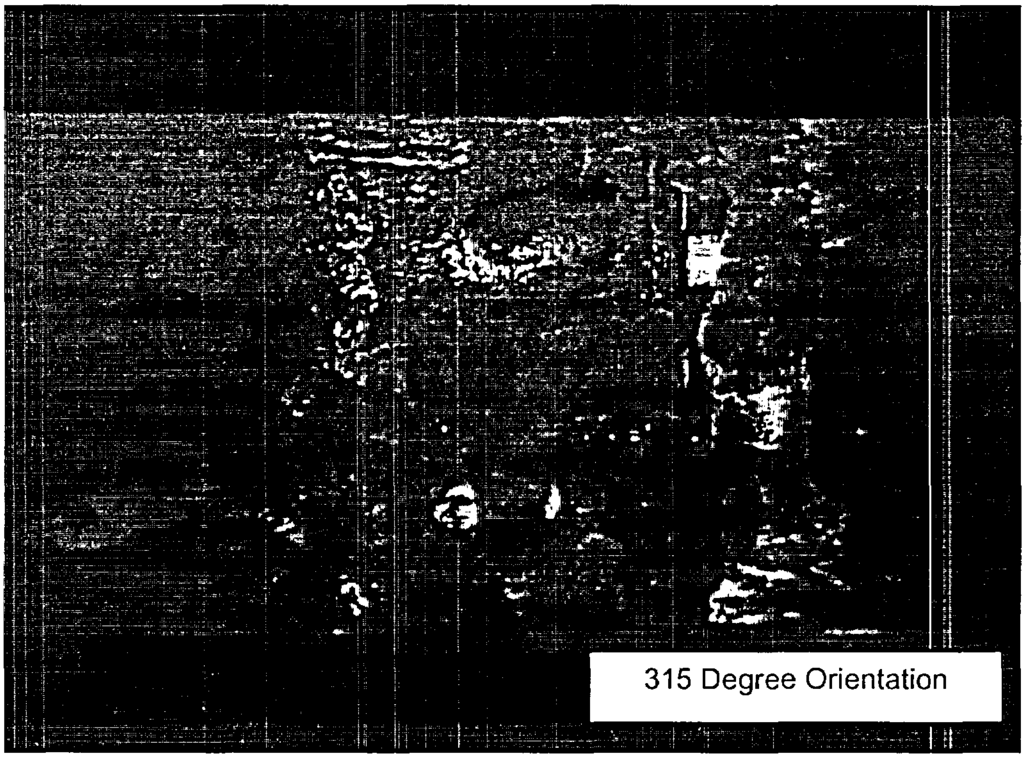


Figure 2-7 (Cont'd)
OD Appearance of R11C41 HL, Piece 3 at H02 Tube Support Plate

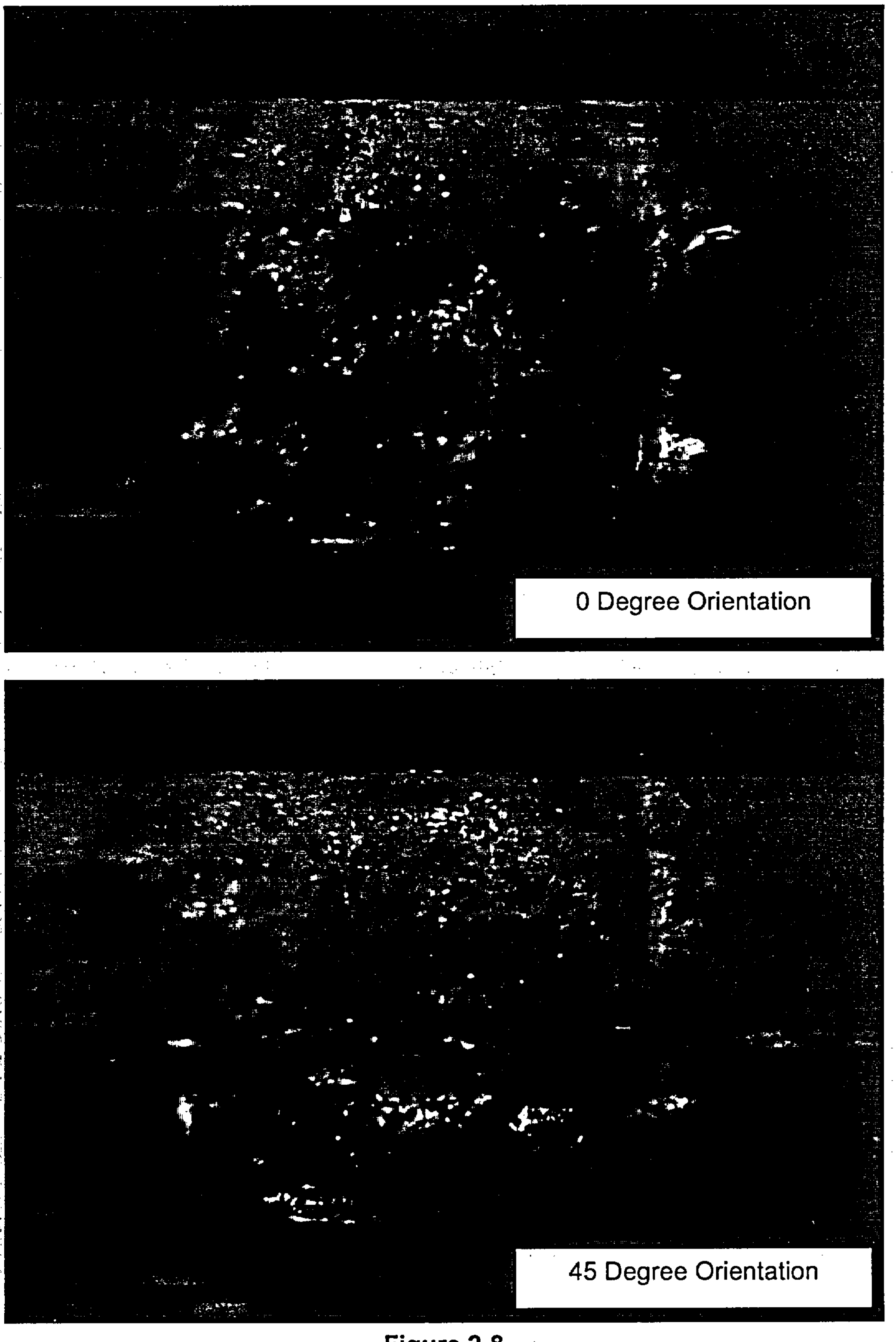
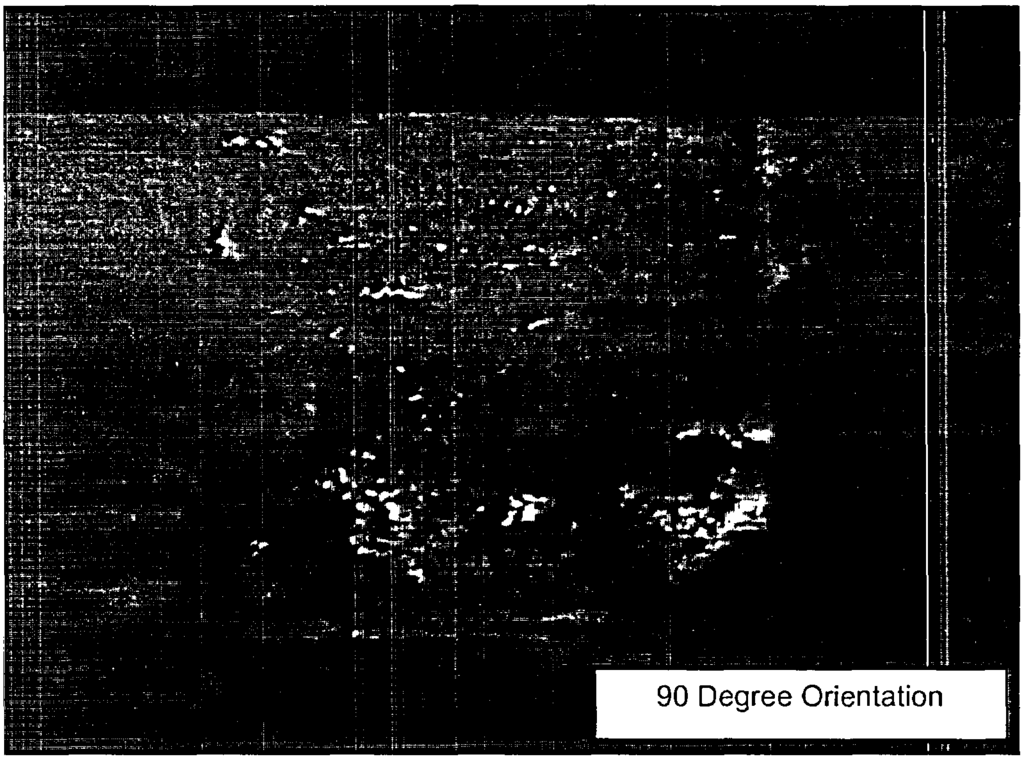


Figure 2-8
OD Appearance of R11C41 HL, Piece 4 at H02 Tube Support Plate



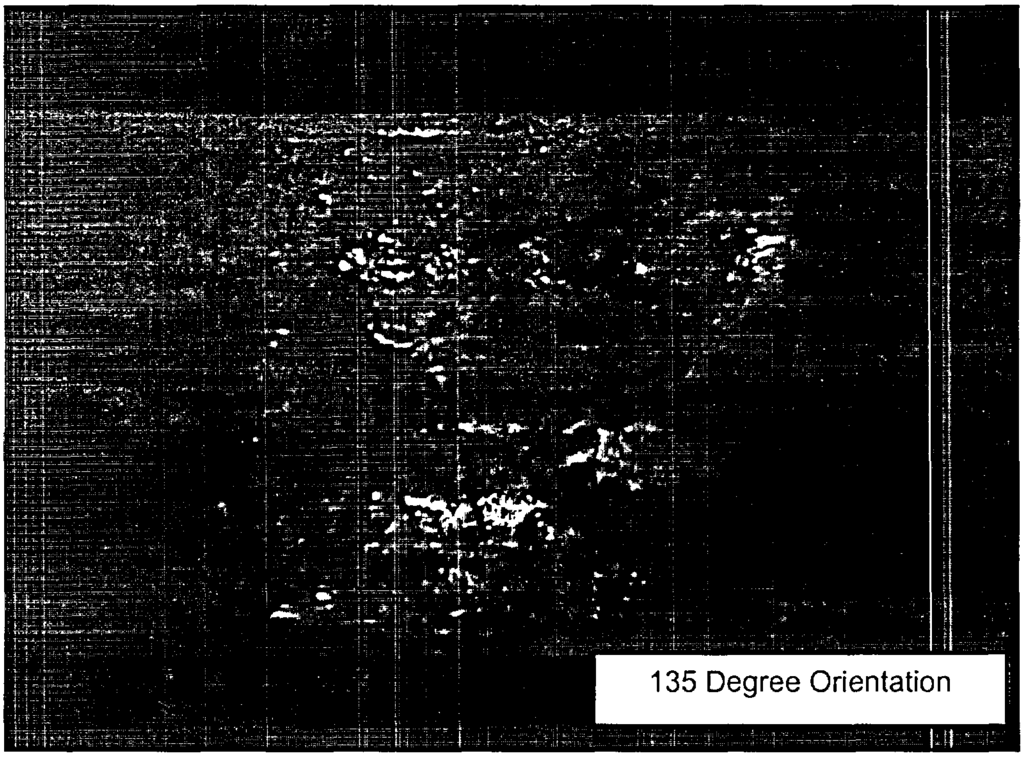


Figure 2-8 (Cont'd)
OD Appearance of R11C41 HL, Piece 4 at H03 Tube Support Plate

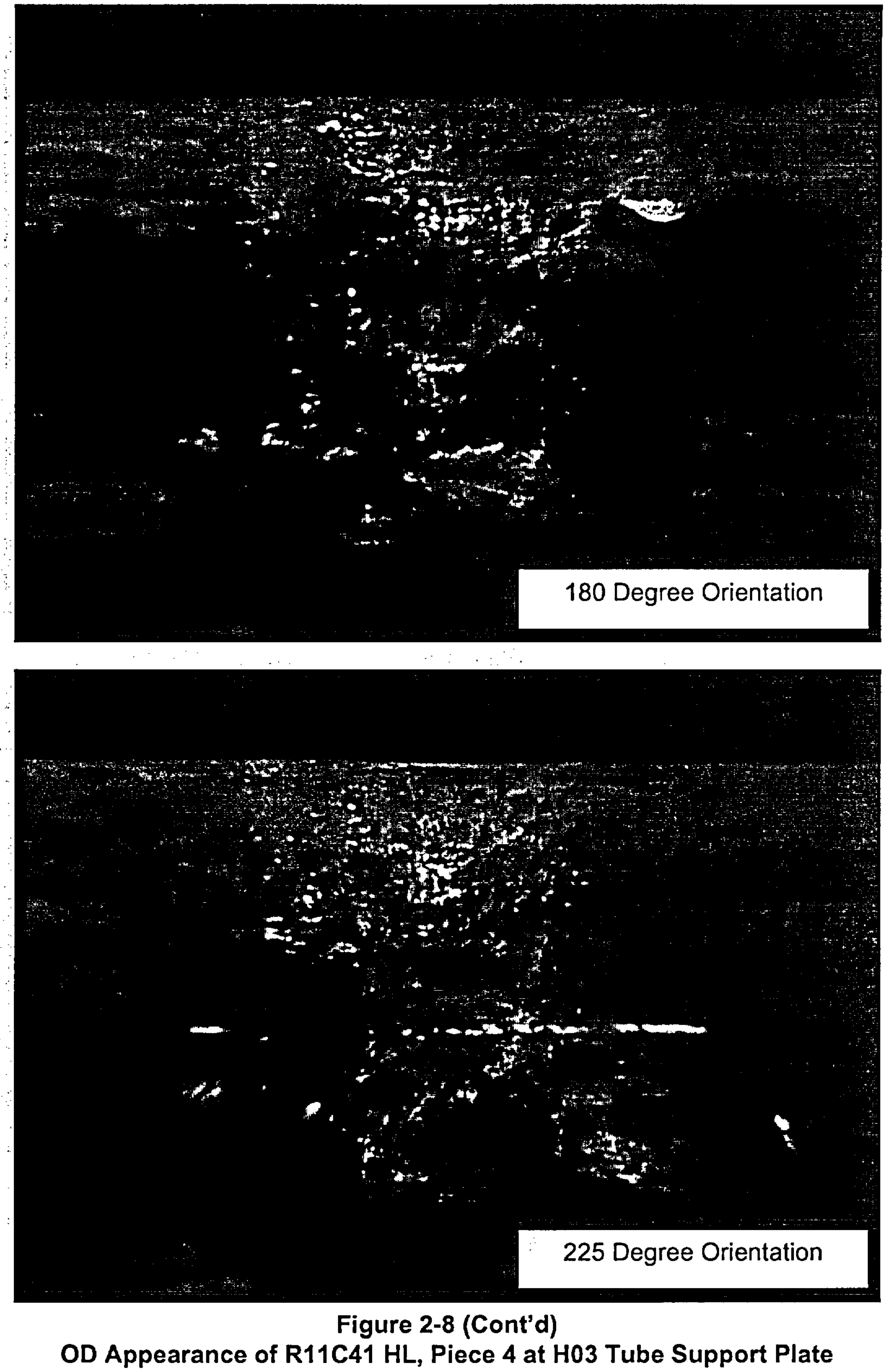
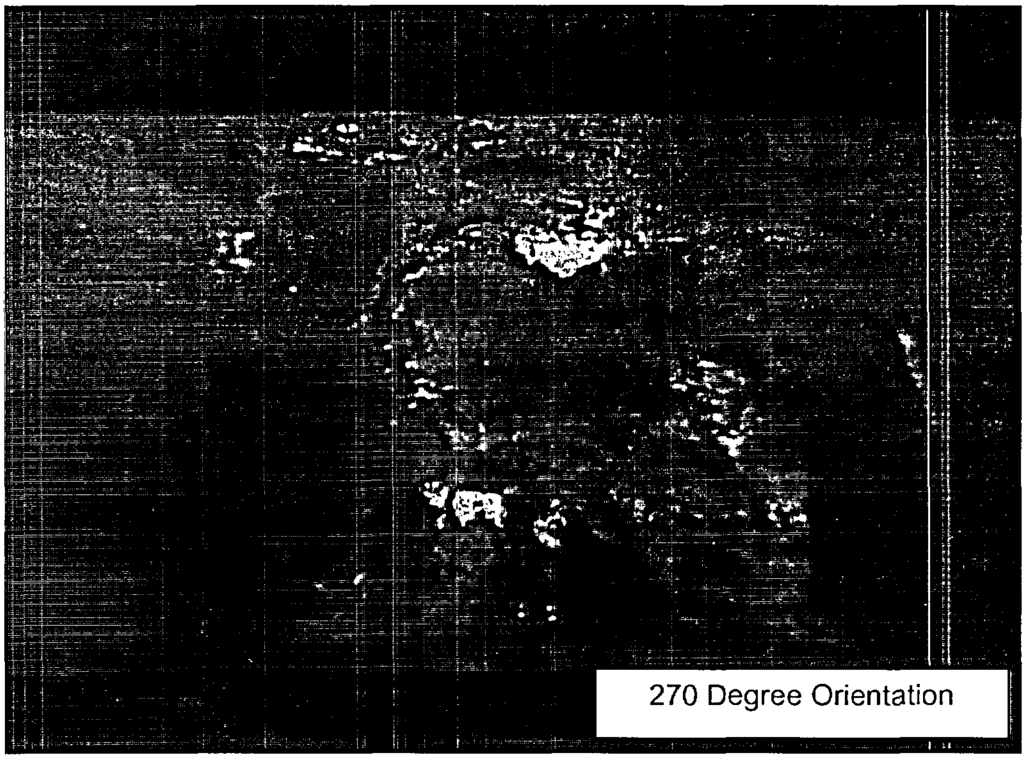


Figure 2-8 (Cont'd)
OD Appearance of R11C41 HL, Piece 4 at H03 Tube Support Plate



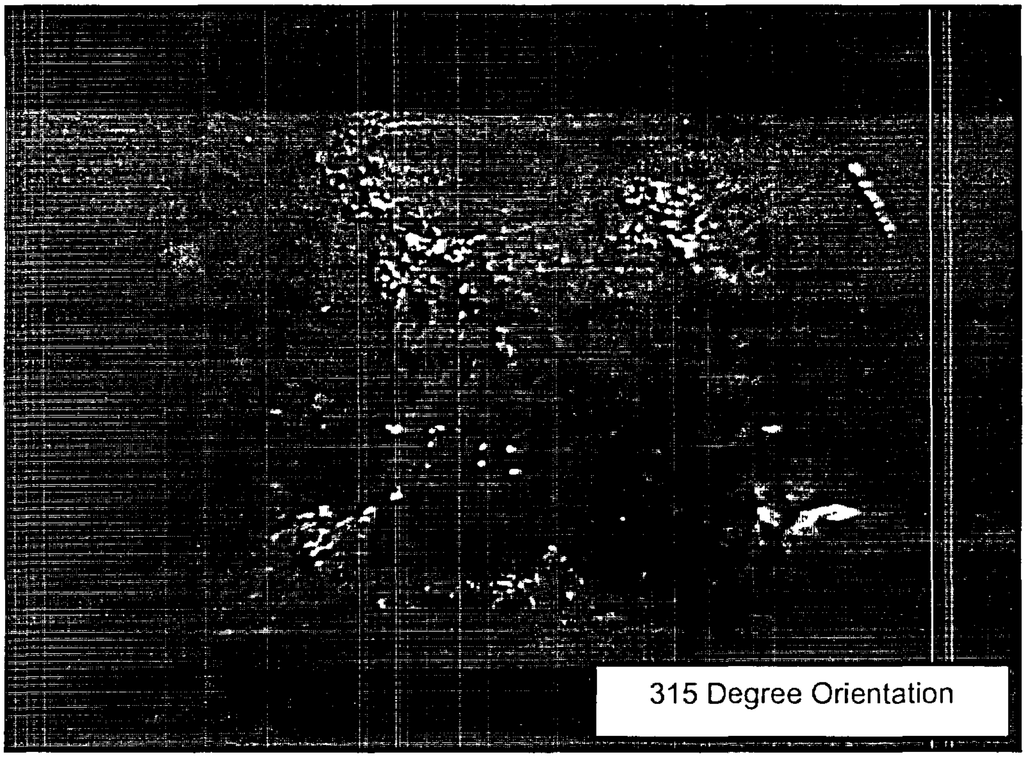


Figure 2-8 (Cont'd)
OD Appearance of R11C41 HL, Piece 4 at H03 Tube Support Plate

SECTION 3

SECTIONING PLANS

Following the receipt inspection of the tube segments, selected segments were cut into sample sizes that were applicable to a particular test. The 0° orientation mark and the top/bottom directions were maintained on each subsection by a small white paint mark. Section labeling was maintained in accordance with the standard laboratory procedure ("Steam Generator Tube Sample Identification," Westinghouse Science and Technology Department Procedure MR 0201, Rev 0, June 18, 2002).

Tables 3-1 through 3-10 and Figures 3-1 through 3-10 present a description of the samples used for each test and the location of each sample on the parent segment. Included on all figures are dimensions showing the elevation of each section relative to the tubesheet primary surface.

Chemistry-sensitive samples were cut using methods that would not contaminate the sample. Microstructure-sensitive samples were cut using methods that generated minimal heat.

In general, the ends of most sections were squared off and deburred prior to eddy current testing. The sections identified as Piece 1 from each of the two tubes were not tested in any way. These sections were from within the tubesheet region and had been significantly altered by the TIG weld heat-relaxation procedure that was performed to facilitate the removal of the tube through the tubesheet. Hence, sketches of these sections are not provided here. In general, sections that contained a region of interest (freespan or the top of the tubesheet) were then cut to manageable length for additional NDE and other examinations.

Table 3-1
Disposition of Samples from R10C39 HL - Piece 2
(See Figure 3-3)

Sample	Support	Tests Performed
2	TTS and H01 (FDB)	♦ Bobbin Coil and Plus Point Inspection ♦ OD Macro Photography

Table 3-2
Disposition of Samples from R10C39 HL - Piece 3
(See Figure 3-4)

Sample	Support	Tests Performed
3	H02	♦ Bobbin Coil and Plus Point Inspection ♦ OD Macro Photography
3A	Freespan	None
3A1	Freespan	None
3A2	Freespan	♦ Huey Test
3A3	Freespan	♦ Huey Test
3B	H02	♦ Elevated Temperature Leak Test ♦ Room Temperature Burst Test
3B1	Freespan	None
3B2	H02	♦ Macro OD Photography of Axial Burst
3B2A	H02	♦ SEM / EDS ♦ Crack Depth Profile
3B2B	H02	None
3B2B1	H02	None
3B2B2	H02	♦ Transverse mount, polish, and etch for crack characterization
3B2B3	H02	None
3B3	Freespan	None
3C	Freespan	♦ Room Temperature Burst Test
3C1	Freespan	None
3C2	Freespan	♦ Macro OD Photography of Axial Burst
3C2A	Freespan	♦ SEM / EDS
3C2B	Freespan	None
3D	Freespan	None

Table 3-3
Disposition of Samples from R10C39 HL- Piece 4
(See Figure 3-5)

Sample	Support	Tests Performed
4	H03	♦ Bobbin Coil and Plus Point Inspection ♦ OD Macro Photography
4A	Freespan	♦ Bulk Chemistry
4B	H03	♦ Room Temperature Burst Test
4B1	Freespan	None
4B2	H03	♦ Macro OD Photography of Axial Burst
4B2A	H03	♦ SEM / EDS ♦ Crack Depth Profile
4B2B	H03	None
4B2B1	H03	None
4B2B2	H03	♦ Transverse mount, polish, and etch for crack characterization
4B2B3	H03	None
4B3	Freespan	None
4C	Freespan	♦ Room Temperature Tensile Test
4D	Freespan	None
4D1	Freespan	♦ Grain Size ♦ Carbide Distribution ♦ Microhardness

Table 3-4
Disposition of Samples from R10C39 HL - Piece 5
(See Figure 3-6)

Sample	Support	Tests Performed
5	Freespan	♦ Bobbin Coil Inspection
5A	Freespan	None
5B	Freespan	♦ Huey Retest
5C	Freespan	♦ Huey Retest
5D	Freespan	♦ Split Ring Residual Stress

Table 3-5
Disposition of Samples from R11C41 HL - Piece 2
(See Figure 3-7)

Sample	Support	Tests Performed
2	TTS and H01(FDB)	♦ Bobbin Coil and Plus Point Inspection ♦ OD Macro Photography
2A	Within Tubesheet	None
2B	TTS	♦ Room Temperature Burst Test
2B1	Within Tubesheet	None
2B2	TTS	♦ OD Macro Photography of Bulged TTS
2B2A	TTS	♦ SEM / EDS ♦ Crack Depth Profile
2B2B	TTS	None
2B3	Freespan	♦ OD Macro Photography of Axial Burst
2B3A	Freespan	♦ SEM / EDS
2B3B	Freespan	None
2B4	Freespan	None
2C	FDB	None

Table 3-8
Disposition of Samples from R11C41 HL - Piece 3
(See Figure 3-8)

Sample	Support	Tests Performed
3	H02	♦ Bobbin Coil and Plus Point Inspection ♦ OD Macro Photography
3A	Freespan	None
3A1	Freespan	None
3A2	Freespan	♦ Huey Test
3A3	Freespan	♦ Huey Test
3B	H02	♦ Elevated Temperature Leak Test ♦ Room Temperature Burst Test
3B1	Freespan	None
3B2	H02	♦ Macro OD Photography of Axial Burst
3B2A	H02	♦ SEM / EDS ♦ Crack Depth Profile
3B2B	H02	None
3B2B1	H02	None
3B2B2	H02	♦ Transverse mount, polish, and etch for crack characterization
3B2B3	H02	None
3B3	Freespan	None
3C	Freespan	None
3C1	Freespan	♦ Huey Retest
3C2	Freespan	♦ Huey Retest
3C3	Freespan	♦ Split Ring Residual Stress
3C4	Freespan	None

Table 3-9
Disposition of Samples from R11C41 HL - Piece 4
(See Figure 3-9)

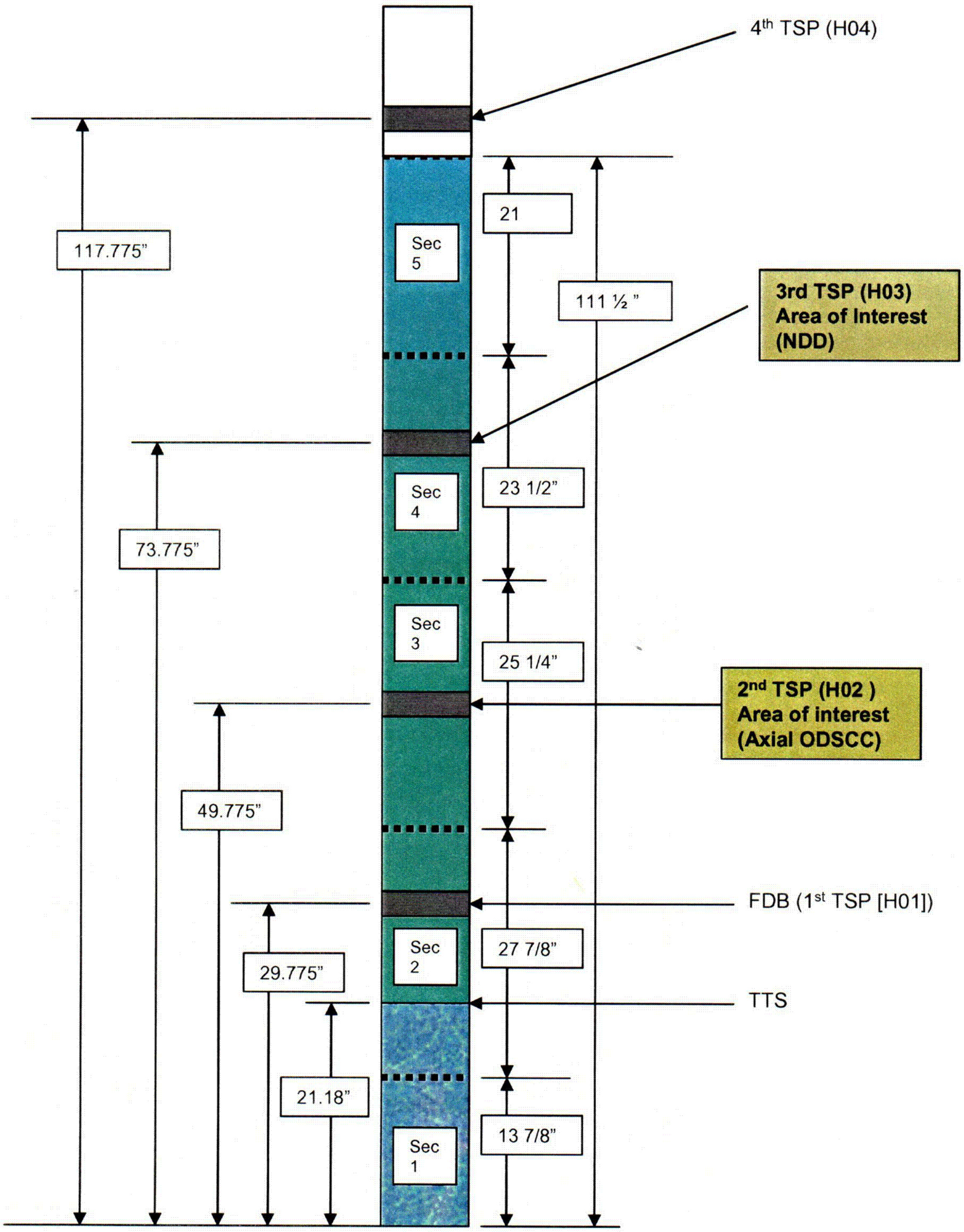
Sample	Support	Tests Performed
4	H03	♦ Bobbin Coil and Plus Point Inspection ♦ OD Macro Photography
4A	Freespan	None
4A1	Freespan	None
4A2	Freespan	♦ Bulk chemistry
4A3	Freespan	♦ Grain Size ♦ Carbide Distribution ♦ Microhardness
4B	H03	♦ Room Temperature Burst Test
4B1	Freespan	None
4B2	H03	♦ Macro OD Photography of Axial Burst
4B2A	H03	♦ SEM / EDS ♦ Crack Depth Profile
4B2B	H03	None
4B2B1	H03	None
4B2B2	H03	♦ Transverse mount, polish, and etch for crack characterization
4B2B3	H03	None
4B3	Freespan	None
4C	Freespan	♦ Room Temperature Tensile Test
4D	Freespan	None

Table 3-10
Disposition of Samples from R11C41 HL - Piece 5
(See Figure 3-10)

Sample	Support	Tests Performed
5	Freespan	♦ Bobbin Probe Inspection
5A	Freespan	♦ Room Temperature Burst Test
5A1	Freespan	None
5A2	Freespan	♦ OD Macro Photography of Axial Burst
5A2A	Freespan	♦ SEM / EDS of Burst Fracture Face
5A2B	Freespan	None
5B	Freespan	♦ Room Temperature Tensile Test
5C	Freespan	None

Figure 3-1

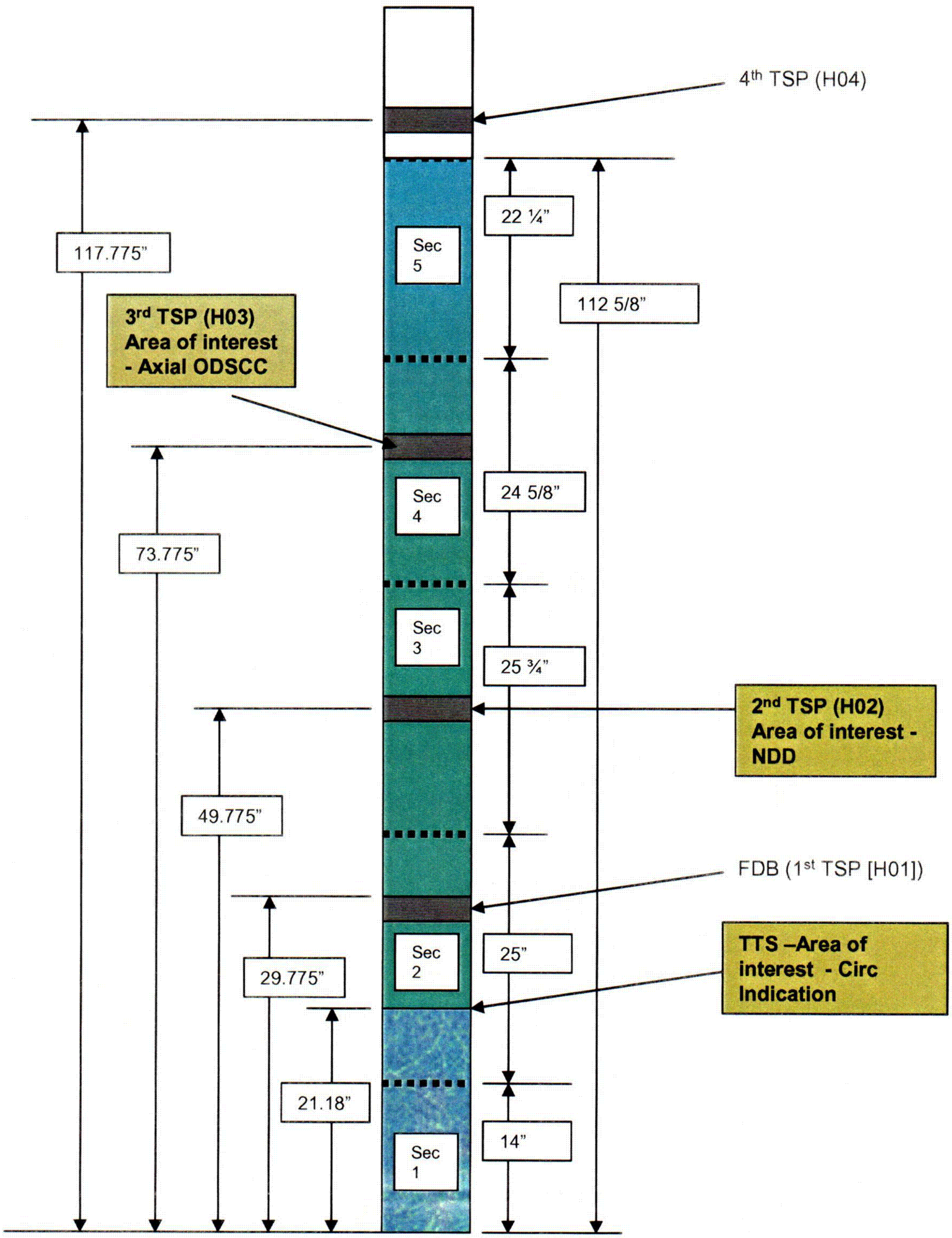
Field Cutting Layout R10C39 HL - SG 2



C01

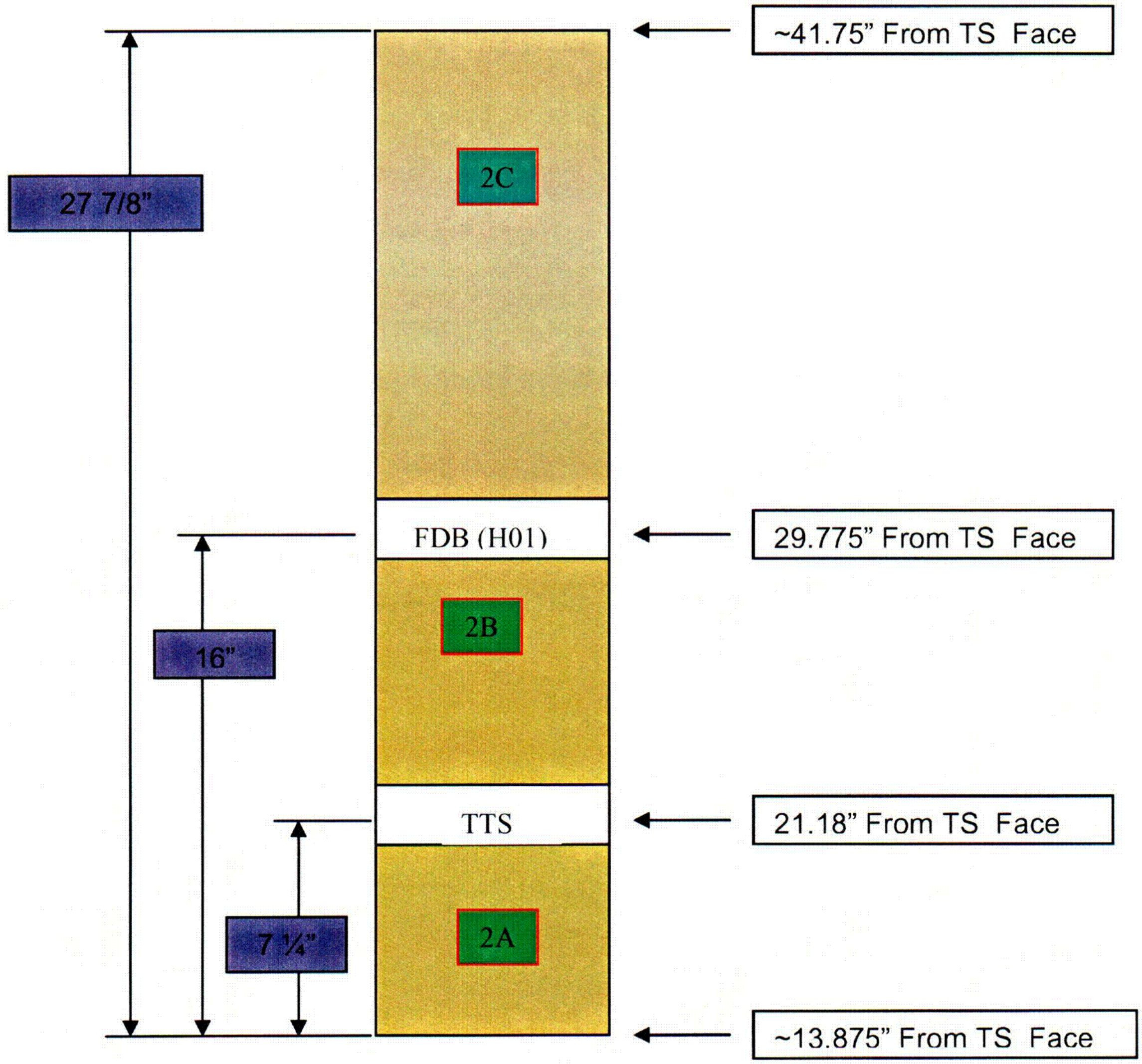
Figure 3-2

Field Cutting Layout R11C41 HL– SG 2



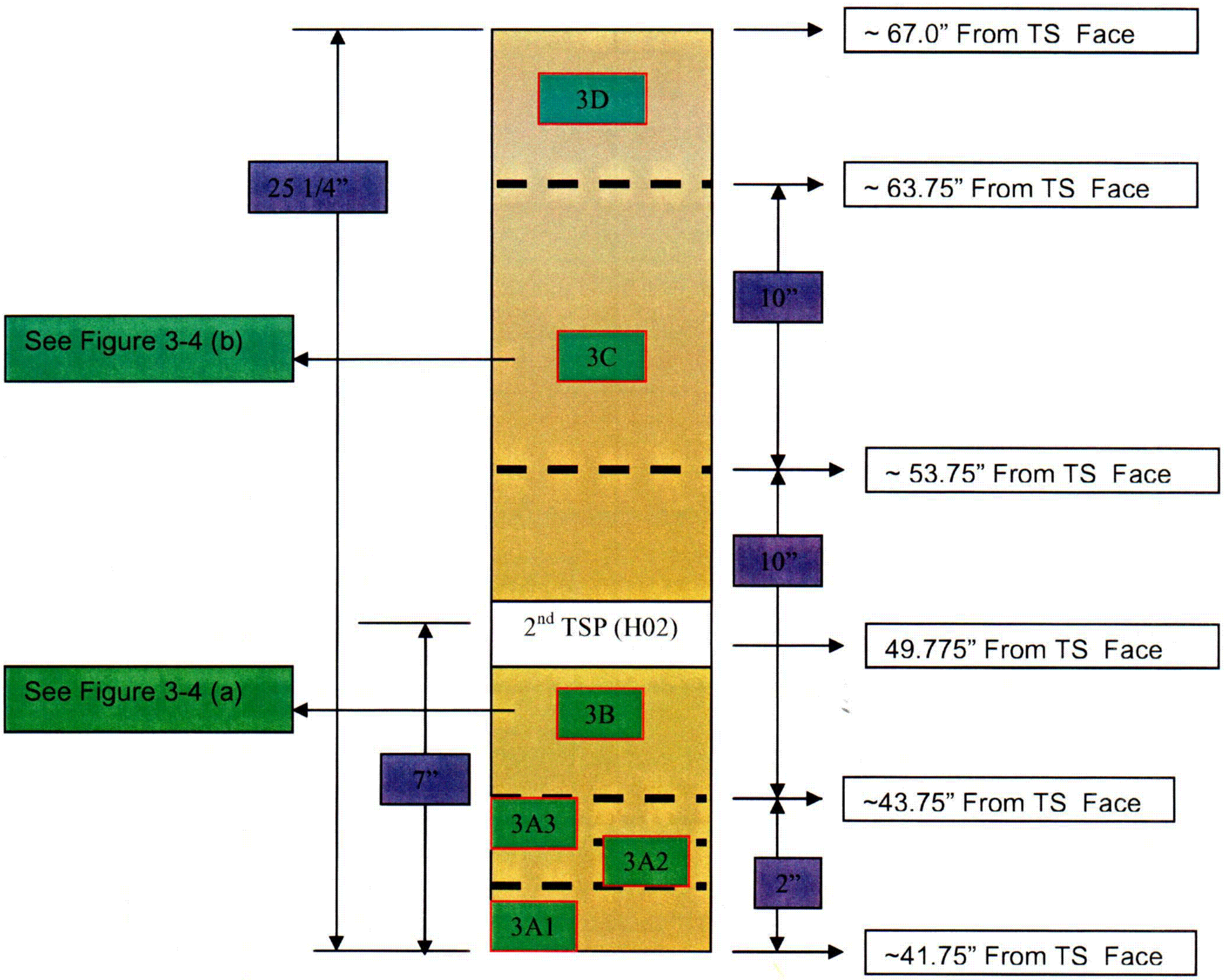
C02

Figure 3-3
R10C39 HL - Piece 2 – Sectioning and Evaluation



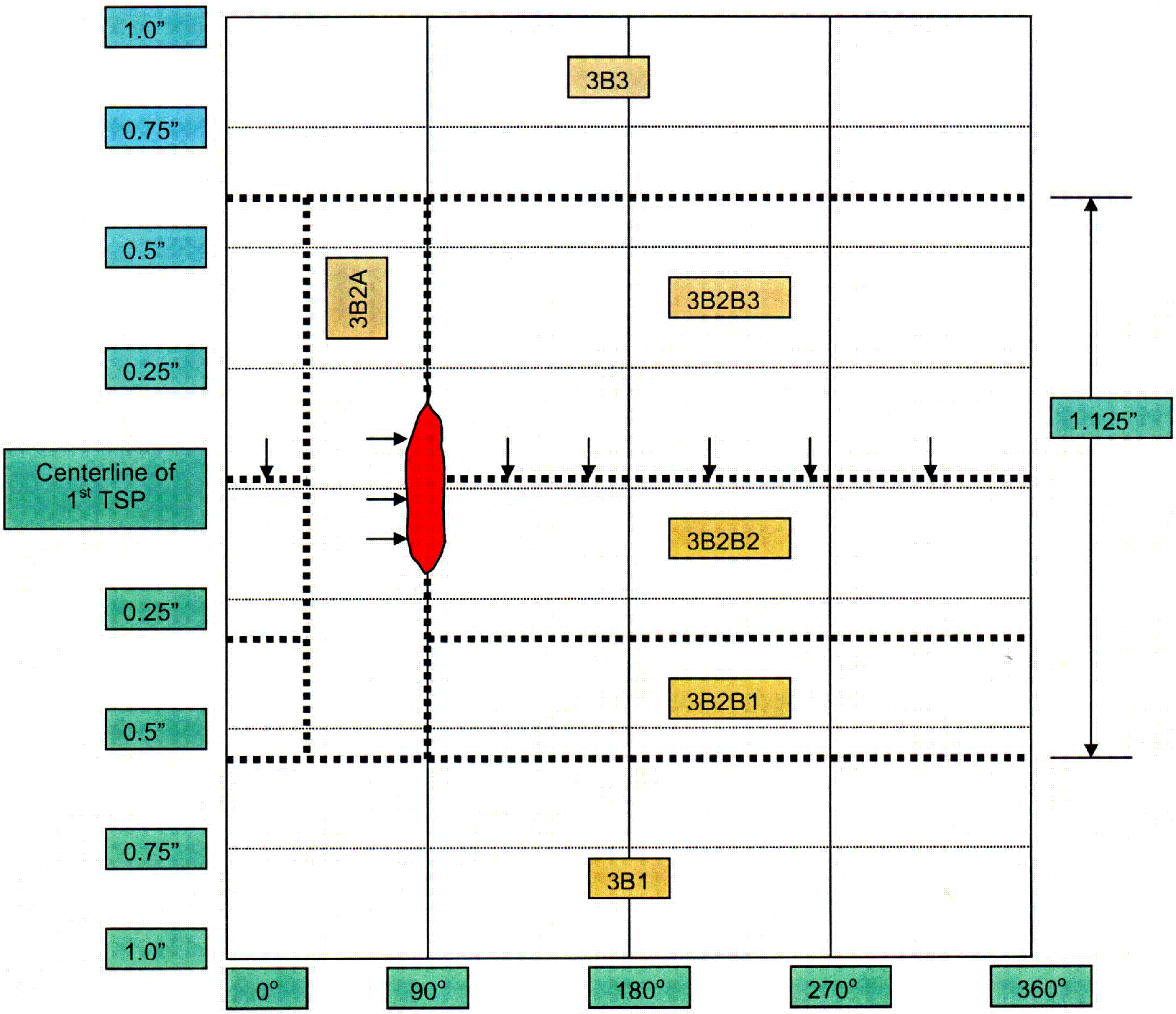
C03

Figure 3-4
R10C39 HL - Piece 3 – Sectioning and Evaluation



C04

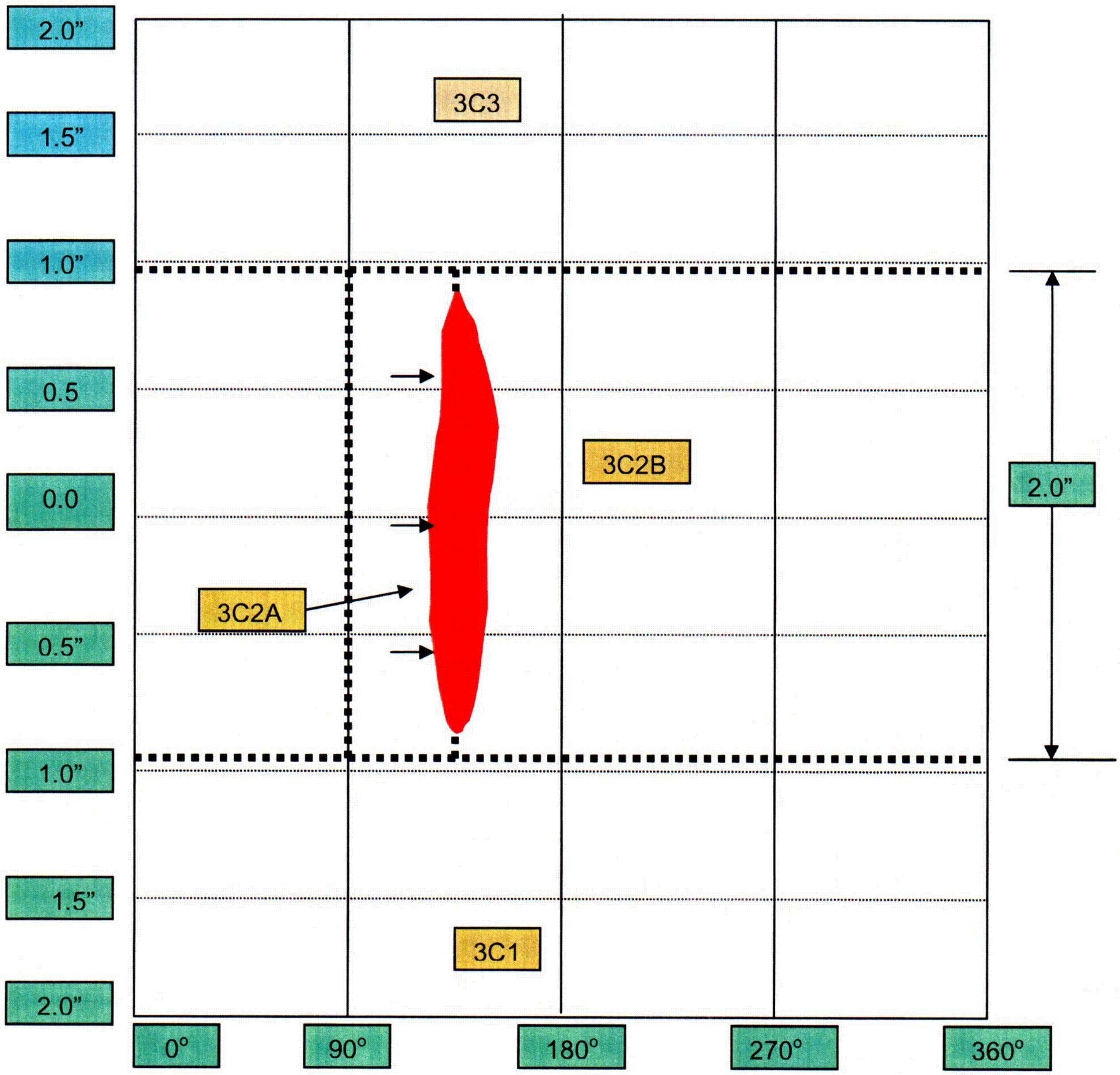
Figure 3-4 (a)
R10C39 HL - Piece 3B – Sectioning and Evaluation



Note: Arrows indicate surfaces examined.

C05

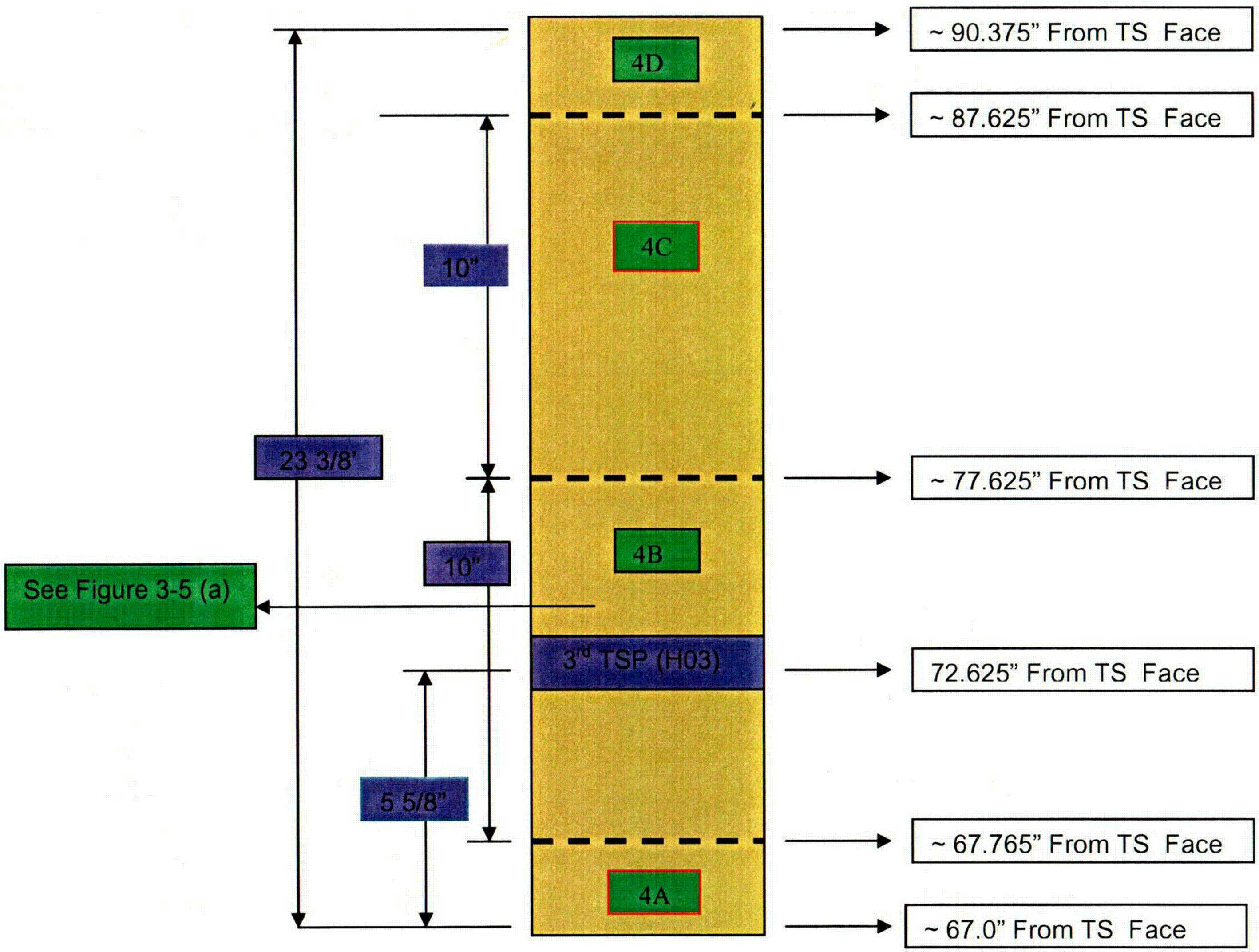
Figure 3-4 (b)
R10C39 HL - Piece 3C – Sectioning and Evaluation



Note: Arrows indicate surface examined.

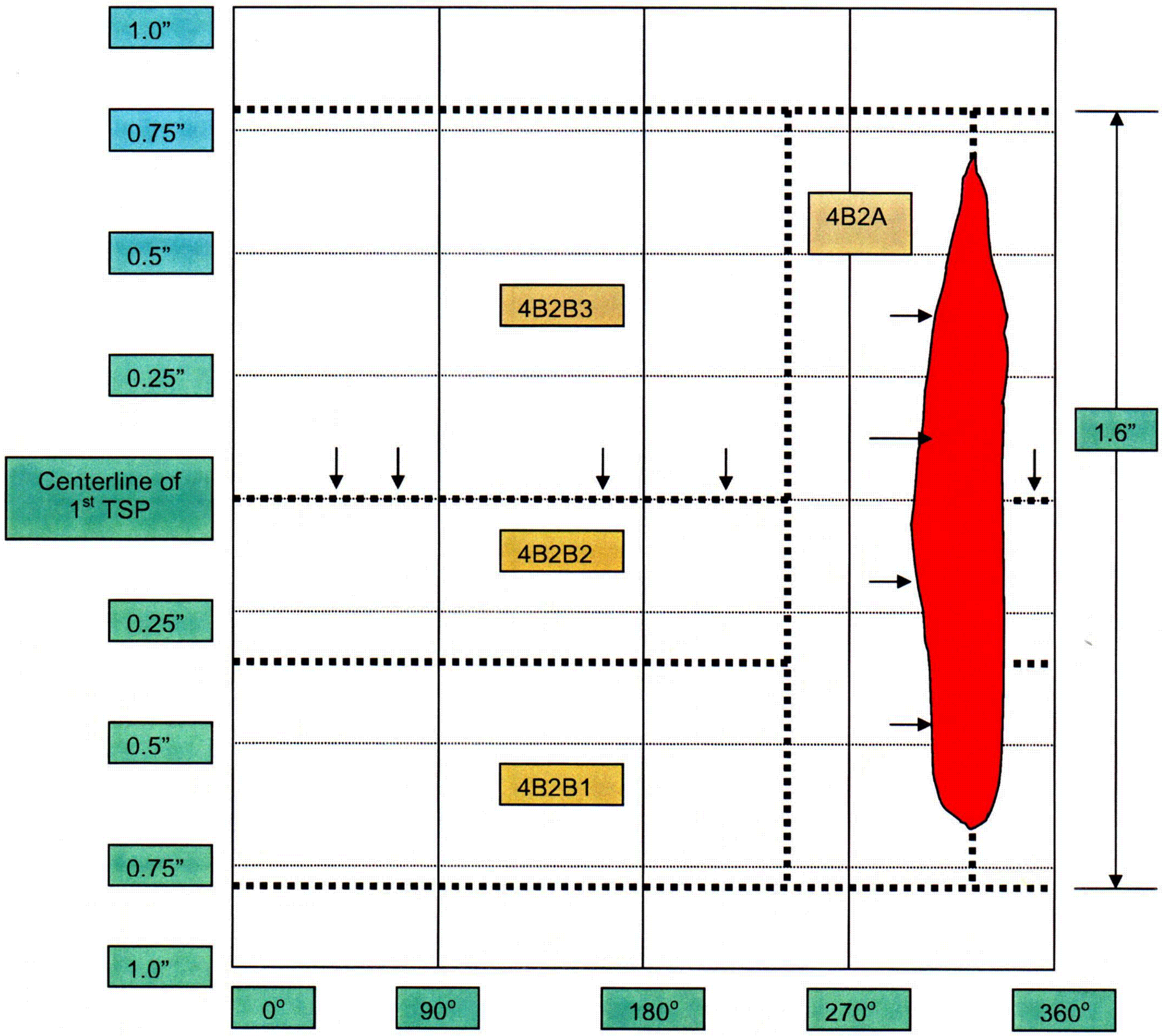
C06

Figure 3-5
R10C39 HL - Piece 4 – Sectioning and Evaluation



C07

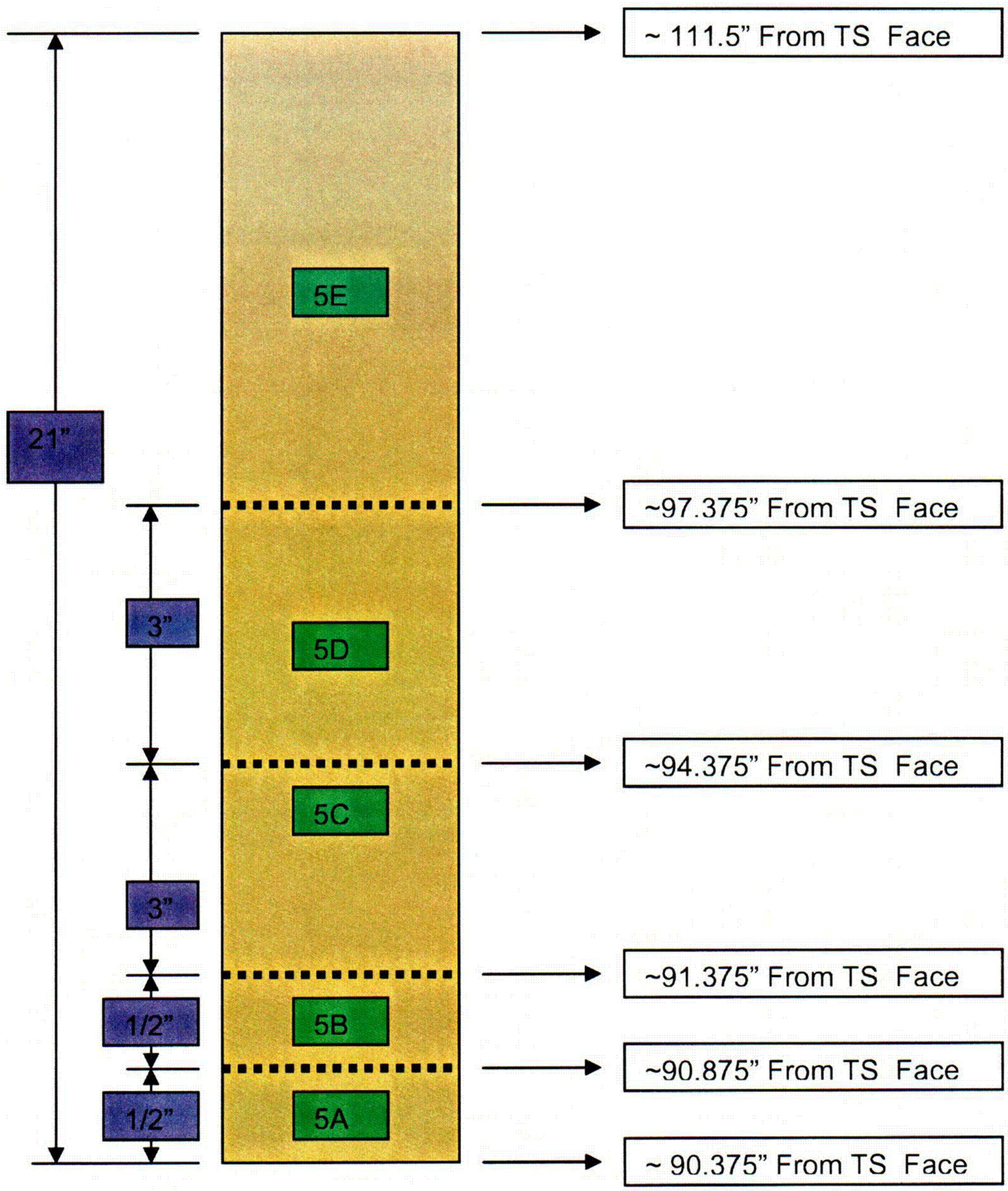
Figure 3-5 (a)
R10C39 HL – Piece 4B2 – Sectioning and Evaluation



Note: Arrows indicate surfaces examined.

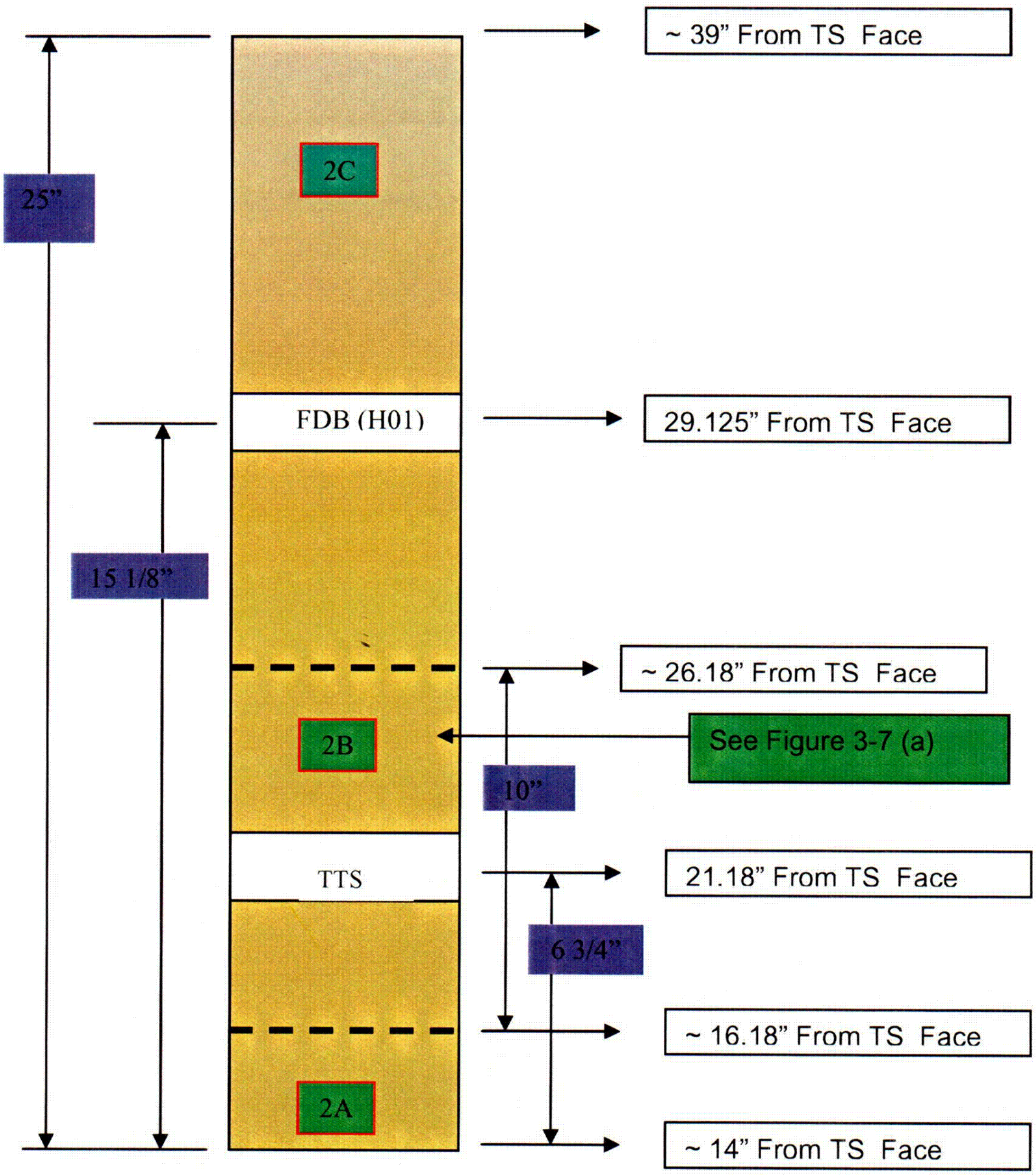
C08

Figure 3-6
R10C39 HL – Piece 5 – Sectioning and Evaluation



C09

Figure 3-7
R11C41HL - Piece 2 – Sectioning and Evaluation



C10

Figure 3-7 (a)
R11C41HL - Piece 2B – Sectioning and Evaluation

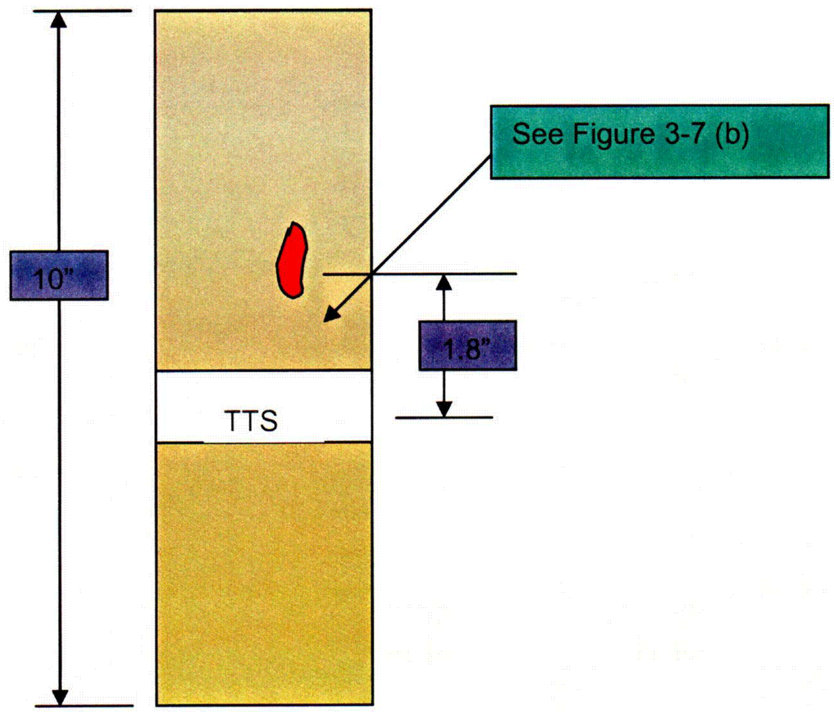
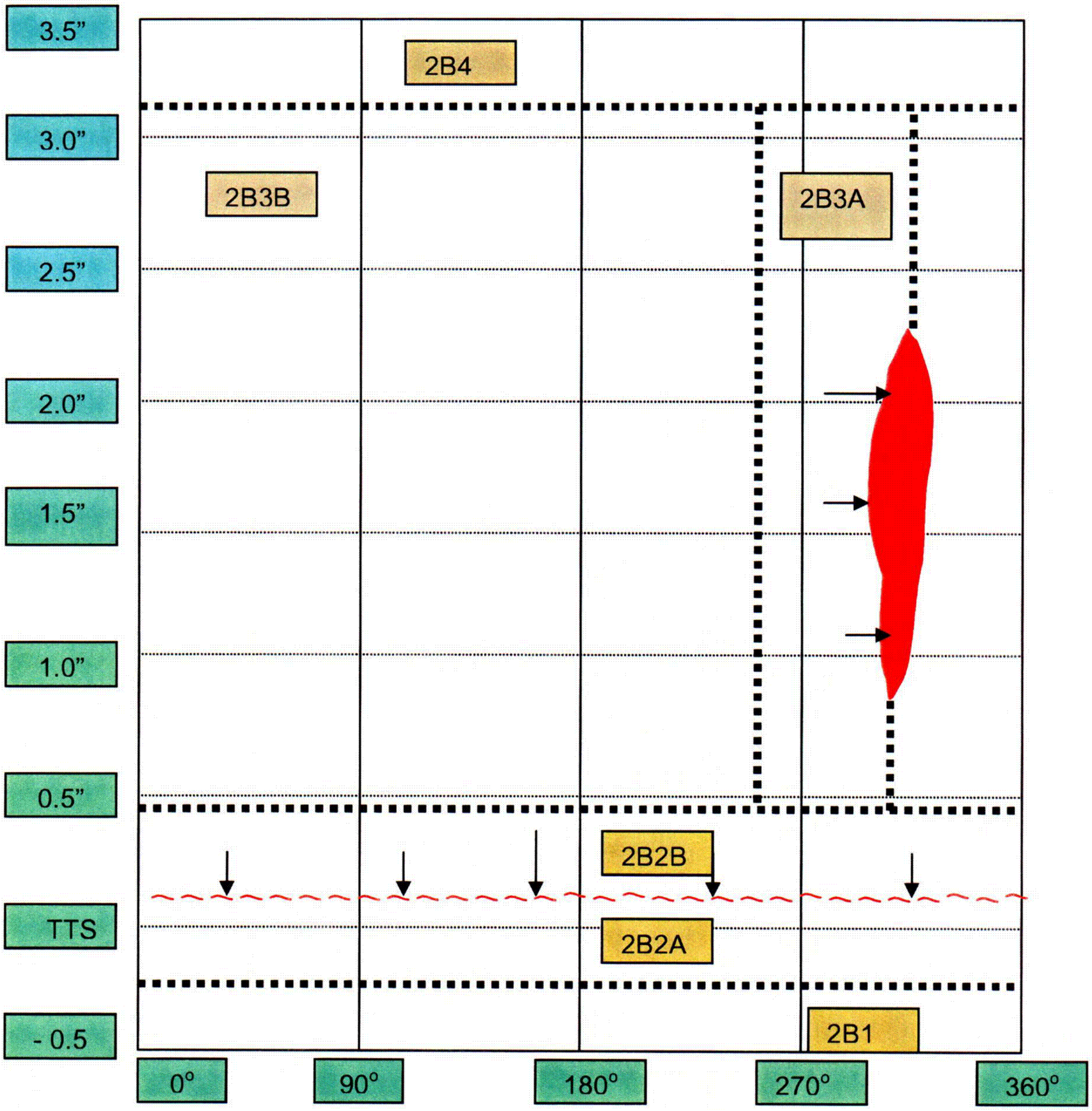


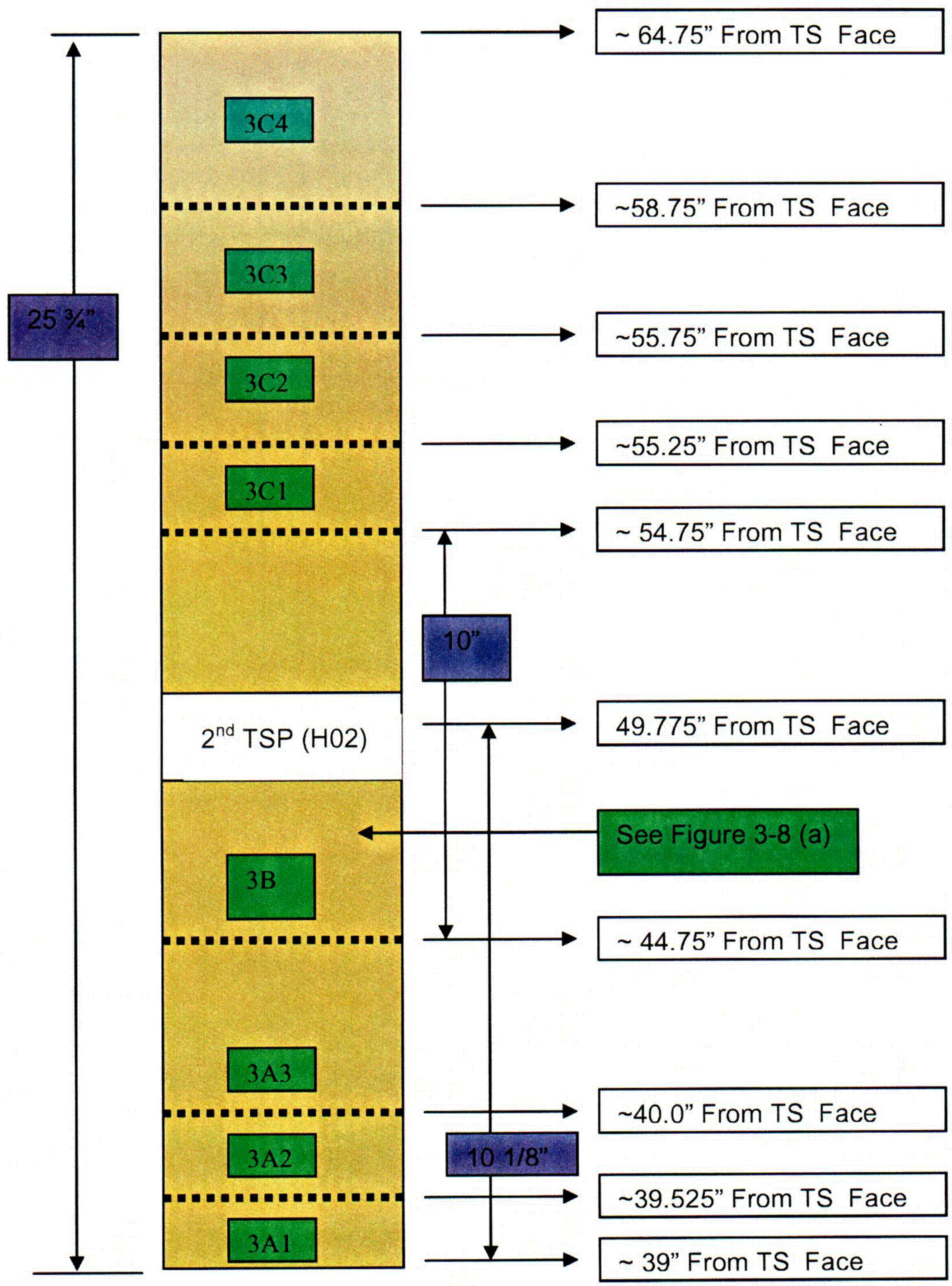
Figure 3-7 (b)
R10C39 HL – Piece 2B – Sectioning and Evaluation



Note: Arrows indicate surfaces examined.

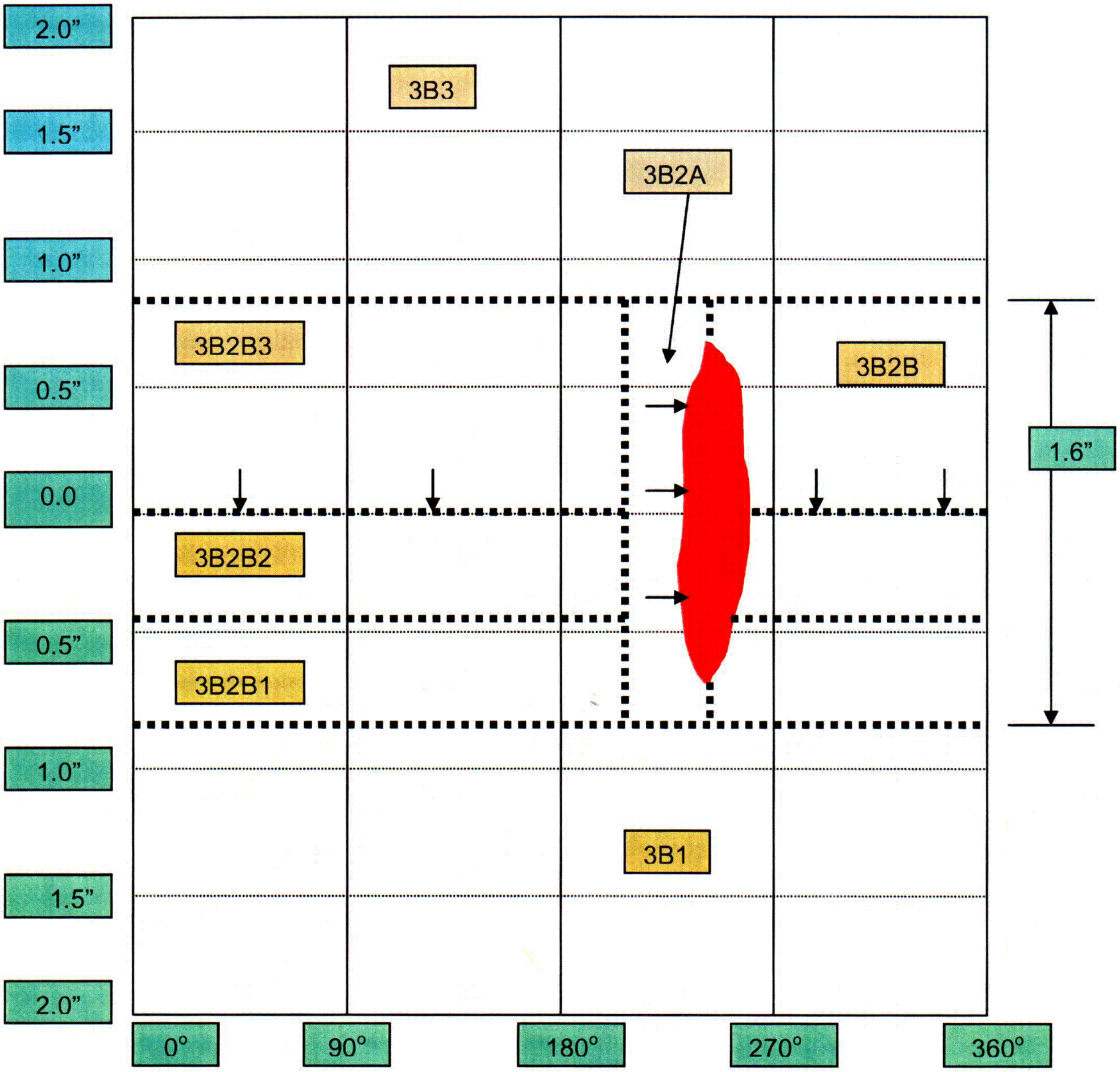
C12

Figure 3-8
R11C41 HL – Piece 3 – Sectioning and Evaluation



C13

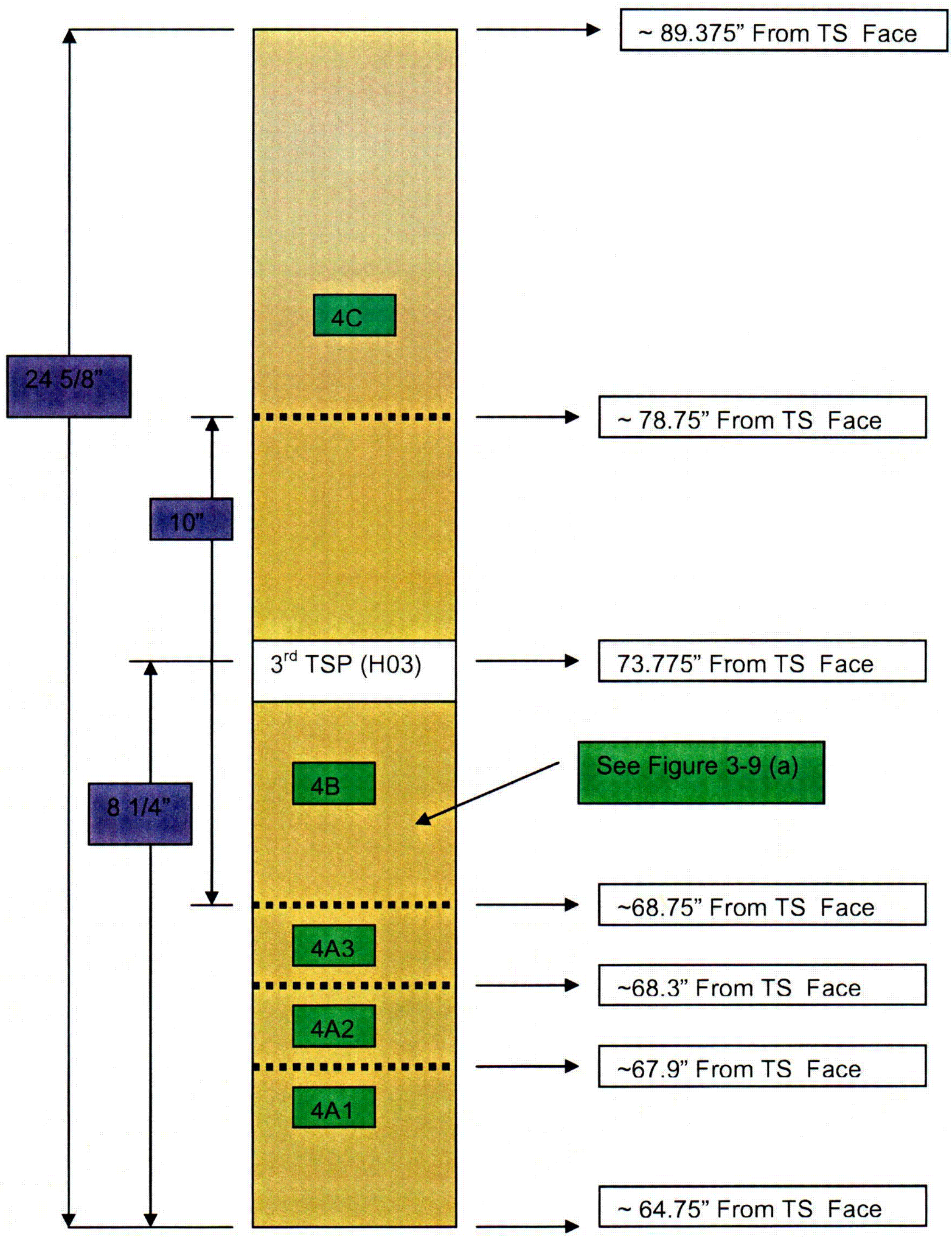
Figure 3-8(a)
R11C41HL – Piece 3B – Sectioning and Evaluation



Note: Arrows indicate surfaces examined

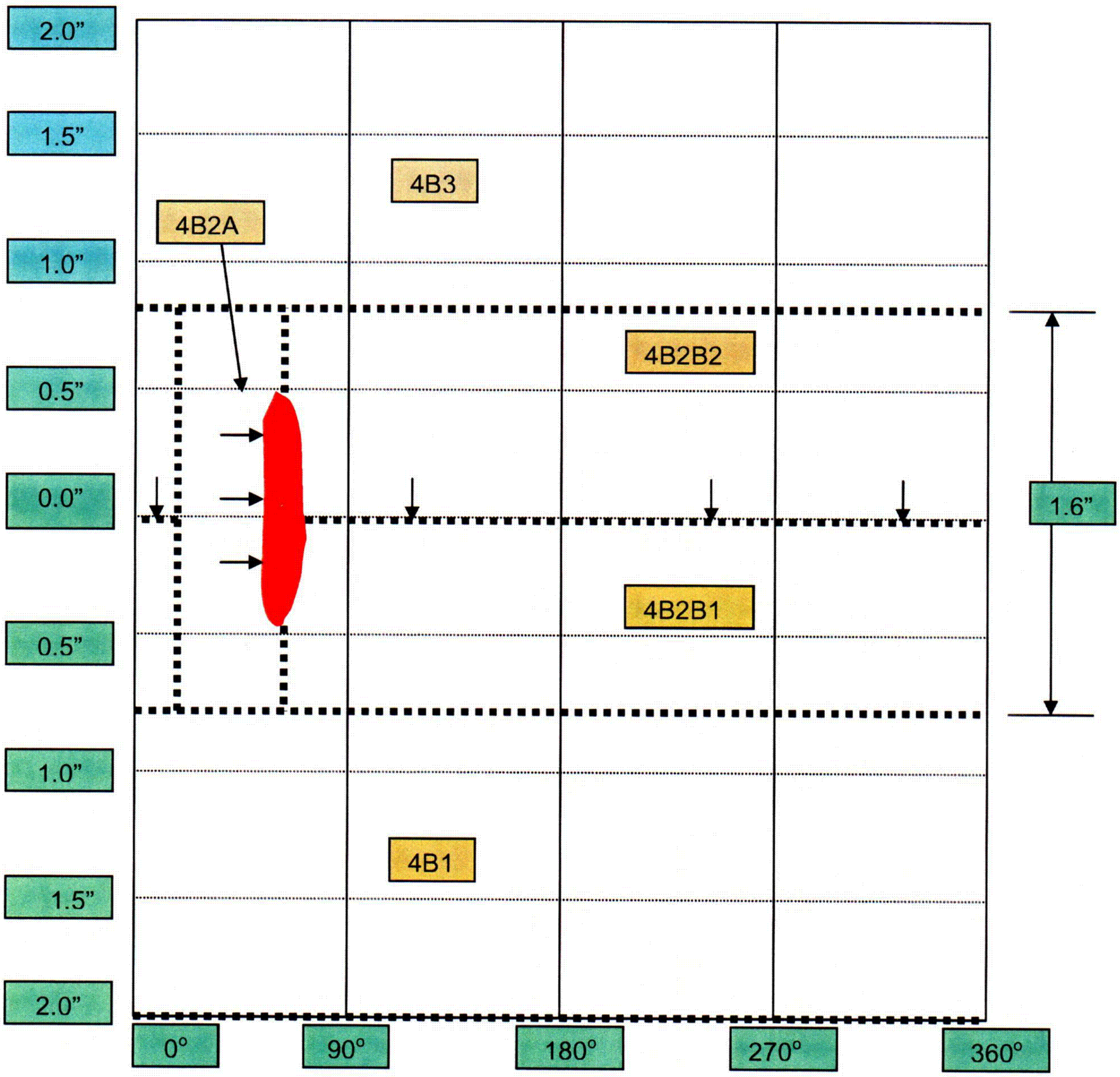
C14

Figure 3-9
R11C41HL – Piece 4 – Sectioning and Evaluation



C15

Figure 3-9 (a)
R11C41HL – Piece 4B – Sectioning and Evaluation

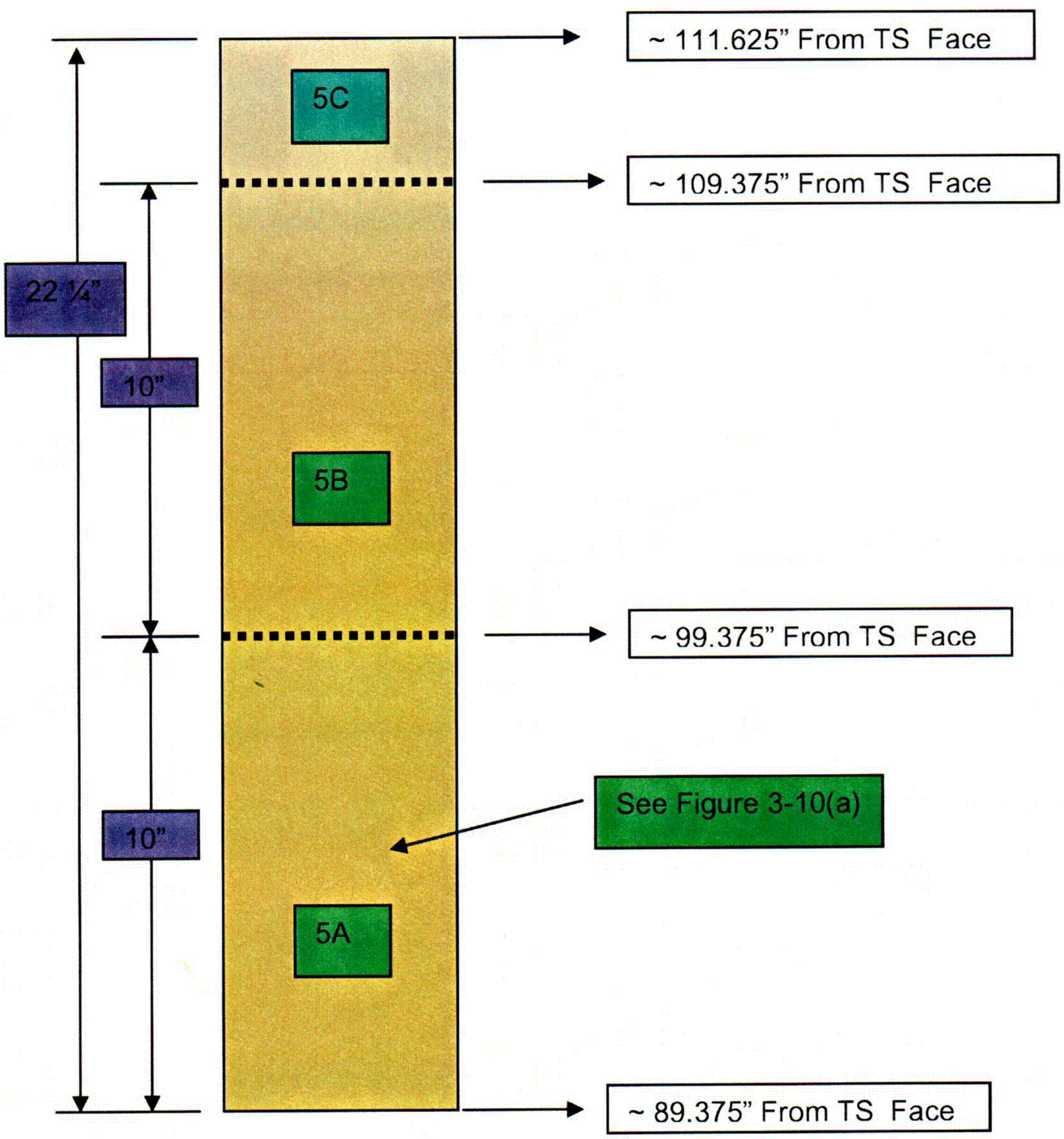


Note: Arrows indicate surfaces examined.

C16

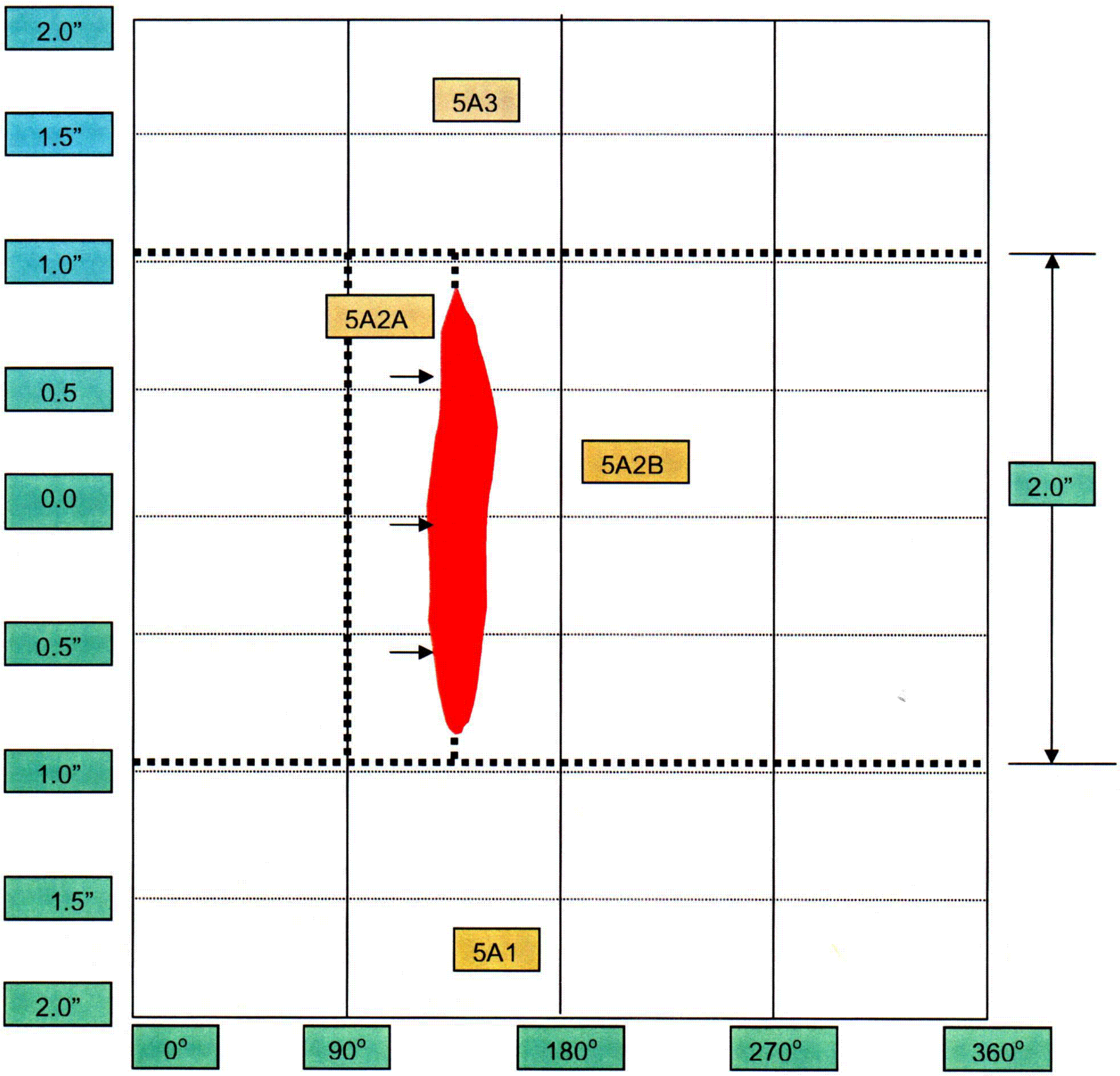
Figure 3-10

R11C41 HL - Piece 5 – Sectioning and Evaluation



C17

Figure 3-10 (a)
R11C41 HL - Piece 5A – Sectioning and Evaluation



Note: Arrows indicate surface examined.

C18

SECTION 4

EDDY CURRENT INSPECTION

4.1 Introduction

After initial visual inspection of the tube sections, the ends of the tube sections were squared–off and deburred to facilitate eddy current inspections. Two tasks were defined for the eddy current inspections:

- Review and reevaluation of field data
- Acquisition and analysis of bobbin coil and +Pt laboratory data

Data are presented and discussed as appropriate to each of these tasks in the following sections.

In the following descriptions of the eddy current inspections, the 0° locations of each specimen was a consistently maintained orientation related to a tube-pull scribe mark at the bottom of the tube piece; subsequent orientations are expressed clockwise of 0° when looking in the direction of the primary flow.

4.2 Eddy Current (EC) Data - General Practices

Prior to the tube pull, the steam generator tubes were examined in the steam generator using eddy current (EC) inspection techniques. A 0.610-inch diameter bobbin probe was used as for the primary inspection and was supplemented by +Pt probes where indications were identified by the bobbin coil. Field data were collected at test frequencies of 35, 130, 300 and 550 kHz for bobbin probes and at 200, 300, 400, 600 and 800 kHz for +Pt probes. The reporting frequency for the +Pt coil was 300 kHz differential. Furthermore, the field data were reevaluated as part of the tube examination. Bobbin calls were made using 130-550 kHz Mix data channel from the differential mode. The +Pt probe contains three coils: 1) a mid-frequency +Pt coil which forces directionality to any indication, 2) a mid-frequency 115 mil diameter pancake coil, and 3) a high frequency 80 mil diameter pancake coil. +Pt probe indications were usually identified with the +Pt coil using 300 kHz differential mode data.

The eddy current re-evaluation of the field data and the laboratory examinations were calibrated in a similar fashion. For the bobbin coil the voltage for all frequency channels except the 550 kHz, Mix and the 15 kHz channel was set to 4.0 volts for the 20% OD calibration holes and the phase to 40 degrees for the through-wall hole. The 550 kHz and Mix channels were set to the appropriate ARC voltage associated with the calibration standard being used for the 20% OD holes and 35 degrees on the through-wall hole. The 15 kHz channel was set to 4.0 volts on the support ring. The rotating probe data were adjusted such that all channels except the trigger and low frequency locator channels were set to 20 Volts on the through wall notch.

After the tubes were pulled, eddy current inspections were conducted in the Hot Cell area of the Westinghouse Remote Metallographic Facility. The inspections were conducted with a bobbin and rotating +Point probe configurations similar to the styles used in the field. All tube sections were inspected with the bobbin coil. The +Point rotating probe was used only for tube sections containing the TTS or structure locations. In all cases the eddy current data were collected using an R/D Tech TC6700 tester and Westinghouse ANSER software (Version 8.8 Rev 34). The data analysis was conducted using the Westinghouse ANSER software (Version 8.4 Rev 38). The laboratory bobbin probe calibration standard was ASV-011-92 and the rotating coil probe calibration standard was AE-001-92. Prior to the +Pt examination conductive material was attached to the tube sections containing the tube support (TSP) crevice regions and the top of tubesheet (TTS) to act as fiducial marks in the eddy current data. The conductive material was in the shape of a large "L" with the leg nominally located at 0 degrees and the bottom portion oriented toward 90 degrees. Thus the azimuthal location of the rotating eddy current probe indications could be determined so that the destructive examinations could be focused to the precise areas of interest.

Table 4-1 presents a summary of field and laboratory eddy current data obtained on the pulled tubes for the TSP crevice and the TTS regions. The laboratory data presented are for the bobbin and +Pt probes used during the field inspection.

The eddy current response of the tube support crevice regions of R10C39 HL and R11C41 HL showed indications at H02 and H03, respectively. No other indications were identified in either the field or laboratory examinations. During the laboratory examination the locations of some of the support regions could be identified with the pancake coil through the presence of deposits and/or subtle material property variations; however, none of these responses indicated degradation. The TSP indications found in the field remained essentially unchanged in the laboratory. What differences exist may reflect differences in the calibration standards used or the details of the probe location within the tube, rather than a significant change in the degradation morphology. Circumferential indications were noted at the TTS of R11C41 HL in the field data analysis. In the laboratory data for tube R11C41 HL the TTS region was distorted by the tube removal process, increasing the amplitude of the indications.

No indications were noted for the TTS region of tube R10C39 HL in the field inspections. Signal distortion likely caused by the tube removal operation was noted in the laboratory examination.

The following presents selected supporting eddy current data for the above observations.

4.3 Field Eddy Current Test Data and Laboratory Reevaluation of Field Eddy Current Test Data for Tube R10C39 HL

Field Eddy Current Test Data for the TTS Region of Tube R10C39 HL

No indications were noted in the +Pt probe data from the vicinity of the top of the tube sheet.

Field Eddy Current Test Data for H01 (FDB) Region of Tube R10C39 HL

The original bobbin probe field analysis for the H01 (FBD) region of Tube R10C39 HL did not identify an indication (NDD). In the reevaluated field bobbin and +Pt probe data, no degradation was identified.

Field Eddy Current Test Data for H02 region of Tube R10C39 HL

The original bobbin probe field call for the H02 region of tube R10C39 HL was a Distorted Support Indication (DSI) of 4.51 V as measured in the Mixed data. Laboratory review confirmed the indication and estimated the through wall extent to be 84%.

Figure 4-1 shows a data display of the reevaluated field bobbin probe data for the indication at H02. Since a bobbin coil indication was identified at this location, the H02 region of the tube was inspected with a +Pt probe. The field analysis identified a single axial indication (SAI) corresponding to the bobbin indication. The laboratory data review of the field +Pt coil data confirmed the SAI of 3.56 volts and estimated the through wall extent to be 76% and an indication length of 0.71 inches. Figure 4-2 presents the +Pt data display showing the axial-sensitive channel at 300 kHz.

Field Eddy Current Test Data for the H03 region of Tube R10C39 HL

The original bobbin probe field analysis for the H03 region of Tube R10C39 HL did not identify an indication (NDD). In the reevaluated field bobbin probe data no degradation was identified. Only a signal associated with the TSP is present in the Mix channel. No degradation was identified in the +Pt data at this location.

4.4 Field Eddy Current Test Data and Laboratory Reevaluation of Field Eddy Current Test Data for Tube R11C41 HL

Field Eddy Current Test Data for the TTS Region of Tube R11C41 HL

The top of the tubesheet was inspected using the +Pt probe. Circumferential indications were reported. Figure 4-3 shows a data display for the 300 kHz +Pt coil with the phase established such that circumferential indications produce a positive vertical deflection. The extent of cracking was determined to be 103 degrees around the circumference.

Field Eddy Current Test Data for the H01 (FDB) Region of Tube R11C41 HL

The original bobbin probe field analysis for the H01 (FDB) region of tube R11C41 HL did not identify any indications (NDD). In the reevaluated field bobbin and +Pt probe data, no degradation was identified.

Field Eddy Current Test Data for the H02 region of Tube R11C41 HL

The original bobbin probe field calls for the region of tube R11C41 HL at H02 was NDD. The laboratory review did not alter this conclusion; only a signal was identified at the TSP location. No +Pt indications were identified.

Field Eddy Current Test Data for the H03 of Tube R11C41 HL

The original bobbin probe field call for the H03 region of tube R11C41 HL was a DSI of 2.45 V as measured in the Mixed data. Laboratory review confirmed the indication and estimated the through wall extent to be 82%.

Figure 4-4 shows a data display of the reevaluated field bobbin probe data for the indication at H03. Since a bobbin coil indication was identified at this location, the H03 region of the tube was inspected with a +Pt probe. The field analysis identified a single axial indication (SAI) corresponding to the bobbin indication. The laboratory data review of the field +Pt coil data confirmed the SAI and estimated the through wall extent to be 76% and an indication length of 0.65 inches. Figure 4-5 presents the +Pt data display showing the axial-sensitive channel at 300 kHz.

4.5 Laboratory Eddy Current Test Data for Tube R10C39 HL

The discussions that follow will center on the analysis of the laboratory eddy current test results. The laboratory +Pt and bobbin coil test configurations were the same as those used in the field.

Laboratory Eddy Current Test Data for the TTS Region of Tube R10C39 HL (Piece 2)

Analysis of the +Pt response found no indications in the free span or at the FDB location. At the TTS, however, the response appears to be the result of artifacts of the tube removal process. Figure 4-6 shows the +Pt response for the TTS.

Laboratory Eddy Current Test Data for the H02 Region of Tube R10C39 HL (Piece 3)

In the laboratory, both bobbin and +Pt probe examinations of the tube section were conducted. One bobbin coil indication (Figure 4-7) was found corresponding to the one found in the field located at H02. The amplitude was 4.5 volts with an apparent depth of 81%. Both these measurements are consistent with the field data.

Figure 4-8 shows the +Pt response of the indication. The indication displays the characteristics principally of an SAI. The indication measures 3.65 volts in amplitude and has an apparent depth of 90% through wall and a total length of 0.71 inches. The measurements of length and amplitude are close to those measured from the field data; however, the apparent depth has increased slightly.

In addition there is a small amplitude indication which is azimuthally displaced from the large indication by approximately 60 degrees. The laboratory review of the field data identified this indication and it is included in Table 4-1. The indication has an apparent depth of 46%.

Based upon the bobbin and plus point probe response the tube removal operation had a minimal impact on the underlying degradation morphology.

Eddy Current Test Data for the H03 Region of Tube R10C39 HL (Piece 4)

In the laboratory, both bobbin and +Pt probe examinations of the tube sections were conducted. No indications were identified with either the bobbin (Figure 4-9) or the +Pt probes.

4.6 Laboratory Eddy Current Test Data for Tube R11C41 HL

The discussions that follow will center on the analysis of the laboratory eddy current test results. The laboratory +Pt and bobbin coil test configurations were the same as those used in the field.

Laboratory Eddy Current Test Data for the TTS and H01 Region of Tube R11C41 HL (Piece 2)

In the laboratory the eddy current +Pt response of the TTS region identified a circumferential indication. Figure 4-10 shows the circumferentially sensitive channel of the 300 kHz channel of the +Pt response. The amplitude of the indication varied significantly around the circumference of the tube and encompassed approximately 291 degrees of the circumference.

Figure 4-11 presents the pancake coil response at 150 kHz at H01 (FDB) location. As can be observed, the presence of the FDB is still apparent. Whether this is a result of a change in deposit morphology or due to a change in the tube's material properties is not certain. All of the other support locations on the HL of R11C41 showed a similar response.

Laboratory Eddy Current Test Data for H02 region of Tube R11C41 HL (Piece 3)

No indications were identified by either the bobbin (Figure 4-12) or +Pt probe inspections.

Laboratory Eddy Current Test Data for the H03 region of Tube R11C41 HL (Piece 4)

In the laboratory, both bobbin and +Pt probe examinations of the tube sections were conducted. A bobbin coil indication was found corresponding to the one found in the field. The bobbin coil indication had an amplitude of 2.44 V and an apparent depth of 75%. Both of these measurements are consistent with the field measurements. Figure 4-13 shows the laboratory bobbin coil response for the H03 region of R11C41 HL.

The +Pt response for this region is shown in Figure 4-14; only one indication is identified. The amplitude of the response was found to be 2.44 Volts with an apparent depth of 88% and a length of 0.67 inches. The bobbin coil response is essentially identical to the field response, while the +Pt response is slightly larger in both apparent depth and amplitude. From the +Pt and bobbin coil measurements, the tube removal process did not significantly alter the underlying degradation morphology.

Laboratory Eddy Current Test Data for the Free Span Region above H03 of Tube R11C41 HL (Piece 5)

This portion of the tube was used for mechanical tensile and burst testing. No bobbin coil or rotating probe indications were identified in this tube section.

4.7 Laboratory Eddy Current Testing After Leak Testing

Two of the tube pieces containing the support intersection with indications, R10C39 HL Piece 3 and R11C41 HL Piece 4 were eddy current inspected after leak testing. In both cases the amplitude of the degradation response grew by more than a factor of 2 for the bobbin and +Pt coils. This indicates the rupture of ligaments during the test.

Figures 4-15 and 4-16 show the bobbin and +Pt coil response for the H02 region of R10C39 HL (Piece 3B). No secondary indications appeared due to the deformation associated with the test conditions. Figures 4-17 and 4-18 show the bobbin and +Pt coil response for the H03 region of R11C41 HI (Piece 4B). The small indication adjacent to the main indication was less discernible as a separate indication after leak testing. This suggests that ligaments separating the degraded regions had been ruptured, causing the indications to blend together.

Table 4-1
Summary of Field and Laboratory Eddy Current Inspection Results

Tube Section	Field Bobbin (Field Review) (Mix) Volts/	Field +Pt (Field Review) 300 kHz Volts/ID/Length (in.)	Field Bobbin (Lab Review) (Mix) Volts/%	Field +Pt (Lab Review) 300 kHz Volts Volts/%/Length	Laboratory Bobbin (Mix) Volts	Laboratory +Pt 300 kHz Orientation Volts/%/Length (Deg.) (in.)	Post Leak Rate Testing Laboratory Bobbin (Mix) Volts	Post Leak Rate Testing Laboratory +Pt 300 kHz Volts/%/Length
R10C39 HL H03	NDD			NDD	NDD	NDD		
R10C39 HL H02	4.51/DSI	3.82/SAI/0.490	4.6/84	3.56/76/0.71	4.5/81	60 3.65/90/0.71 0 0.16/46	11.37/85	8.18/95/0.90
R10C39 HL H01 (FDB)	NDD			NDD	NDD	NDD		
R10C39 HL TTS	N/A				N/A	NDD		
R11C41 HL H03	2.45/DSI	1.58/SAI/0.580	2.4/82	1.88/76/0.65	2.44/75	44 2.44/88/0.67	6.67/81	5.14/92/.79
R11C41 HL H02	NDD	NDD	NDD	NDD	NDD	NDD		
R11C41 HL H01 (FDB)	NDD	NDD	NDD	NDD	NDD	NDD		
R11C41 HL TTS	N/A	0.16/SCI/103°	N/A	0.14/64/101°	N/A	SCI 291° 0.68/56 0.46/74		

SCI- Single Circumferential Indication PI-Possible Indication N/A-Not Appropriate NDD-No Detectable Degradation SAI- Single Axial Indication

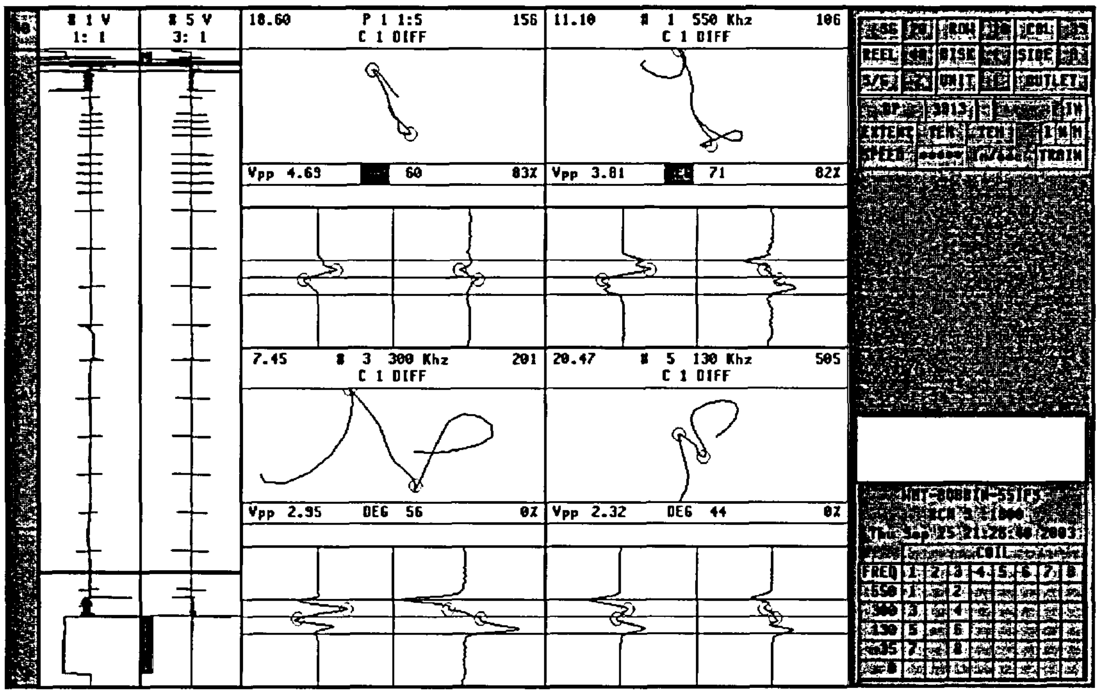


Figure 4-1 Field bobbin coil response for the H02 tube support intersection of Watts Bar Unit 1 steam generator 2 tube R10 C39 HL, Piece 3. A distorted support indication was identified at this location

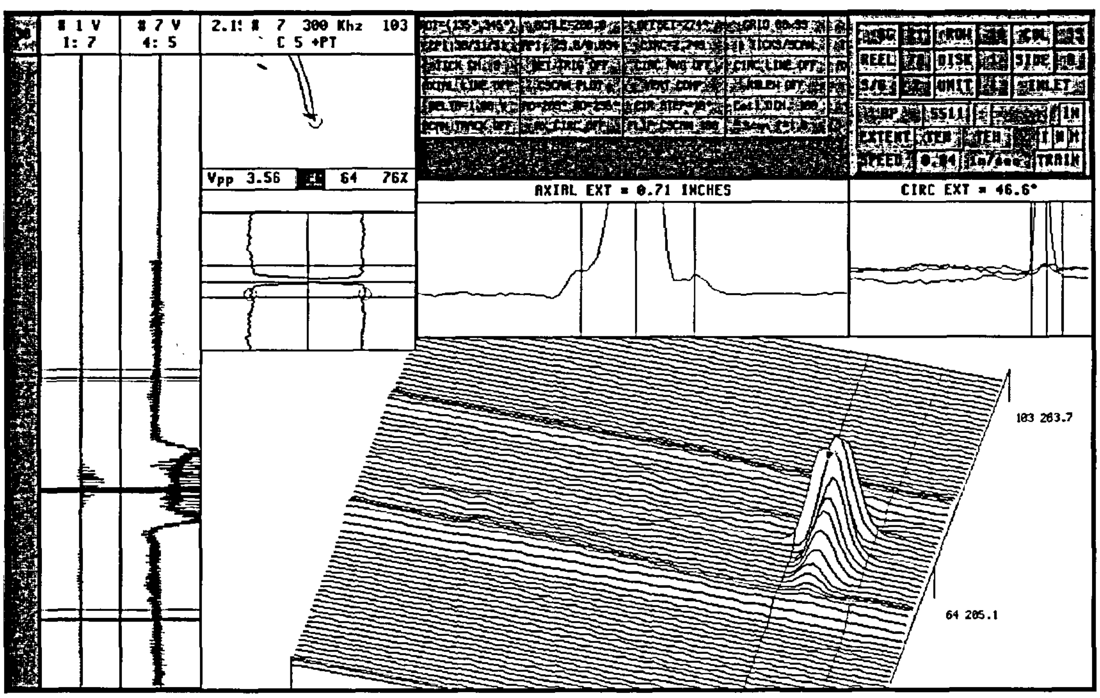


Figure 4-2 +Pt response for the H02 tube support intersection of Watts Bar Unit 1 steam generator 2 tube R10 C39 HL. Two axially oriented indications were identified at this location.

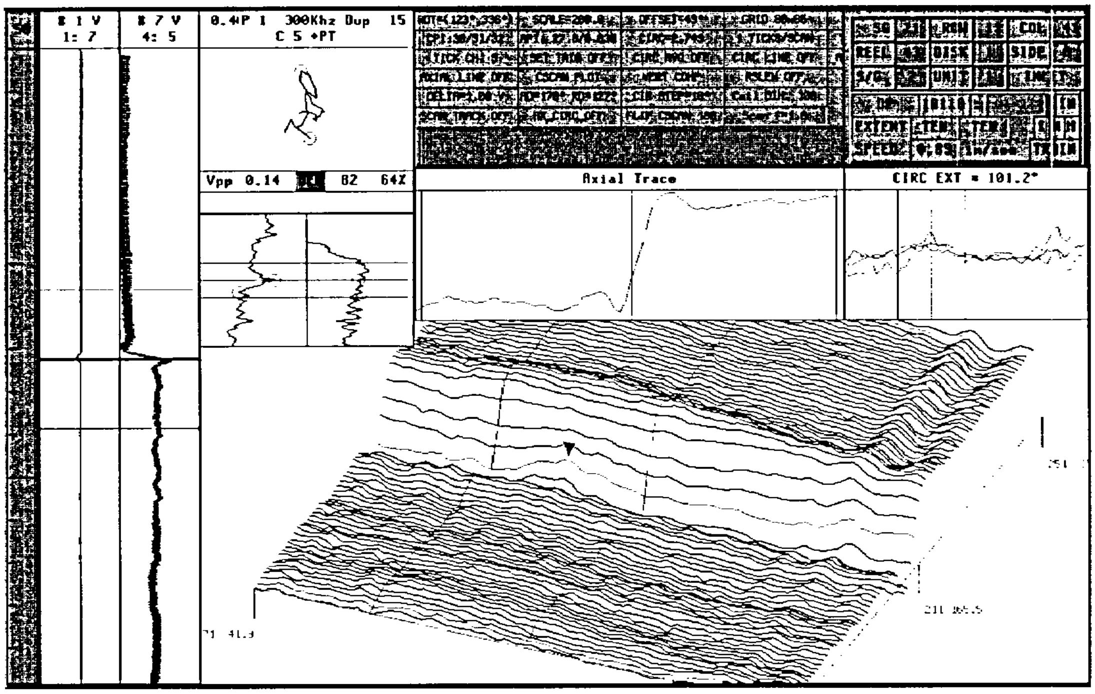


Figure 4-3 Field +Pt response at the top of tube sheet (TTS) for Watts Bar Unit 1 steam generator 2 tube R11 C41 HL, Piece 2. A circumferentially oriented indication was identified at this location.

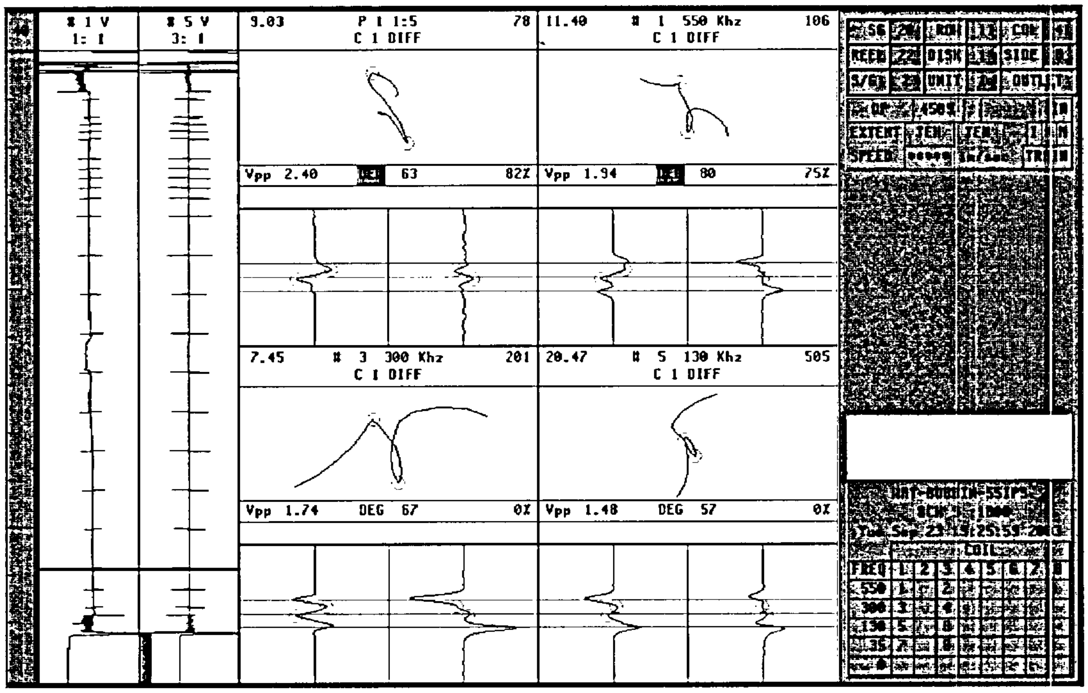


Figure 4-4 Field bobbin coil response for the H03 tube support intersection of Watts Bar Unit 1 steam generator 2 tube R11 C41 HL, Piece 4. A distorted support indication was identified at this location.

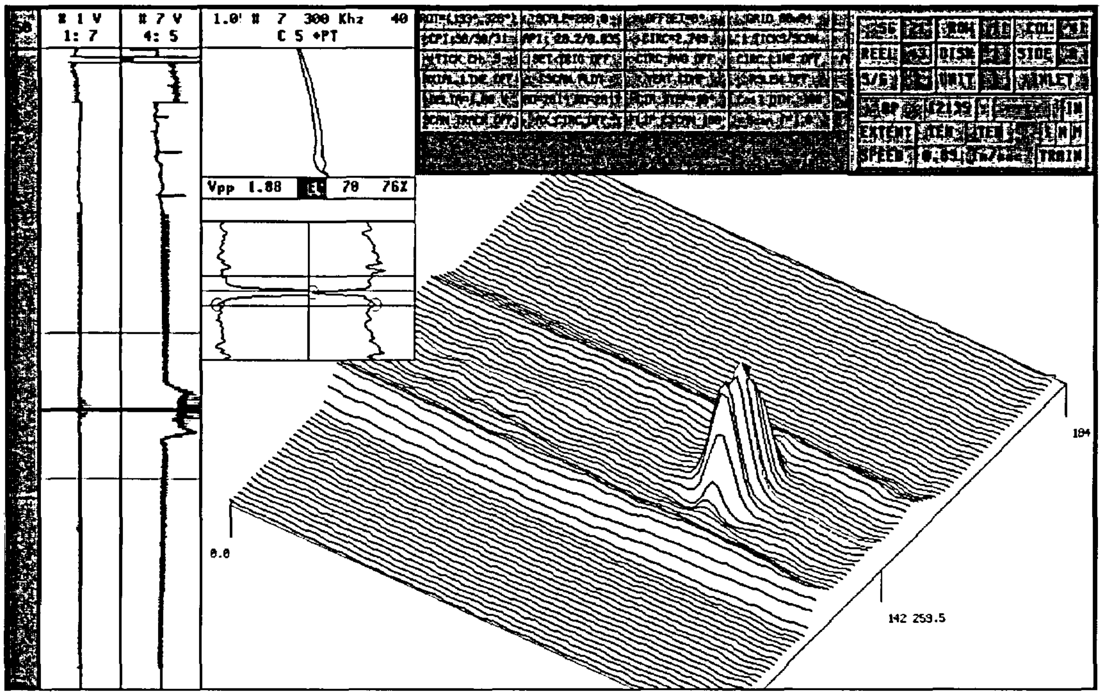


Figure 4-5 Field plus point coil response for the H03 tube support intersection of Watts Bar Unit 1 steam generator 2 tube R11 C41 HL, Piece 4. An axially oriented indication was identified at this location.

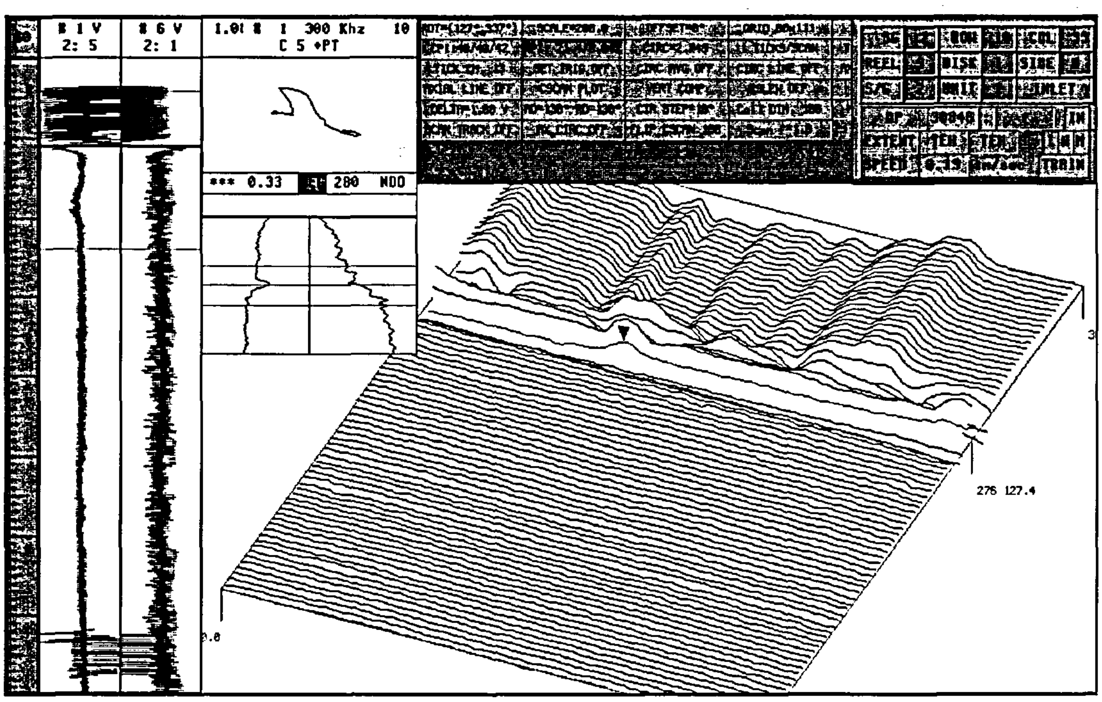


Figure 4-6 Laboratory +Pt response for the top of tube sheet (TTS) of Watts Bar Unit 1 steam generator 2 tube R10 C39 HL, Piece 2. No indication noted. The region was distorted by the tube removal operation.

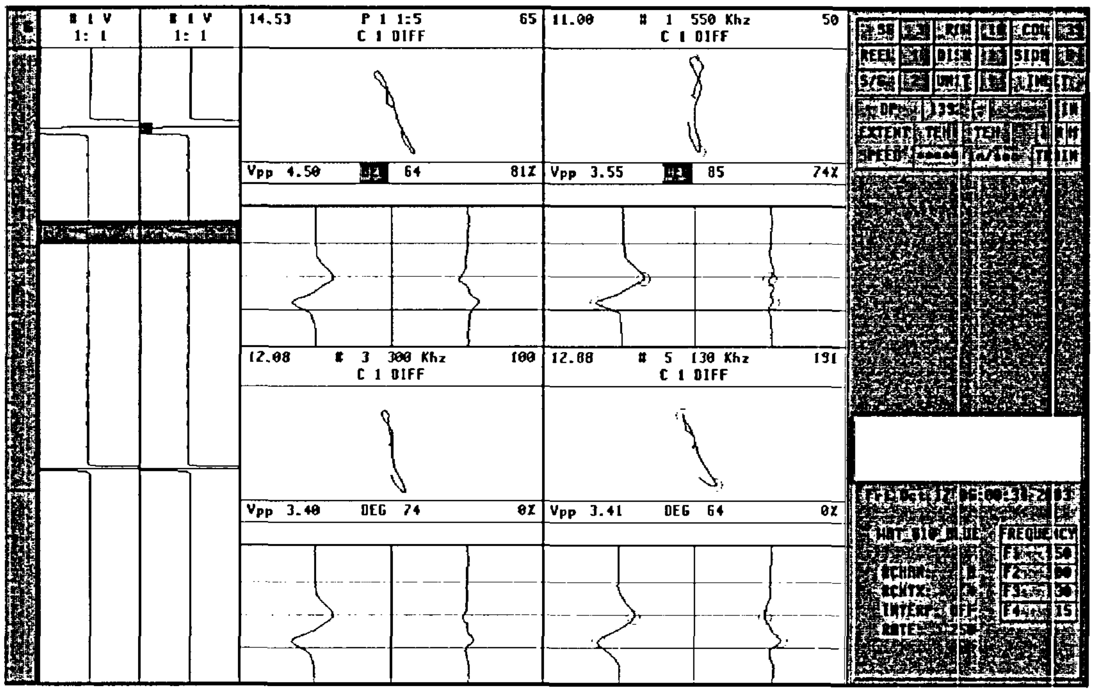


Figure 4-7 Laboratory bobbin coil response for the H02 tube support intersection of Watts Bar Unit 1 steam generator 2 tube R10 C39 HL, Piece 3. A distorted support indication was identified at this location.

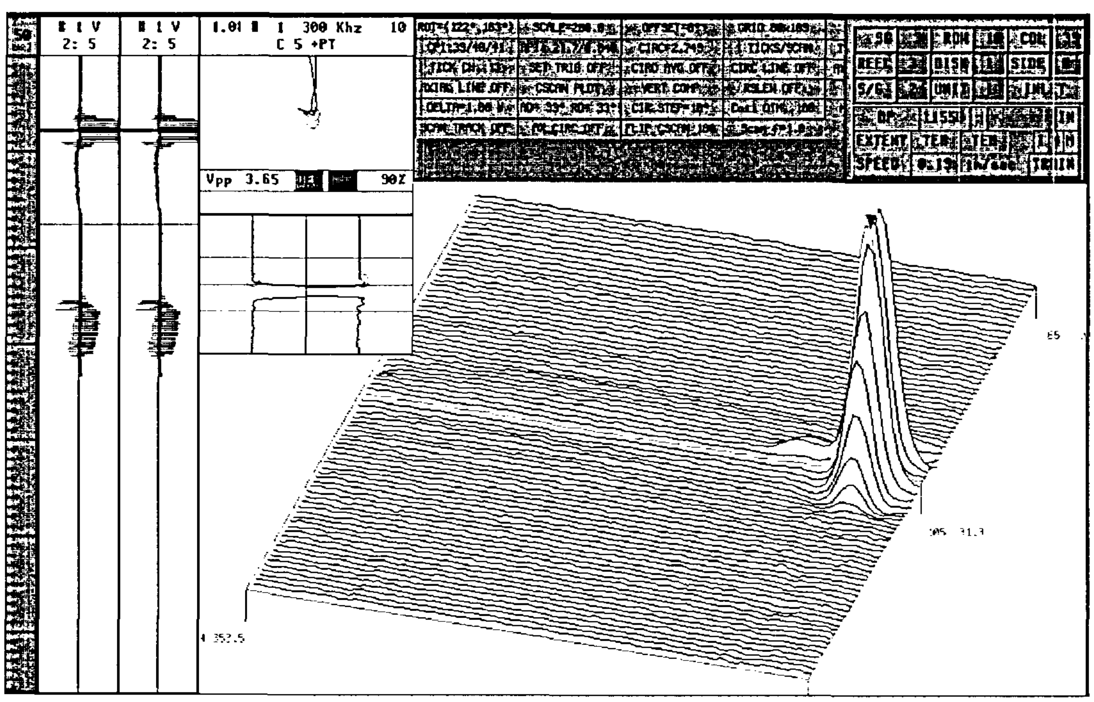


Figure 4-8 Laboratory plus point response for the H02 tube support intersection of Watts Bar Unit 1 steam generator 2 tube R10 C39 HL, Piece 3. Two axial indications were identified at this intersection.

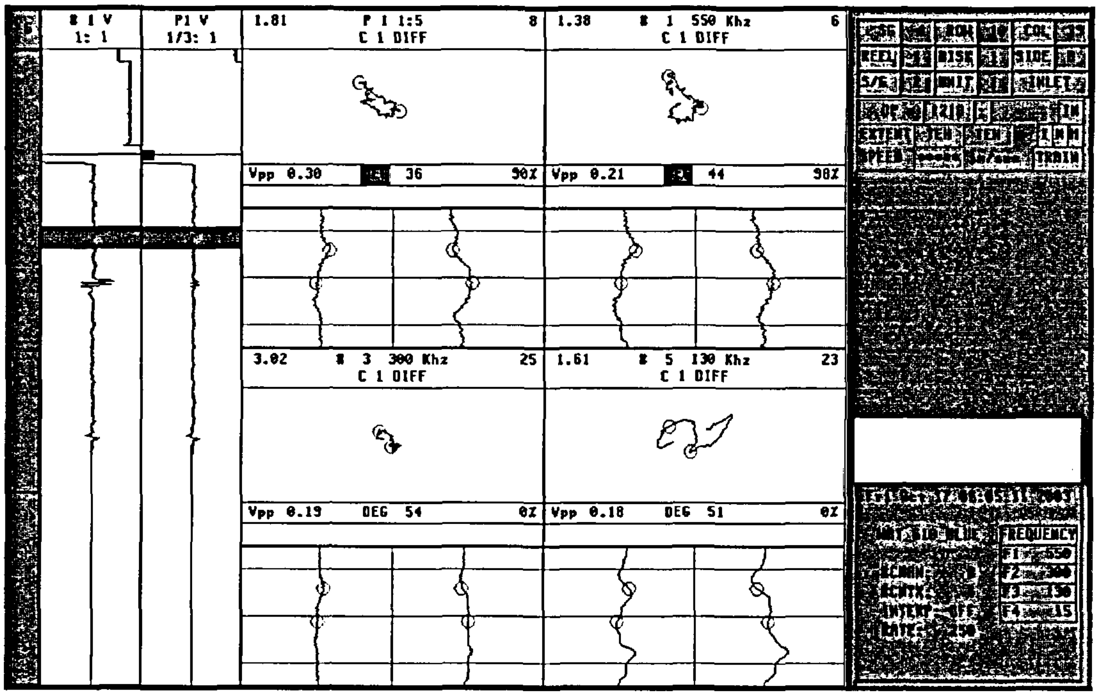


Figure 4-9 Laboratory bobbin coil response for the H03 tube support intersection of Watts Bar Unit 1 steam generator 2 tube R10C39 HL, Piece 4. No indication was identified at this location.

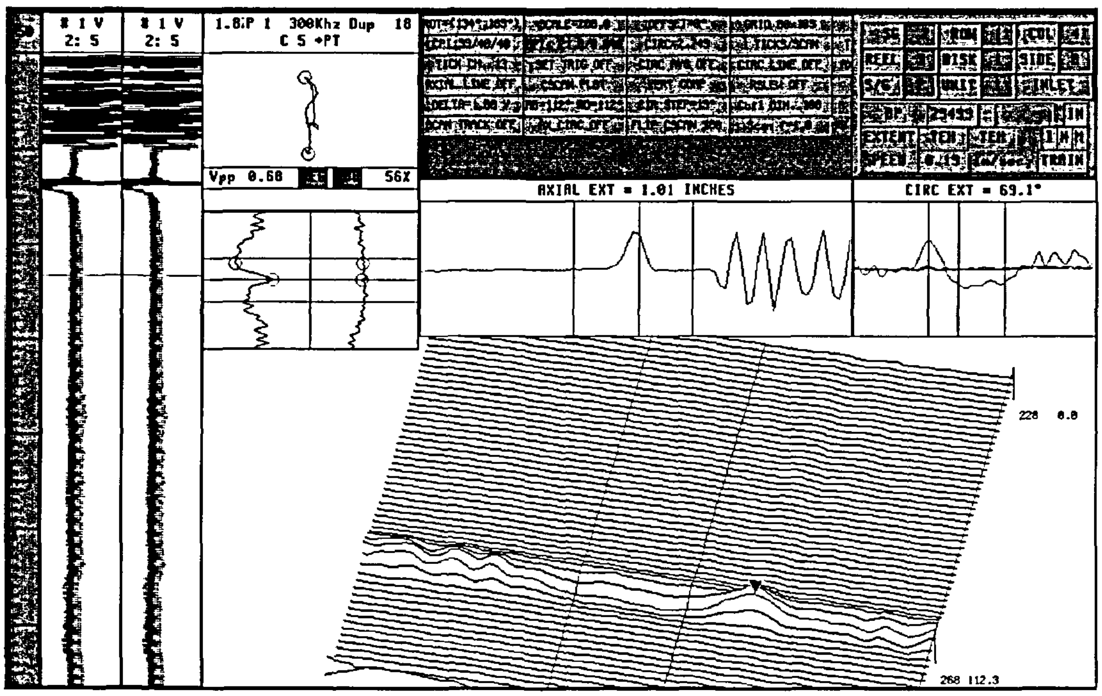


Figure 4-10 Laboratory +Pt response for the top of tube sheet (TTS) of Watts Bar Unit 1 steam generator 2 tube R11 C41 Piece 2. A circumferential indication was identified at this location.

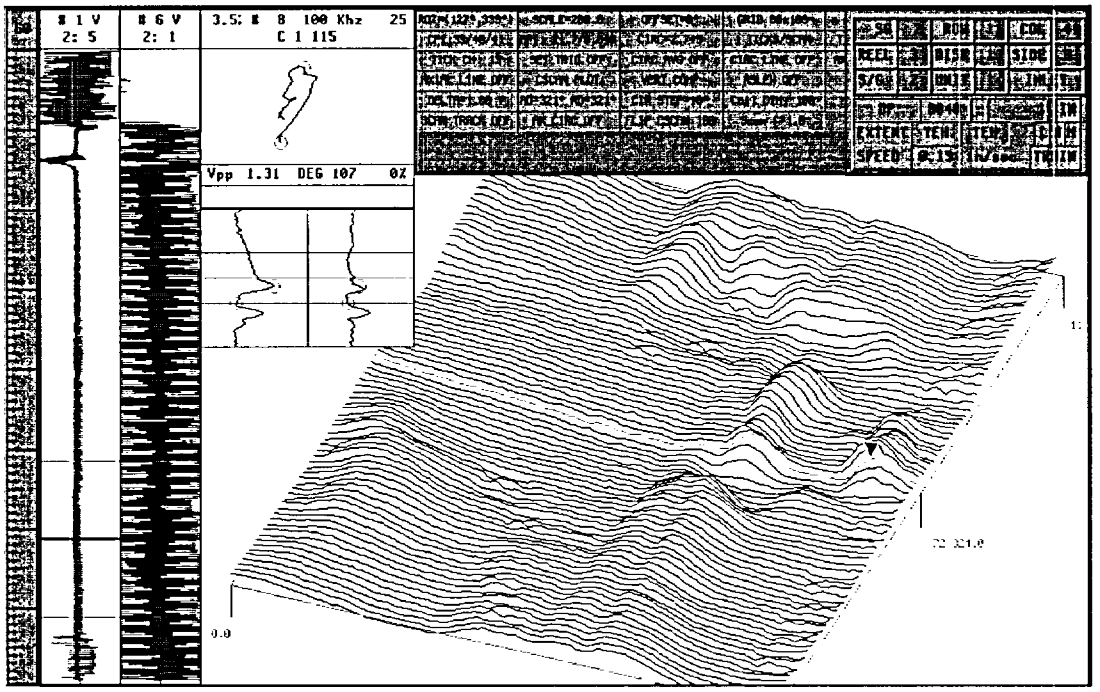


Figure 4-11 Laboratory 115 pancake coil response for the H01 (Flow Distribution Baffle) of Watts Bar Unit 1 steam generator 2 tube R11 C41 HL Piece 2.

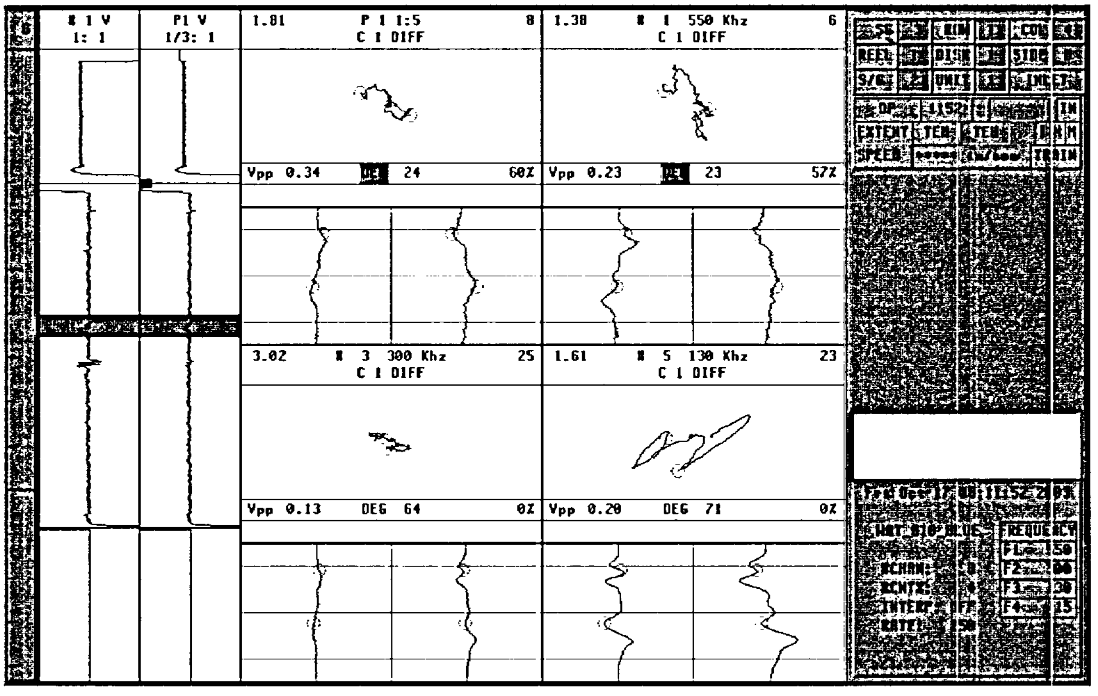


Figure 4-12 Laboratory bobbin coil response for H02 tube support intersection of Watts Bar Unit 1 steam generator 2 tube R11 C41 HL Piece 3. No indication was identified at this location.

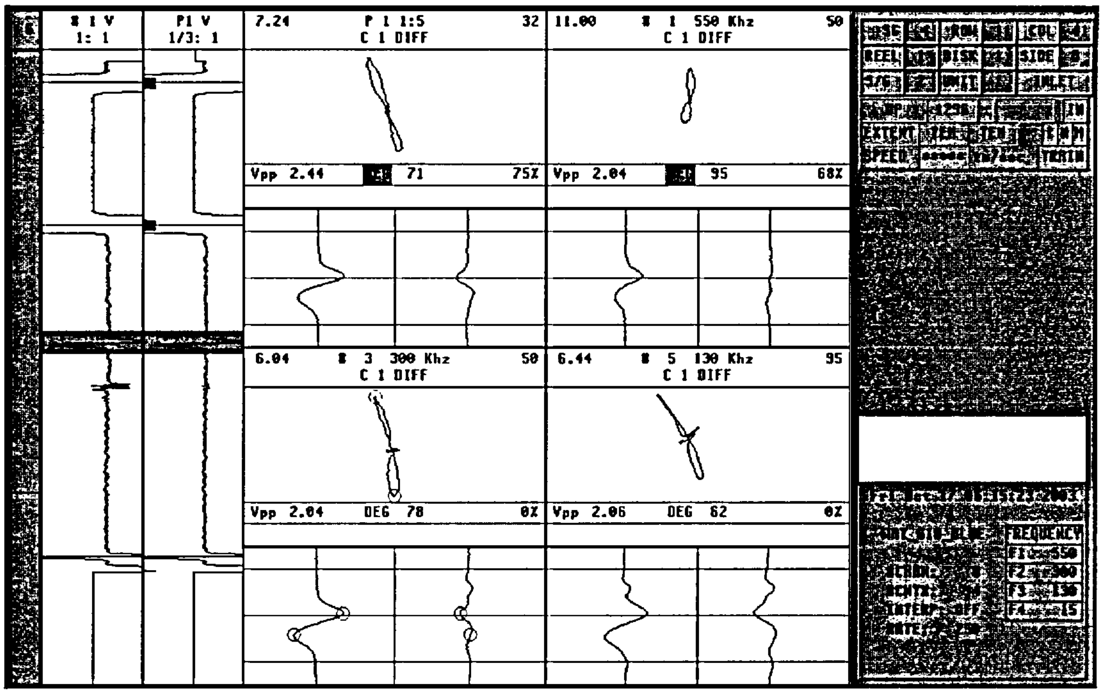


Figure 4-13 Laboratory bobbin coil response for H03 tube support intersection of Watts Bar Unit 1 steam generator 2 tube R11 C41 HL Piece 4. A distorted support indication was identified at this location.

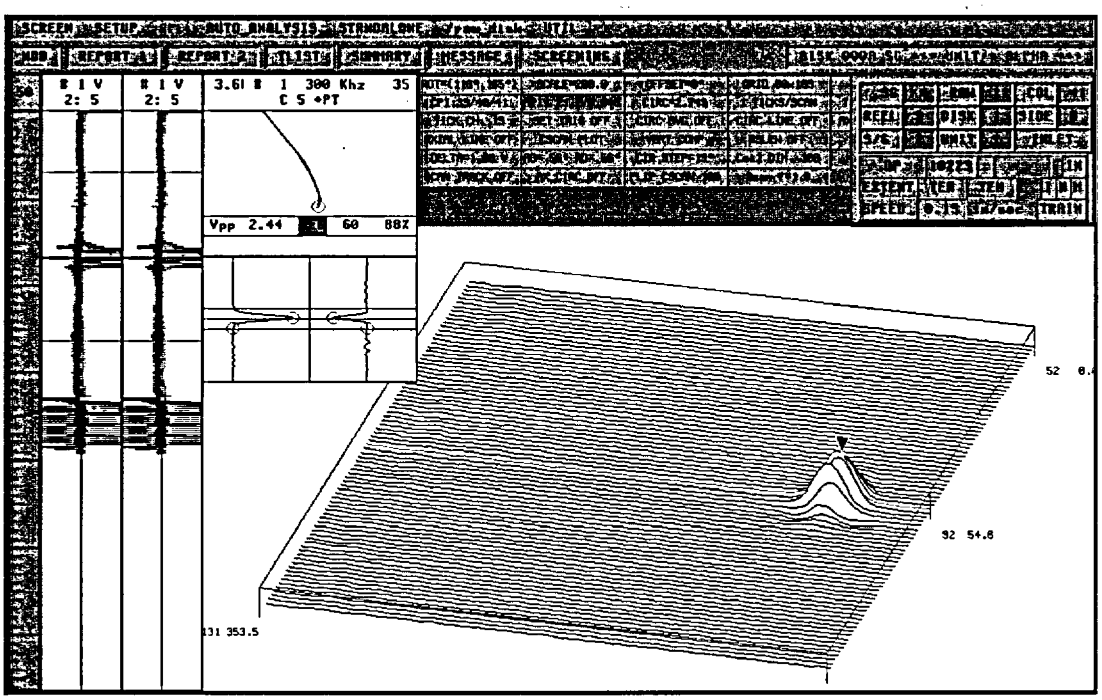


Figure 4-14 Laboratory +Pt response for H03 tube support intersection of Watts Bar Unit 1 steam generator 2 tube R11 C41 HL Piece 4. A single axial indication was identified at this intersection.

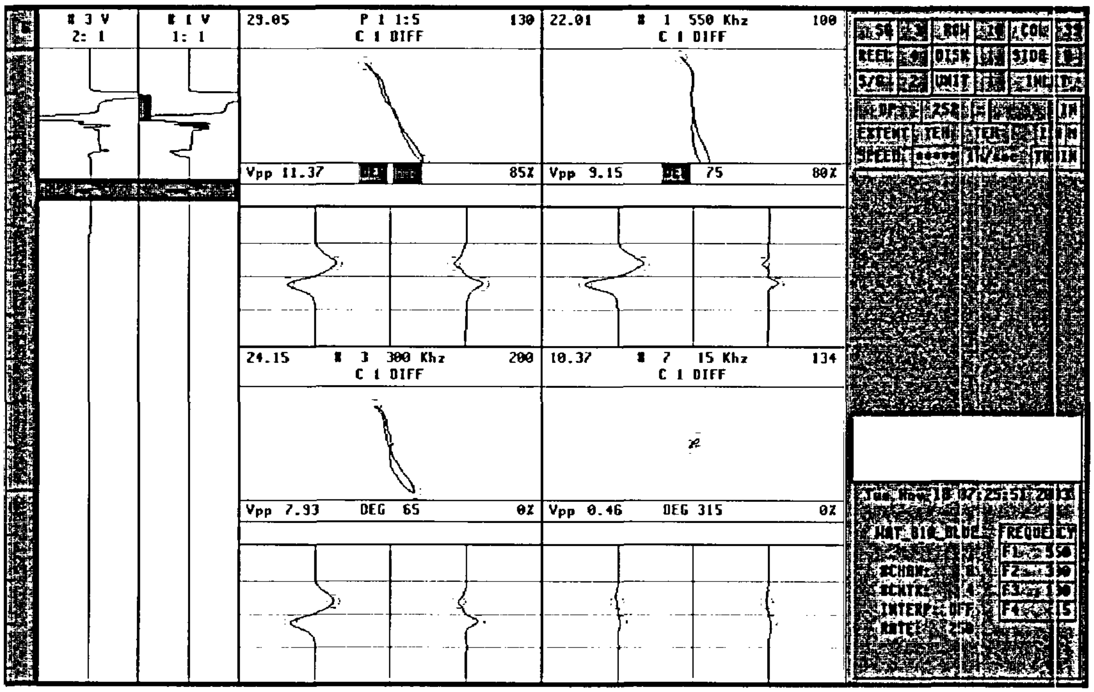


Figure 4-15 Laboratory bobbin coil response for the H02 tube support intersection of Watts Bar Unit 1 steam generator 2 tube R10 C39 Piece 3B after elevated temperature leak testing.

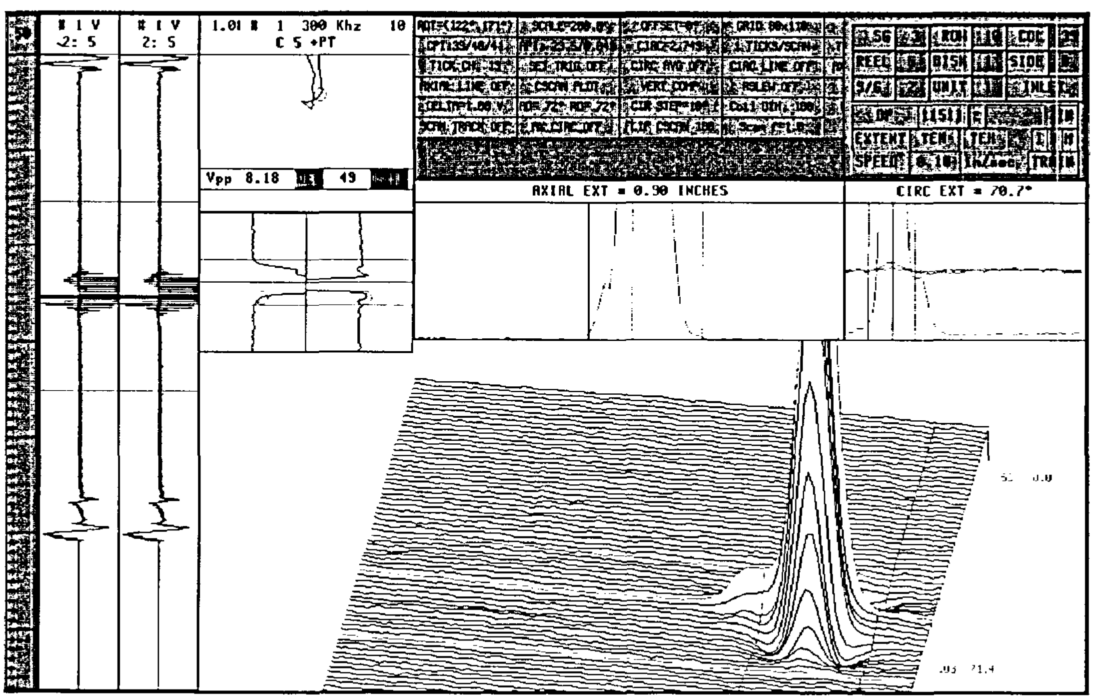


Figure 4-16 +Pt coil response for the H02 tube support intersection of Watts Bar Unit 1 steam generator 2 tube R10 C39 Piece 3B after elevated temperature leak testing.

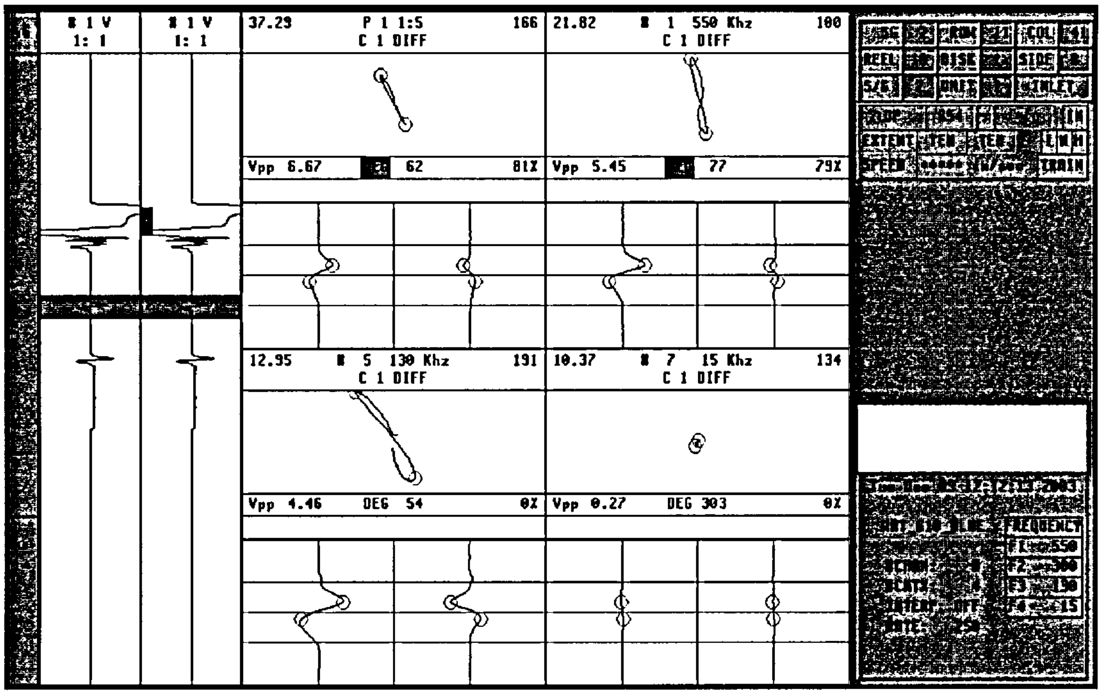


Figure 4-17 Laboratory bobbin coil response for the H03 tube support intersection of Watts Bar Unit 1 steam generator 2 tube R11C41 HL Piece 4B after elevated temperature leak testing.

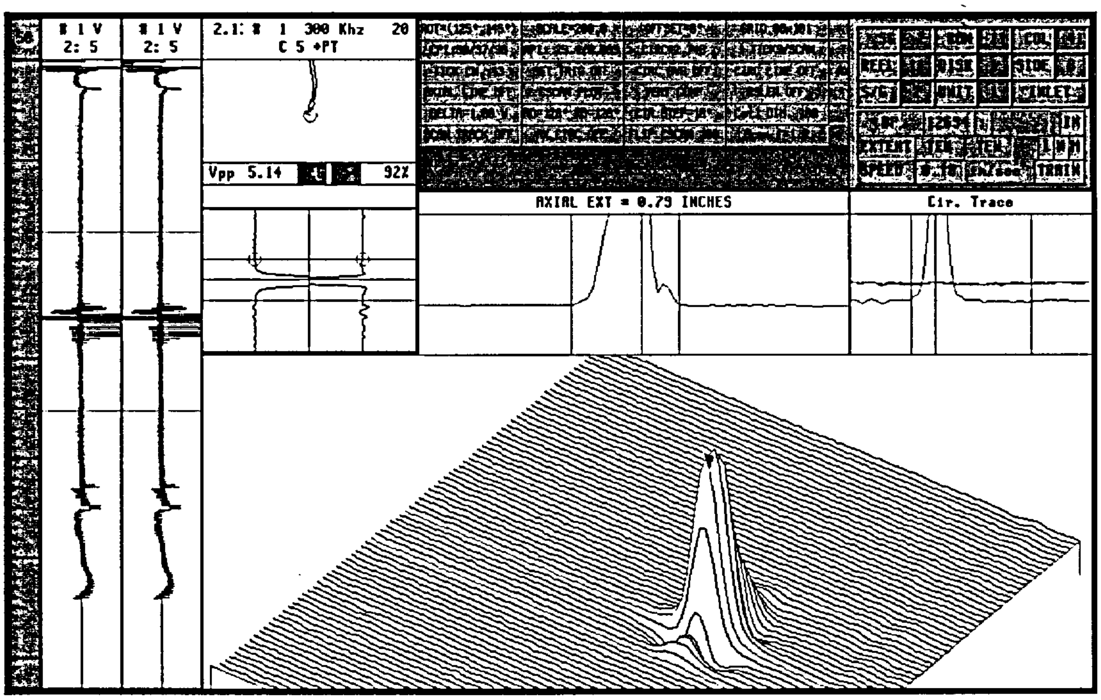


Figure 4-18 Laboratory +Pt coil response for the H03 tube support intersection of Watts Bar Unit 1 steam generator 2 tube R11C41 HL Piece 4B after elevated temperature leak testing.

SECTION 5

LEAK AND BURST TESTS

5.1 Introduction

A steam generator tube with degradation may burst at a lower pressure than an undegraded tube. The burst pressure is a function of the type and size of the degradation, the tube material properties, and applied loads. The primary purpose of these tests is to determine if degraded tube sections met the US NRC Regulatory Guide 1.121 requirements for burst strength. The most limiting aspect of that requirement is that the tube must withstand three times normal operating pressure differential (3ΔNOP) without burst. NRC Generic Letter 95-05 describing the "Voltage Based Repair Criteria for Westinghouse Steam Generator Tubes Affected by Outside Diameter Stress Corrosion Cracking" is presented in Reference 5-1. The site specific operating conditions for the Watts Bar Unit 1 steam generators were provided in Reference 5-2. The normal operating pressure differential (ΔP_{NOP}) for Watts Bar is 1283 psi, therefore the $3\Delta P_{NOP}$ value is 3849 psi at operating temperature, or 4223 psi for room temperature testing (9.7% correction factor). The less limiting requirement of 1.4 times steam line break (SLB) pressure is also of interest. For Watts Bar, 1.4 times SLB (2355 psi) is 3297 psi at operating temperature, or 3617 psi corrected to room temperature. GL 95-05 states, "Leak rate data should be collected at temperature for the differential pressure loadings associated with maximum steam line break (MSLB). When it is not practical to perform hot temperature leak tests, room temperature leak rate testing may be performed". The Westinghouse approach is to perform an elevated temperature leak test whenever the indication is potentially 100% through wall or it is determined that the specimen contains a 100% through wall indication based on a helium pressure test. Table 5-1 provides a listing of the tube pieces tested.

The procedures used for these tests, and a brief discussion of results and observations, are provided in this section. A detailed discussion of the examination of the burst openings and OD surface conditions is provided in Section 6.

5.2 Test Methods

For the elevated temperature testing the ends of the tubes were sealed with Swagelok fittings with connectors that allowed simulated primary water to flow in and out of the test piece. Primary side conditions were obtained by connecting the test piece to a primary side autoclave (AC1) using insulated pressure tubing. The primary side pressure was regulated by a tank of nitrogen gas and the temperature was regulated by an internal autoclave heater. The secondary side was simulated by placing the test piece into a second autoclave (AC2). The pressure in AC2 was adjusted to obtain the required pressure differential between the primary and secondary side by means of a back side pressure regulator. Any water vapor in excess of the AC2 pressure was cooled by passing it through coils immersed in ice water before it entered the back pressure regulator. The condensed water was measured to obtain the primary side leak rate. Pressures and temperatures were monitored and recorded digitally through a data acquisition system. As a back-up, they were also monitored by analog gages.

Elevated temperature leak test conditions for the tubes ranged from Normal Operating Conditions (NOC) to Main Steam Line Break (MSLB) conditions. For the NOC tests, the primary side pressure and temperature were nominally 2235 psi at a temperature of 619°F. The target secondary side pressure was 952 psi, producing a target pressure differential of 1283 psi. At SLB conditions the AC2 pressure was decreased to produce a nominal differential pressure of 2355 psi. Actual test temperatures and pressures varied slightly during the test. After completion of the elevated temperature leak tests, the test pieces were eddy current tested. These results were discussed in Section 4 of this report.

Room temperature burst tests were performed using a system separate from the elevated temperature leak test system. The pressurized water for the burst test was supplied by a large volume, piston-delivery system. Pressure was increased and supplied to the test piece with a single, controlled-stroke piston. The rate of movement was fixed so as to increase the rate of pressurization at 200 psi/second or less. The internal pressure of the test piece was recorded digitally through a data acquisition system. The pressure was also monitored by analog gages with a strip chart recorder as a back-up. The pressure was increased directly to 3500 psi and then by 500 psi increments until burst was achieved. A hold time of two minutes at each 500 psi increment was included for all specimens with confirmed eddy current indications. Burst specimens with no reported indications were attached to the pressurization equipment using Swagelok fittings and were pressurized to failure without any intermediate hold points. For test pieces with reported eddy current indications, it was necessary to cover the indication with a bladder and a foil. A length of Tygon tubing, used as a bladder, and a 0.006-inch thick brass foil, cut to 1.0 inch wide by 1.75 inches long, were inserted into the test piece with the foil placed over the largest ECT indication. The foil was lubricated using stopcock grease.

All burst tests, except for the R11C41 Piece 2B (top of tubesheet indication), were performed without the use of simulated restraints. Piece 2B was semi-restrained by a simulated support system designed to mock the top of tubesheet conditions in the Watts Bar Unit 1 steam generators under accident conditions. A non-pressurized extension was added to the top end of Piece 2B. A tubesheet simulant was placed one inch below the reported SCI (single circumferential indication) and a flow distribution plate and first support plate simulant were positioned along the length of the test piece. The flow distribution simulant was positioned approximately 8 inches above the reported SCI while the first support plate simulant was located approximately 27 inches above the reported SCI.

Following the completion of burst testing, the burst areas were visually characterized and photographed. Photographs and sketches of the full 360° circumference of the tubes were completed to characterize the burst opening as well as any other surface conditions that were not part of the burst opening. The diameter of the tubing near the burst openings was also recorded for each burst. Any OD deposits which spalled-off during the burst test of specimens were captured by adhesive tape during the burst process and retained.

5.3 Elevated Temperature Leak Tests

As discussed earlier, the decision to perform an elevated temperature leak test is based on the eddy current inspection data and the results of a 400 psi helium pressure test. The original plan was to perform the leak test at elevated temperature for Piece 3B (H02) from R10C39 HL and at room temperature for Piece 4B (H03) from R11C41 HL. During the room temperature leak test on Piece 4B, a water droplet formed on the OD of the tube in the area of the eddy current indication at a pressure of 1000 psi. As a result of this observation, the room temperature leak test was terminated and an elevated temperature leak test performed.

R10C39 HL, Piece 3B (H02 Plate)

Table 5-2 presents a summary of the elevated temperature leak test results on Piece 3B from R10C39. Figure 5-1 presents a plot of the leak rate as a function of average pressure differential. A leak rate of 0.0004 gpm at approximately the Normal Operating Condition pressure differential (1283 psi) and 0.0032 gpm at approximately the Steam Line Break pressure (2355 psi) was established for this tube. As can be seen from this figure, the leak rate through the indication displays an exponential function of the pressure differential. This behavior is likely due to a change in the orifice size. It is likely that the width of the indication opened at higher pressures (rather than staying the same size), probably tearing ligaments as it opened. Post leak test eddy current data indicate a marked change in the voltage of the reported indication. This change was discussed previously in Section 4 of this report. Temperature and pressure plots measured during the elevated temperature test are provided in Figures 5-2 and 5-3. Visual examination of the OD surface was performed following the leak test. No unusual features were noted.

R11C41 HL, Piece 4B (H03 Plate)

Table 5-3 presents a summary of the elevated temperature leak test results on Piece 4B from R11C41. Figure 5-4 presents a plot of the leak rate as a function of average pressure differential. A leak rate of 0.0001 gpm at Normal Operating Condition pressure differential (1283 psi) and 0.0002 gpm at Steam Line Break pressure (2355 psi) was established for this tube. As can be seen from this figure, the leak rate through the indication displays an exponential function of the pressure differential and is lower in magnitude than that observed for Piece 3B from R10C39, although the shape of the curve is similar. Temperature and pressure plots measured during the elevated temperature test are provided in Figures 5-5 and 5-6. Visual examination of the OD surface was performed following the leak test. No unusual features were noted.

Post Leak Testing Eddy Current Inspection

After leak testing had been completed, Pieces 3B and 4B were tested with the bobbin and +Pt probes. These results were presented in Table 4-1 and are discussed in Section 4.7. As is seen in Table 4-1 the bobbin coil response grew in amplitude by a factor of approximately 2.7 for both test pieces, whereas the +Pt response changed by a factor of 2.1. While the bobbin amplitude changed, the Lissajous pattern remained the same. This suggests that the leak testing did not propagate the degradation, but more likely ruptured pre-existing ligaments. Upon completion of the eddy current testing following the leak testing, room temperature burst tests were performed.

5.4 Burst Test Results and Post Test Observations

The primary purpose of the burst test is to determine if the degraded tube section met or exceeded the US NRC Regulatory Guide 1.121 requirements for burst strength. Table 5-1 lists the tube locations tested, while test results for all specimens are shown in Tables 5-4 and 5-5. Included in these tables are pre and post bust test dimensional measurements.

R10C39 HL – Piece 3B (H02 Plate)

The H02 plate region of R10C39 HL was identified with an SAI by both field and laboratory eddy current. The burst pressure for Piece 3B was 4,931 psi. This burst pressure is less than the undegraded freespan sections and above the limiting $3\Delta P_{NOP}$. The axial burst opening was centered on the centerline of the H02 plate and was 0.438 inches in length and 0.168 inches in width. The burst opening, Figure 5-7, had an azimuthal orientation of 90°. Both ductile and intergranular fracture features were noted on the burst face. Cracking was not observed outside of the H02 plate to tube intersection region. The length and width of the burst opening was smaller than expected and may have been the result of improper positioning of the thin brass foil.

R10C39 HL – Piece 4B (H03 Plate)

The H03 plate region of R10C39 HL was NDD by both field and laboratory eddy current. The burst pressure for Piece 4B was 12,058 psi. This burst pressure is slightly less than the undegraded freespan sections and well above the limiting $3\Delta P_{NOP}$. The axial burst opening was centered on the centerline of the H03 plate and was 1.510 inches in length and 0.384 inches in width. The burst opening, Figure 5-8, had an azimuthal orientation of 315°. Both ductile and intergranular fracture features were noted on the burst face. Cracking was not observed outside of the H03 plate to tube intersection region.

R10C39 HL – Piece 3C (Freespan)

This piece was selected based on field and laboratory eddy current data to represent a non-degraded freespan area. This burst piece encompassed the freespan region above the 1st TSP (H02). The burst pressure was 12,991 psi. The burst pressure for a non-degraded 0.045 inch thick by ¾" diameter mill annealed Alloy 600 tube is expected to be approximately 13,000 psi. The axial burst opening was 1.87 inches long and 0.393 inches in width. The burst opening had an azimuthal orientation of 120° and is shown in Figure 5-9. The burst facture face was totally ductile with no evidence of corrosion.

R11C41 HL – Piece 2B (TTS)

The TTS region of R11C41 HL was identified with an SCI by both field and laboratory eddy current. The section with the TTS region burst at 13,028 psi. The burst did not occur at the location of the SCI, but in the freespan above the indication. This burst pressure is similar to that observed for a non-degraded freespan section. The axial burst was located approximately 1.8 inches above the TTS and had an azimuthal orientation of 300°. The burst opening measured 1.728 inches in length and 0.342 inches in width. The burst opening is shown in Figure 5-10. The burst facture face was totally ductile with no evidence of corrosion. The TTS area containing the single circumferential indication "bulged" but did not burst. Visual examination of this area revealed multiple short circumferential cracks positioned around the circumference of the expansion transition and basically located at the same elevation. Figure 5-11 is a montage of the OD surface showing the indications observed following pressurization. As can be seen, the cracks are relatively short in circumferential extent and separated by non-degraded material.

R11C41 HL – Piece 3B (H02 Plate)

The H02 plate region of R11C41 HL was NDD by both field and laboratory eddy current. The burst pressure for Piece 3B was 12,649 psi, slightly less than the undegraded freespan sections but well above the limiting $3\Delta P_{NOP}$. The axial burst opening was centered on the centerline of the H02 plate and was 1.461 inches in length and 0.382 inch in width, at an azimuthal orientation of 220°. The burst opening is shown in Figure 5-12. Both ductile and intergranular fracture features were noted on the burst face. Cracking was not observed outside of the H02 plate to tube intersection region.

R11C41 HL – Piece 4B (H03 Plate)

The H03 plate region of R11C41 HL was identified with a SAI by both field and laboratory eddy current. The burst pressure for Piece 4B was 6,999 psi. This burst pressure is less than the undegraded freespan sections but well above the limiting $3\Delta P_{NOP}$. The axial burst opening was centered on the centerline of the H03 plate and was 0.905 inch in length and 0.193 inch in width. The burst opening, Figure 5-13, had an azimuthal orientation of 60° and was centered within the thin brass foil. Both ductile and intergranular fracture features were noted on the burst face. Cracking was not observed outside of the H03 plate to tube intersection region.

R11C41 HL – Piece 5A (Freespan)

This piece was selected based on field and laboratory eddy current data to represent a non-degraded freespan area. The burst pressure for Piece 5A was 13,234 psi and had an azimuthal orientation of 330°. This burst pressure is approximately the same as that for a non-degraded mill annealed Alloy 600 tube. This burst piece encompassed the freespan region above H03 plate. The axial burst opening was 1.748 inches in length and 0.355 inch in width. The burst opening, Figure 5-14, had an azimuthal orientation of 330°. The burst facture face was totally ductile with no evidence of corrosion.

5.5 Leak and Burst Data Correlation

The leak and burst results obtained for R10C39 HL and R11C41 HL specimens were evaluated for inclusion into the ODSCC database. The results of this evaluation were documented in Reference 5-3 and are included in this report as Appendix A. It was concluded that the leak and burst results were consistent with the existing ODSCC ARC database and the data was appropriate to be used in the determination of the parameters of the correlations used in the analysis of SG tube indications.

References:

5-1 NRC Generic Letter 95-05, "Voltage-Based Repair Criteria for Westinghouse Steam Generator Tubes Affected by Outside Diameter Stress Corrosion Cracking" USNRC Office of Nuclear Reactor Regulation, August 3, 1995.

5-2 Email from D.F. Helms to M.H. Cothron of TVA "Watts Bar Nuclear Plant (WBN) – U1C5 Steam Generator Tube Integrity Inspection", dated September 12, 2003.

5-3 "Update of ODSCC Database for ¾" Diameter Tubes", LTR-SGDA-03-326, dated December 11, 2003.

Table 5-1
Listing of Leak and Burst Tests Performed

Tube	Piece Designation	Description	Leak Test	Burst Test
R10C39 HL	3B	SAI @ H02 Plate	Yes @ elevated temperature	Yes @ room temperature
	4B	NDD @ H03 Plate	No	Yes @ room temperature
	3C	Freespan	No	Yes @ room temperature
R11C41 HL	2B	SCI @ TTS)	Yes @ room temperature	Yes @ room temperature
	3B	NDD @ H02 Plate	No	Yes @ room temperature
	4B	SAI @ H03 Plate	Note 1	Yes @ room temperature
	5A	Freespan	No	Yes @ room temperature

Note 1: Since the test piece did not leak during helium pressure test, no elevated temperature leak test was planned. During room temperature leak test, a water droplet formed on the OD of the tube in the area of the eddy current indication at a pressure of 1000 psi. As a result of this observation, the room temperature leak test was terminated and an elevated temperature leak test performed.

Table 5-2
Elevated Temperature Leak Rate Test Data
R10C39 Piece 3B (H02 Plate)

		Delta P	Primary Pressure	Secondary Pressure	Primary Temperature	Leak Rate (gal/min)
Test 1	Min	1182	2204	1022	618	0.0004
	Max	1327	2351	1024	620	
	Average	1260	2283	1023	619	
Test 2	Min	1165	2185	1020	618	0.0004
	Max	1191	2211	1022	619	
	Average	1181	2202	1021	618	
Test 3	Min	1270	2185	914	617	0.0005
	Max	1364	2280	916	619	
	Average	1306	2221	915	618	
Test 4	Min	1418	2237	818	611	0.0008
	Max	1431	2250	819	613	
	Average	1425	2244	819	612	
Test 5	Min	1515	2234	717	604	0.0013
	Max	1605	2324	720	607	
	Average	1563	2282	719	606	
Test 6	Min	1557	2276	718	600	0.0013
	Max	1594	2312	720	603	
	Average	1579	2297	719	601	
Test 7	Min	1604	2223	619	594	0.0013
	Max	1717	2338	621	597	
	Average	1654	2274	620	596	
Test 8	Min	1713	2234	519	584	0.0019
	Max	1792	2311	521	587	
	Average	1753	2273	520	586	
Test 9	Min	1810	2237	426	575	0.0019
	Max	1837	2264	427	578	
	Average	1828	2255	427	576	
Test 10	Min	1892	2319	427	560	0.0032
	Max	1922	2351	429	562	
	Average	1904	2332	428	561	
Test 11	Min	2070	2499	428	560	0.0057
	Max	2091	2520	429	561	
	Average	2085	2514	429	560	
Test 12	Min	2374	2781	396	578	0.0220
	Max	2419	2816	407	582	
	Average	2402	2803	401	580	
Test 13	Min	2379	2770	390	581	0.0216
	Max	2404	2797	394	584	
	Average	2390	2781	392	583	

Table 5-3
Elevated Temperature Leak Rate Test Data
R11C41 Piece 4B (H03 Plate)

		Delta P	Primary Pressure	Secondary Pressure	Primary Temperature	Leak Rate (gal/min)
Test 1	Min	1332	2400	1065	631	0.0001
	Max	1391	2458	1069	632	
	Average	1375	2443	1067	632	
Test 2	Min	1284	2345	1060	631	0.0001
	Max	1323	2386	1064	632	
	Average	1300	2362	1062	632	
Test 3	Min	1462	2377	915	630	0.0002
	Max	1529	2448	919	631	
	Average	1500	2417	917	630	
Test 4	Min	1525	2343	818	629	0.0002
	Max	1628	2447	820	630	
	Average	1596	2415	819	630	
Test 5	Min	1536	2353	815	628	0.0002
	Max	1612	2430	818	630	
	Average	1573	2390	817	629	
Test 6	Min	1726	2401	674	624	0.0002
	Max	1767	2442	677	626	
	Average	1754	2429	675	625	
Test 7	Min	1783	2304	520	614	0.0005
	Max	1872	2392	521	615	
	Average	1817	2337	521	615	
Test 8	Min	1960	2480	519	611	0.0005
	Max	2056	2576	520	614	
	Average	2000	2519	519	613	
Test 9	Min	1961	2479	518	611	0.0004
	Max	2033	2553	520	613	
	Average	1999	2518	519	612	
Test 10	Min	2063	2487	420	599	0.0016
	Max	2115	2537	424	609	
	Average	2095	2517	422	602	
Test 11	Min	2025	2452	425	598	0.0014
	Max	2042	2469	428	600	
	Average	2032	2458	426	599	
Test 12	Min	2264	2694	430	596	0.0013
	Max	2292	2722	431	598	
	Average	2278	2709	430	597	
Test 13	Min	2401	2716	314	584	0.0020
	Max	2428	2744	316	589	
	Average	2411	2726	315	586	

Table 5-4
Results of Burst Tests of Tube R10C39 HL

Piece	3B	Piece 4B	3C
Location	H02 Plate	H03 Plate	Freespan
Burst Pressure, psi	4,931	12,058	12,991
Orientation	Axial @ 90°	Axial @ 315°	Axial @ 120°
Burst Length, inch	0.438	1.510	1.87
Burst Width, inch	0.168	0.384	0.393
Pressurization Rate, psi/s	200	200	200
Pre-Burst Outer Diam., inch	0.7502/0.7600 (Note 1)	0.7501/0.7570 (Note 1)	0.754/0.752
Post-Burst Maximum Diam., inch	0.932	0.952	1.114
Post-Burst, 90° from Max. Diam., inch	0.771	0.846	0.981

Note 1: Largest diameter likely reflects deposit on the OD tube surface.

Table 5-5
Results of Burst Tests of R11C41 HL

Piece	2B	3B	4B	5A
Location	(TTS)	H02 Plate	H03 Plate	Freespan
Burst Pressure , psi	13,028	12,649	6,999	13,234
Orientation	Axial above TTS @ 300°	Axial @ 220°	Axial @ 60°	Axial @ 330°
Burst Length, inch	1.728	1.461	0.905	1.748
Burst Width, inch	0.342	0.382	0.193	0.355
Pressurization Rate, psi/s	200	200	200	200
Pre-Burst Outer Diam. , inch	0.752/0.753	0.7500/0.7602 (Note 1)	0.7500/0.7607 (Note 1)	0.755/0.753
Post-Burst Maximum Diam., inch	1.078	0.956	0.871	1.046
Post-Burst, 90° from Max. Diam., inch	0.931	0.849	0.763	0.928

Note 1: Largest diameter likely reflects deposit on the OD tube surface

Figure 5-1
Elevated Temperature Leak Rate Curve for R10C39 HL – Piece 3B (H02 Plate)

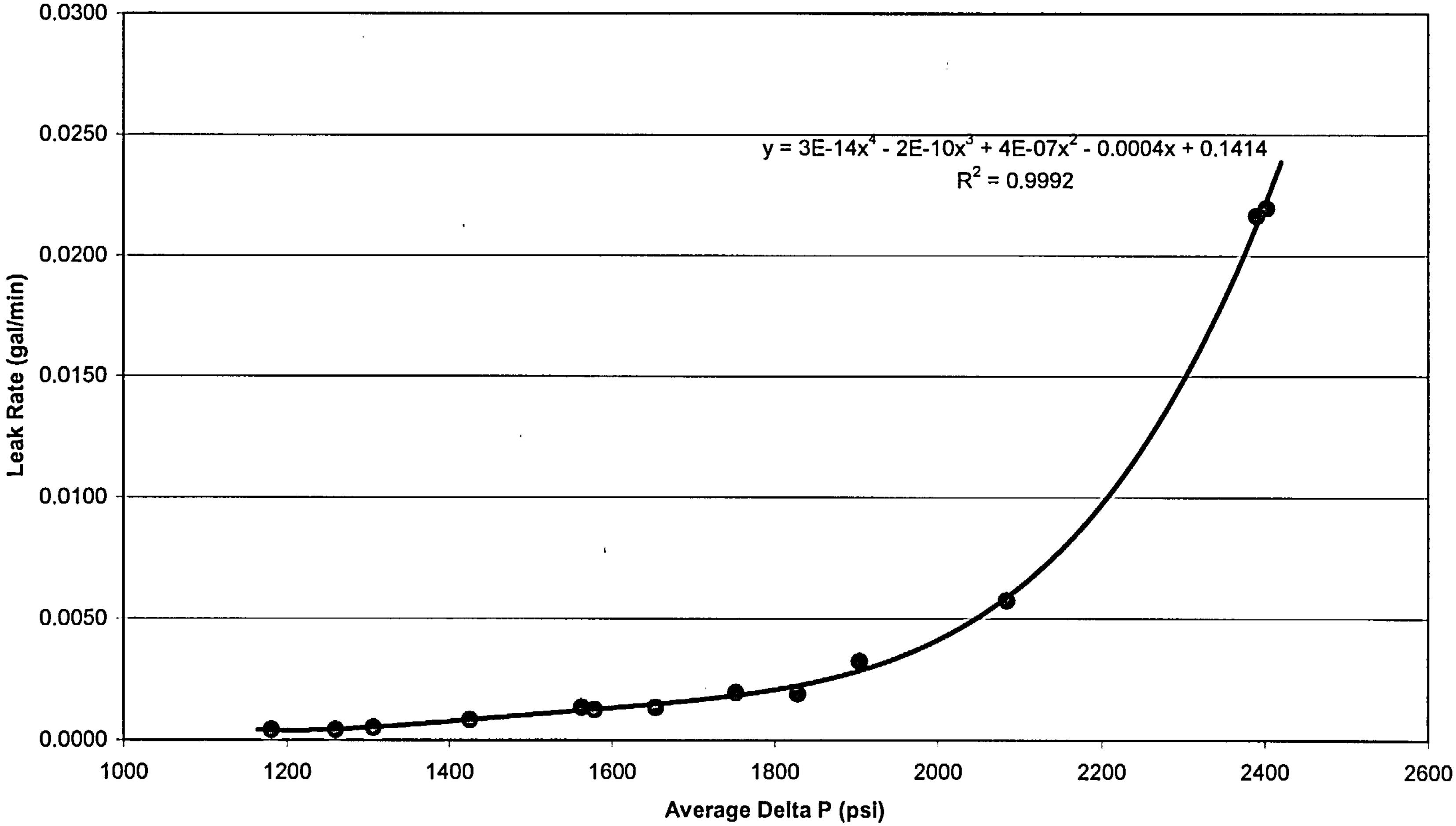
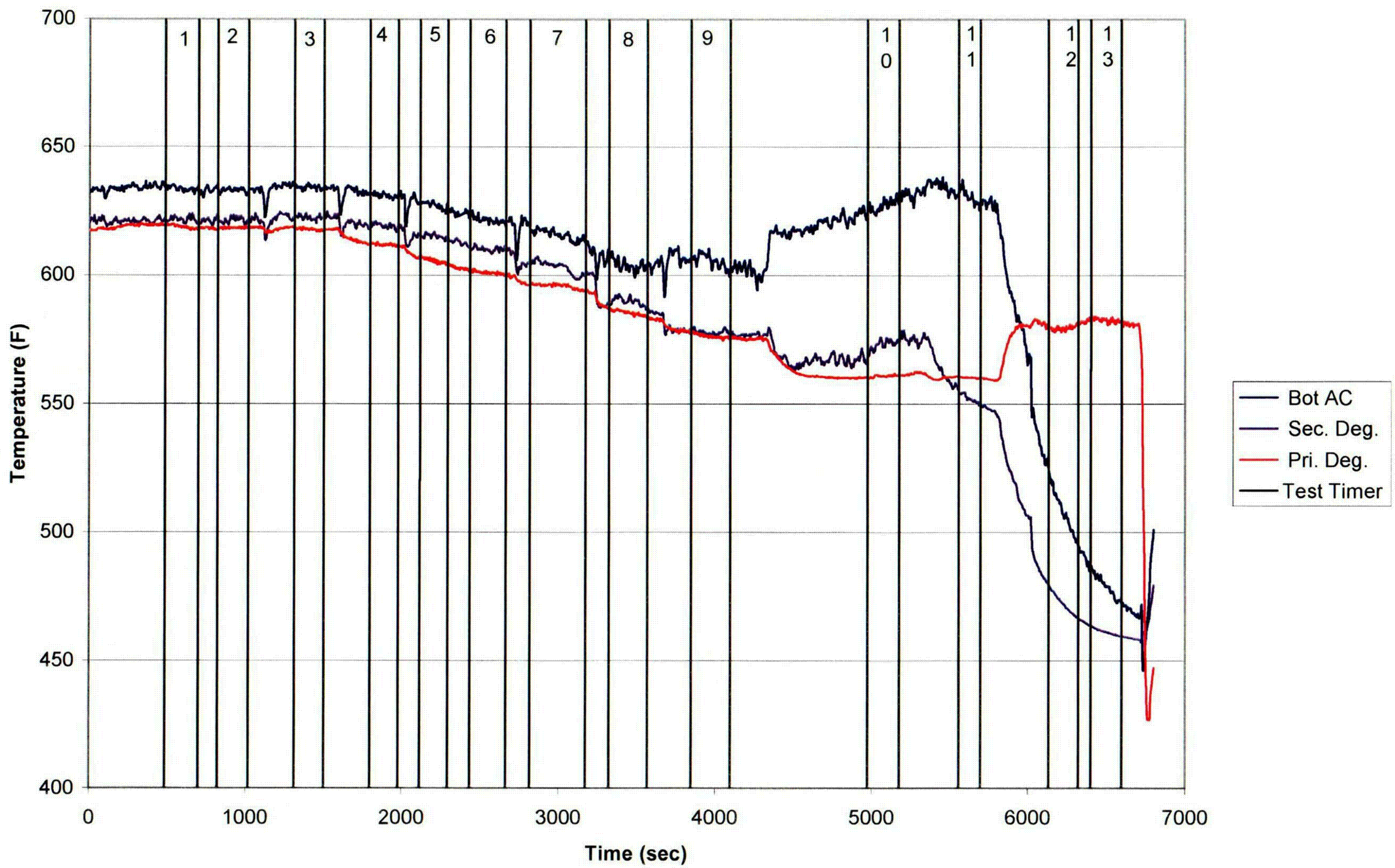
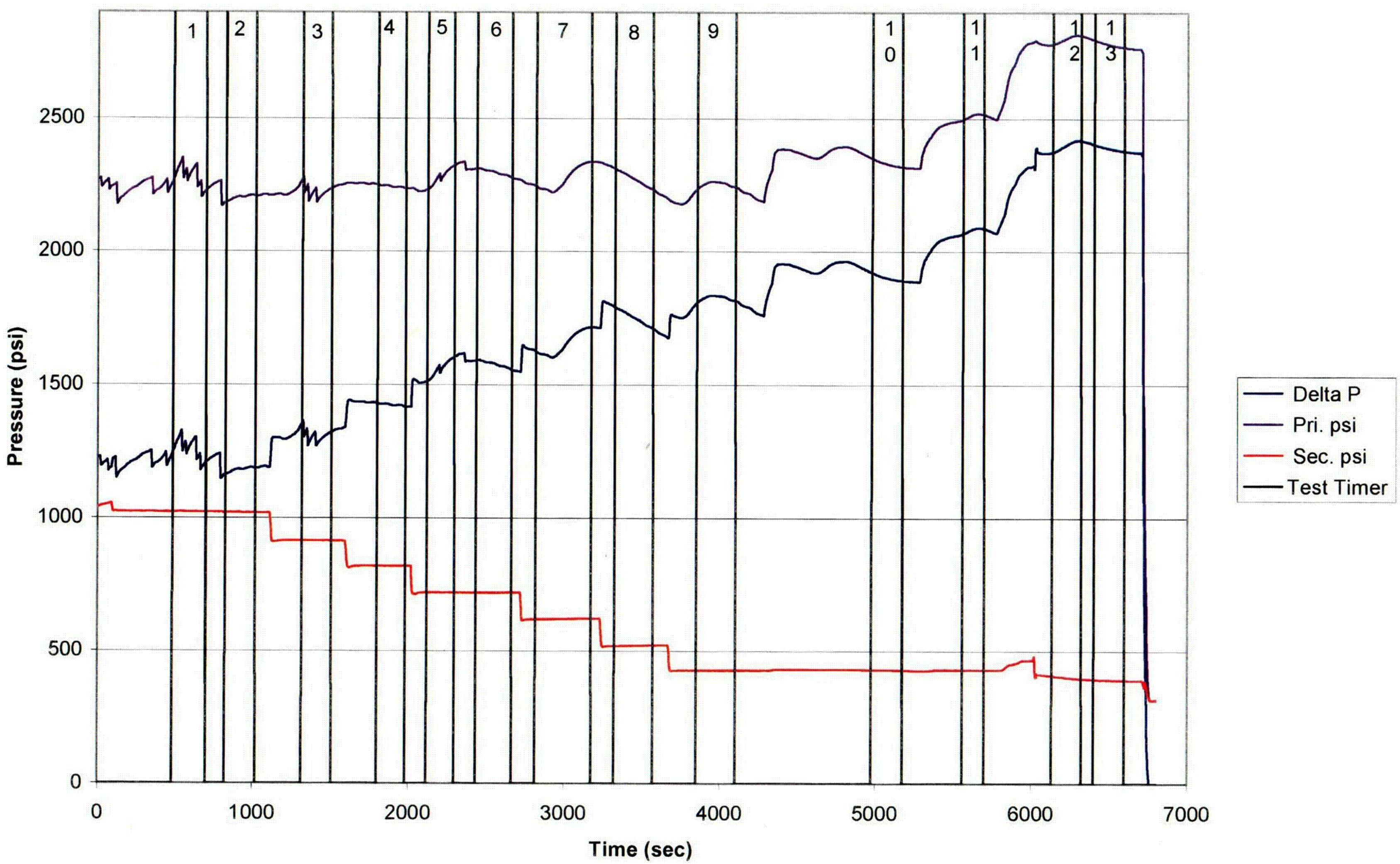


Figure 5-2
Temperature Profile for R10C39 HL – Piece 3B Elevated Temperature Leak Test



C19

Figure 5-3
Pressure Profile for R10C39 HL – Piece 3B Elevated Temperature Leak Test



C20

Figure 5-4
Elevated Temperature Leak Rate Curve for R11C41 HL – Piece 4B (H03 Plate)

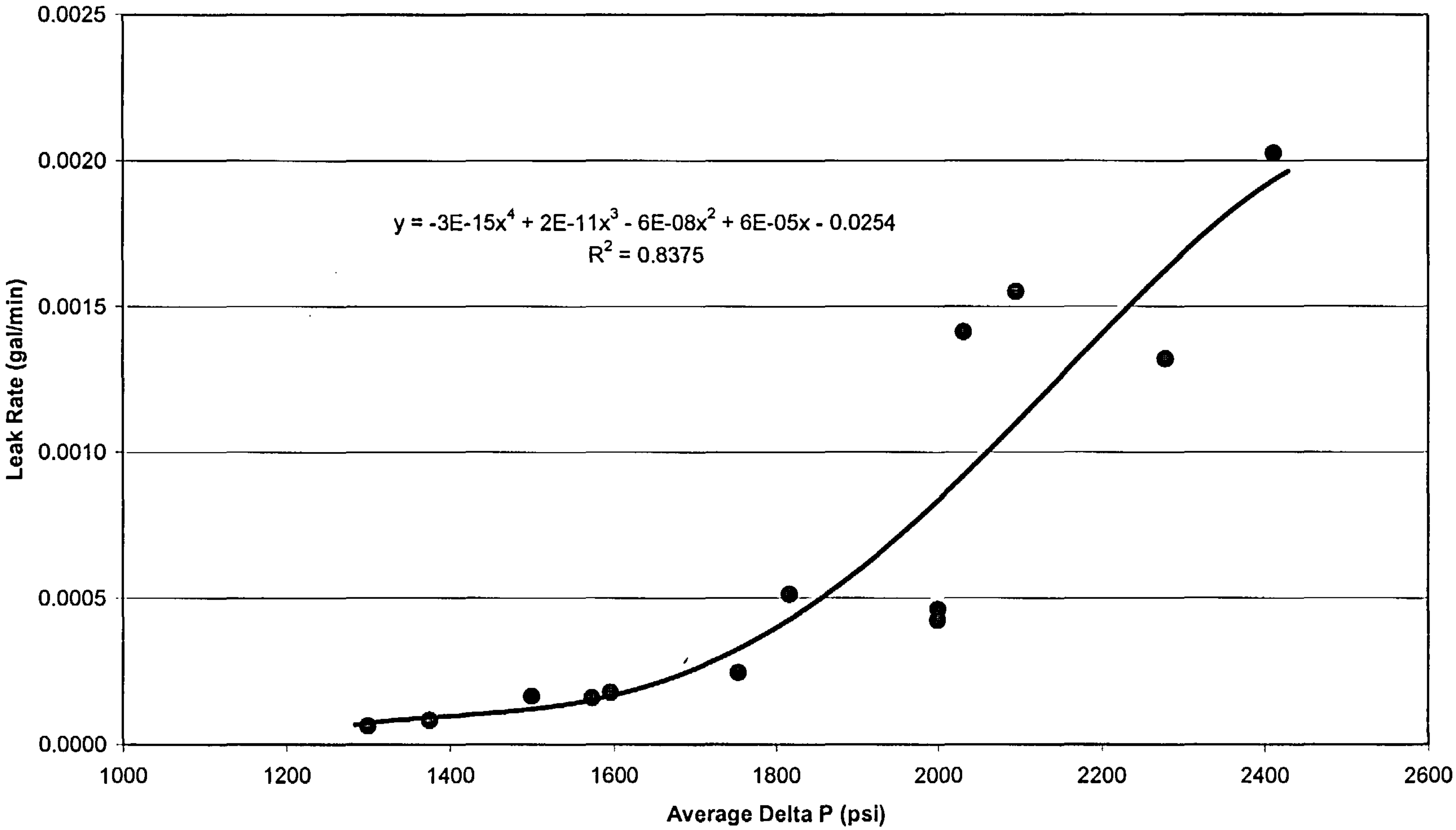
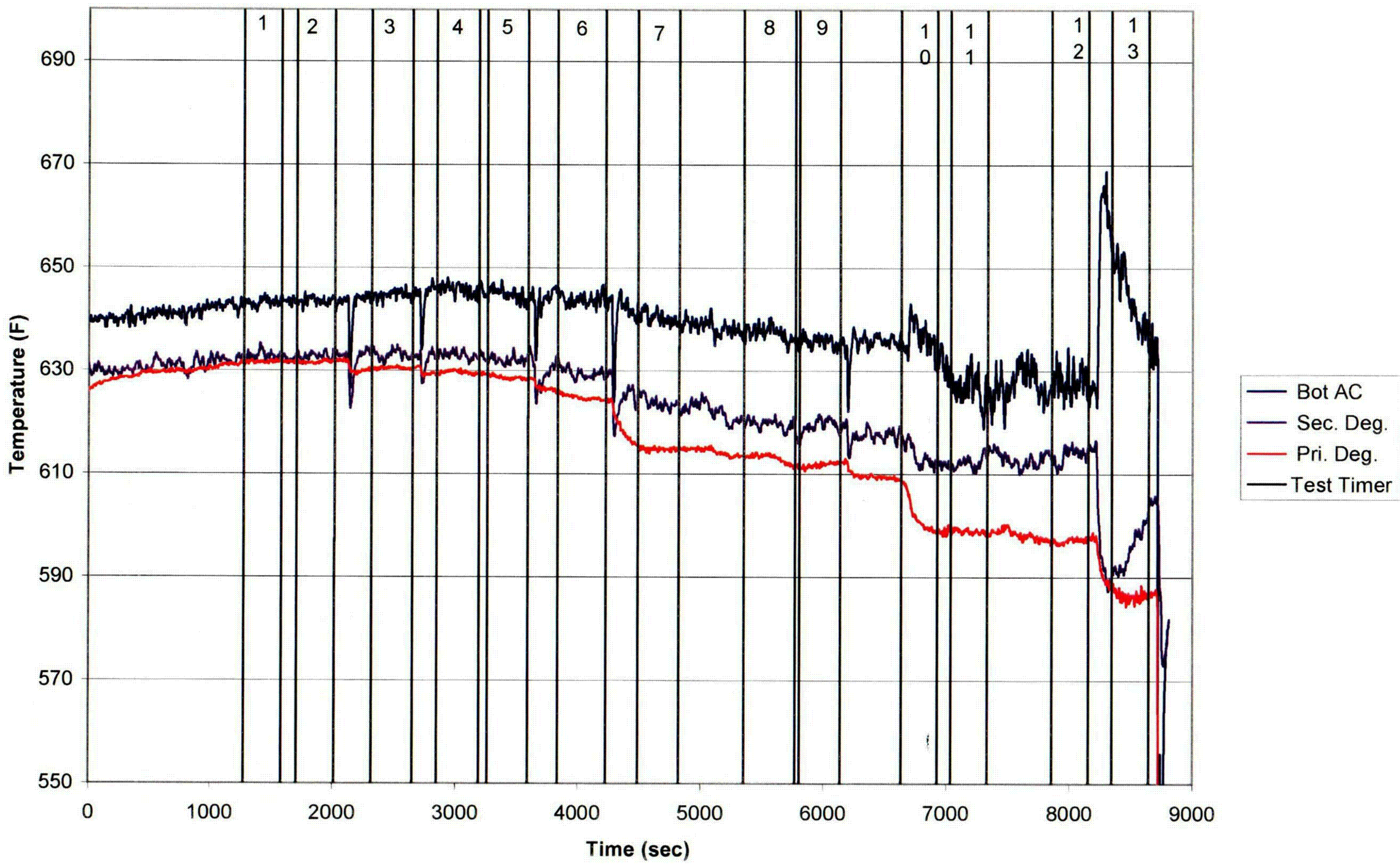
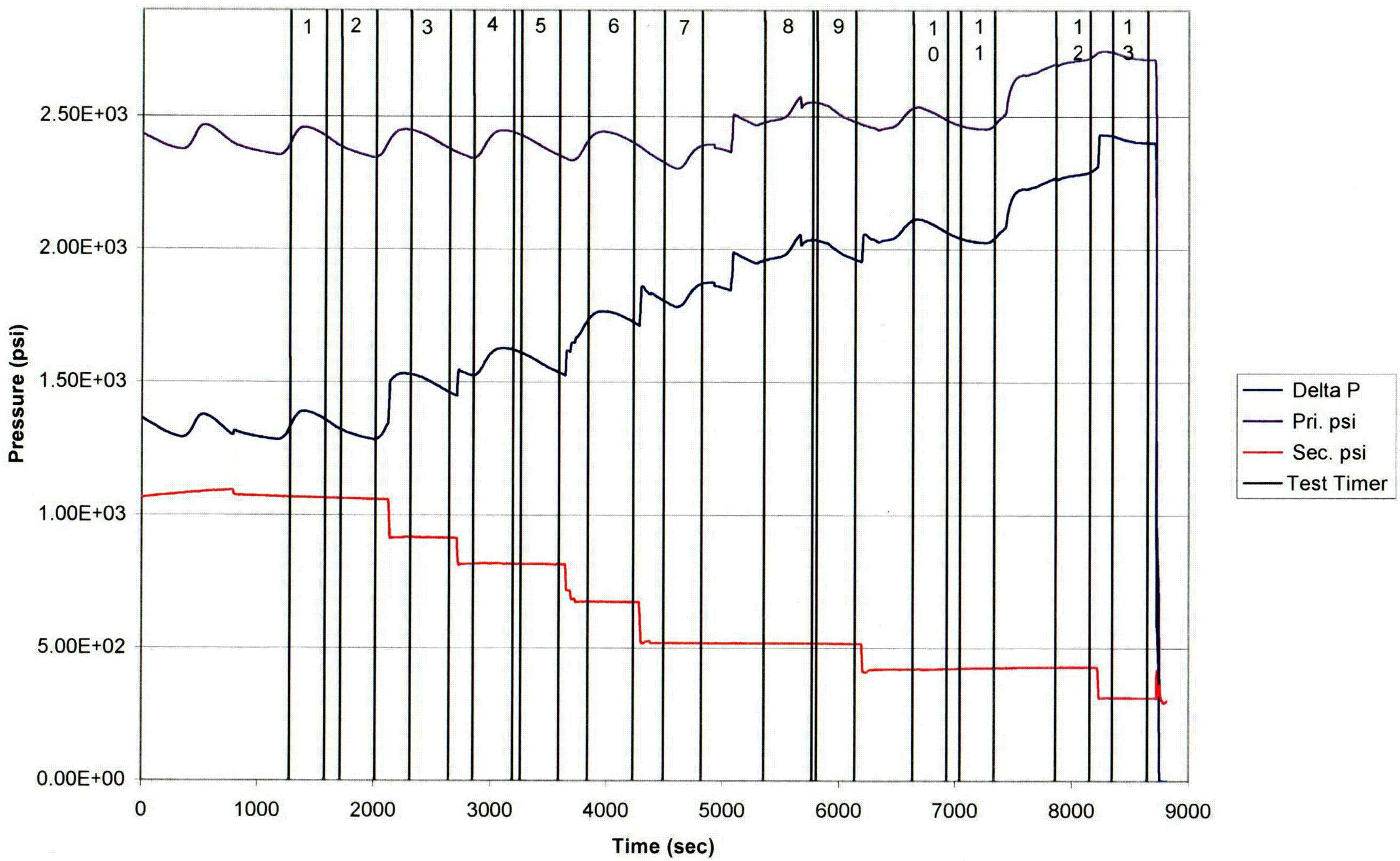


Figure 5-5
Temperature Profile for R11C41 – Piece 4B Elevated Temperature Leak Test



C21

Figure 5-6
Pressure Profile for R11C41 – Piece 4D Elevated Temperature Leak Test



C22

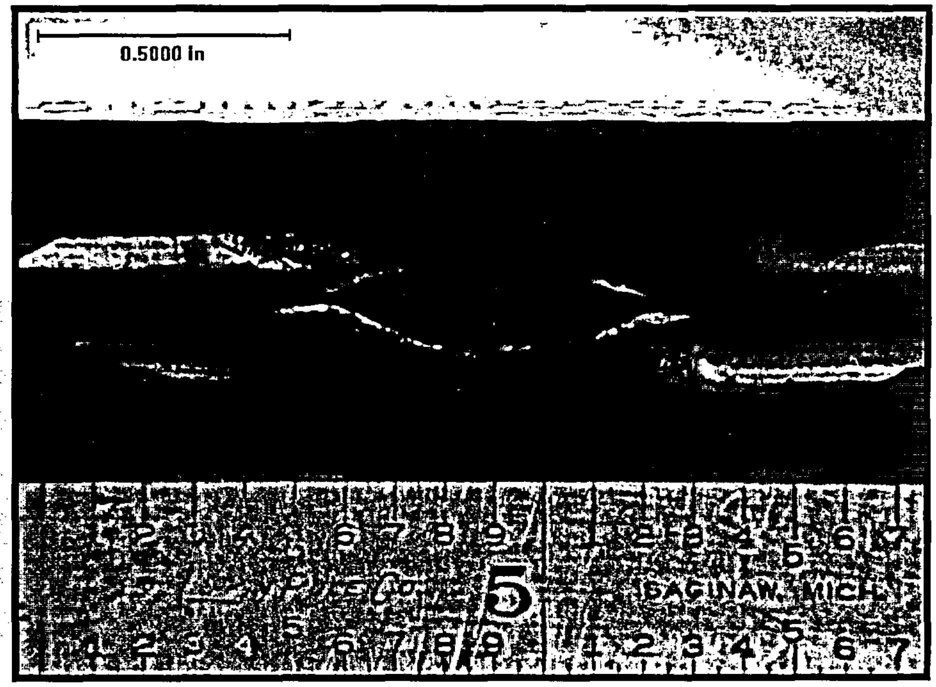


Figure 5-7
Burst Opening for R10C39 HL, Piece 3B (H02 Plate) @ 90° Orientation

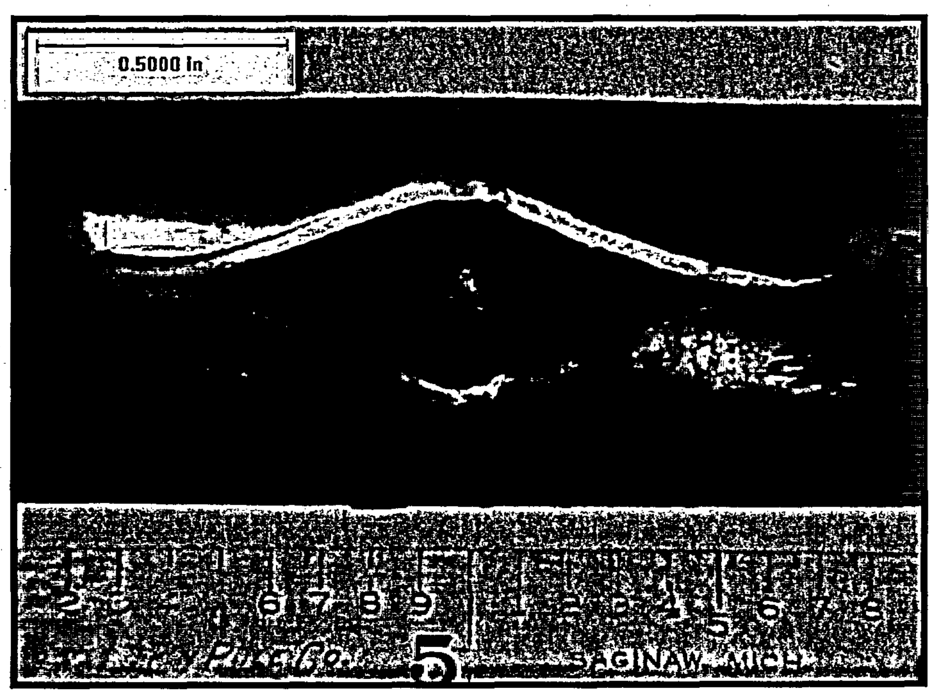


Figure 5-8
Burst Opening for R10C39 HL, Piece 4B (H03 Plate) @ 315° Orientation

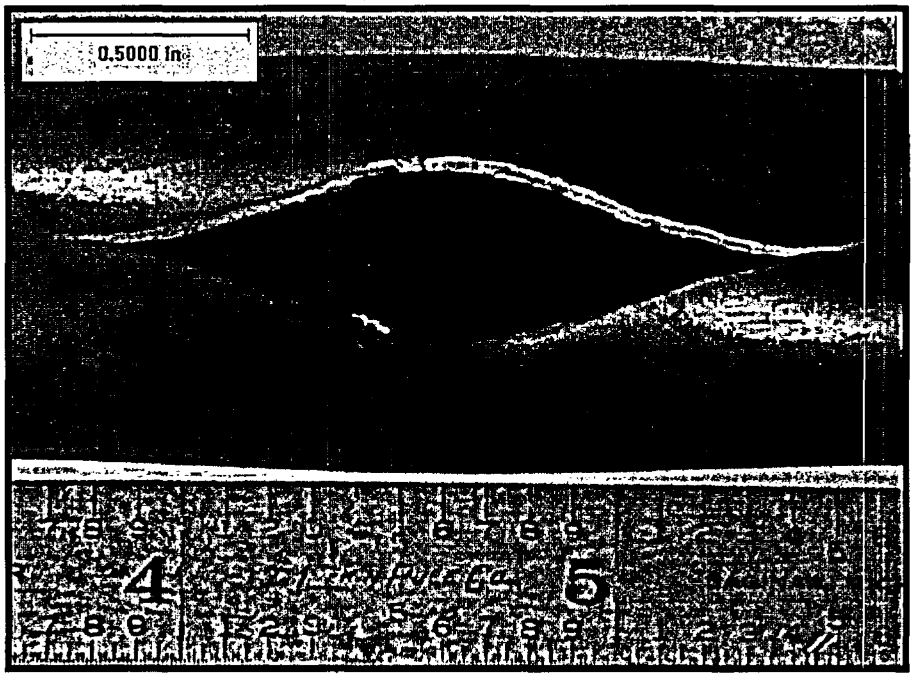


Figure 5-9
Burst Opening for R10C39 HL, Piece 3C (Freespan) @ 120° Orientation

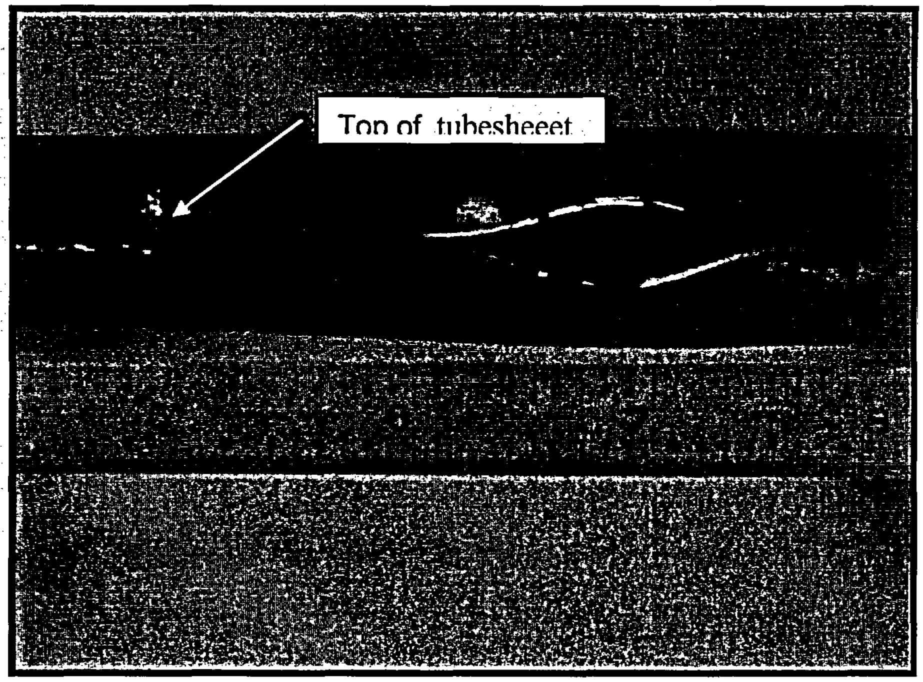


Figure 5-10
Burst Opening for R11C41 HL, Piece 2B @ 300° Orientation
Note: Center of burst opening located approximately 1.8 inches above TS

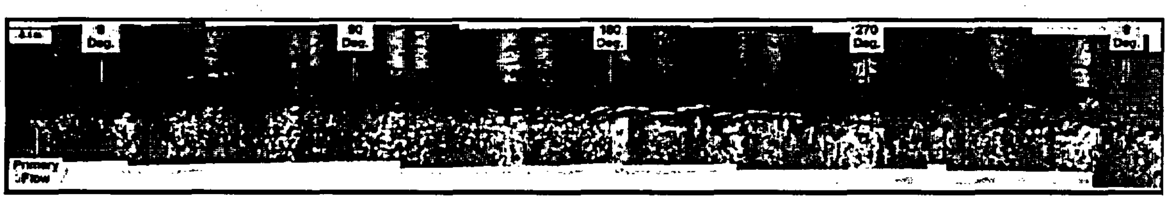


Figure 5-11
OD Appearance of R11C41 HL, Piece 2B @ Top of Tubesheet Following Burst Test

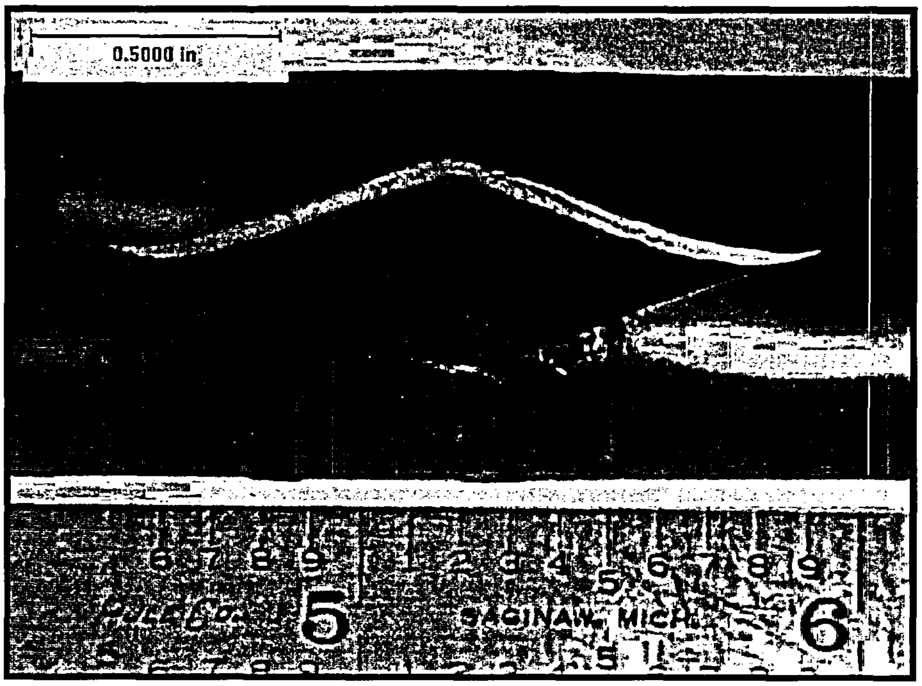


Figure 5-12
Burst Opening for R11C41 HL, Piece 3B (H02 Plate) @ 220° Orientation

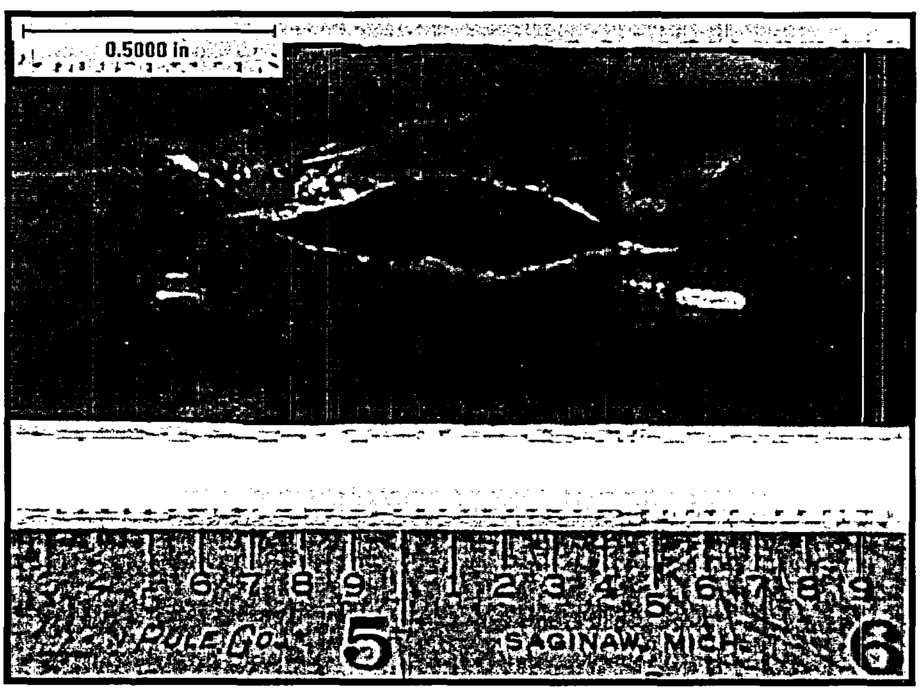


Figure 5-13
Burst Opening for R11C41 HL, Piece 4B (H03 Plate) @ 60° Orientation

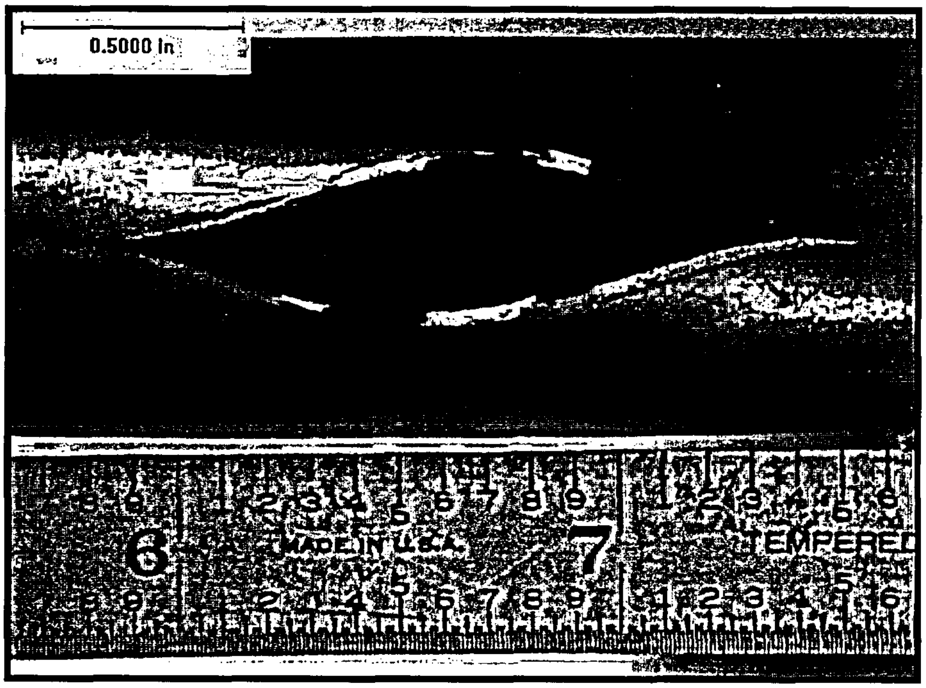


Figure 5-14
Burst Opening for R11C41 HL, Piece 5A (Freespan) @ 330° Orientation