TVA

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May 5, 2003

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, D.C. 20555

Gentlemen:

| | | |
|---|---|---|
| In the Matter of | ) | Docket No. 50-328 |
| Tennessee Valley Authority | ) | |

**SEQUOYAH NUCLEAR PLANT - UNIT 2 CYCLE 11 (U2C11) 12-MONTH STEAM GENERATOR (SG) INSPECTION REPORT AND METALLURGICAL EXAMINATION REPORT ON TUBE REMOVED FROM SG**

Reference: Sequoyah Nuclear Plant (SQN) - Unit 2 - Unit 2 Cycle 11 (U2C11) 90-Day Steam Generator Report for Voltage Based Alternate Repair Criteria

In accordance with the requirements of Sequoyah Unit 2 Technical Specification 4.4.5.5.b, TVA is submitting the 12-month SG Inspection Report that includes the results of inservice inspections performed during the U2C11 refueling outage.

In addition, TVA is providing the final report for the metallurgical examination of SG tube R12C45 that was pulled from SG No. 4 during the SQN U2C11 refueling outage. The final report is a follow-up to the preliminary report that was provided by TVA's reference letter.

Enclosure 1 provides the 12-month SG Inspection Report.
Enclosure 2 provides the Metallurgical Examination Report.

There are no commitments contained in this letter. This letter is being sent in accordance with NRC RIS 2001-05.

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Please direct questions concerning this issue to me at (423) 843-7170 or J. D. Smith at (423) 843-6672.

Sincerely,

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I:License/Steam Generators/U2C11 12-Month SG Report and Final Metallurgical Report

# ENCLOSURE 1

# TENNESSEE VALLEY AUTHORITY
# SEQUOYAH NUCLEAR PLANT (SQN) UNIT 2

# UNIT 2 CYCLE 11 REFUELING OUTAGE

# 12-MONTH STEAM GENERATOR INSPECTION REPORT

# Sequoyah Nuclear Plant

## Unit 2 Cycle 11 Refueling Outage
## April 2002

## 12 Month Report

Prepared By: Emmett Carr 11 Oct 02

Verified By: William David James 10/15/02

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# INTRODUCTION

During the scheduled Sequoyah Nuclear Plant (SQN) Unit 2 End of Cycle 11 (EOC-11) refueling outage, extensive inservice inspections were conducted in all four steam generators (SGs). The SQN Unit 2 Cycle 11 Degradation Assessment projected the extent of the various active and potential degradation mechanisms based on industry experience of plants with Westinghouse Model 51 SGs. The inspection was focused on the detection and evaluation of the active and potential degradation mechanisms.

The results of the inspections were classified as follows:

| | SG1 | SG2 | SG3 | SG4 |
|---|---|---|---|---|
| Bobbin Coil | C-2 | C-2 | C-2 | C-3 |
| U-Bend +Pt | C-3 | C-1 | C-1 | C-1 |
| TTS +Pt | C-2 | C-2 | C-2 | C-2 |
| Dented TSP +Pt | C-2 | C-3 | C-1 | C-1 |
| Freespan Dents +Pt | C-1 | C-1 | C-3 | C-1 |

The Alternate Repair Criteria (ARC) for axial outside diameter stress corrosion cracking (ODSCC) at tube support plates (TSPs) continued during this inspection. The report required within 90 days by Generic Letter 95-05, Attachment 1, Section 6.b. was transmitted to NRC by a separate transmittal.

During SQN Unit 2 Cycle 11 Refuel Outage tube support plate intersections were removed from a SQN steam generator to confirm axial ODSCC as required by Generic Letter 95-05 and industry correspondence with the NRC. Attached is the metallurgical examinations performed for tube intersections removed from the Steam Generator.

This report fulfills the reporting requirements of SQN Technical Specification section 4.4.5.5.b for reporting results of SG inservice inspection within 12 months.

## SG TUBE INSERVICE INSPECTION SCOPE

The SQN Unit 2 SG tube inservice inspection (ISI) initial sample and expansion samples for all SGs and all damage mechanisms was as follows:

100% full-length bobbin examination in all 4 SGs

100% hot leg top of tubesheet (TTS) WEXTEX expansion transition region examination in all 4 SGs with +Point probe.

100% Row 1, 2, and 3 and 20% of Row 4 U-Bend examinations in all 4 SGs with magnetic biased ZETEC +Point Low Row U-Bend Rotating probe.

100% $\geq$2 volt hot leg dented TSP intersections in all 4 SGs with +Point probe.

100% of <2 volt dented TSP intersections were examined during the bobbin coil examination utilizing the qualified technique for detection of PWSCC. This required extensive analyst training and testing.

20% sample of hot leg freespan dents from TTS to the second hot leg TSP

All test techniques used for detection were EPRI Appendix H qualified examination techniques and validated for use at SQN. NDE uncertainties were quantified for analysts and techniques utilized for sizing.

Refer to Attachment 1 for the quantity of the above examinations.

## SG TUBE INSPECTION RESULTS

As a result of plugging 91 tubes EOC-11, Unit 2 SGs are 2.9% plugged. SQN Unit 2 is analyzed for up to 15% tube plugging. SQN Unit 2 utilized the Westinghouse rolled plugs during Cycle 11 RFO. Refer to Attachment 2 for a summary of tubes plugged and Attachment 3 for the identification of tubes plugged by damage mechanism.

The plugging status of each SG is described in Table 1 below:

**Table 1**

| | SG1 | SG2 | SG3 | SG4 | Total |
|---|---|---|---|---|---|
| Previously Plugged | 47 | 123 | 82 | 51 | 303 |
| Plugged EOC-11 | 20 | 19 | 18 | 34 | 91 |
| Total Tubes Plugged | 67 | 142 | 100 | 85 | 394 |
| Percent Plugged | 2.0% | 4.2% | 3.0% | 2.5% | 2.9% |

Main steam line break accident differential pressure is 2560 psi (Pressurizer safety valve setpoint plus 3 percent), and 1.43 times this value provides the accident structural pressure lower limit of 3661 psi. The Steam Generator tubing operating pressure differential during fuel cycle 11 was 1387 psi (2235 psi RCS pressure minus 848 psi Main Steam pressure). Three times the normal differential pressure provides the normal operating structural pressure lower limit of 4162 psi.

Calculation for tube lower limit burst pressures were performed using TubeWorks Version 1.10 by E-Mech Technology, Inc.

### Degradation Mechanisms Detected

#### PWSCC U-Bend

The U2C11 Degradation Assessment predicted ten tubes to be plugged due to axial or circumferential PWSCC in the Row 1, 2, or 3 U-bend region. Row 1 and 2 U-Bends were heat treated In-Situ during the Cycle 6 RFO, however, they had operated several cycles prior to heat treating. It is believed that cracking initiated in the first few cycles in Row 1 and 2 and may have continued to grow to detectable levels.

One PWSCC U-bend axial indication was identified in SG 1 R1 C78 at H07+3.95. The NDE indicated values were 67.92% average depth, 0.24 inches in length, 99% max. depth, and 1.32 max. volts. Condition Monitoring was performed on this indication with a lower limit burst pressure determined to be 4453 psi. This indication did not exceed the voltage screening criteria for performing In-Situ pressure testing.

Two PWSCC U-bend circumferential indications were identified in SG1. The most limiting of these indications was in SG1 R1 C21 located at H07+4.22 which had a circumferential extent of 45 degrees (i.e. 0.38 inches), 98% Max. Depth, and 1.67 Max. volts. The other indication was in SG1 R1C28 which had a circumferential extent of 45 degrees (i.e. 0.38 inches), 64% Max. Depth, and 2.58 Max. Volts. These two tubes were In-Situ pressure tested to confirm structural and leakage integrity. Both tubes withstood 3 times normal operating pressure differential with zero leakage detected.

All PWSCC U-bend axial and circumferential indications satisfied Condition Monitoring performance criteria and all were plugged.

#### PWSCC TTS Axial

The U2C11 Degradation Assessment predicted twenty tubes to be plugged due to axial PWSCC at TTS. All PWSCC TTS axial indications were plugged on detection and sized using the +Point probe.

A total of 20 PWSCC axial indications were identified. All of these axial indications were below the top-of-tubesheet and therefore could not burst due to the additional structural strength provided by the tubesheet. Also, axial indications will not allow a tube to be pulled out of the tubesheet. The most limiting PWSCC axial indication was in SG4 R2 C37 at HTS-1.55 (located 1.55 inches below the top of the tubesheet) which had NDE indicated values for average depth of 74.65%, maximum depth of 99%, length of 0.17 inches and 0.22 max. volts. Condition Monitoring assumed this indication was free-span and calculated a lower limit burst pressure of 4562 psi. None of the PWSCC TTS Axial indication exceeded the voltage screening criteria for In-Situ pressure testing.

All PWSCC TTS axial indications satisfied Condition Monitoring performance criteria and all were plugged.

## PWSCC TTS Circumferential

The U2C11 Degradation Assessment predicted ten tubes to be plugged due to circumferential PWSCC at TTS. All PWSCC TTS circumferential indications were plugged on detection and sized using +Point probe.

A total of 6 circumferential indications were identified. All of the PWSCC TTS circumferential indications were below the top-of-tubesheet, however all were analyzed as if they were freespan. Condition Monitoring was performed on all these indications with the most limiting indication in SG4 R12 C60 located at HTS-0.36. This indication had NDE indicated variables which measured 82% max. depth, 97 degrees circumferential extent, and 0.98 max. volts. Condition Monitoring assumed this indication was free span and calculated a lower limit burst pressure of 6955 psi

All PWSCC TTS circumferential indications were below the screening criteria for performing In-Situ pressure testing for leakage. All PWSCC TTS indications met condition monitoring performance criteria. All PWSCC TTS circumferential indications were plugged.

## ODSCC TTS Axial

The U2C11 Degradation Assessment predicted eighteen tubes to be plugged for axial ODSCC at TTS. All ODSCC-TTS axial indications were plugged on detection and sized using the +Point probe.

A total of eight ODSCC axial indications were identified. Condition Monitoring was performed on each. The most limiting ODSCC axial TTS indication was SG3 R6 C80 located at HTS -0.02. This indication had an NDE indicated length of 0.25 inches, average depth of 27.83%, maximum depth of 76% and a max. volts of 0.18 (indications with low voltage such as this one are very likely to have the phase angle pulled by other signals such as deposit or sludge and therefore it is very unlikely that this flaw is as severe as the depth indicates). Condition Monitoring assumed this indication was free span and conservatively calculated a lower limit burst pressure of 5680 psi

All ODSCC TTS axial indications were below the In-Situ voltage screening criteria for performing In-Situ pressure testing for leakage. All ODSCC TTS axial indications met condition monitoring performance criteria. All ODSCC TTS axial indications were plugged.

## ODSCC TTS Circumferential

The U2C11 Degradation Assessment predicted ten tubes to be plugged for circumferential ODSCC at TTS. All ODSCC TTS circumferential indications were plugged on detection and sized using the +point probe.

A total of three TTS ODSCC circumferential indications were identified. Condition Monitoring was performed on each. The limiting ODSCC TTS circumferential indication is SG2 R10 C39 located at HTS +0.00. This indication had NDE indicated variables which measured a circumferential extent of 65°,a maximum depth of 72% and max. volts of 0.17. Condition monitoring calculated a lower limit burst pressure of 7394 psi.

All ODSCC TTS circumferential indications were below the screening criteria for performing In-Situ pressure testing for leakage. All ODSCC TTS circumferential indications met condition monitoring performance criteria. All ODSCC TTS circumferential indications were plugged.

## ODSCC Axial Free Span at Dent

One tube (SG3 R12 C2) was discovered with a ODSCC axial indication in the free span just above the top of tubesheet (HTS+0.98). This indication was associated with a dent. Condition Monitoring was performed on this indication. The indication had NDE indicated values of 0.15 inches long, an average depth of 35.40%, a maximum depth of 75%, and a max. voltage of 0.30. The calculated lower limit burst pressure for this indication was 8218 psi.

This indication was below the screening criteria for performing In-Situ pressure testing for leakage, however, TVA choose to perform In-Situ pressure testing on this tube with the results being zero leakage detected at 3ΔP. This ODSCC Axial Free Span at dent indication met condition monitoring performance criteria. This tube was plugged.

## PWSCC TSP Axial

The U2C11 Degradation Assessment predicted ten tubes to be plugged for PWSCC TSP Axial indications. All PWSCC TSP Axial indications were plugged on detection and sized by +Point probe.

Two PWSCC TSP axial indications were detected. The limiting indication was SG1 R8 C67 with NDE indicated values of 37.06% average depth, 0.34 inches in length, 62% max. depth, and 0.87 max. volts. The calculated lower limit burst pressure for this indication was 6803 psi.

All PWSCC TSP axial indications were below the screening criteria for performing In-Situ pressure testing for leakage. The PWSCC TSP axial indications met condition monitoring performance criteria. All PWSCC TSP axial indications were plugged.

## ODSCC TSP Axial

The ARC for axial ODSCC at TSPs continued to be implemented this inspection and a detailed condition monitoring and operational assessment report has been transmitted separately.

## AVB WEAR

Based on past indications and growth rate data from past outages, two tubes were predicted to be plugged for AVB wear. A total of 85 indications in 50 tubes were detected. One tube (SG1 R33 C51) exceeded the 40% repair limit and was plugged. The 40% repair limit is conservative for SQN Unit 2 SGs for structural and leakage performance criteria (i.e. the 40% Max. Depth plugging limit precludes leakage). Condition Monitoring assumed the axial length of the AVB Wear indications to be the width of the AVB (0.375") Therefore, the most limiting indication of 42% maximum depth had a calculated lower limit burst pressure of 6049 psi.

AVB Wear indications met condition monitoring performance criteria.

## Cold Leg Thinning

The U2C11 Degradation Assessment predicted two tubes to be plugged for cold leg thinning. A total of 126 indications were detected in 118 tubes with four indications exceeding the repair limit of 40% through wall and therefore plugged. The 40% repair limit is conservative for SQN Unit 2 SGs for structural and leakage performance criteria. Condition Monitoring assumed the axial length of Cold Leg Thinning to be the tube support plate thickness (0.75"). Therefore, the most limiting indication with an NDE indicated value of 53% maximum depth had a calculated lower limit burst pressure of 4431 psi.

Cold Leg Thinning indications met condition monitoring performance criteria.

## Volumetric Indications

Four volumetric indications were identified during the U2C11 inspection. +Point probe examinations and bobbin coil examinations were performed on each. Three indications were OD and one was ID.

For the OD indications, the best available sizing technique used a combination of two examinations. The sizing qualification for ODSCC HTS +Point was utilized to obtain axial length. Cold Leg Thinning maximum depth sizing (determined by bobbin coil - ETSS 96001.1 Rev 6 Jan 2001) was utilized. Condition Monitoring was performed on all indications. The most limiting indication was SG2 R22 C25 at H02+44.84. This indication had an NDE indicated axial length of 0.27 inches and a maximum depth of 27%. The calculated lower limit burst pressure was 7411 psi. Two of these Volumetric indications were at the top-of -tubesheet and characterized as most probably wear from a loose part. The third volumetric

indication was in the free span between the second and third hot leg tube support plate. This indication was detected by the bobbin coil examination and confirmed as a volumetric by +Point examinations. This indication was non-crack-like.

The ID indication was approximately one half inch below the top-of-tubesheet. WCAP-15128 sizing was utilized for this indication. The NDE indicated values were 0.26 inches in axial length, 85% max. depth, 47.07% average depth, and 0.71 max. volts. The calculated lower limit burst pressure was 5978 psi. This indication was found in history and the max. volts were relatively unchanged, therefore it was characterized as a manufacturing flaw.

The volumetric indications met condition monitoring performance criteria. All four volumetric indications were plugged.

## Preventive Plugging

During the SQN Unit 2 Cycle 11 refuel outage, TVA took a very conservative approach to disposition two tubes. Two tubes (SG3 R1 C17 and SG4 R3 C8) were examined in the U-bend region multiple times by the Low-Row-+Point probe and acceptable data could not obtained. TVA made the decision to plug these tubes because a flaw could have been present where the data was not acceptable. TVA also plugged 4 tubes in each channel head in order for the Flexi-Rail to be installed during future outages. FlexiRail will be mounted to these plugs in future outages and this enables the manipulators moves to be performed remotely via computer instead of by personnel. This will expedite manipulator movements and therefore reduce personnel dose. In summary, TVA conservatively plugged tubes preventively during the Unit 2 Cycle 11 outage to ensure compliance with all industry standards and to ensure the safe and reliable operation of the unit until the next refuel outage.

## SECONDARY SIDE INSPECTION SCOPE AND RESULTS

### Cracked Support Plate Indications

Cracked tube support plate indications (CSIs) are indications of cracks in the tube support plates and not necessarily indicative of tube degradation. These are detected during 100% automated analysis of bobbin data.

SQN Unit 2 SGs do not have extensive support plate cracking. Cracked TSPs were evaluated for potential star drop-out conditions and none were identified. Therefore, design basis function of the support plate has not been lost. There is also no evidence of wrapper drop or wrapper degradation.

### Upper Internals Inspection

Upper internals inspections were performed in SGs 1 and 4 during this inspection. The inspection is performed for evidence of erosion / corrosion , cracked welds, deposit buildup, or any other service-induced degradation. No degradation was detected.

### Sludge Lancing

Sludge lancing was performed during the Unit 2 Cycle 11 RFO. The following amounts of sludge was removed: SG1 - 46 pounds; SG2 - 23 pounds; SG3 - 35 pounds; SG4 - 26 pounds.

### Foreign Object Search and Retrieval (FOSAR)

Foreign object search and retrieval was completed on all four SGs prior to closure and all identified foreign objects were retrieved.

## CONCLUSIONS

The NDE testing completed on the SQN Unit 2 SGs and plugging of defective tubes met the Technical Specification and ASME Section XI code requirements for inservice inspection and structural and leakage integrity has been demonstrated; therefore, each SG has been demonstrated operable.

Utilization of one Alternate Repair Criteria continued in accordance with the Unit 2 Technical Specification Surveillance Requirement 3/4.4.5.4.a.10.

Based on the criteria of 10 CFR 50.59, TVA concludes that the integrity of the SQN Unit 2 SGs was maintained during Cycle 11 operation and will be maintained through fuel Cycle 12 and does not represent an unreviewed safety question.

# REFERENCES


1. WCAP-15579, "Burst Pressure Data for Steam Generator Tubes with Combined Axial and Circumferential Cracks", Westinghouse Proprietary Class 2, Westinghouse Electric Company LLC, September, 2000.

2. WCAP-15128, Rev. 3, "Depth-Based SG Tube Repair Criteria for Axial PWSCC at Dented TSP Intersections", Westinghouse Proprietary Class 2, Westinghouse Electric Company LLC, June, 2000.

3. Keating, R. F., and Begley, J. A., "Steam Generator Tubing Flaw Handbook", EPRI Report TR-1001191-L, EPRI, Palo Alto, CA, January 2001.

4. "PWR Steam Generator Examination Guidelines", Performance Demonstration Database, Appendix A, Technique Specification Sheets, ETSS 96702, EPRI, Palo Alto, CA, January, 1999.

5. EPRI TR-107197, "Depth Based Structural Analysis Methods for SG Circumferential Indications, EPRI, Palo Alto, CA, November, 1997.

## DEFINITIONS

+Point - An RPC eddy current probe in which two coils are placed against the same contact surface with their axis 90 degrees apart. When the probe face is viewed, the coils create the appearance of a '+'. This configuration minimizes the eddy current response to tubing geometry changes or support structures and is presently considered the probe with the best overall crack detection capabilities.

ARC - Alternate Repair Criteria

C01 - First cold leg tube support plate intersection

C02 - Second cold leg tube support plate intersection

C03 - Third cold leg tube support plate intersection

C04 - Fourth cold leg tube support plate intersection

C05 - Fifth cold leg tube support plate intersection

C06 - Sixth cold leg tube support plate intersection

C07 - Seventh cold leg tube support plate intersection

EOC - End of Cycle

EPRI - Electric Power Research Institute

H01 - First hot leg tube support plate intersection

H02 - Second hot leg tube support plate intersection

H03 - Third hot leg tube support plate intersection

H04 - Fourth hot leg tube support plate intersection

H05 - Fifth hot leg tube support plate intersection

H06 - Sixth hot leg tube support plate intersection

H07 - Seventh hot leg tube support plate intersection

ODSCC - Outside Diameter Stress Corrosion Cracking

PDA - Percent Degraded Area

PWSCC - Primary Water Stress Corrosion Cracking

RFO - Refuel Outage

RPC - Literally 'Rotating Pancake Coil' eddy current probe. This term is also used to describe eddy current probes in which the coil face contacts the tube wall while rotating and being pulled through the tube axially such that the examination path is helical.

SQN - Sequoyah Nuclear Power Plant

TSP - Tube Support Plate

TTS - Top of Tubesheet

WEXTEX - Westinghouse Explosive Tube Expansion

# ATTACHMENT 1
# SQN UNIT 2
# CYCLE 11 RFO
# NUMBER AND EXTENT OF TUBES EXAMINED

## SUMMARY OF SEQUOYAH UNIT 2 CYCLE 11
## SG EDDY CURRENT INSPECTION/TUBE PLUGGING RESULTS

| EDDY CURRENT EXAM TYPE | SG 1 | SG 2 | SG 3 | SG 4 | Total |
|---|---|---|---|---|---|
| Full Length Bobbin Coil | 3341 | 3265 | 3306 | 3337 | 13249 |
| U-Bend Plus Point | 281 | 257 | 275 | 287 | 1100 |
| Top of Tubesheet Plus Point | 3341 | 3265 | 3306 | 3337 | 13249 |
| Freespan Plus Point | 26 | 30 | 30 | 4 | 90 |
| H01 Plus Point | 13 | 22 | 33 | 3 | 71 |
| H02 Plus Point | 2 | 4 | 2 | 0 | 8 |
| H03 Plus Point | 6 | 14 | 1 | 0 | 21 |
| H04 Plus Point | 4 | 4 | 2 | 2 | 12 |
| H05 Plus Point | 23 | 7 | 2 | 5 | 37 |
| H06 Plus Point | 37 | 11 | 14 | 3 | 65 |
| H07 Plus Point | 83 | 30 | 87 | 38 | 238 |
| Diagnostic/PID Plus Point | 36 | 40 | 33 | 132 | 241 |
| Total Exams Completed | 7193 | 6949 | 7091 | 7148 | 28381 |
| Total Tubes Examined | 3341 | 3265 | 3306 | 3337 | 13249 |

## ATTACHMENT 2

# SQN UNIT 2 CYCLE 11 RFO
# SUMMARY OF SG TUBE PLUGGING

### SUMMARY OF SEQUOYAH UNIT 2 CYCLE 11
### SG EDDY CURRENT INSPECTION/TUBE PLUGGING RESULTS

| PLUGGING STATUS | SG 1 | SG 2 | SG 3 | SG 4 | Total |
|---|---|---|---|---|---|
| Previously Plugged Tubes | 47 | 123 | 82 | 51 | 303 |
| Damage Mechanism | | | | | |
| AVB WEAR | 1 | 0 | 0 | 0 | 1 |
| COLD LEG WASTAGE | 1 | 3 | 2 | 5 | 11 |
| ODSCC HTS AXIAL | 1 | 0 | 2 | 4 | 7 |
| ODSCC HTS CIRC | 0 | 1 | 0 | 2 | 3 |
| ODSCC TSP AXIAL | 0 | 0 | 1 | 2 | 3 |
| ODSCC AXIAL FREESPAN DNT | 0 | 0 | 1 | 0 | 1 |
| PREVENTATIVE | 0 | 0 | 1 | 1 | 2 |
| PWSCC HTS AXIAL | 3 | 4 | 3 | 6 | 16 |
| PWSCC HTS CIRC | 0 | 1 | 0 | 5 | 6 |
| PWSCC TSP AXIAL | 1 | 1 | 0 | 0 | 2 |
| PWSCC U-BEND AXIAL | 1 | 0 | 0 | 0 | 1 |
| PWSCC U-BEND CIRC | 2 | 0 | 0 | 0 | 2 |
| VOLUMETRIC INDICATION | 2 | 1 | 0 | 1 | 4 |
| FOR FLEXI RAIL SYSTEM | 8 | 8 | 8 | 8 | 32 |
| Plugged Cycle 11 | 20 | 19 | 18 | 34 | 91 |
| TOTAL TUBES PLUGGED | 67 | 142 | 100 | 85 | 394 |

Effective Plugging Percentages

| | |
|---|---|
| SG 1 | 2.0% |
| SG 2 | 4.2% |
| SG 3 | 3.0% |
| SG 4 | 2.5% |

# ATTACHMENT 3
# SQN UNIT 2 CYCLE 11 RFO
# STEAM GENERATOR 1
# TUBES PLUGGED BY DAMAGE MECHANISM

| | SG | | ROW | COL | INDICATION | LOCATION | CHARACTERIZATION |
|---|---|---|---|---|---|---|---|
| | 1 | | 33 | 51 | 42 | AV2-.11 | AVB WEAR |
| Total: | | 1 | | | | | |
| | 1 | | 43 | 60 | 47 | C01+.00 | C/L WASTAGE |
| Total: | | 1 | | | | | |
| | 1 | | 19 | 80 | SVI | HTS+.58 | LOOSE PART WEAR |
| Total: | | 1 | | | | | |
| | 1 | | 1 | 23 | SAI | HTS+.05 | ODSCC HTS AXIAL |
| Total: | | 1 | | | | | |
| | 1 | | 2 | 36 | TBP | +0.00 | OTHER-Flexi Rail |
| | 1 | | 2 | 44 | TBP | +0.00 | OTHER-Flexi Rail |
| | 1 | | 2 | 52 | TBP | +0.00 | OTHER-Flexi Rail |
| | 1 | | 2 | 60 | TBP | +0.00 | OTHER-Flexi Rail |
| | 1 | | 6 | 36 | TBP | +0.00 | OTHER-Flexi Rail |
| | 1 | | 6 | 44 | TBP | +0.00 | OTHER-Flexi Rail |
| | 1 | | 6 | 52 | TBP | +0.00 | OTHER-Flexi Rail |
| | 1 | | 6 | 60 | TBP | +0.00 | OTHER-Flexi Rail |
| Total: | | 8 | | | | | |
| | 1 | | 2 | 9 | SAI | HTS-.50 | PWSCC HTS AXIAL |
| | 1 | | 2 | 34 | SAI | HTS-.89 | PWSCC HTS AXIAL |
| | 1 | | 19 | 39 | SAI | HTS-2.51 | PWSCC HTS AXIAL |
| Total: | | 3 | | | | | |
| | 1 | | 8 | 67 | SAI | H06-.10 | PWSCC TSP AXIAL |
| Total: | | 1 | | | | | |
| | 1 | | 1 | 78 | SAI | H07+4.11 | PWSCC UBEND AXIAL |
| Total: | | 1 | | | | | |
| | 1 | | 1 | 21 | SCI | H07+4.27 | PWSCC UBEND CIRC |
| | 1 | | 1 | 28 | SCI | H07+10.61 | PWSCC UBEND CIRC |
| Total: | | 2 | | | | | |
| | 1 | | 44 | 55 | SVI | HTS+.50 | VOLUMETRIC |
| Total: | | 1 | | | | | |
| Grand Total SG-1: | | 20 | | | | | |

# ATTACHMENT 3
# SQN UNIT 2 CYCLE 11 RFO
# STEAM GENERATOR 2
# PLUGGED TUBES BY DAMAGE MECHANISM

| | SG | | ROW | COL | INDICATION | LOCATION | CHARACTERIZATION |
|---|---|---|---|---|---|---|---|
| | 2 | | 33 | 75 | SVI | C02-.10 | C/L WASTAGE |
| | 2 | | 36 | 77 | SVI | C01-.23 | C/L WASTAGE |
| | 2 | | 44 | 34 | SVI | C01-.03 | C/L WASTAGE |
| Total: | | 3 | | | | | |
| | 2 | | 10 | 39 | SCI | HTS+.00 | ODSCC HTS CIRC |
| Total: | | 1 | | | | | |
| | 2 | | 2 | 36 | TBP | +0.00 | OTHER-Flexi Rail |
| | 2 | | 2 | 44 | TBP | +0.00 | OTHER-Flexi Rail |
| | 2 | | 2 | 52 | TBP | +0.00 | OTHER-Flexi Rail |
| | 2 | | 2 | 60 | TBP | +0.00 | OTHER-Flexi Rail |
| | 2 | | 6 | 36 | TBP | +0.00 | OTHER-Flexi Rail |
| | 2 | | 6 | 44 | TBP | +0.00 | OTHER-Flexi Rail |
| | 2 | | 6 | 52 | TBP | +0.00 | OTHER-Flexi Rail |
| | 2 | | 6 | 60 | TBP | +0.00 | OTHER-Flexi Rail |
| Total: | | 8 | | | | | |
| | 2 | | 6 | 56 | SAI | HTS-.60 | PWSCC HTS AXIAL |
| | 2 | | 7 | 24 | SAI | HTS-.19 | PWSCC HTS AXIAL |
| | 2 | | 18 | 17 | SAI | HTS-3.17 | PWSCC HTS AXIAL |
| | 2 | | 22 | 60 | SOI | HTS-.80 | PWSCC HTS AXIAL |
| Total: | | 4 | | | | | |
| | 2 | | 37 | 64 | SCI | HTS-6.34 | PWSCC HTS CIRC |
| Total: | | 1 | | | | | |
| | 2 | | 39 | 48 | SAI | H01+.36 | PWSCC TSP AXIAL |
| Total: | | 1 | | | | | |
| | 2 | | 22 | 25 | SVI | H02+44.84 | VOLUMETRIC |
| Total: | | 1 | | | | | |
| Grand Total SG-2: | | 19 | | | | | |

# ATTACHMENT 3
# SQN UNIT 2 CYCLE 11 RFO
# STEAM GENERATOR 3
# TUBES PLUGGED BY DAMAGE MECHANISM

| SG | | ROW | COL | INDICATION | LOCATION | CHARACTERIZATION |
|---|---|---|---|---|---|---|
| 3 | | 41 | 32 | 46 | C02-.24 | C/L WASTAGE |
| 3 | | 45 | 37 | 48 | C02-.26 | C/L WASTAGE |
| Total: | 2 | | | | | |
| 3 | | 12 | 2 | SAI | HTS+.98 | ODSCC F-SPAN AXIAL |
| Total: | 1 | | | | | |
| 3 | | 4 | 78 | SAI | HTS-.07 | ODSCC HTS AXIAL |
| 3 | | 6 | 80 | SAI | HTS-.03 | ODSCC HTS AXIAL |
| Total: | 2 | | | | | |
| 3 | | 34 | 32 | DSI | H01+.02 | ODSCC TSP AXIAL |
| Total: | 1 | | | | | |
| 3 | | 2 | 36 | TBP | +0.00 | OTHER-Flexi Rail |
| 3 | | 2 | 44 | TBP | +0.00 | OTHER-Flexi Rail |
| 3 | | 2 | 52 | TBP | +0.00 | OTHER-Flexi Rail |
| 3 | | 2 | 60 | TBP | +0.00 | OTHER-Flexi Rail |
| 3 | | 6 | 36 | TBP | +0.00 | OTHER-Flexi Rail |
| 3 | | 6 | 44 | TBP | +0.00 | OTHER-Flexi Rail |
| 3 | | 6 | 52 | TBP | +0.00 | OTHER-Flexi Rail |
| 3 | | 6 | 60 | TBP | +0.00 | OTHER-Flexi Rail |
| Total: | 8 | | | | | |
| 3 | | 1 | 17 | TBP | +0.00 | PREVENTIVE-Geometry |
| Total: | 1 | | | | | |
| 3 | | 1 | 54 | SAI | HTS-.48 | PWSCC HTS AXIAL |
| 3 | | 5 | 16 | SAI | HTS-5.26 | PWSCC HTS AXIAL |
| 3 | | 19 | 65 | SOI | HTS-2.92 | PWSCC HTS AXIAL |
| Total: | 3 | | | | | |
| Grand Total SG-3: | 18 | | | | | |

# ATTACHMENT 3
# SQN UNIT 2 CYCLE 11 RFO
# STEAM GENERATOR 4
# TUBES PLUGGED BY DAMAGE MECHANISM

| | SG | | ROW | COL | INDICATION | LOCATION | CHARACTERIZATION |
|---|---|---|---|---|---|---|---|
| | 4 | | 35 | 19 | SVI | C02-.08 | C/L WASTAGE |
| | 4 | | 39 | 73 | SVI | C02-.12 | C/L WASTAGE |
| | 4 | | 43 | 32 | SVI | C01-.12 | C/L WASTAGE |
| | 4 | | 44 | 35 | SVI | C01-.13 | C/L WASTAGE |
| | 4 | | 46 | 41 | SVI | C02-.10 | C/L WASTAGE |
| Total: | | 5 | | | | | |
| | 4 | | 9 | 17 | SAI | HTS-.01 | ODSCC HTS AXIAL |
| | 4 | | 15 | 34 | SAI | HTS-.04 | ODSCC HTS AXIAL |
| | 4 | | 19 | 26 | SAI | HTS-.03 | ODSCC HTS AXIAL |
| | 4 | | 29 | 45 | SAI | HTS-.18 | ODSCC HTS AXIAL |
| Total: | | 4 | | | | | |
| | 4 | | 7 | 24 | SCI | HTS-.14 | ODSCC HTS CIRC |
| | 4 | | 9 | 59 | SCI | HTS-.14 | ODSCC HTS CIRC |
| Total: | | 2 | | | | | |
| | 4 | | 12 | 16 | SAI | H02+.32 | ODSCC TSP AXIAL |
| | 4 | | 12 | 45 | DSI | H01+.09 | ODSCC TSP AXIAL |
| Total: | | 2 | | | | | |
| | 4 | | 2 | 36 | TBP | +0.00 | OTHER-Flexi Rail |
| | 4 | | 2 | 44 | TBP | +0.00 | OTHER-Flexi Rail |
| | 4 | | 2 | 52 | TBP | +0.00 | OTHER-Flexi Rail |
| | 4 | | 2 | 60 | TBP | +0.00 | OTHER-Flexi Rail |
| | 4 | | 6 | 36 | TBP | +0.00 | OTHER-Flexi Rail |
| | 4 | | 6 | 44 | TBP | +0.00 | OTHER-Flexi Rail |
| | 4 | | 6 | 52 | TBP | +0.00 | OTHER-Flexi Rail |
| | 4 | | 6 | 60 | TBP | +0.00 | OTHER-Flexi Rail |
| Total: | | 8 | | | | | |
| | 4 | | 3 | 8 | TBP | H07+7.85 | PREVENTIVE-RBD |
| Total: | | 1 | | | | | |
| | 4 | | 2 | 37 | SAI | HTS-1.55 | PWSCC HTS AXIAL |
| | 4 | | 2 | 40 | SAI | HTS-1.02 | PWSCC HTS AXIAL |
| | 4 | | 11 | 26 | SAI | HTS-5.58 | PWSCC HTS AXIAL |
| | 4 | | 13 | 60 | SAI | HTS-4.40 | PWSCC HTS AXIAL |
| | 4 | | 15 | 8 | SAI | HTS-2.75 | PWSCC HTS AXIAL |
| | 4 | | 15 | 70 | SOI | HTS-4.22 | PWSCC HTS AXIAL |
| Total: | | 6 | | | | | |
| | 4 | | 12 | 60 | SCI | HTS-.34 | PWSCC HTS CIRC |
| | 4 | | 15 | 60 | SCI | HTS-3.61 | PWSCC HTS CIRC |
| | 4 | | 18 | 60 | SCI | HTS-3.37 | PWSCC HTS CIRC |
| | 4 | | 20 | 45 | SCI | HTS-3.63 | PWSCC HTS CIRC |
| | 4 | | 24 | 9 | SCI | HTS-2.67 | PWSCC HTS CIRC |
| Total: | | 5 | | | | | |
| | 4 | | 25 | 44 | SVI | HTS-.62 | VOLUMETRIC |
| Total: | | 1 | | | | | |
| Grand Total SG-4: | | 34 | | | | | |

ENCLOSURE 2

TENNESSEE VALLEY AUTHORITY
SEQUOYAH NUCLEAR PLANT (SQN) UNIT 2

# FINAL METALLURGICAL REPORT FOR STEAM GENERATOR TUBE R12C45

Westinghouse Non-Proprietary Class 3

SG-SGDA-03-12
Revision 00

April 2003

# TUBE EXAMINATIONS FOR THE SUPPORT OF SEQUOYAH UNIT 2 STEAM GENERATORS VOLTAGE-BASED REPAIR CRITERIA

# TUBE EXAMINATIONS FOR THE SUPPORT OF SEQUOYAH UNIT 2 STEAM GENERATORS VOLTAGE-BASED REPAIR CRITERIA

FINAL REPORT

SG-SGDA-03-12

APRIL 2003

Prepared for the

Tennessee Valley Authority

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## Section 1.0

## INTRODUCTION

Sequoyah Unit 2 (Sequoyah-2) is owned and operated by the Tennessee Valley Authority (TVA). Sequoyah-2 is a four loop Westinghouse designed pressurized water reactor sited on the banks of the Chickamauga Reservoir. The plant, which has a nominal rating of 1117 net MWe, commenced commercial operation in 1982 and has since accumulated over 13 EFPY of operation. The steam generators are of the Model 51 type manufactured by the Westinghouse Electric Corporation. Each steam generator contains 3388 heat transfer tubes. The mill annealed NiCrFe Alloy 600 steam generator tubes are nominally 0.875 inch in outer diameter and have a nominal wall thickness of 50 mils. The tubes are mounted in a low alloy steel tubesheet that is approximately 21.7 inches thick (including cladding). The tube-to-tubesheet crevices were closed using the WEXTEX process, in which tubes were explosively expanded. The tubes pass through seven carbon steel tube support plates (TSPs) that are 0.75 inch thick each, through drilled holes that have a nominal diameter of 0.891 inch.

To reduce the number of tubes that needed to be plugged due to the presence of detectable axial outside diameter stress corrosion cracking (ODSCC), Sequoyah-2 initiated an alternative repair criteria (ARC) program.

During the cycle 11 refueling outage (spring 2002), TVA selected one steam generator tube from Sequoyah Unit 2 for removal and laboratory non-destructive and destructive examinations to maintain the ARC. The tube selection and laboratory examination were in compliance with ARC requirements that were established in GL95-05 (Reference 1). The tube that was removed, R12C45, was from steam generator 4, and included three support plate intersections.

The tube was cut below the fourth support, pulled from the generator and delivered to Westinghouse's Remote Metallographic Facility of the Science and Technology Department (STD) for non-destructive and destructive examinations. The emphasis of the laboratory

activities was to perform tube integrity testing and to characterize the depth and type of defects that caused the ECT indications. All examinations and testing presented in this report were treated as safety-related and are in accordance with the Westinghouse Quality Assurance program (Reference 2), which satisfies the requirements of 10CFR50 Appendix B. This examination was initiated by the Reference 3 work authorization and was monitored under the Westinghouse SAP network number 110118.

## Section 2.0

## REMOVED TUBE CHARACTERISTICS

Westinghouse removed sections from the hot leg side of R12C45 from Sequoyah-2 steam generator 4 during the cycle 11 refueling outage. The tube sections were removed by cutting just below the fourth tube support plate. A maximum force of 3578 lbs was required to pull the tube out of the generator (Reference 4). This translates to a tensile stress of 27,600 psi. This was well below the yield strength of the material.

The tube was cut into eight sections as it was pulled through the tubesheet (the terms "section" and "piece" are used interchangeably throughout this report). Most cuts were made at an angle that was slightly less than 90° to the axis of the tube. The tube was "nicked" as a means of establishing orientation at the top of each tube section on the side of the tube opposite the divider plate. The tube was cut in convenient lengths to preserve the areas of interest. Each section was identified with the tube section number. Care was taken to avoid contaminating the outer surface of the tube by lead shielding.

Table 2-1 lists the sections, their lengths and their location. Sections 4 and 5 dropped out of the tubesheet during the pulling operation and into the steam generator channel head. They were still attached to the remaining tube in the tubesheet and because of radiation exposure concerns, were cut to longer lengths and later cut into smaller sections with a tube cutter at an angle of 90° to the axis of the tube. These sections were identified and marked as to the top and bottom of each section.

The table also compares the lengths measured in the field, as noted in Reference 4, with the lengths measured in the laboratory. The laboratory measured lengths are used in this report. Based on the labeling that was placed on each tube and the match between lengths in Reference 4 and those measured in the lab, it was verified that the correct pieces were received and were labeled correctly.

After initial inspection the end of the tube sections were deburred to facilitate the laboratory examinations. As the tube sections were cut into smaller pieces, the identification and traceability of specimens was maintained in accordance with the Reference 5 procedure. The designation of each cut specimen includes the number of the original piece. For instance, specimen 2B was cut from piece 2. Pieces cut from section 4 and 5 were given labels that began with a "41" and "51", respectively. Pieces cut from section 4A and 5A were given labels that began with a "4A" and "5A", respectively. An orientation system was arbitrarily chosen to aid in the description of the tube specimens. The 0° orientation of each specimen was related to a tube pull grind mark at the bottom of the tube piece (the tube sections were marked on the side facing the periphery), and 90° is clockwise of 0° when looking in the upward (primary flow) direction. Unless otherwise stated, this orientation system is used throughout this report.

The field eddy current (ECT) data were re-evaluated as part of the tube examination. Also, as part of the laboratory examination, the TSP crevice regions of the tubes were eddy current inspected in a manner consistent with the field inspection. Table 2-2 presents a summary of field and laboratory eddy current data obtained on the pulled tubes for the TSP crevice regions of interest. The data is presented in a manner to allow for one-to-one comparison of the field and laboratory results. Bobbin coil calls were made using 400/100 kHz MIX data from the differential mode. +Point probe calls were made from the +Point coil using 300 kHz differential mode data.

Table 2-2 shows that the re-evaluation of the bobbin data showed results that were similar to the original field evaluation. The re-evaluation of the TSP1 +Point data confirmed the presence of one large amplitude indication, but two additional low-amplitude indications were identified. The re-evaluation of the TSP2 and TSP3 +Point data also identified additional low-amplitude indications.

In general, the laboratory examinations, without the support and its associated deposits, the signal to noise ratio for the indications improved. The laboratory ECT data for TSP1 showed indication responses that were significantly larger in amplitude than the field data. The large

change in the amplitude response is consistent with the opening of ligaments within the degraded regions by the tube removal process. The similarity of the shape of the Lissajous responses (pre- and post-tube removal) suggests that there was no extension of the degraded region. The +Point responses had characteristics of circumferential involvement suggesting the opening of cellular corrosion by the axial stresses of the tube removal. The laboratory ECT data showed a bobbin coil indication that was identified at the location of TSP2. The indication, however, was distorted by the tube removal process such that meaningful measurement of the degradation response could not be performed. As with the indications in TSP1, the indications in TSP2 had +Point response characteristics indicative of circumferential involvement suggesting the opening of cellular corrosion by the axial stresses of the tube removal. The laboratory ECT data for TSP3 showed that the indication, as was determined in the MIX channel, was slightly different than that observed in the field.

TABLE 2-1

PULLED TUBE R12C45 SECTION LENGTHS AND CHARACTERISTICS

| Section | Length, As Reported in Reference 4 (inches) | Length, As Measured in Lab (inches) | Remarks |
|---|---|---|---|
| 1 | 30.750 | 30 3/4 | Included TTS Region |
| 2 | 30.750 | 30 3/4 | |
| 3 | 34.000 | 33 3/4 | Included TSP1 Region |
| 4A | 9.000 | 9 | |
| 4 | 30.000 | 29 5/8 | Included TSP2 Region |
| 5A | 25.000 | 25 | |
| 5 | 32.063 | 32 | Included TSP3 Region |
| 6 | 26.625 | 26 3/4 | |

## TABLE 2-2

## SUMMARY OF NDE RESULTS

| Loc. | Field Eddy Current | | Re-Evaluated Field ECT | | Laboratory Eddy Current | |
|---|---|---|---|---|---|---|
| | Bobbin Coil | +Point | Bobbin Coil | +Point | Bobbin Coil | +Point |
| | Volts / Designation | Volts / Designation / Length (in.) | Volts / % | Volts / % / l(in.) | Volts / % | Volts / % / l (in.) |
| TSP1 | 3.35 / DSI | 1.89 / SAI / 0.58<br>0.24 / SAI / 0.29<br>0.24 / SAI / 0.32 | 3.26 / 91 | A 0.24 / 54 / 0.33<br>B 0.15 / <20 / 0.30<br>C 0.08 / PI / 0.24<br>D 0.22 / 28 / 0.21<br>E 2.02 / 87 / 0.7 | 6.92 / 88 | A 0.38 / 48 / 0.29<br>B 0.16 / 25 / 0.35<br>C 0.09 / 25 / 0.19*<br>D 0.32 / 23 / 0.35<br>E 4.33 / 95 / 0.72 |
| TSP2 | 0.95 / DSI | 0.26 / SAI / 0.52 | 0.60 / 66 | A 0.24 / 44 / 0.71<br>B 0.13 / PI / 0.58 | Dist. | A 0.24 / 35 / 0.73<br>B 0.21 / 36 / 0.73 |
| TSP3 | 0.44 / DSI | 0.16 / SAI / 0.49 | 0.46 / DSI | A 0.20 / 51 / 0.28<br>C 0.19 / 22 / 0.71 | 0.59 / 53 | A 0.22 / 25 / 0.38<br>B 0.09 / <20 / 0.18<br>C 0.22 / <20 / 0.75 |

* - Measurement from the Pancake coil

NDD - No Detectable Degradation

SAI - Single Axial Indication

DSI – Distorted Support Indication

PI - Possible Indication

N/A - Not Appropriate

Dist. – Data distorted by tube removal artifact such that a meaningful measurement was not possible

## Section 3.0

## SECTIONING PLANS

Figures 3-1 through 3-5 show how relevant pieces from tube R12C45 were sectioned. The 0° orientation and the top/bottom direction were maintained on each subsection by a small white paint mark.

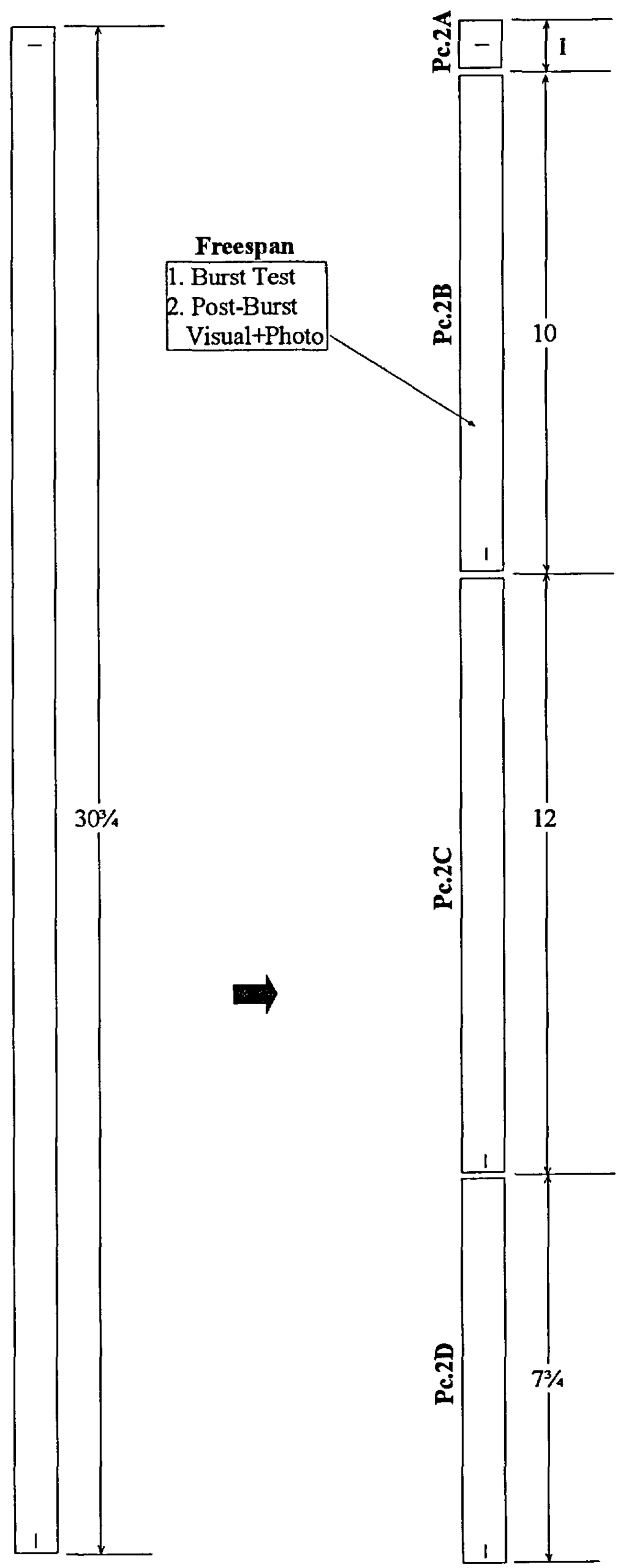


Figure 3-1. Sectioning Diagram for Piece 2.

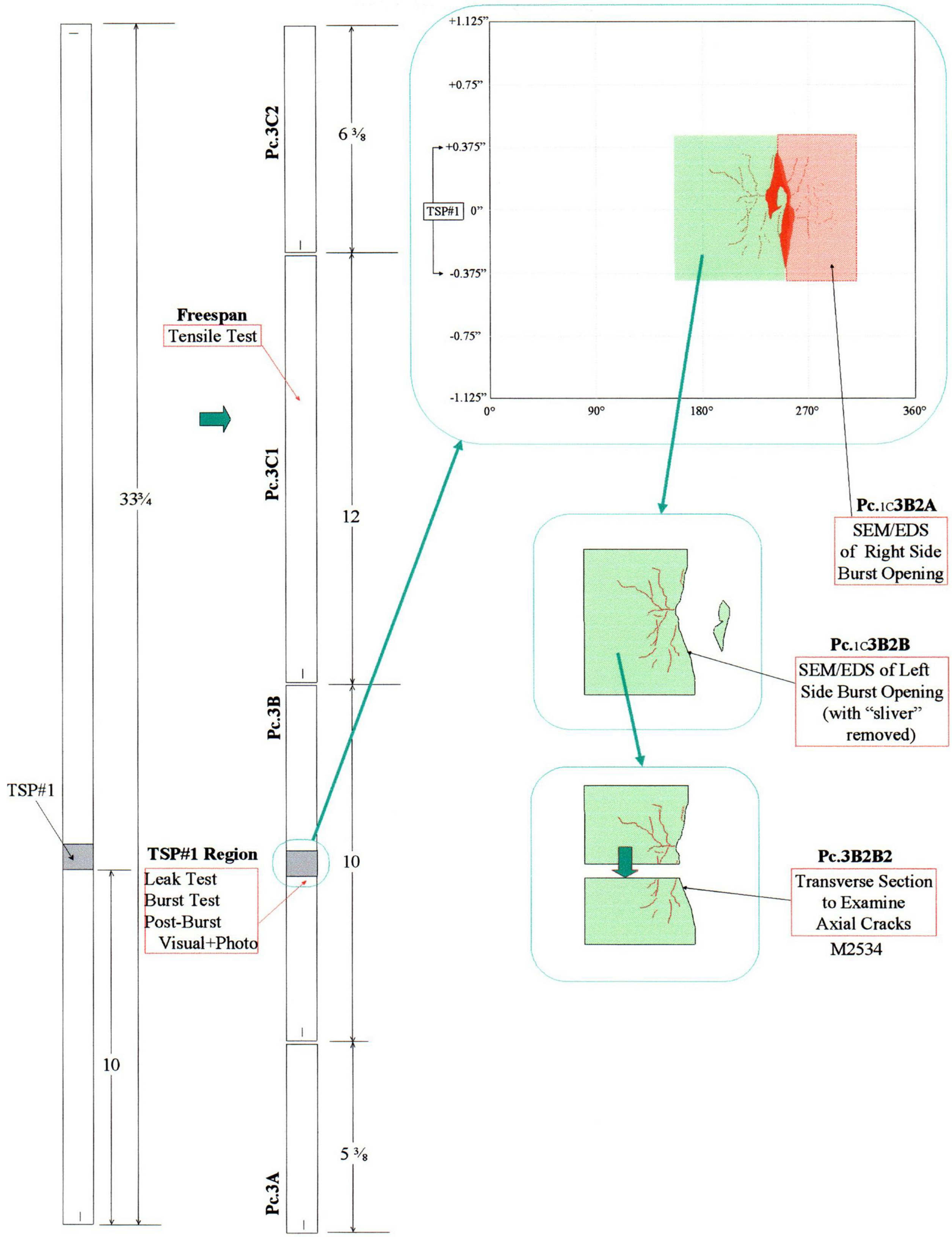


Figure 3-2. Sectioning Diagram for Piece 3.

C01

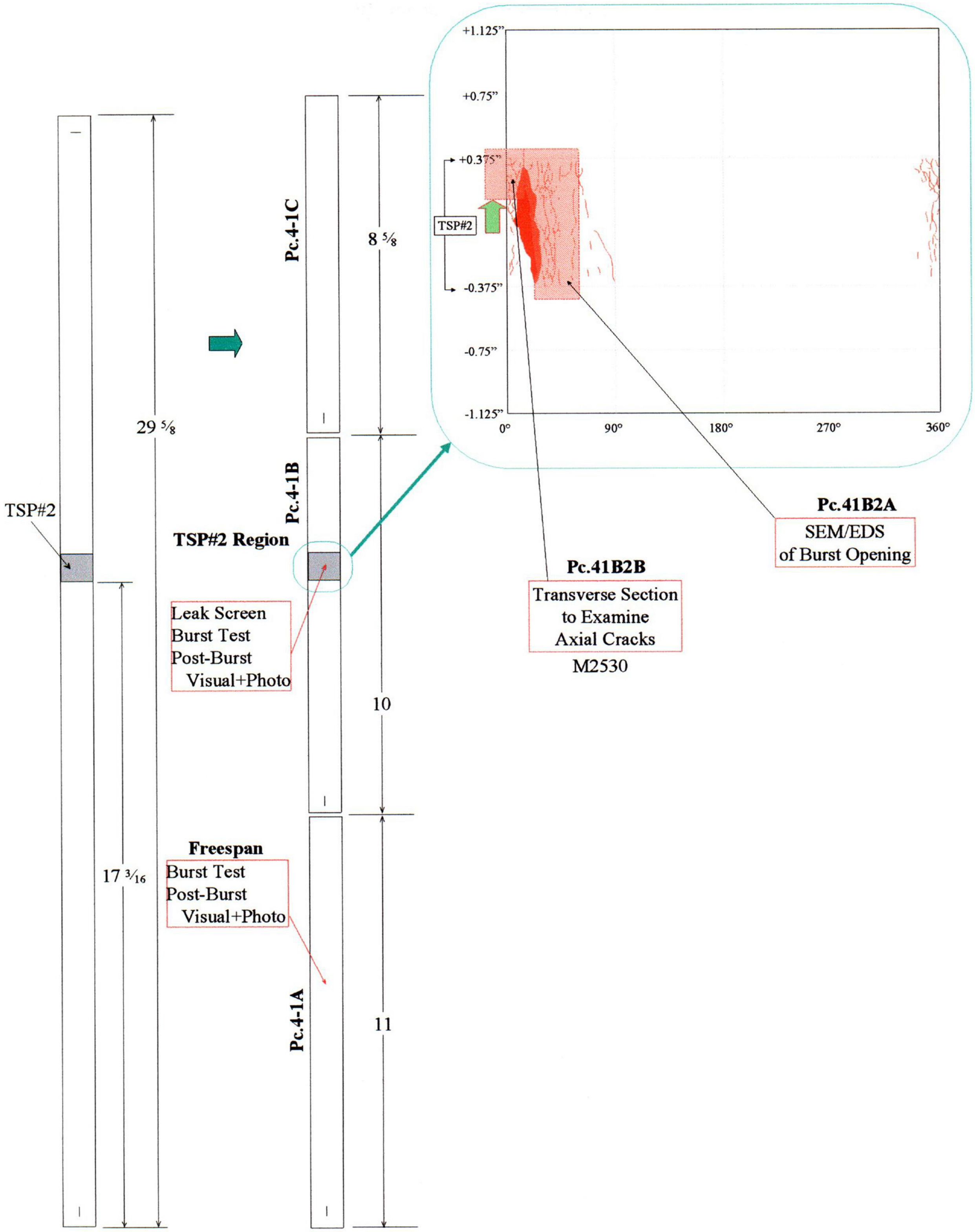


Figure 3-3. Sectioning Diagram for Piece 4.

C02

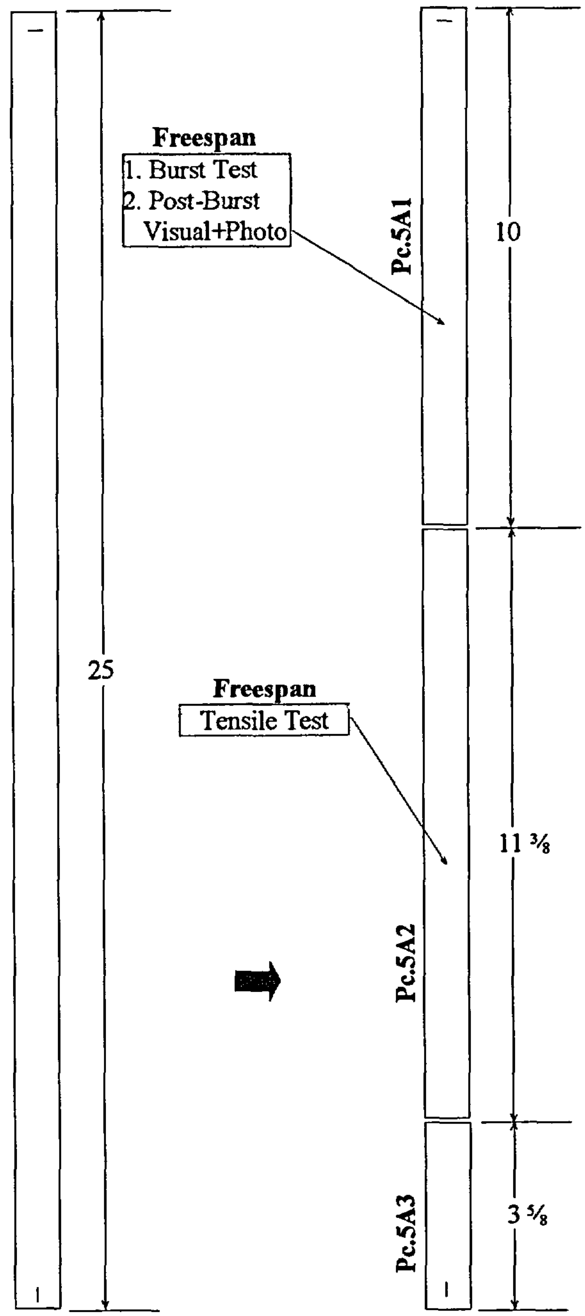


Figure 3-4. Sectioning Diagram for Piece 5A.

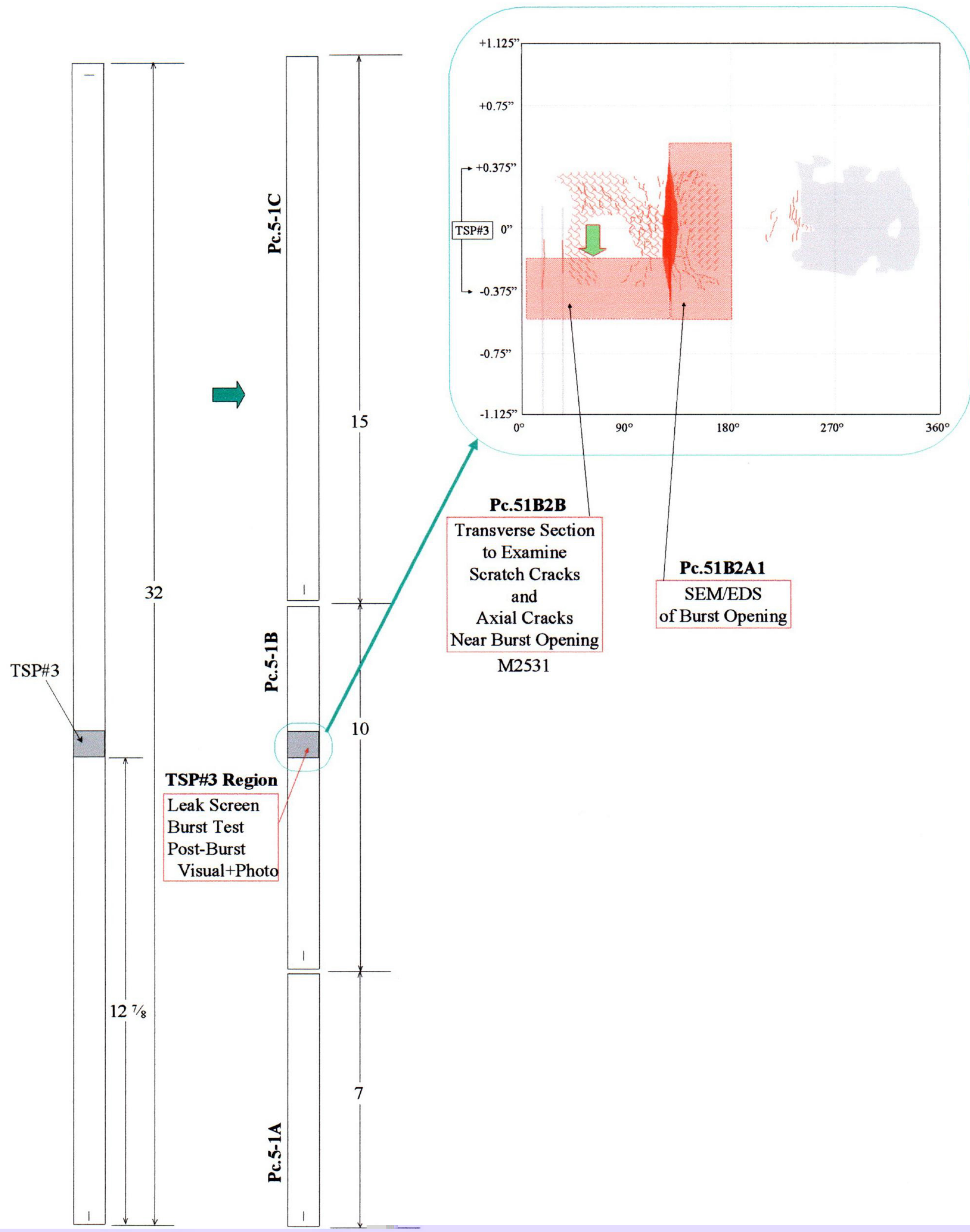


Figure 3-5. Sectioning Diagram for Piece 5.

## Section 4.0

## LEAK RATE AND BURST TESTING

### 4.1 Introduction

The primary purpose of the leak and burst testing was to provide information to support Generic Letter 95-05 (Reference 1) requirements. Also of importance was determining if degraded tube sections exceeded the US Nuclear Regulatory Commission Regulatory Guide 1.121 (Reference 6) requirements on burst strength. The most limiting requirement is that the tube must sustain three times normal operating pressure differential (3NOP) without burst. 3NOP is approximately 4142 psi for Sequoyah-2 (Reference 7) at temperature, or 4544 psi for room temperature testing (9.7% correction factor – Reference 8). The less limiting requirement of 1.4 times steam line break (SLB) pressure is also of interest. For Sequoyah-2, 1.4 x SLB is 3584 psi at temperature (Reference 7), or 3932 psi for room temperature testing. Lubricated foil was used during the Sequoyah-2 burst test; Reference 9 demonstrated that an additional correction factor was not needed for lubricated foil.

The details of how the leak and burst test results support GL 95-05 are not provided in this report.

The TTS region was not leak tested, since it did not have a field NDE indication. The TSP2 and TSP3 regions were only screened for leakage, in accordance with the Reference 10 request and the Reference 7 and Reference 11 responses. The screening test consisted of pressurizing the inside of the test specimens using 400 psig helium followed by pressurization to MSLB pressure at room temperature. Since neither TSP2 or TSP3 leaked during any part of the screening tests, they were not subjected to at temperature leak tests. TSP1 was subjected to the helium leak test and leakage was discovered. TSP1 (section 3B) was consequently subjected to leak tests at an elevated temperature. Leak testing was performed at normal operating pressure (NOP), at steam line break (SLB), and at intermediate pressures. Burst testing was performed on all three TSP regions, the TTS section and three freespan sections without NDE indications (sections 2B, 4-1A and 5A1). Burst testing was performed at room temperature.

## 4.2 Test Methods

The leak test was performed without fixtures that simulate the constraints of TSP intersections. The ends of the tube were sealed with Swagelok fittings with connectors that allowed simulated primary water to flow in and out of the sample. Primary side conditions of the tube sample were obtained by connecting the tube sample to a primary side autoclave (AC1) using insulated pressure tubing. The secondary side was simulated by placing the tube sample into a second autoclave (AC2). The pressure of AC2 was adjusted to obtain the required pressure differential between the primary and secondary side. Any water vapor in excess of the AC2 pressure was condensed. The condensed water was measured to obtain the primary side leak rate.

Leak test conditions for the tubes ranged from Normal Operating Conditions (NOC) to Steam Line Break (SLB) conditions. For the NOC tests, the primary side pressure and temperature were nominally 2235 psi and 611°F, respectively. The NOC secondary side temperature and pressure, provided by AC2, were nominally 610°F and 854 psi, respectively, producing a target pressure differential of 1381 psi. At SLB conditions, the AC2 pressure was dropped to produce a nominal differential pressure of 2560 psi. Actual test temperatures for section 3B were significantly different from nominal conditions due to the presence of a relatively large leak.

Room temperature burst tests were performed using a system separate from the leak test system. The rate of pressurization was 200 psi/second or less. The internal pressure of the specimen was recorded digitally through a data acquisition system.

TSP2 (section 4-1B), TSP3 (section 5-1B), TTS (section 1B) and three freespan sections (sections 2B, 4-1A and 5A1) showed no evidence that they would leak during burst testing. These specimens were tested without restraints, bladders or foils. These specimens were pressurized to failure without intermediate hold points.

The other burst test specimen, section 3B (TSP1), had shown significant leakage during leak testing. To complete a valid burst test, it was necessary to cover the source of the leakage with a bladder and lubricated foil. This specimen was semi-restrained by a simulated support system (that included a tubesheet and support plate simulation) designed to mock the conditions in the

Sequoyah-2 steam generators under accident conditions. The centerline of the TSP1 region on section 3B was positioned 2 inches above the centerline of the support plate simulation. The specimen was pressurized through a fitting that connected the top of the specimen with the pressurization equipment.

Following the completion of burst testing, the burst areas were visually characterized and photographed. Photographs were taken and sketches were made of the full 360° circumference of tube to characterize other shallow OD patches not part of burst crack. The diameter of the tubing near each burst opening was also recorded.

### 4.3 Leak Test Results

Table 4-1 presents a summary of the leak test results from TSP1. Figure 4-1 presents a plot of the leak rates as a function of average pressure differential. Figure 4-1 shows that the leak rate through the crack was an exponential function of the pressure differential. This behavior is due to a change in the orifice size.

Figure 4-2 presents plots of the pressures and temperatures that were measured during the tests and in between tests. Of particular interest is the temperature and pressure on the secondary side. Figure 4-3 presents a plot of the secondary side temperatures and pressures alongside the saturated vapor line. Figure 4-3 shows that the first nine tests were conducted to the right of the saturation line. Tests 10 and 11 were conducted on the saturated vapor curve and thus condensation occurred within the secondary side autoclave; there is a possibility that some of the leakage was not measured from these two tests only. However, the secondary side autoclave was designed with its exit at the bottom of the autoclave, thus causing any condensation to exit the autoclave so that it can be measured. Also, test 10 was repeated by test 11, suggesting that a steady state condition had been reached. The test 10 and 11 leak measurements are therefore considered accurate.

A leak rate of less than 0.0012 gpm at NOC pressure and 0.1666 gpm at SLB pressure was established for this tube.

## 4.4 Burst Test Results

The burst test results are shown in Table 4-2.

Section 1B (TTS)

The section with the TTS region burst at 11,453 psig. This burst pressure is only 300 psi less than that of the undegraded freespan section 2B. This burst was well above 3NOP. An artifact of the tube pulling operation may have influenced this burst pressure. In this particular case, the burst did not occur at the crack with the deepest corrosion (located roughly at the 68° orientation).

The burst opening was centered at the TTS and was an axial fishmouth opening. The burst opening was located at the 260° orientation. Corrosion was evident on the burst opening. Numerous short secondary cracks were noted around the circumference of the tube at the TTS elevation. These were oriented mostly in the axial direction but there was some circumferential element that opened during the burst test. Corrosion was not noted outside of the TTS region.

Section 3B (TSP1)

The section containing TSP1 burst at 5391 psig. This was the lowest burst pressure observed from the pulled Sequoyah-2 tubing. This sample was burst tested under semi-restrained conditions and utilized foil and a bladder to allow for a valid burst. The burst occurred in the center of the foil.

The 5391 psig burst pressure was above the temperature corrected 1.4 x SLB pressure (3932 psig) and the temperature corrected 3NOP pressure (4544 psig). This pressure exceeds all GL 95-05 (Reference 1) requirements. Since this support plate intersection had the largest eddy current indication, it can be inferred that the corrosion in the Sequoyah-2 generators does not present an integrity concern.

The burst opening was centered on the centerline of the TSP1 region. The burst opening occurred at the 230° orientation and was an axial fishmouth opening with a significant secondary

opening attached to the main opening. This closely coincides with observed reddish deposits noted in Figure 3-3. It also occurred within 90° of the thinnest part of the tube wall. Corrosion was evident on the burst face and numerous secondary cracks were observed. However, cracking was not observed outside of the TSP1 region.

Section 4-1B (TSP2)

The section with the TSP2 region burst at 6579 psig. This burst pressure is less than the undegraded freespan sections. However, this burst was well above 3NOP. The burst opening was centered on the centerline of the TSP2 region and was an axial fishmouth opening. The burst opening was located at the 15° orientation.

Corrosion was evident on the burst face and numerous secondary cracks were observed. However, cracking was not observed outside of the TSP2 region.

Section 5-1B (TSP3)

The section with the TSP3 region burst at 8237 psig. This burst pressure is less than the undegraded freespan sections. However, this burst was well above 3NOP. The burst opening was centered on the centerline of the TSP3 region and was an axial fishmouth opening. The burst opening was located at the 130° orientation.

Corrosion was evident on the burst face and numerous secondary cracks were observed. However, cracking was not observed outside of the TSP3 region.

Sections 2B, 4-1A and 5A1 (Freespan)

Three freespan burst tests were conducted. All were within 82 psi of each other; the lowest burst pressure was 11,743 psig. Corrosion was not observed on any of the burst test specimens from freespan sections. All freespan bursts were axial fishmouth openings.

## 4.5 Post-Burst Observations

Table 4-2 presents a summary of the post-burst dimensions.

Section 1B (TTS)

Figure 4-4 presents a drawing that summarizes some of the post-burst visual observations of the TTS vicinity. Figures 4-5a through 4-5e present photographs of the burst area. The figures show an axial burst opening. The burst was centered on the TTS. The burst opening was mainly composed of non-corroded metal; only the center 0.11 inch had evidence of corrosion.

There was a band of axial cracks and some cellular corrosion that extended around the circumference of the tube, centered on the TTS, that was 0.2-0.3 inch wide. This corrosion appeared to be very shallow between 315° and 45° (including 0°). There was no corrosion noted outside of this narrow band at the TTS.

Section 3B (TSP1)

Figure 4-6 presents a drawing that summarizes some of the post-burst visual observations of the TSP1 region. Figures 4-7a through 4-7e present photographs of the TSP1 region. The figures show a burst opening that was mostly axial; the opening was composed of a main crack and a significant secondary crack, separated by a "sliver" of metal that remained partially attached to the left side of the burst opening. It was evident that a portion of the burst opening crack had been throughwall. The burst occurred close to where reddish deposits had been noted (Figure 3-3); it is unlikely that an external heat source had converted magnetite to hematite as was the case at the top of the tubesheet. The burst opening occurred entirely within the bounds of the TSP region. There was cracking above and below the burst opening (which was captured in the SEM depth profile measurements); however this cracking was also bound by the TSP region. No corrosion was observed outside the TSP region.

There was some significant secondary cracking on both sides of the burst opening. These secondary cracks that were opened by the burst test were both axial and circumferential and had

the appearance of cellular corrosion mixed with some IGA. The axial component of the secondary corrosion was documented by metallography.

Section 4-1B (TSP2)

Figure 4-8 presents a drawing that summarizes some of the post-burst visual observations of the TSP2 region. Figures 4-9a through 4-9e present photographs of the TSP2 region. The figures show a burst opening that was mostly axial, but was slightly out of parallel with the axis of the tube. The top of the burst opening occurred entirely within the bounds of the TSP region; however there was some ductile tearing that extended just below the bottom of the TSP region. This ductile tearing was a result of the burst test but was not a result of corrosion; there was no corrosion observed outside the TSP region.

Secondary cracks were found on both sides of the burst opening. These secondary cracks were almost entirely axial; however some minor cellular corrosion was observed. No thick deposits remained within the TSP2 region after the burst test.

Section 5-1B (TSP3)

Figure 4-10 presents a drawing that summarizes some of the post-burst visual observations of the TSP3 region. Figures 4-11a through 4-11e present photographs of the TSP3 region. The figures show a burst opening that was axial and was centered on the TSP region. The burst opening itself extended above and below the TSP region; however corrosion on the burst opening was bound by the TSP region. All of the secondary corrosion was also found within the bounds of the TSP region.

There was secondary corrosion found on most of the circumference of the TSP3 region, although about a fourth of the circumference was obscured by the presence of thick gray deposits that remained on the tube even after the swelling of the tube from the burst test. These secondary cracks were mostly axial; there was a lot of shallow cellular corrosion however.

Two axial cracks were found entirely within two installation scratches. These scratch cracks were observed to be "medium deep". These scratch cracks were also bound by the bottom of the TSP region, but did not extend the full length of the scratch that was within the TSP3 region.

Sections 2B, 4-1A and 5A1 (Freespan)

Figures 4-12a through 4-12e present photographs of the burst area for section 2B. Figures 4-13a through 4-13e present photographs of the burst area for section 4-1A. Figures 4-14a through 4-14e present photographs of the burst area for section 5A1. These freespan bursts all had similar results. In each of the three tests the figures show that the tube swelling has occurred evenly around the circumference of the tube, that each had an axial burst opening, and in no case was corrosion of any kind observed on a freespan burst test sample.

TABLE 4-1

LEAK RATE SUMMARY FOR TSP1

| Test | | Pressure (psi) | | | Temperature (°F) | | Leak Rate (gal/min) |
|---|---|---|---|---|---|---|---|
| | | Delta P | Primary | Secondary | Primary | Secondary | |
| 1 | Min | 1434 | 2298 | 864 | 598 | 605 | 0.0012 |
| | Max | 1457 | 2323 | 867 | 600 | 611 | |
| | Avg | 1443 | 2309 | 865 | 599 | 608 | |
| 2 | Min | 1483 | 2348 | 862 | 596 | 606 | 0.0020 |
| | Max | 1511 | 2374 | 865 | 601 | 610 | |
| | Avg | 1504 | 2368 | 864 | 598 | 609 | |
| 3 | Min | 1428 | 2293 | 864 | 593 | 607 | 0.0020 |
| | Max | 1489 | 2354 | 866 | 595 | 611 | |
| | Avg | 1460 | 2325 | 865 | 595 | 609 | |
| 4 | Min | 1681 | 2153 | 466 | 571 | 533 | 0.0132 |
| | Max | 1765 | 2231 | 472 | 581 | 554 | |
| | Avg | 1706 | 2175 | 469 | 573 | 540 | |
| 5 | Min | 1695 | 2167 | 472 | 576 | 519 | 0.0125 |
| | Max | 1707 | 2179 | 472 | 578 | 527 | |
| | Avg | 1704 | 2176 | 472 | 577 | 523 | |
| 6 | Min | 2108 | 2139 | 31 | 576 | 406 | 0.0405 |
| | Max | 2158 | 2193 | 35 | 581 | 470 | |
| | Avg | 2124 | 2156 | 32 | 579 | 429 | |
| 7 | Min | 2125 | 2155 | 29 | 582 | 353 | 0.0403 |
| | Max | 2126 | 2156 | 30 | 584 | 372 | |
| | Avg | 2125 | 2155 | 30 | 583 | 363 | |
| 8 | Min | 2129 | 2157 | 28 | 586 | 325 | 0.0396 |
| | Max | 2131 | 2159 | 29 | 590 | 334 | |
| | Avg | 2130 | 2159 | 29 | 588 | 329 | |
| 9 | Min | 2350 | 2413 | 62 | 592 | 328 | 0.0691 |
| | Max | 2359 | 2422 | 63 | 598 | 346 | |
| | Avg | 2356 | 2418 | 62 | 596 | 338 | |
| 10 | Min | 2597 | 2705 | 107 | 603 | 346 | 0.1639 |
| | Max | 2603 | 2710 | 110 | 605 | 347 | |
| | Avg | 2600 | 2708 | 108 | 604 | 346 | |
| 11 | Min | 2584 | 2694 | 106 | 603 | 346 | 0.1666 |
| | Max | 2591 | 2698 | 111 | 605 | 347 | |
| | Avg | 2588 | 2696 | 109 | 604 | 346 | |

TABLE 4-2

BURST TEST RESULTS

| Section | 1B | 3B | 4-1B | 5-1B | 2B | 4-1A | 5A1 |
|---|---|---|---|---|---|---|---|
| Location | TTS | TSP1 | TSP2 | TSP3 | Freespan | Freespan | Freespan |
| Burst Pressure (psig) | 11,453* | 5391 | 6579 | 8237 | 11,743 | 11,809 | 11,825 |
| Burst Angular Position | 260° | 230° | 15° | 130° | 200° | 15° | 115° |
| Burst Length (inch) | 1.575 | 0.600 | 0.638 | 0.875 | 1.938 | 2.007 | 2.007 |
| Burst Width (inch) | 0.425 | 0.123 | 0.138 | 0.238 | 0.391 | 0.459 | 0.391 |
| Pre-Burst Wall Thickness, 0° (inch) | 0.0560 | 0.0548 | 0.051 | 0.051 | 0.0563 | 0.050 | 0.0543 |
| Pre-Burst Wall Thickness, 90° (inch) | 0.0546 | 0.0580 | 0.051 | 0.051 | 0.0541 | 0.051 | 0.0480 |
| Pre-Burst Wall Thickness, 180° (inch) | 0.0484 | 0.0526 | - | - | 0.0484 | - | 0.0504 |
| Pre-Burst Wall Thickness, 270° (inch) | 0.0511 | 0.0503 | - | - | 0.0504 | - | 0.0563 |
| Post-Burst Max. Diameter (inch) | 1.135 | 0.975 | 0.950 | 1.000 | 1.184 | 1.190 | 1.190 |
| Post-Burst, 90° from Max. Diameter (inch) | 0.950 | 0.875 | 0.875 | 0.875 | 1.020 | 1.010 | 1.007 |

*Note – this burst pressure was influenced by the TIG weld. See the discussion in the Metallography section.

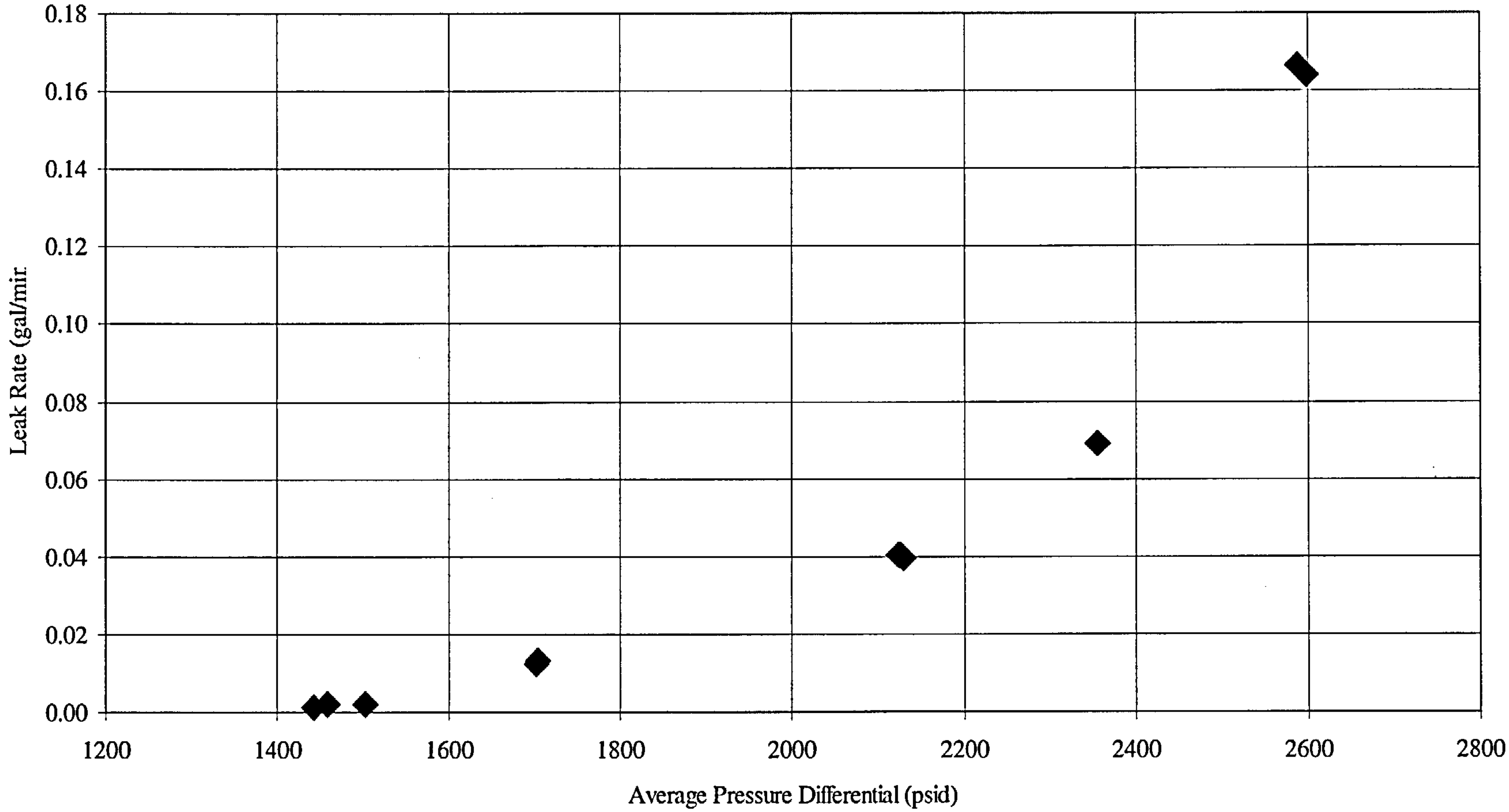


Figure 4-1. Leak Rate as a Function of Pressure Differential for TSP1 (Section 3B).

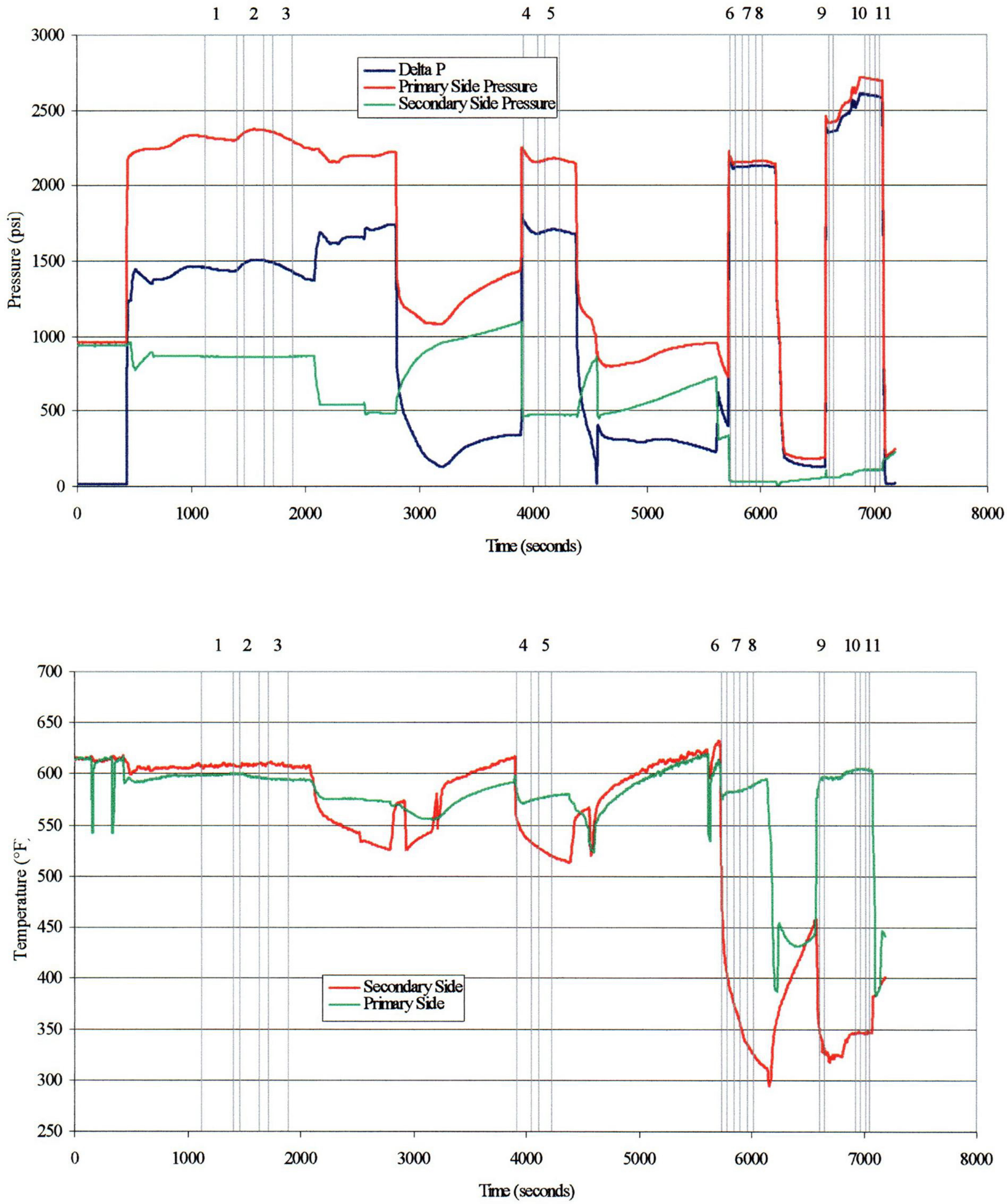


Figure 4-2. Pressure and Temperature Plots for TSP1.

C04

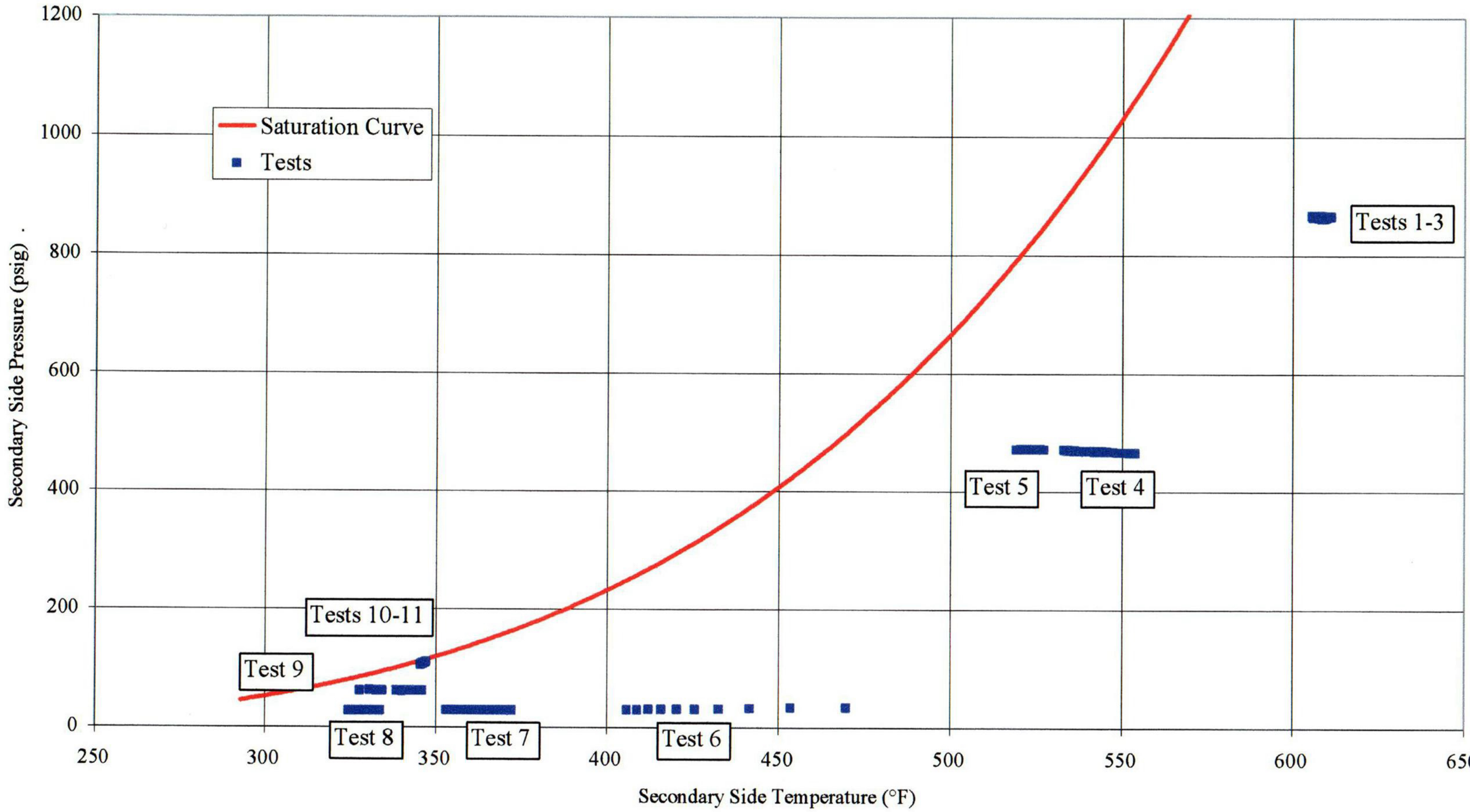


Figure 4-3. Secondary Side Autoclave Temperatures and Pressures.

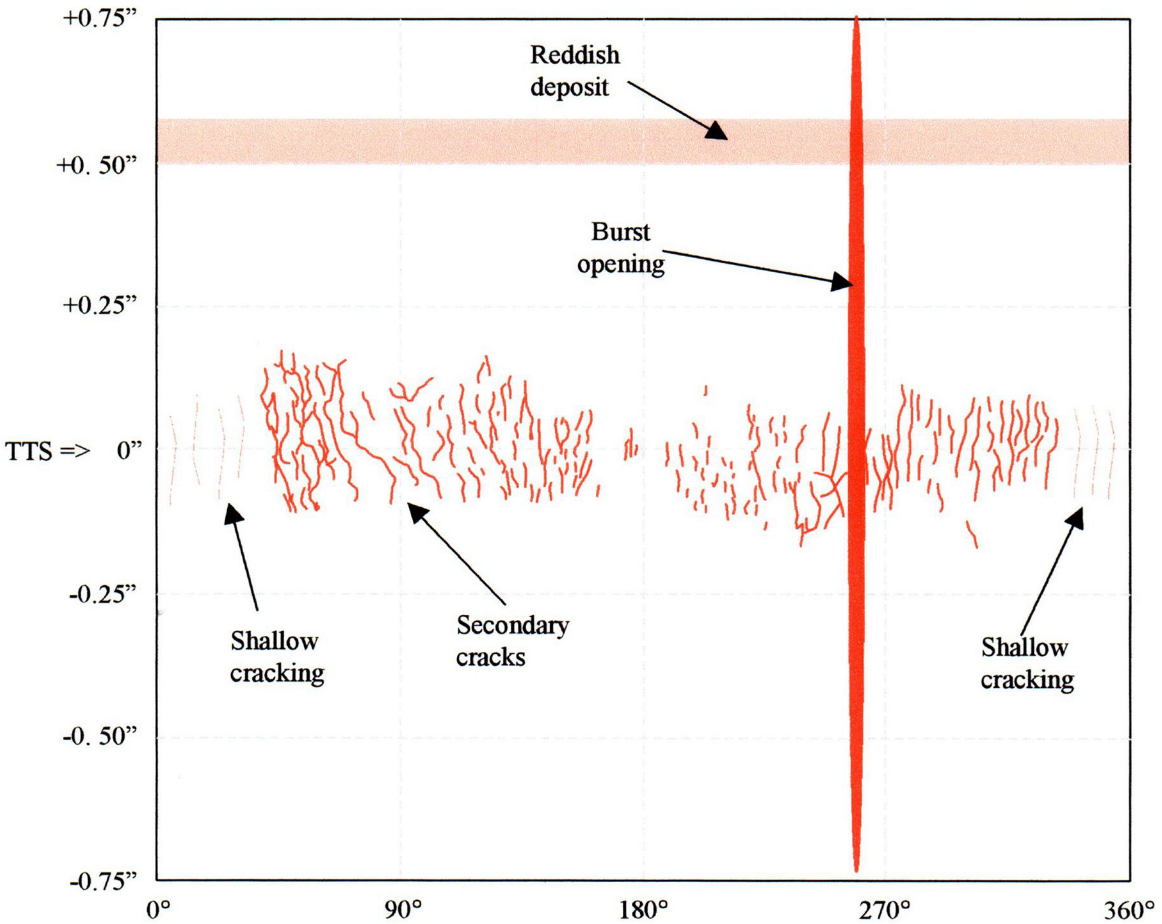


Figure 4-4. Post-Burst Visual Observations of TTS Region.



C06

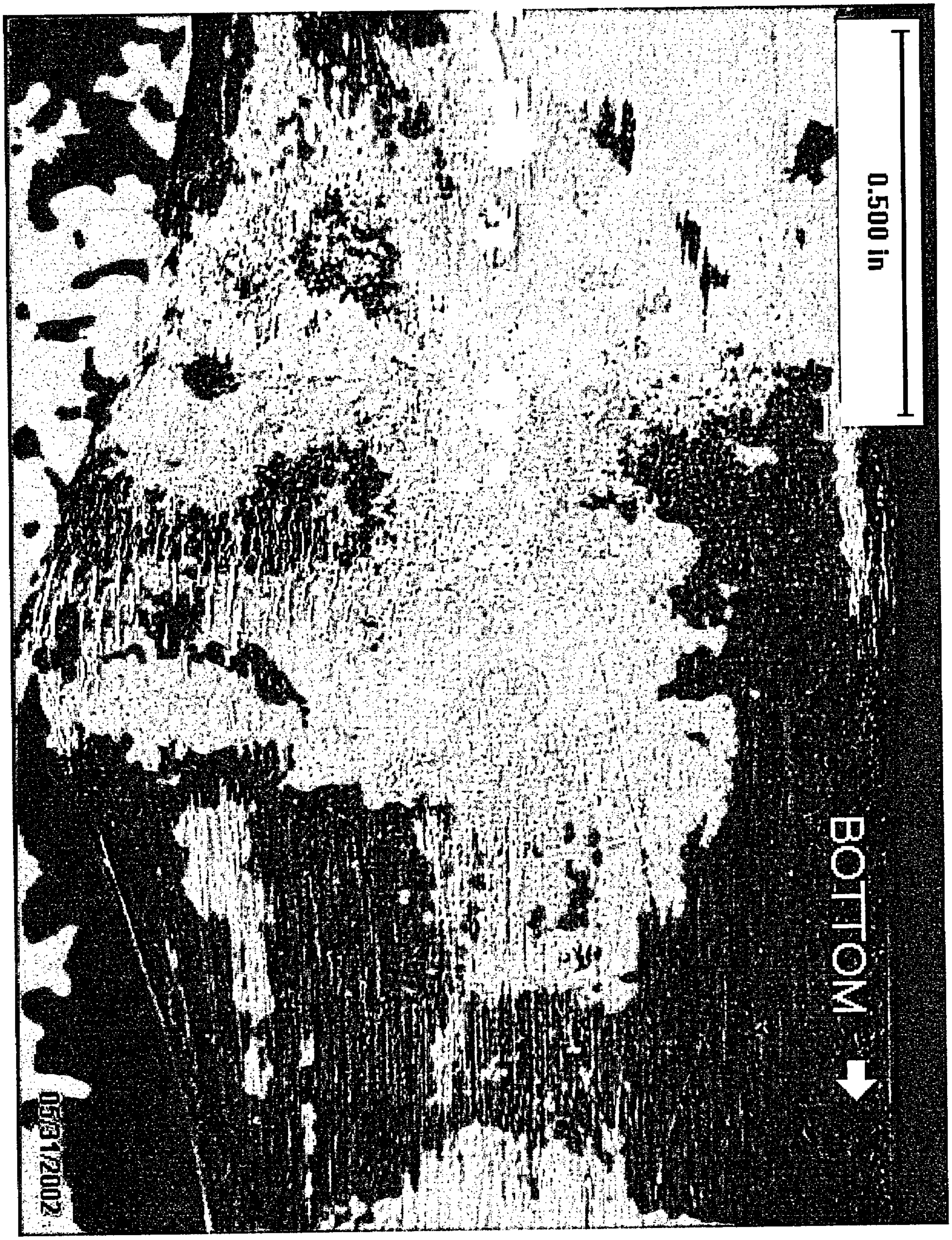


Figure 4-5a. Photograph of TTS Burst Area, 0° Face.


Figure 4-5b. Photograph of TTS Burst Area, 90° Face.


Figure 4-5c. Photograph of TTS Burst Area, 180° Face.

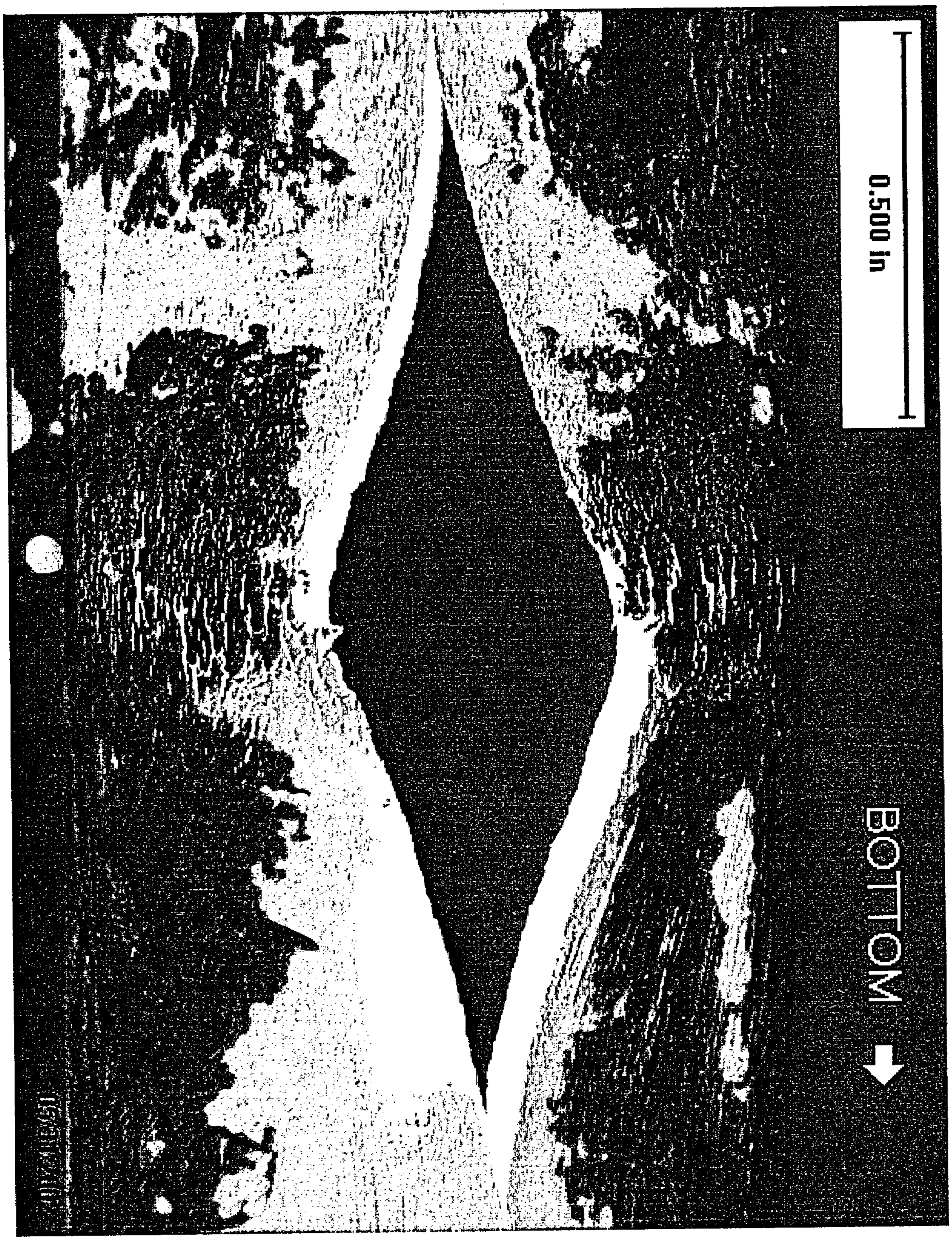


Figure 4-5d. Photograph of TTS Burst Area, 260° Face.

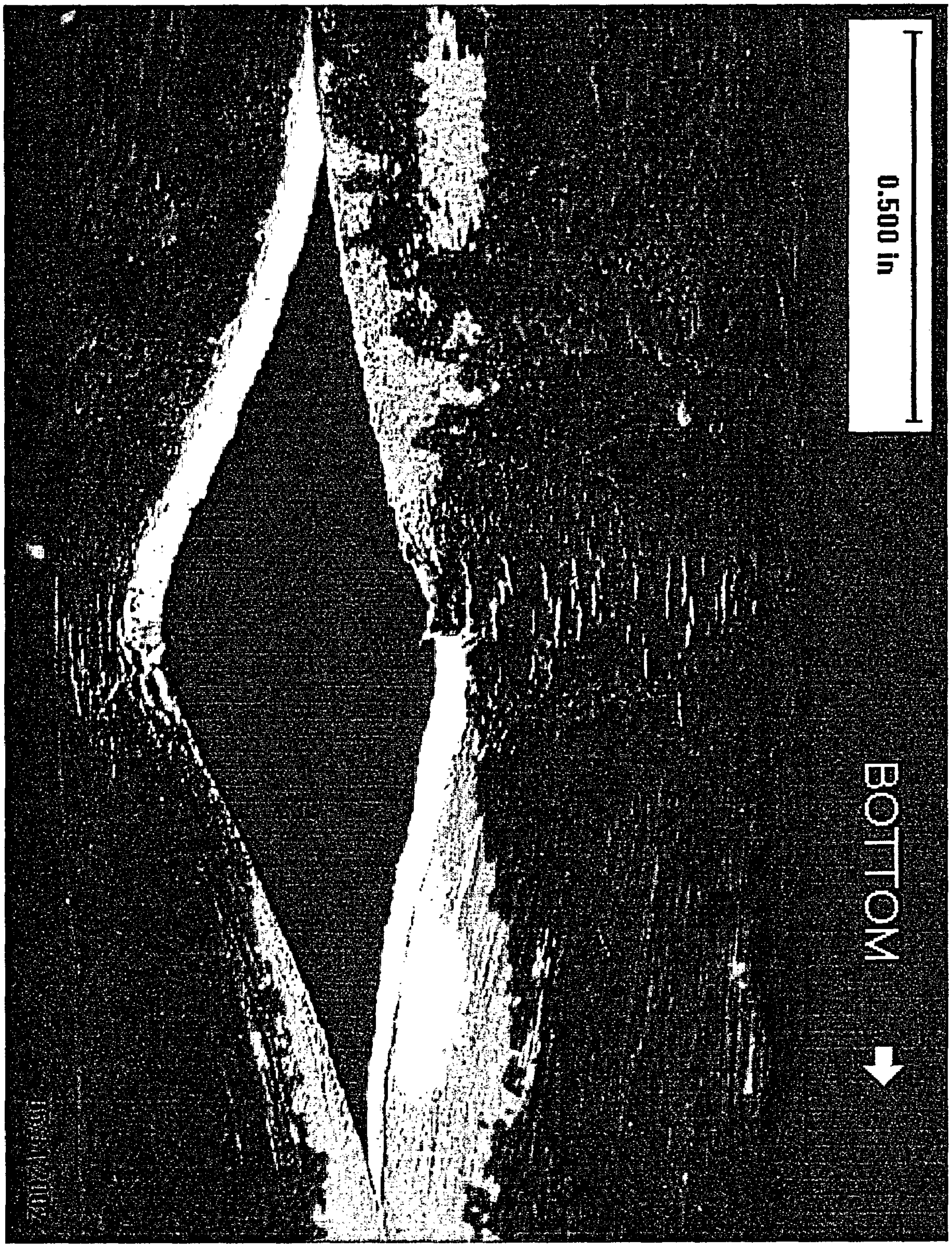


Figure 4-5e. Photograph of TTS Burst Area, 270° Face.

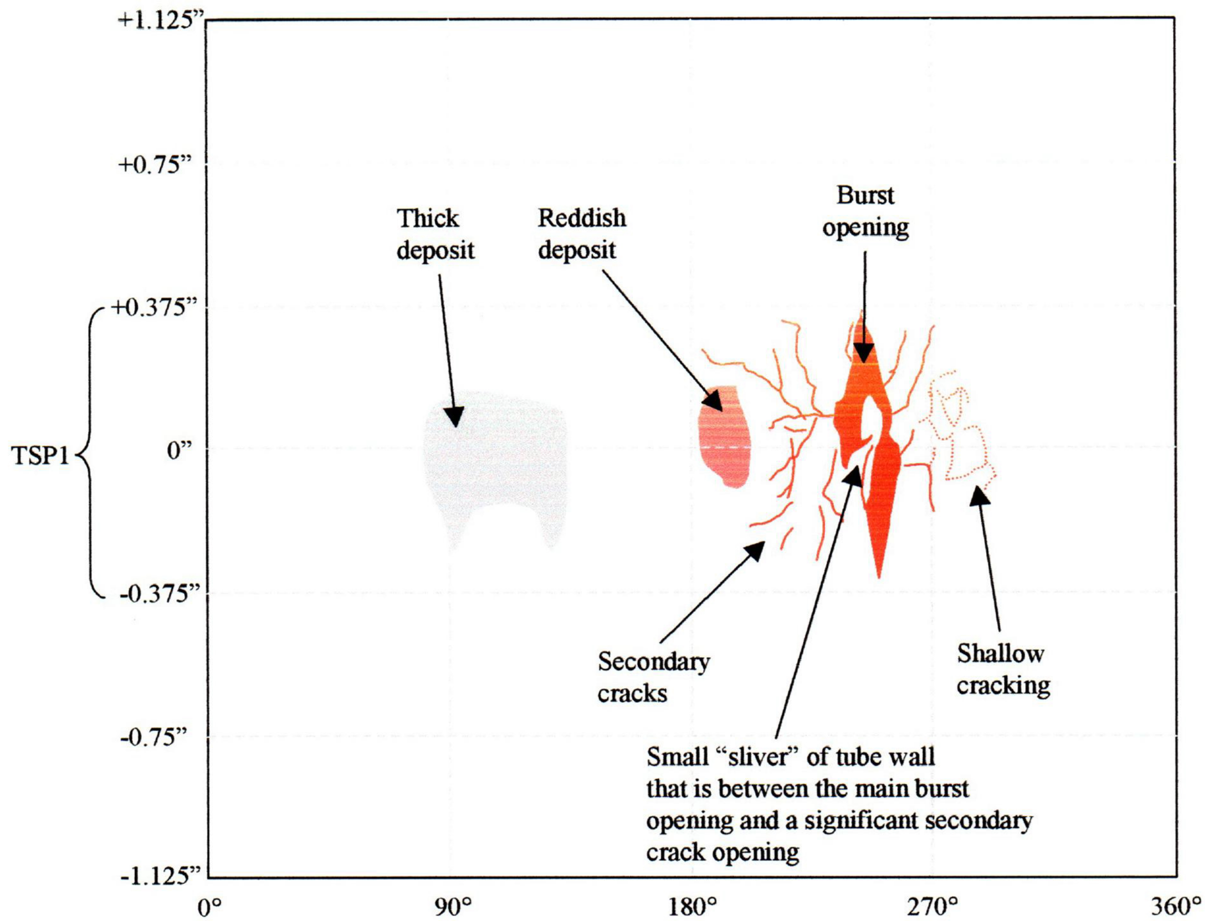


Figure 4-6. Post-Burst Visual Observations of TSP1 Region.

COT

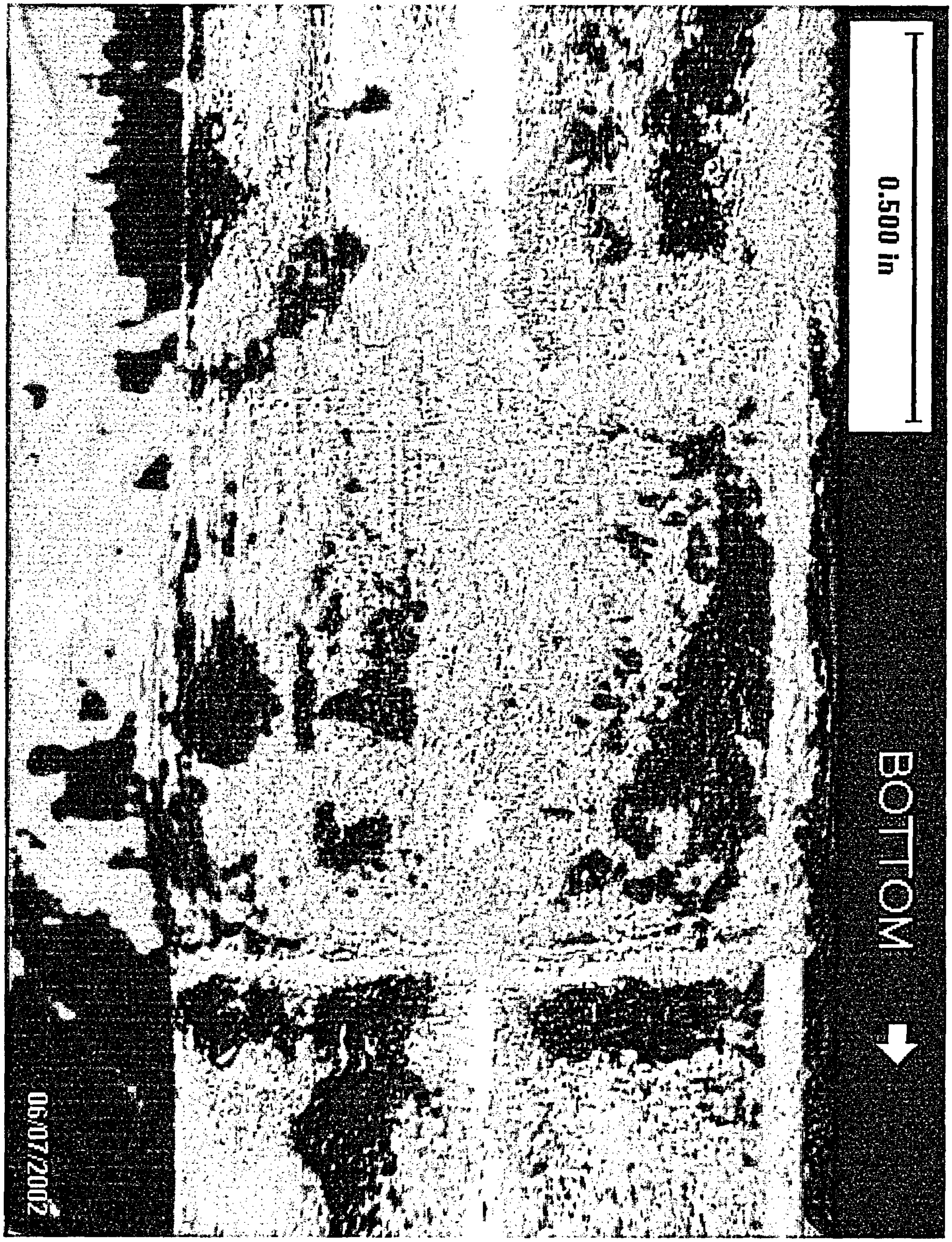


Figure 4-7a. Photograph of TSP1 Burst Area, 0° Face.

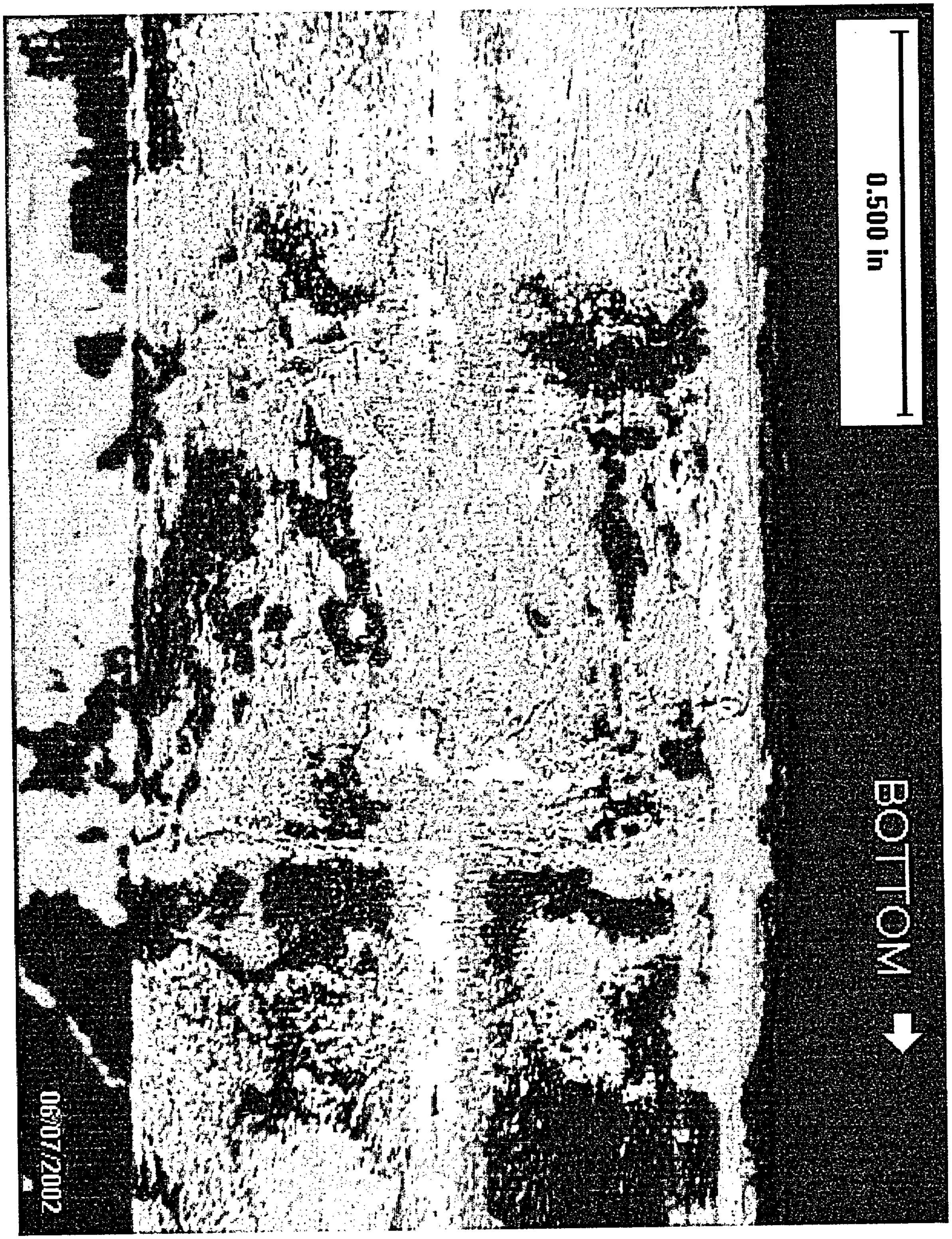


Figure 4-7b. Photograph of TSP1 Burst Area, 90° Face.

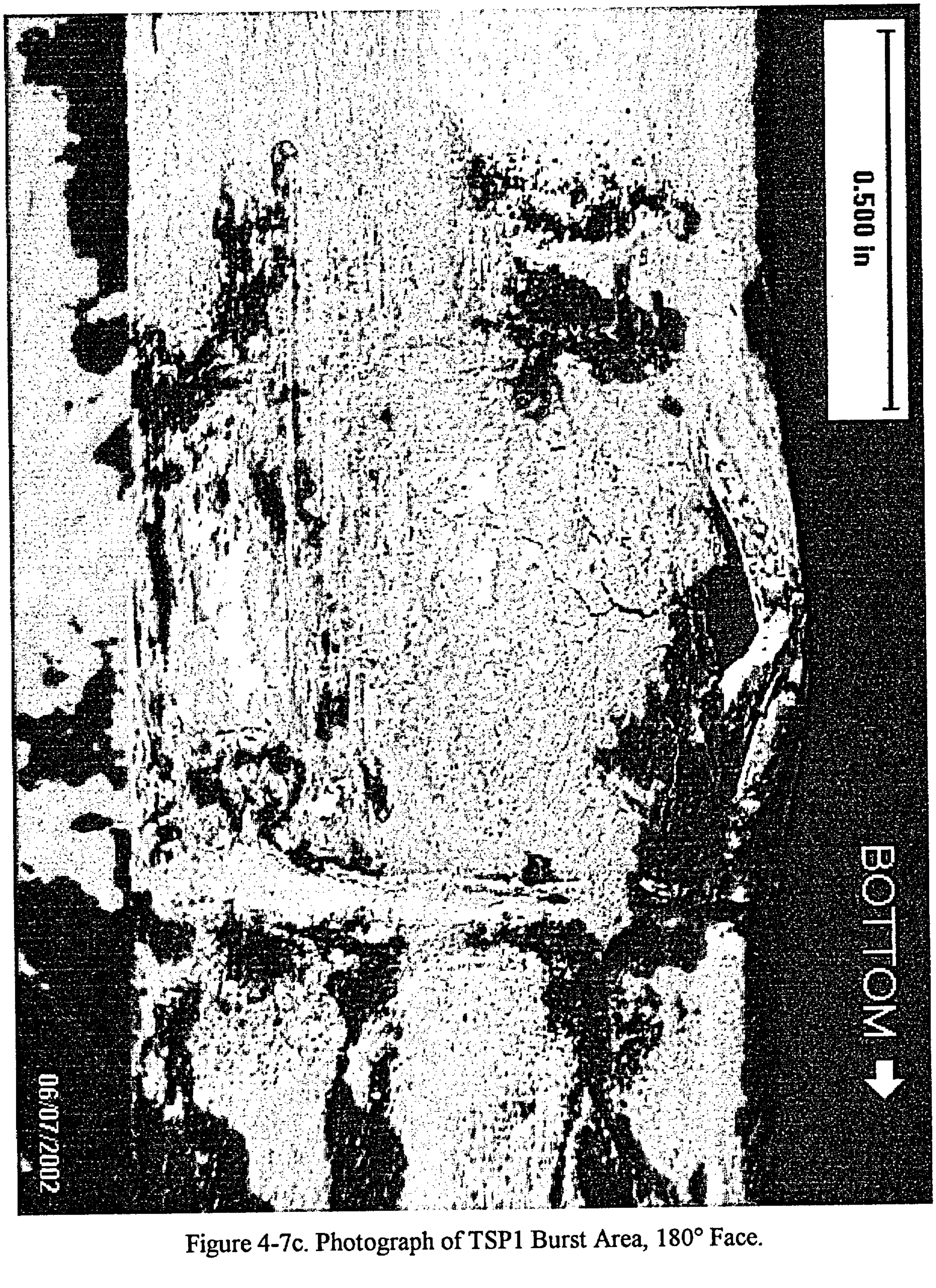


Figure 4-7c. Photograph of TSP1 Burst Area, 180° Face.

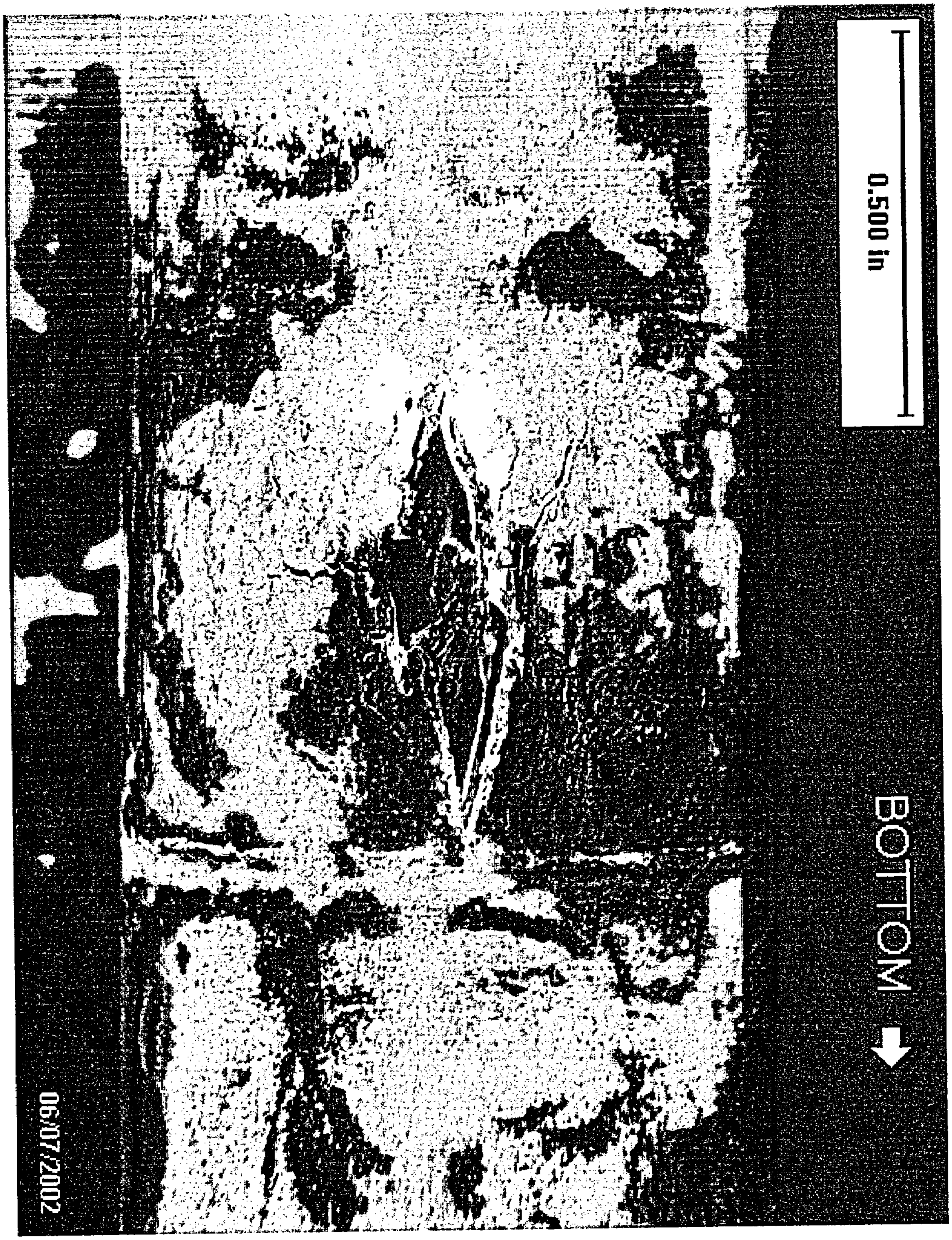


Figure 4-7d. Photograph of TSP1 Burst Area, 230° Face.

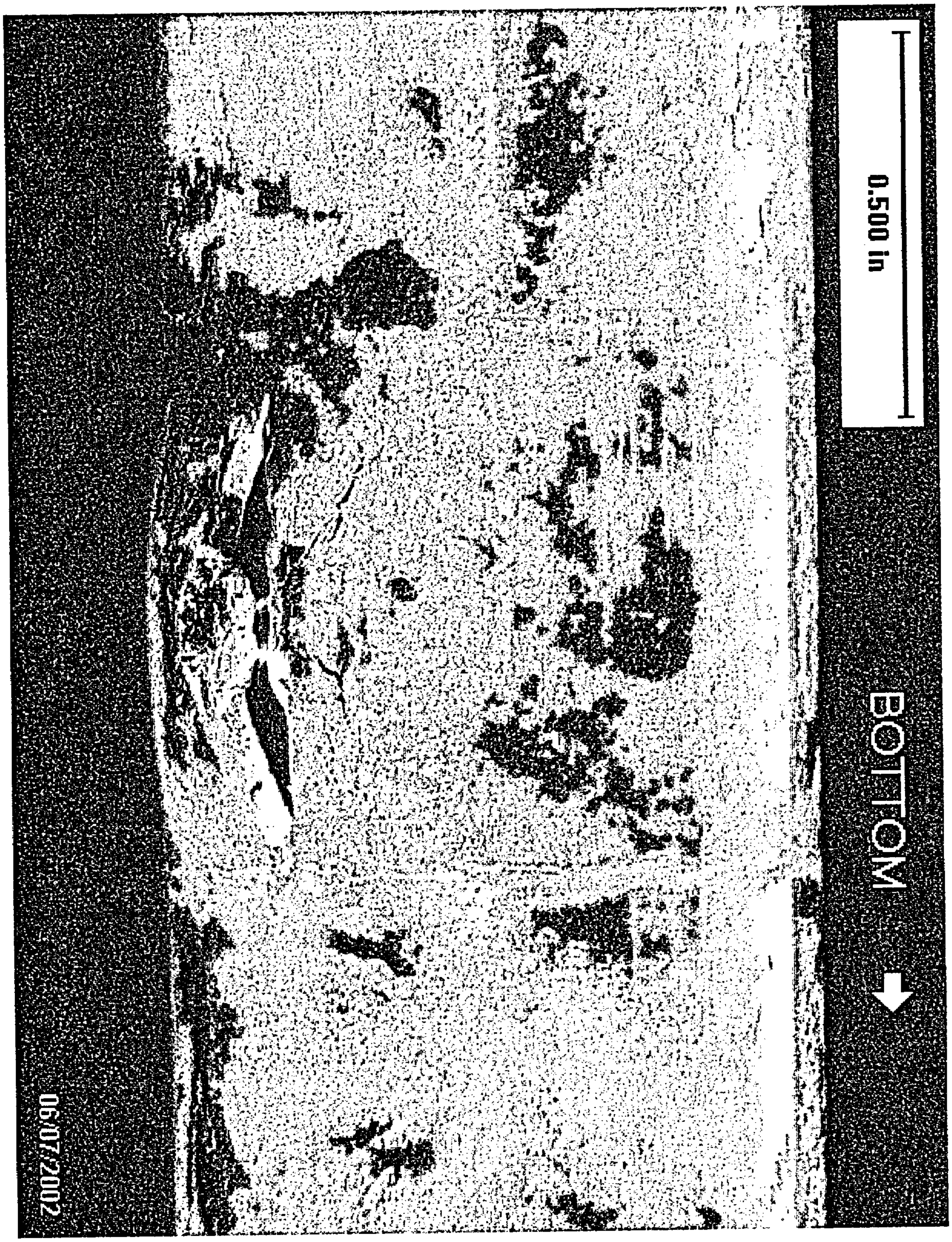


Figure 4-7e. Photograph of TSP1 Burst Area, 270° Face.

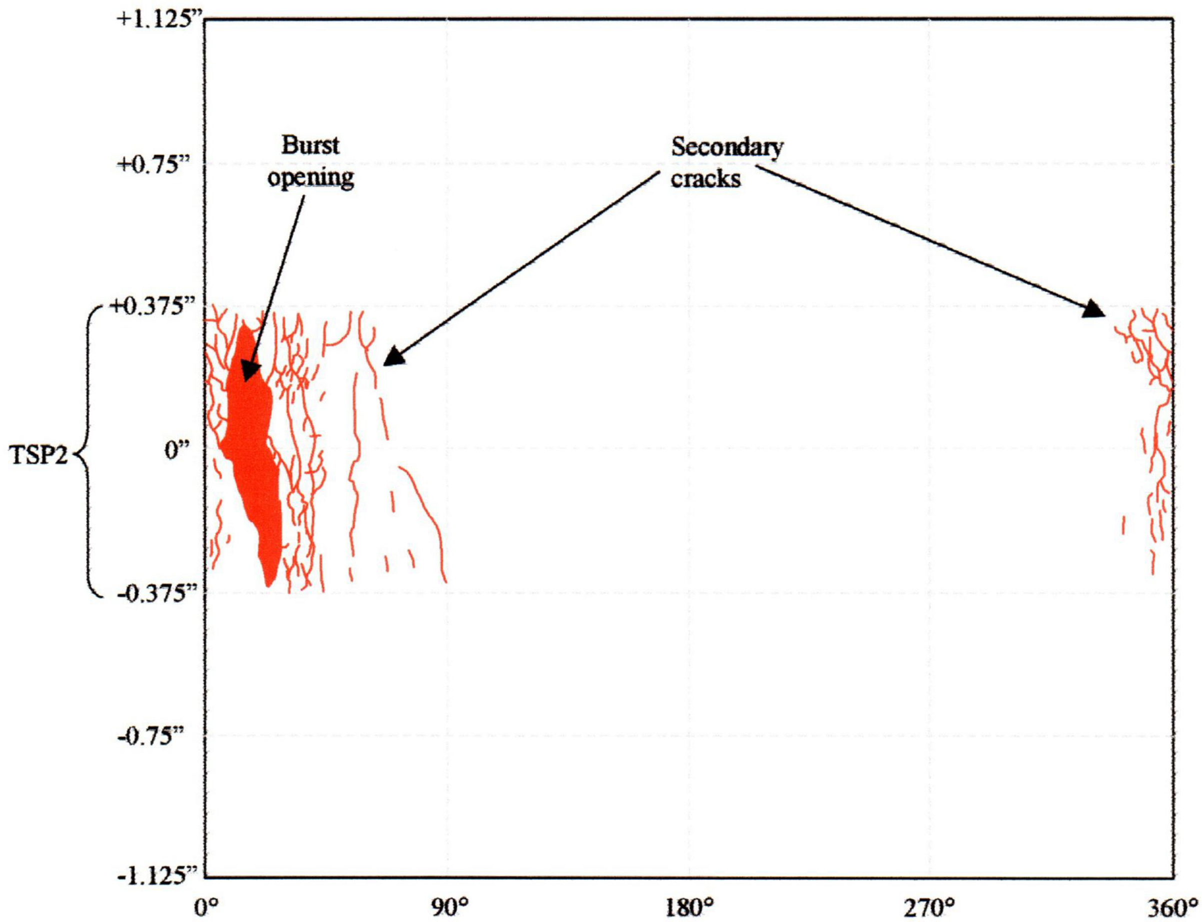


Figure 4-8. Post-Burst Visual Observations of TSP2 Region.

C08


Figure 4-9a. Photograph of TSP2 Burst Area, 0° Face.


Figure 4-9b. Photograph of TSP2 Burst Area, 15° Face.


Figure 4-9c. Photograph of TSP2 Burst Area, 90° Face.

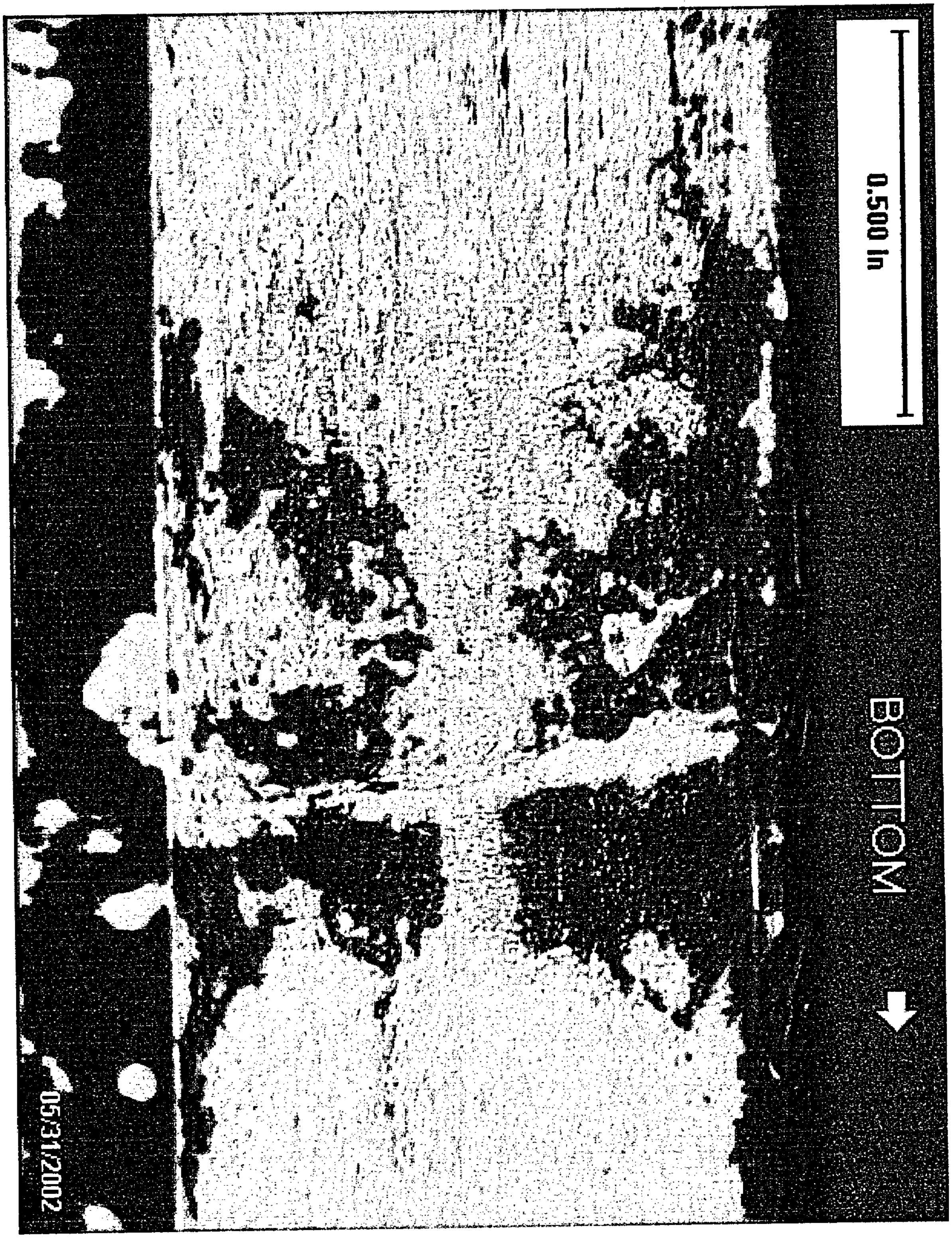


Figure 4-9d. Photograph of TSP2 Burst Area, 180° Face.

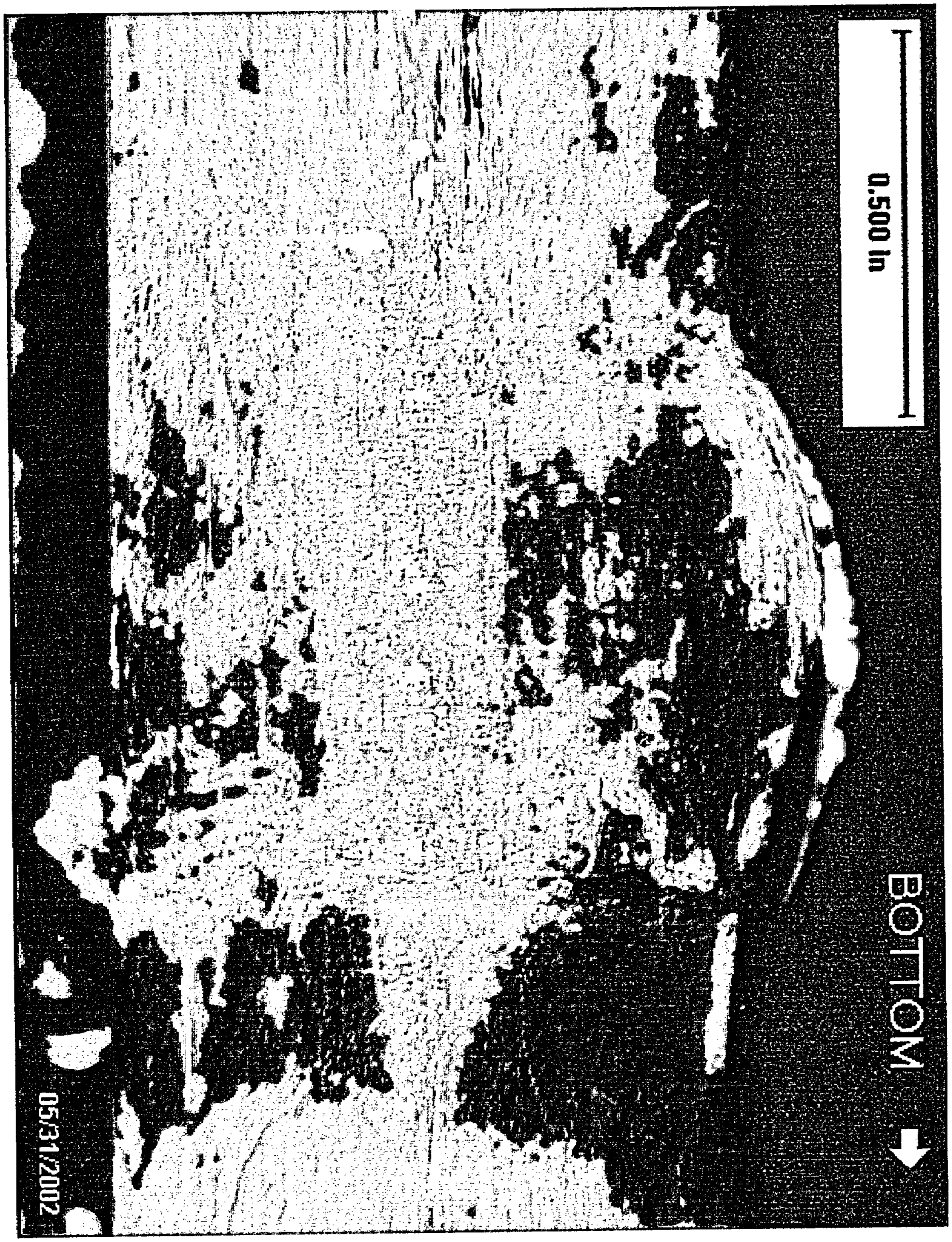


Figure 4-9e. Photograph of TSP2 Burst Area, 270° Face.

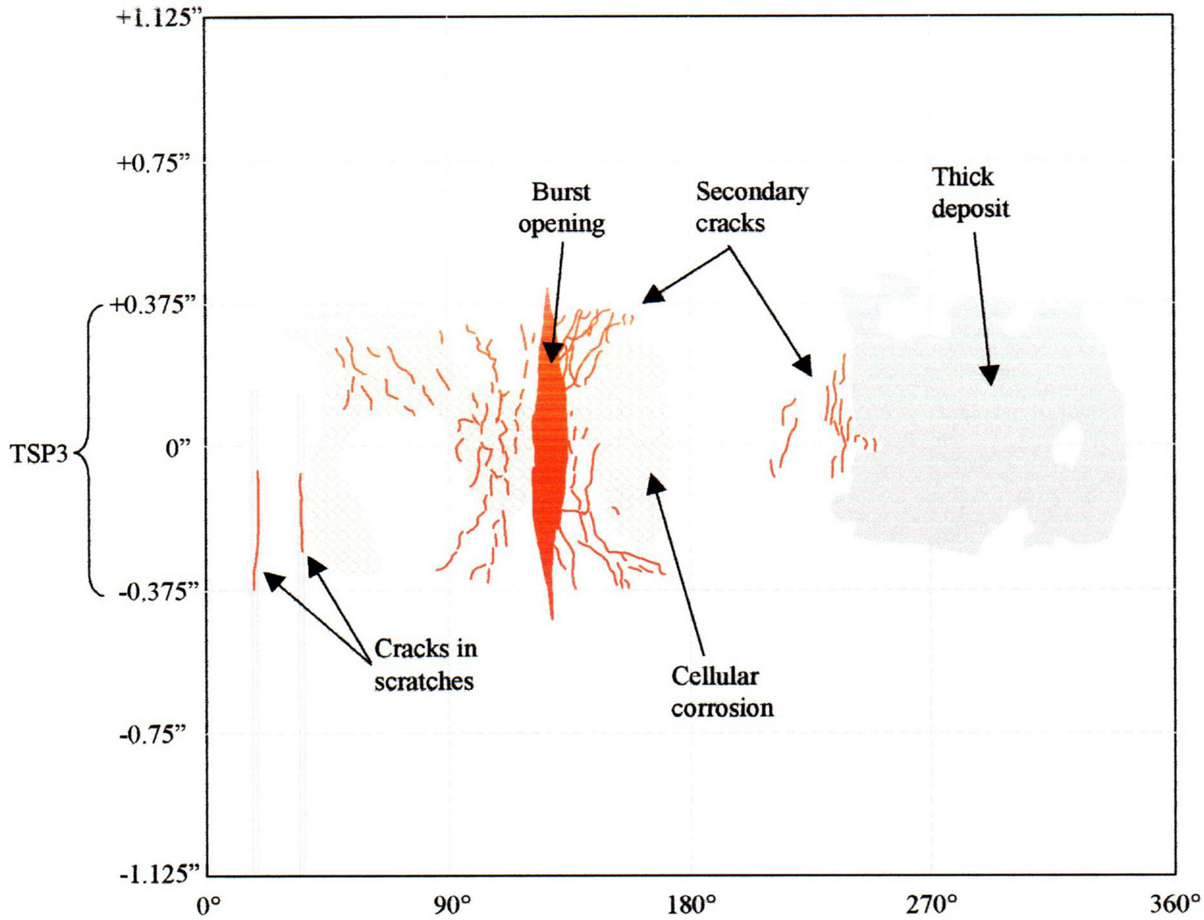


Figure 4-10. Post-Burst Visual Observations of TSP3 Region.

C09

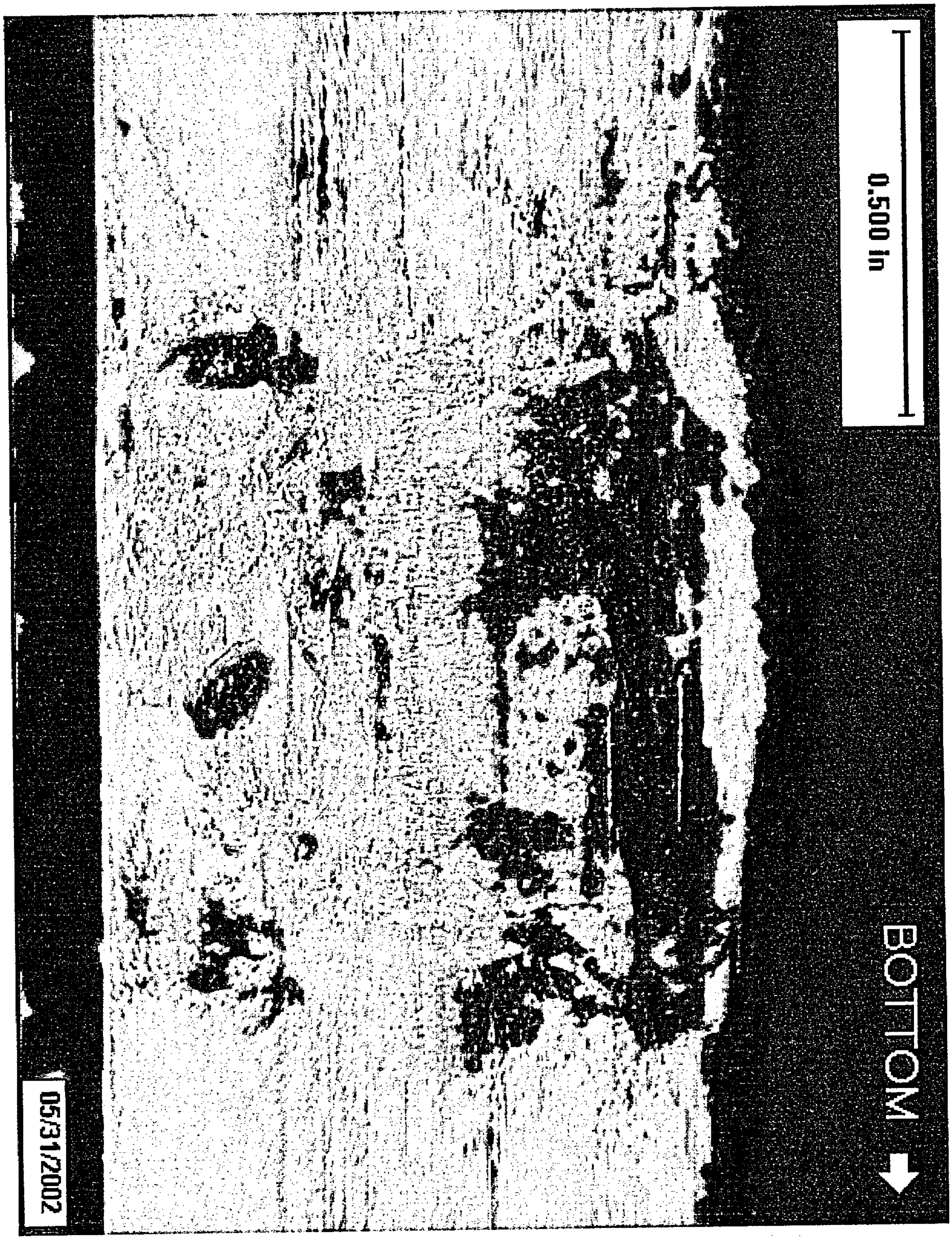


Figure 4-11a. Photograph of TSP3 Burst Area, 0° Face.

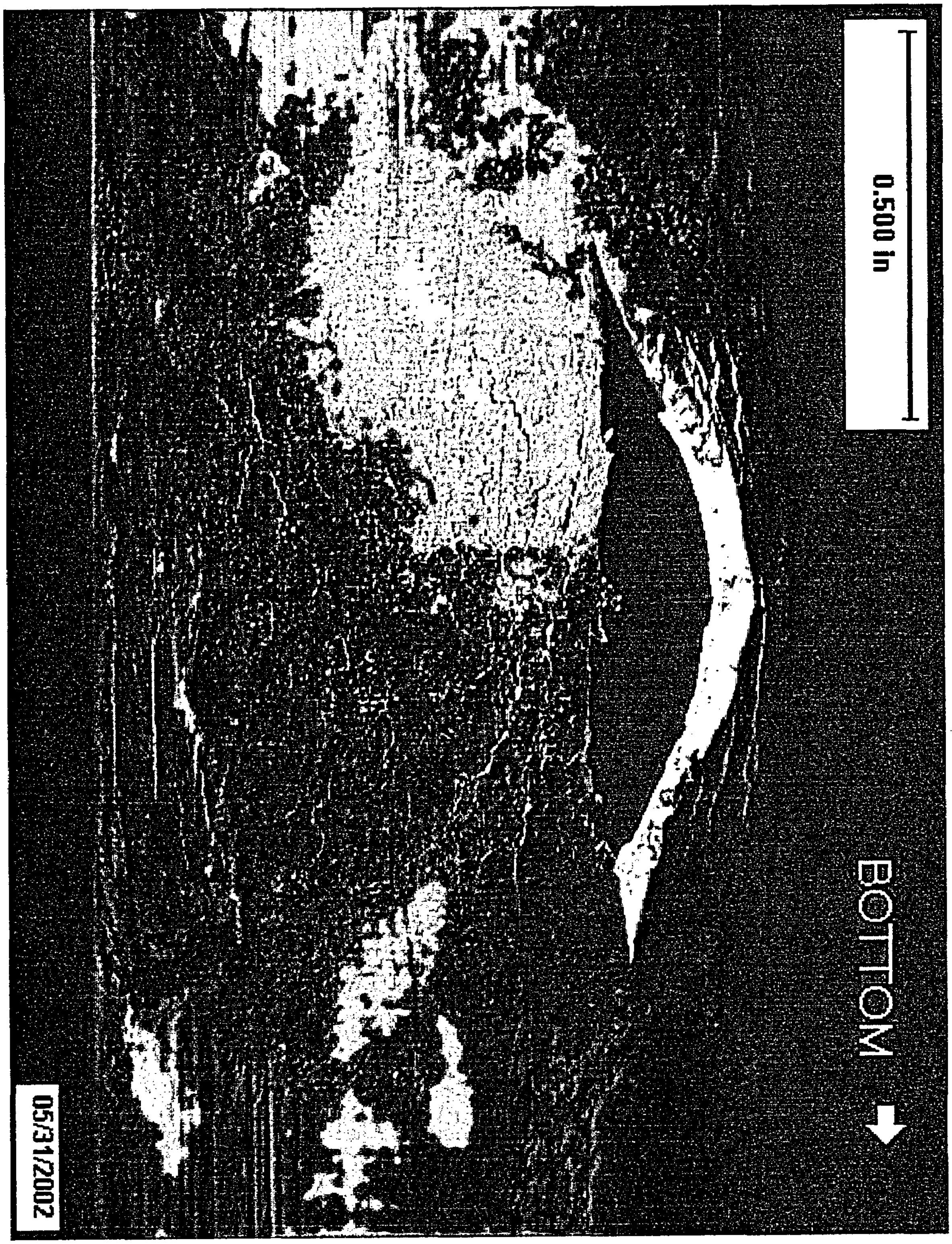


Figure 4-11b. Photograph of TSP3 Burst Area, 90° Face.

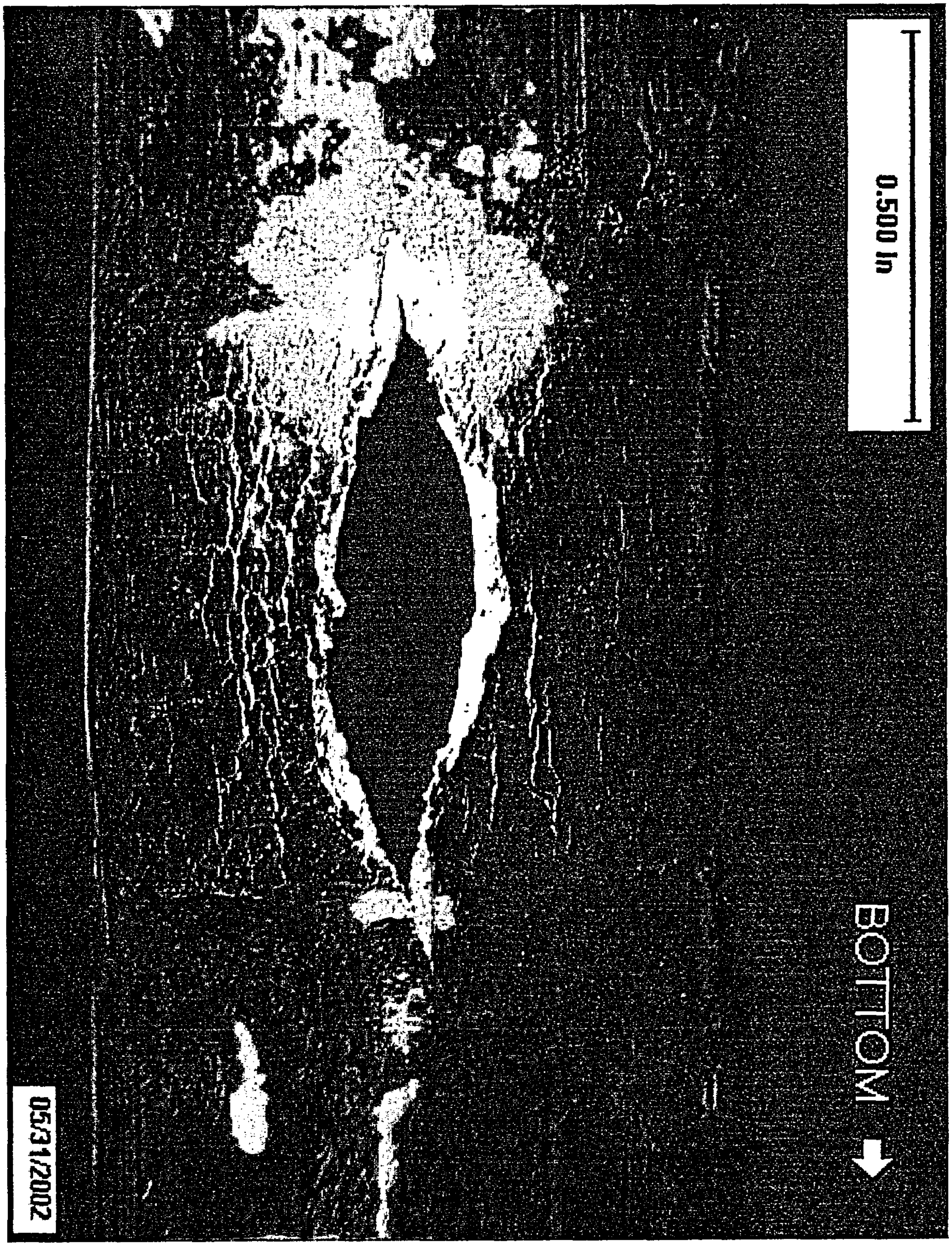


Figure 4-11c. Photograph of TSP3 Burst Area, 130° Face.

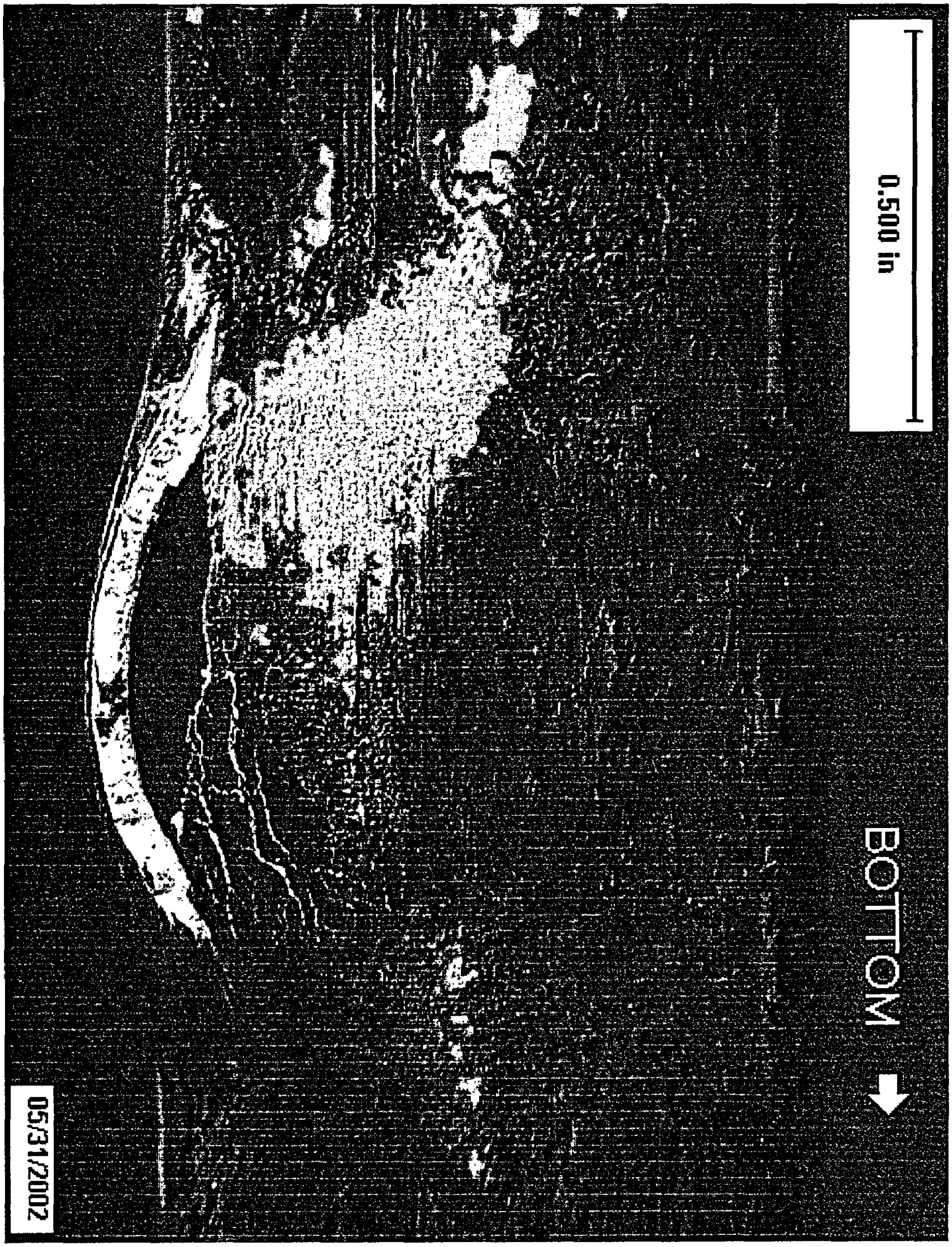


Figure 4-11d. Photograph of TSP3 Burst Area, 180° Face.

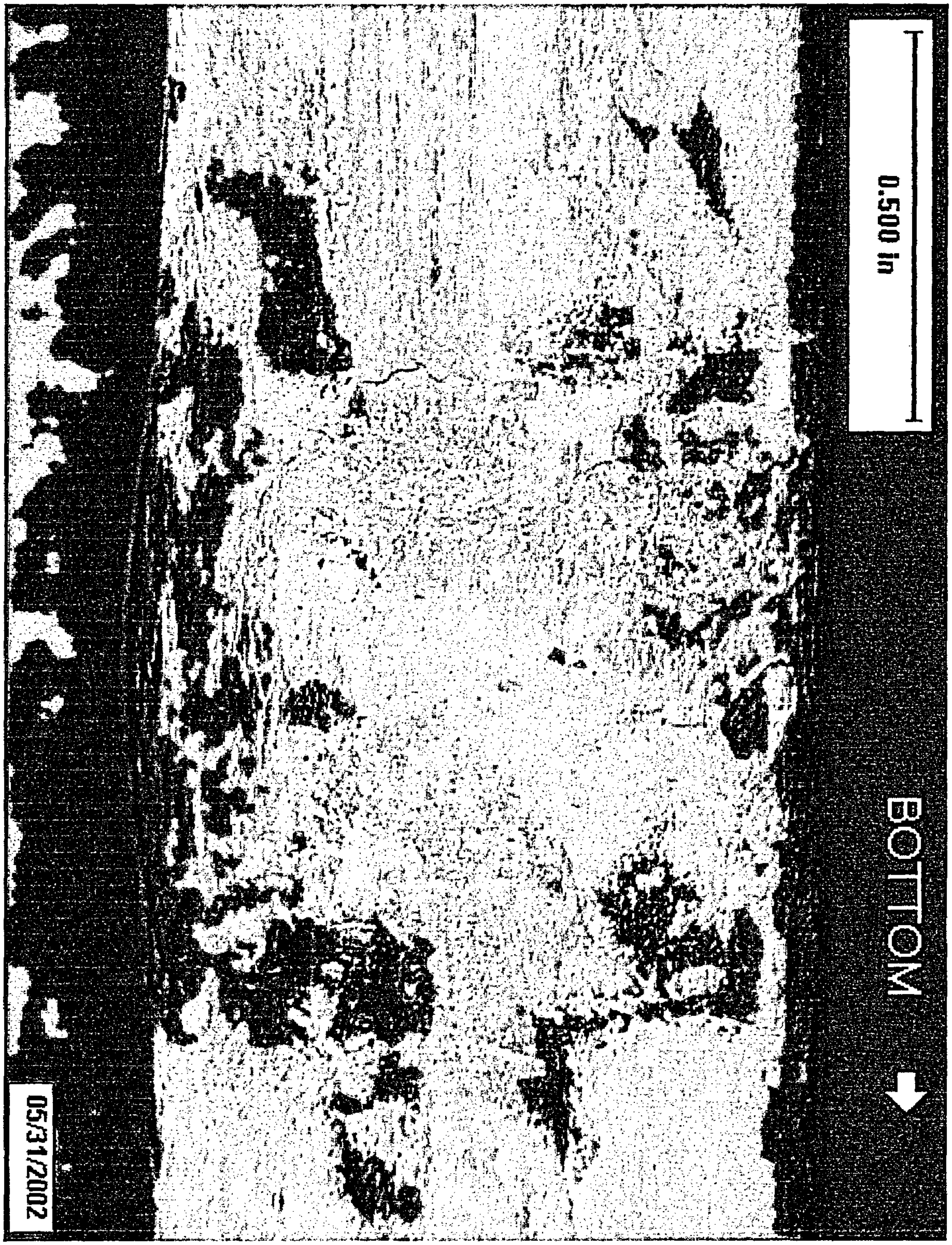


Figure 4-11e. Photograph of TSP3 Burst Area, 270° Face.

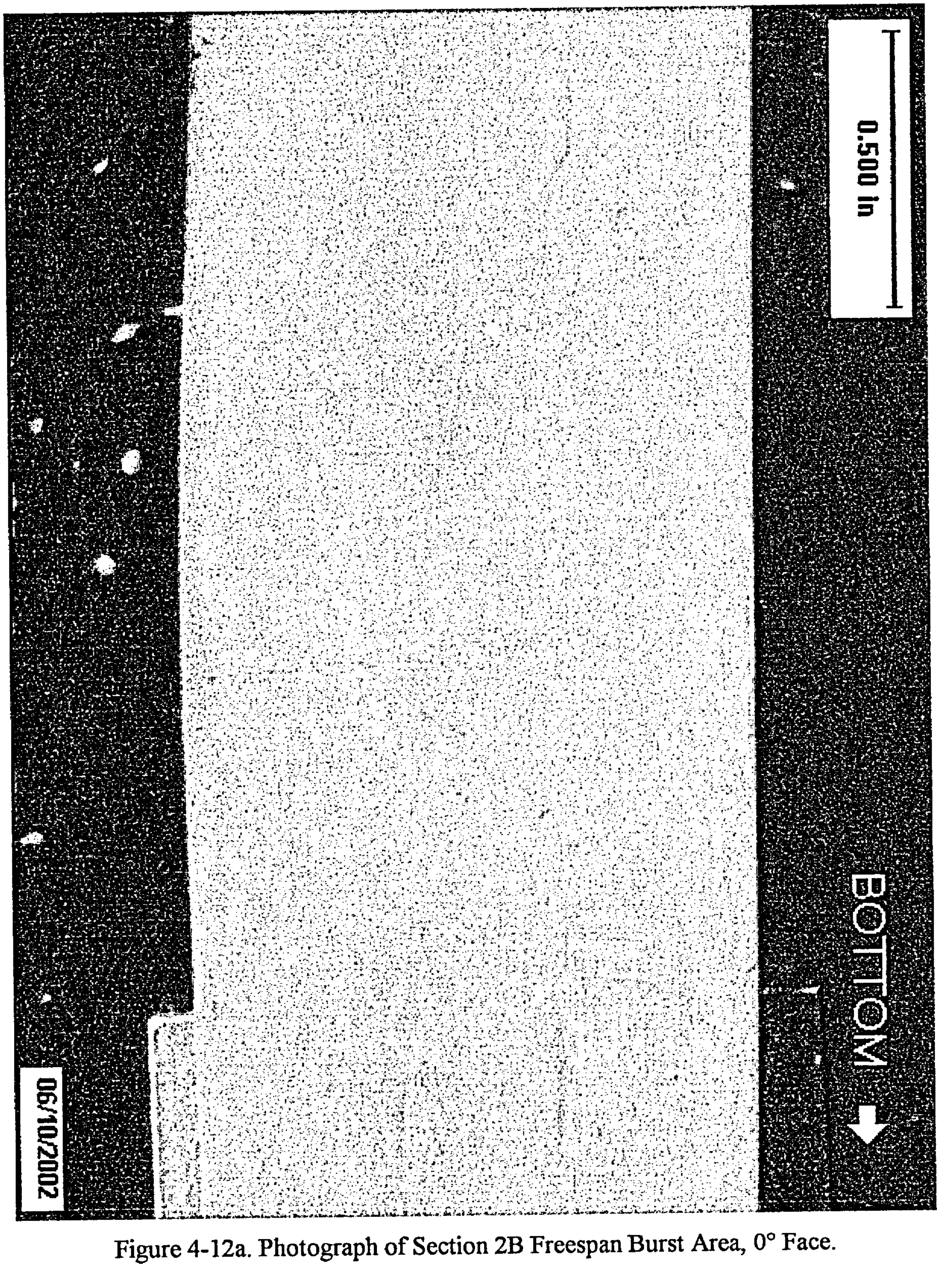


Figure 4-12a. Photograph of Section 2B Freespan Burst Area, 0° Face.

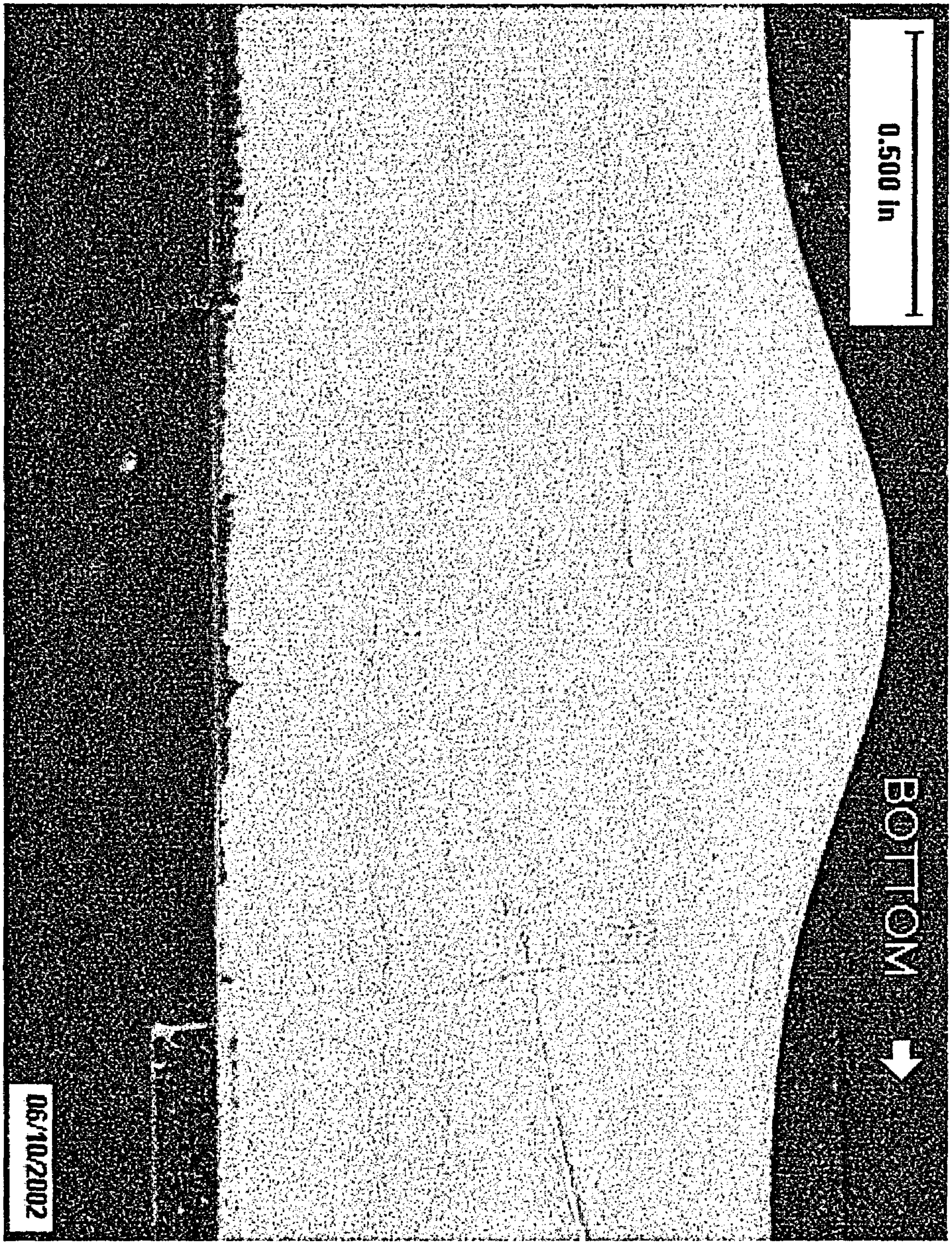


Figure 4-12b. Photograph of Section 2B Freespan Burst Area, 90° Face.

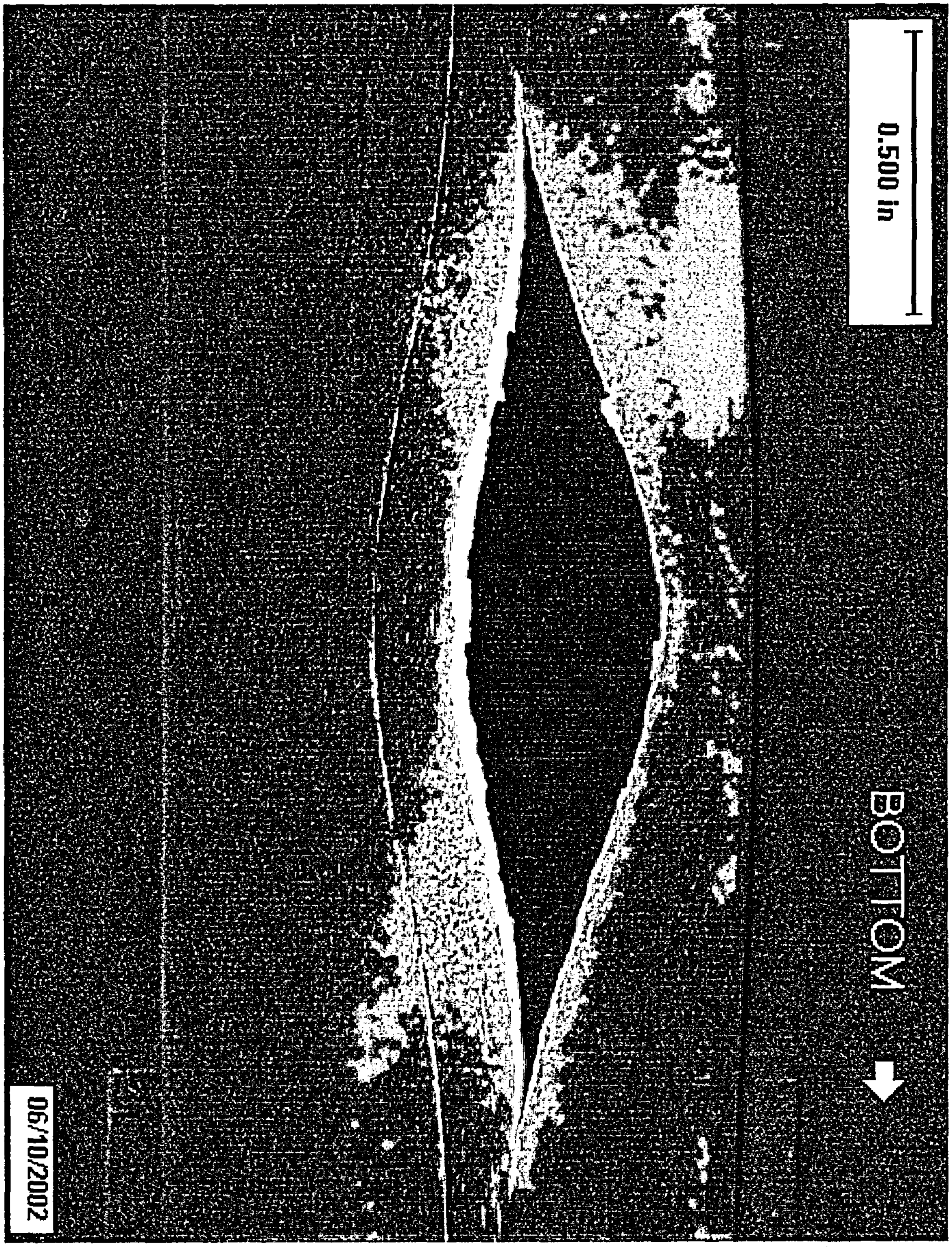


Figure 4-12c. Photograph of Section 2B Freespan Burst Area, 180° Face.

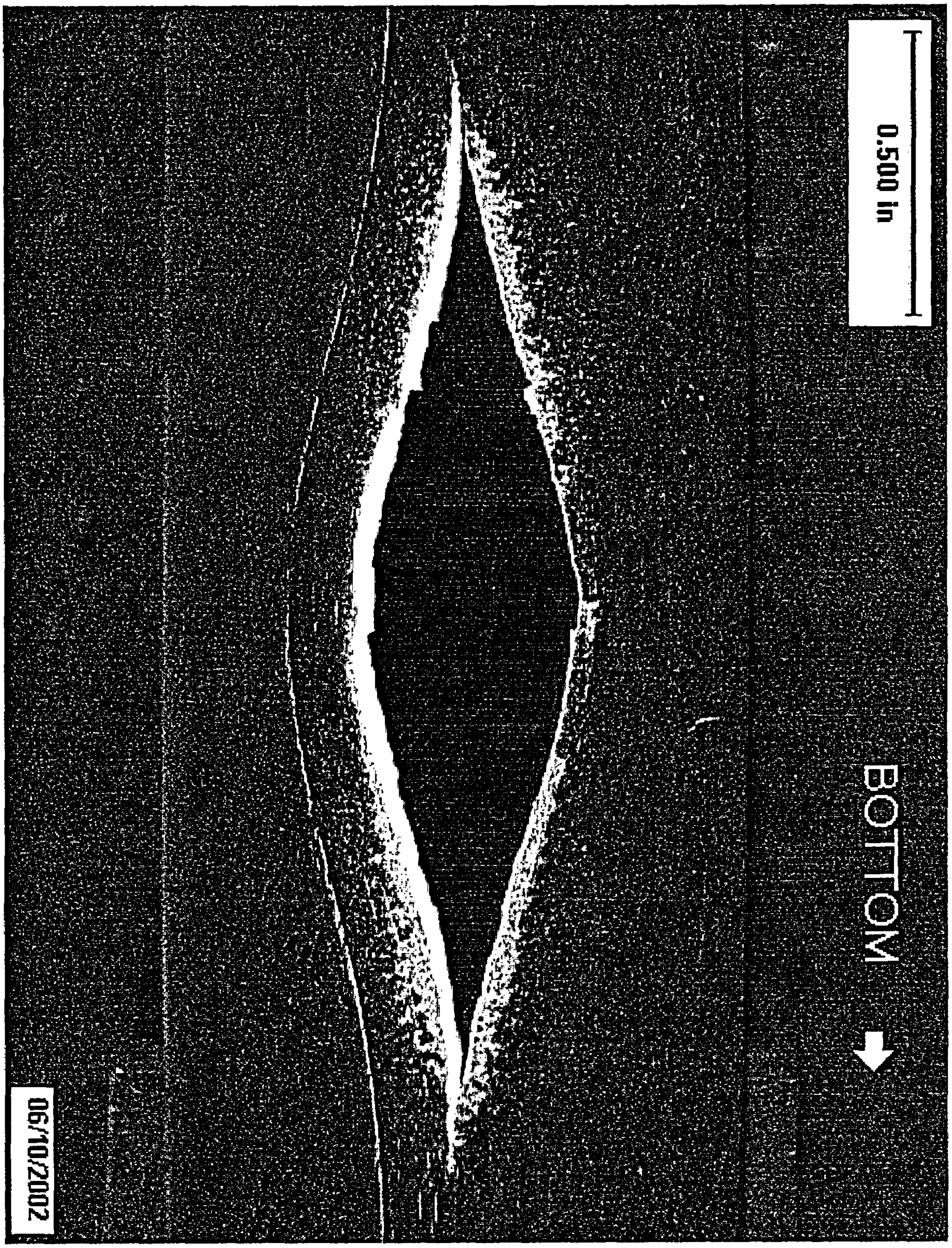


Figure 4-12d. Photograph of Section 2B Freespan Burst Area, 200° Face.

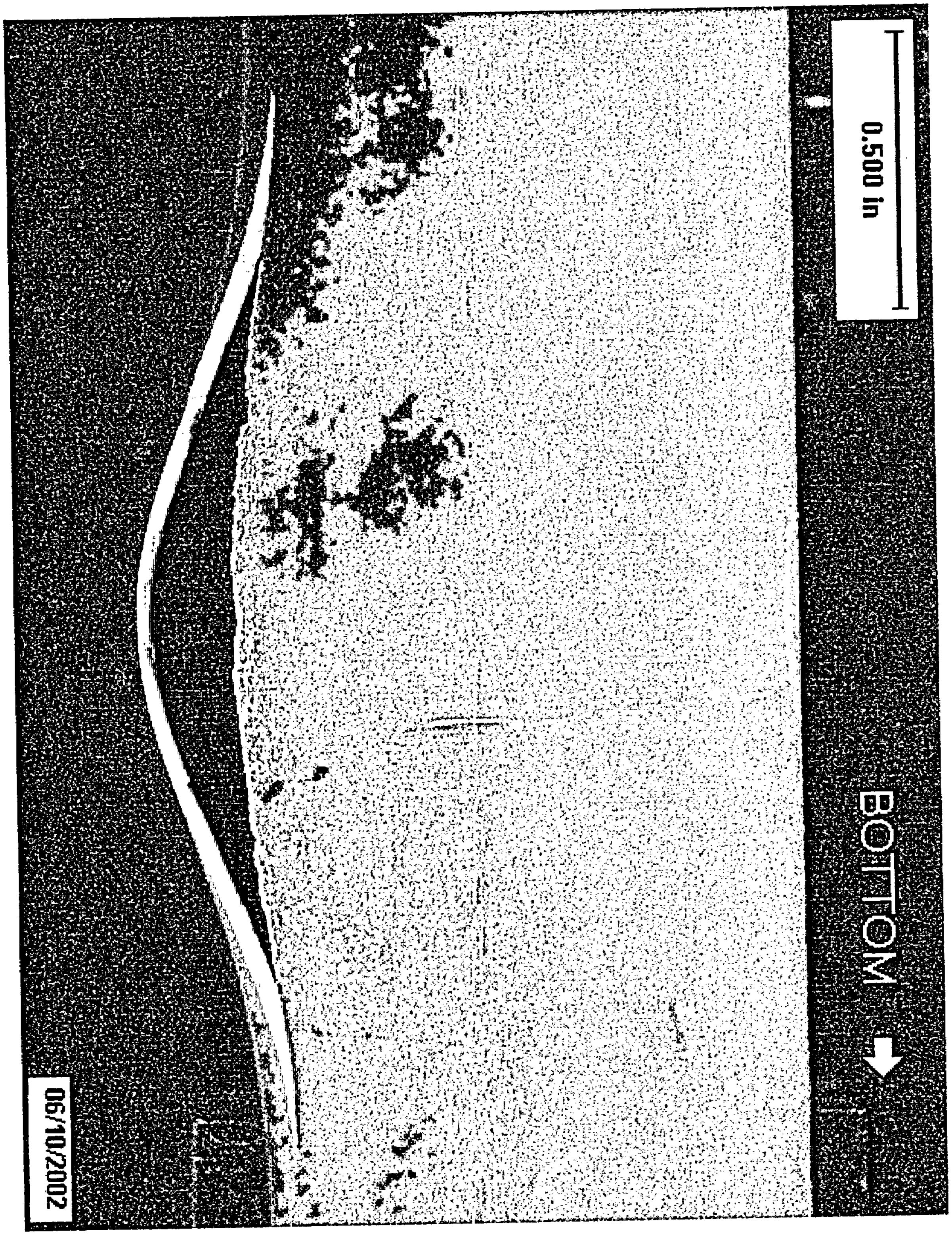


Figure 4-12e. Photograph of Section 2B Freespan Burst Area, 270° Face.

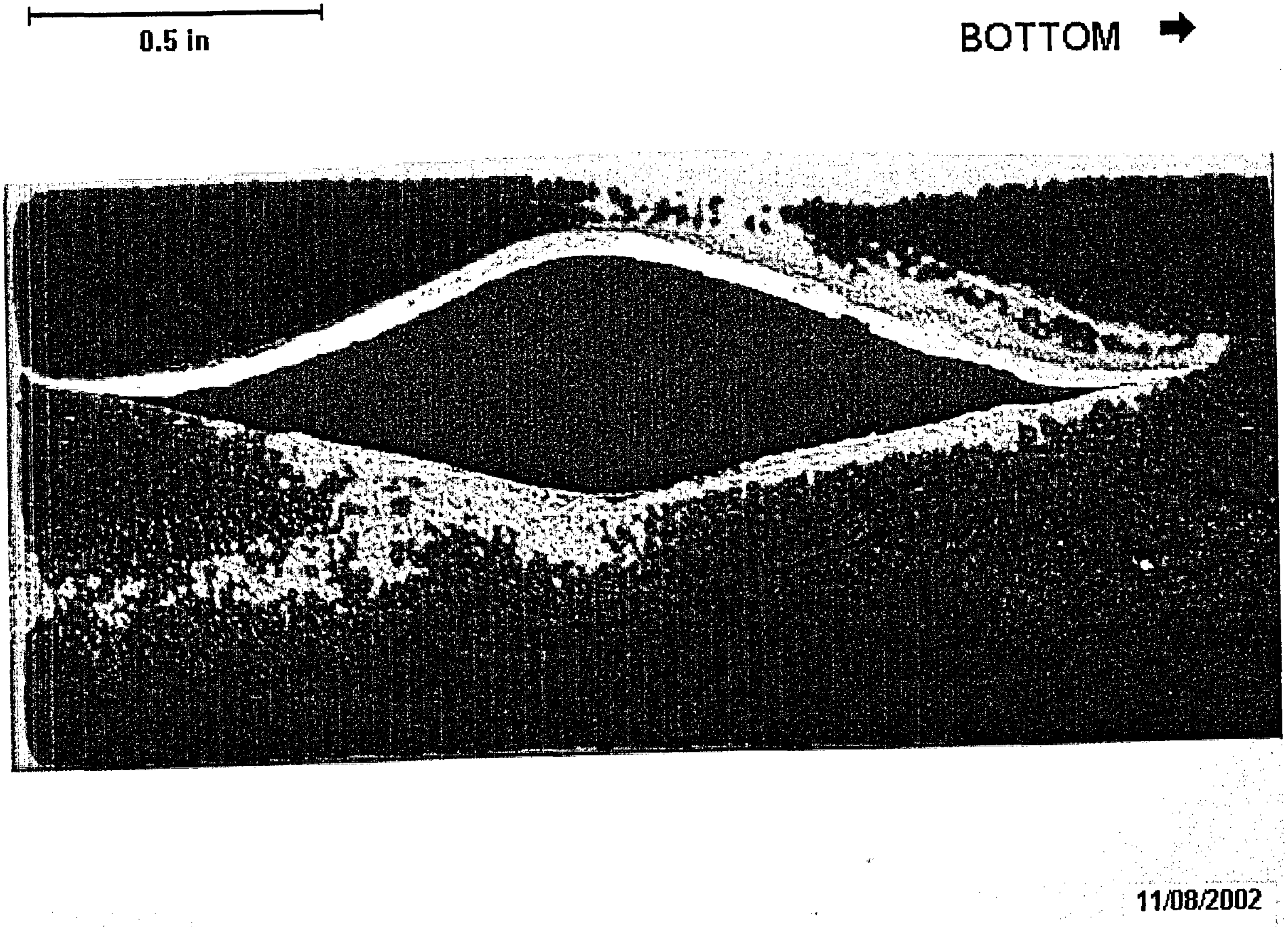


Figure 4-13a. Photograph of Section 4-1A Freespan Burst Area, 0° Face.

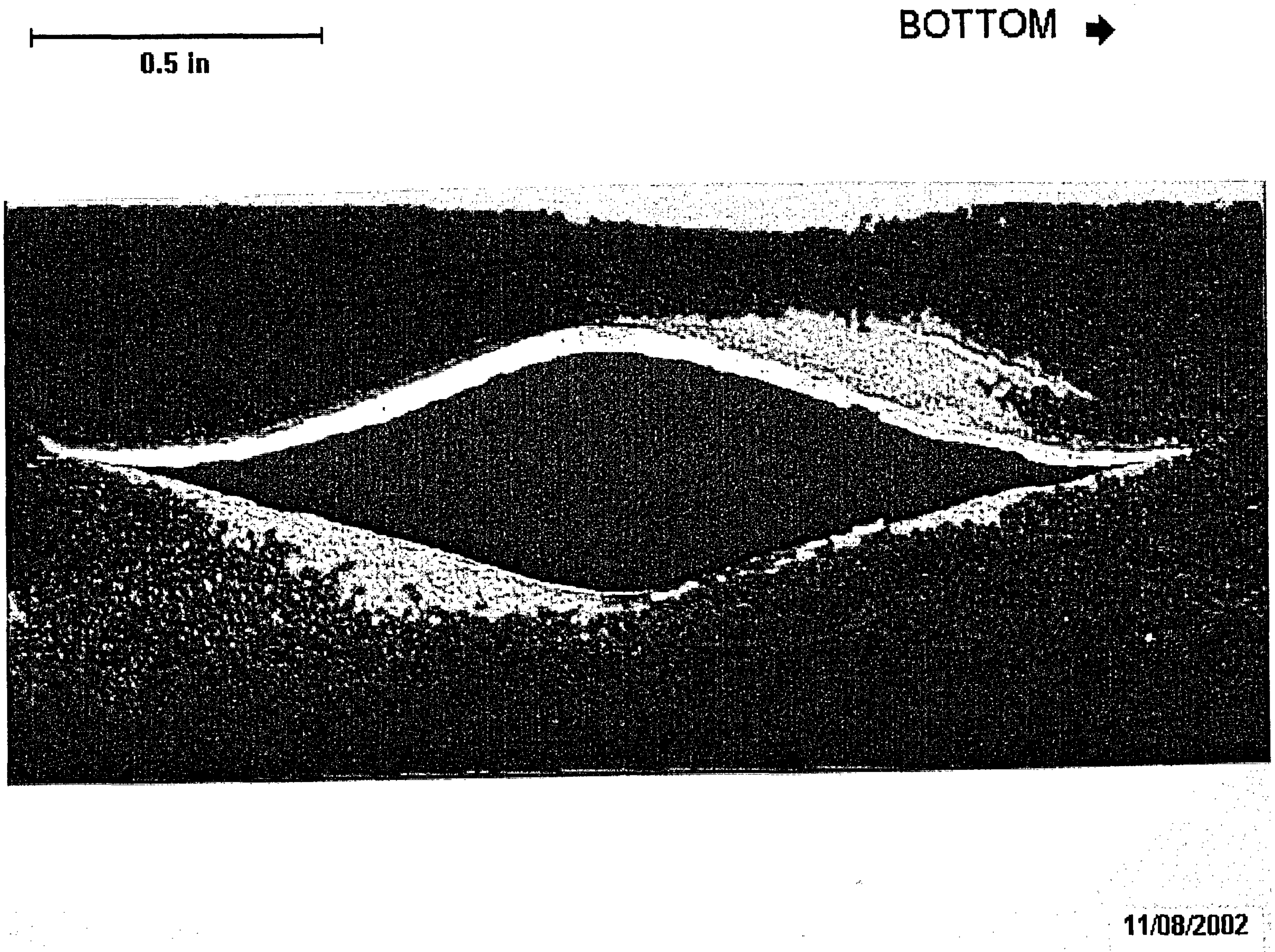


Figure 4-13b. Photograph of Section 4-1A Freespan Burst Area, 15° Face.


Figure 4-13c. Photograph of Section 4-1A Freespan Burst Area, 90° Face.

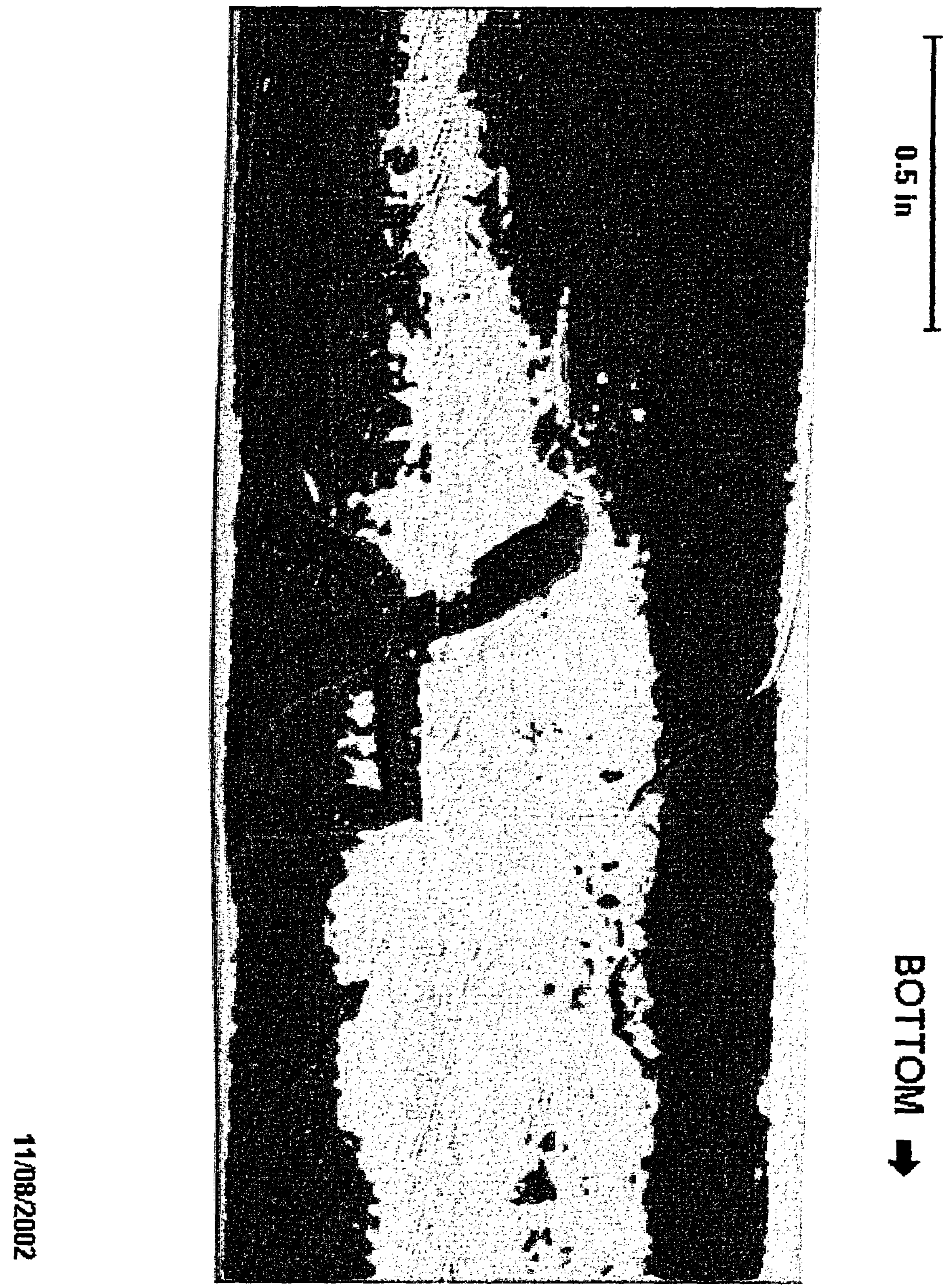


Figure 4-13d. Photograph of Section 4-1A Freespan Burst Area, 180° Face.

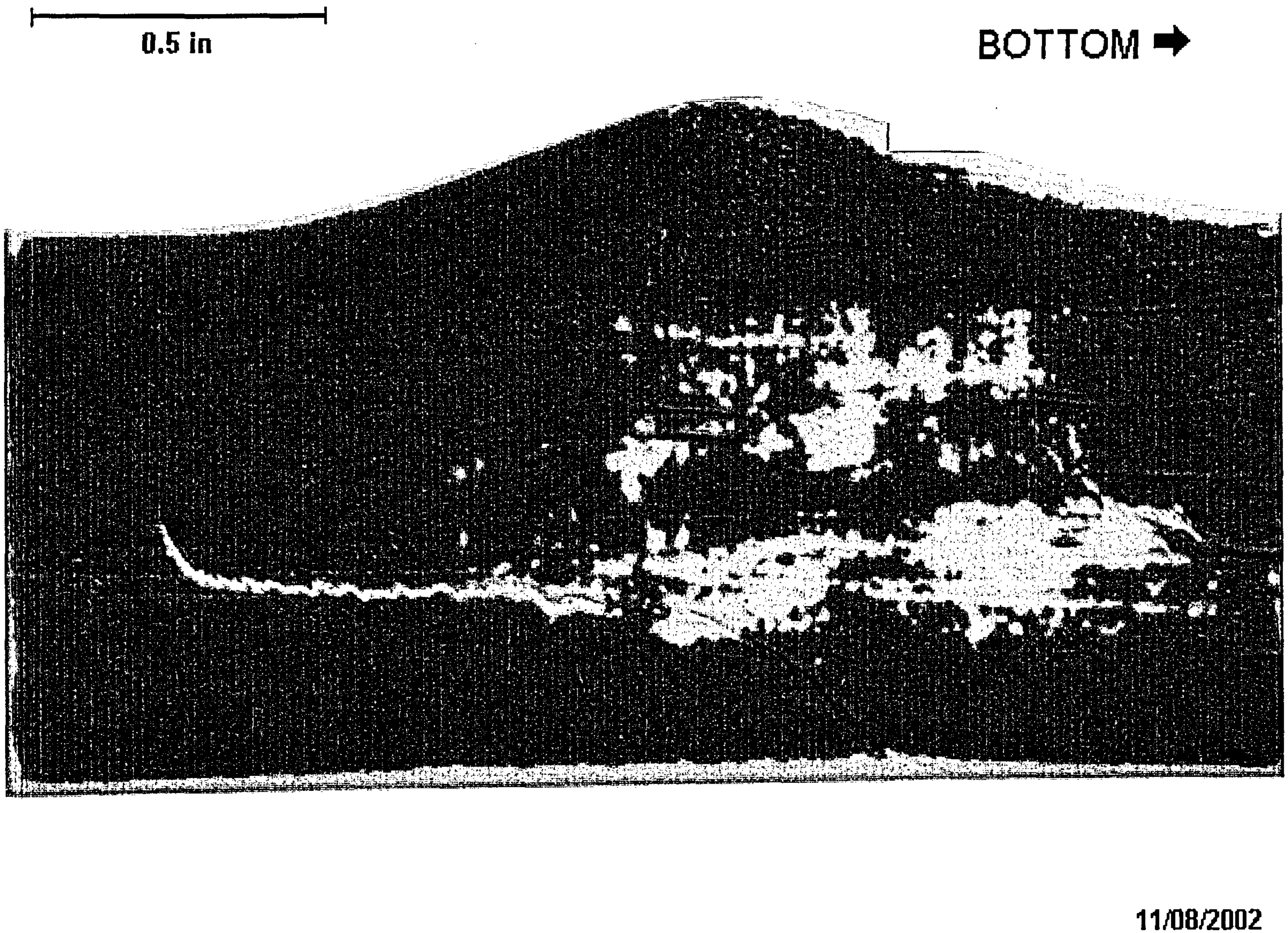


Figure 4-13e. Photograph of Section 4-1A Freespan Burst Area, 270° Face.

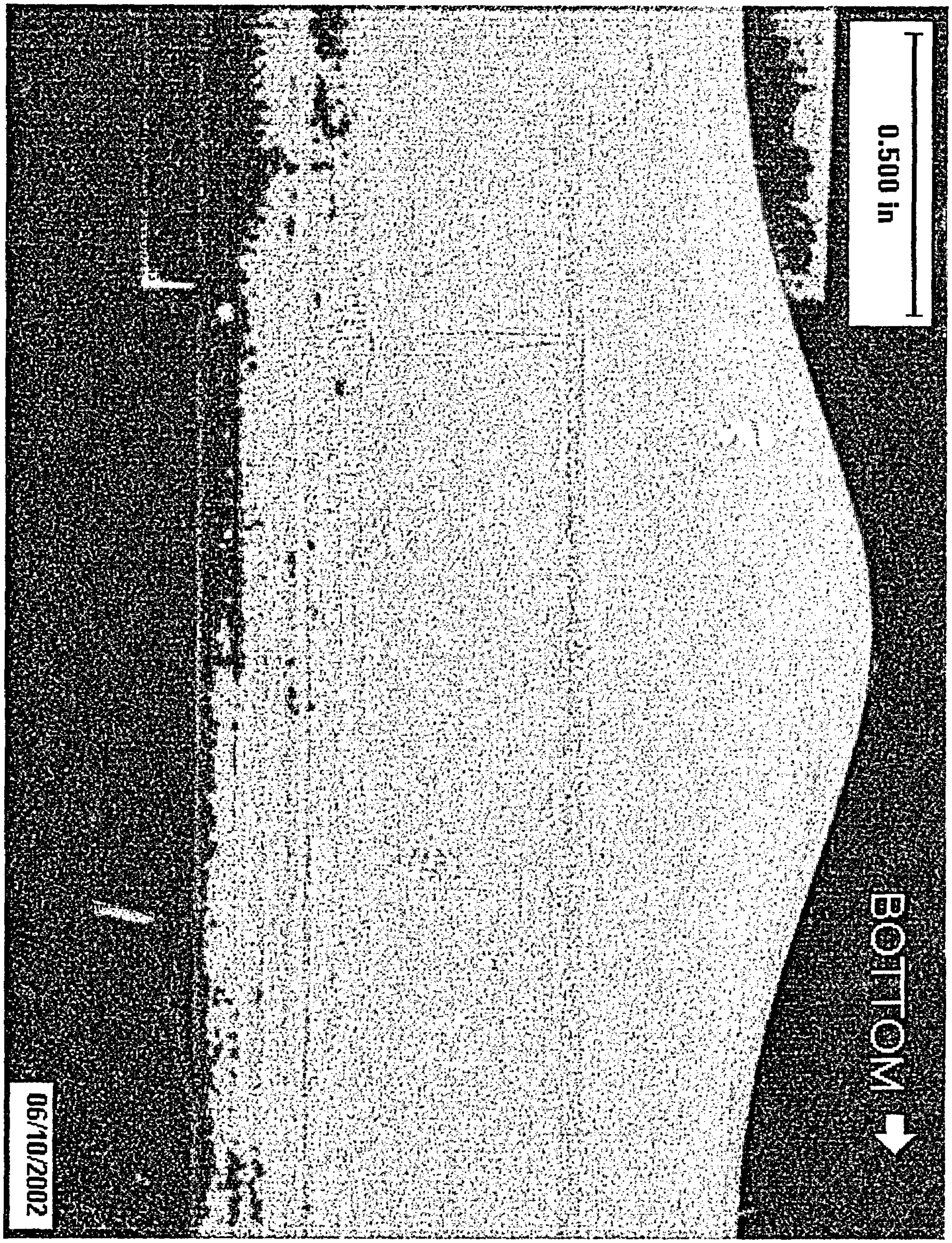


Figure 4-14a. Photograph of Section 5A1 Freespan Burst Area, 0° Face.

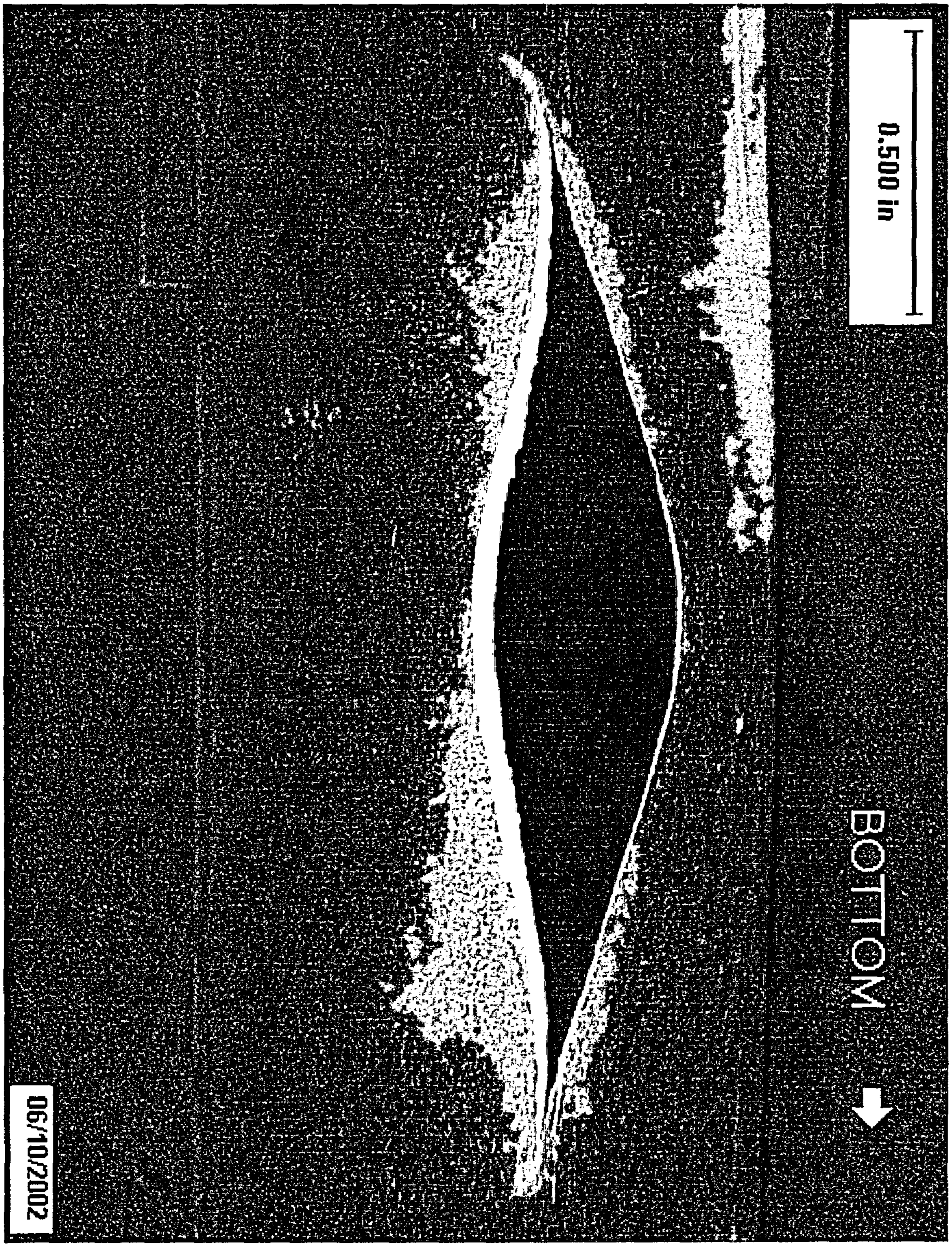


Figure 4-14b. Photograph of Section 5A1 Freespan Burst Area, 90° Face.

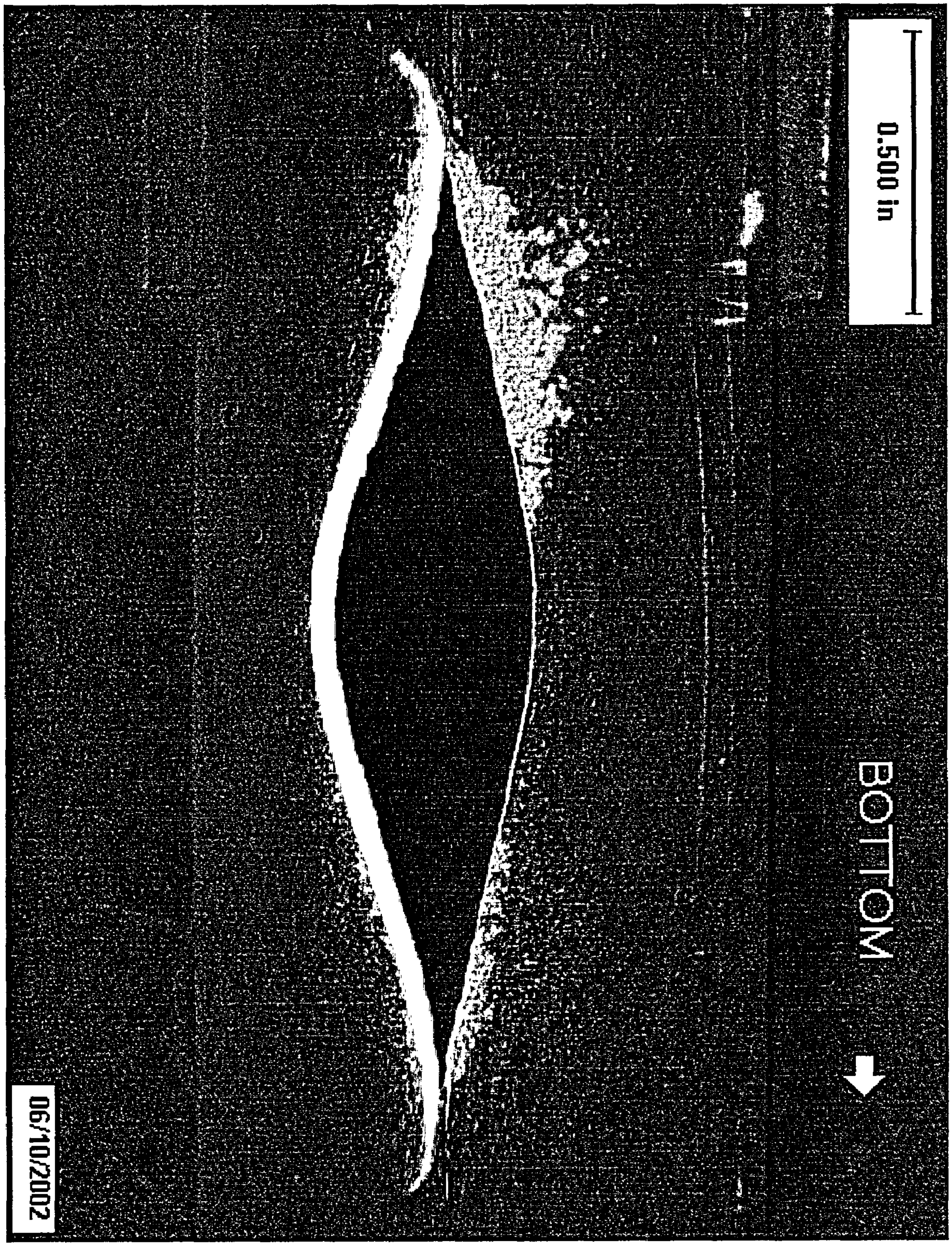


Figure 4-14c. Photograph of Section 5A1 Freespan Burst Area, 115° Face.

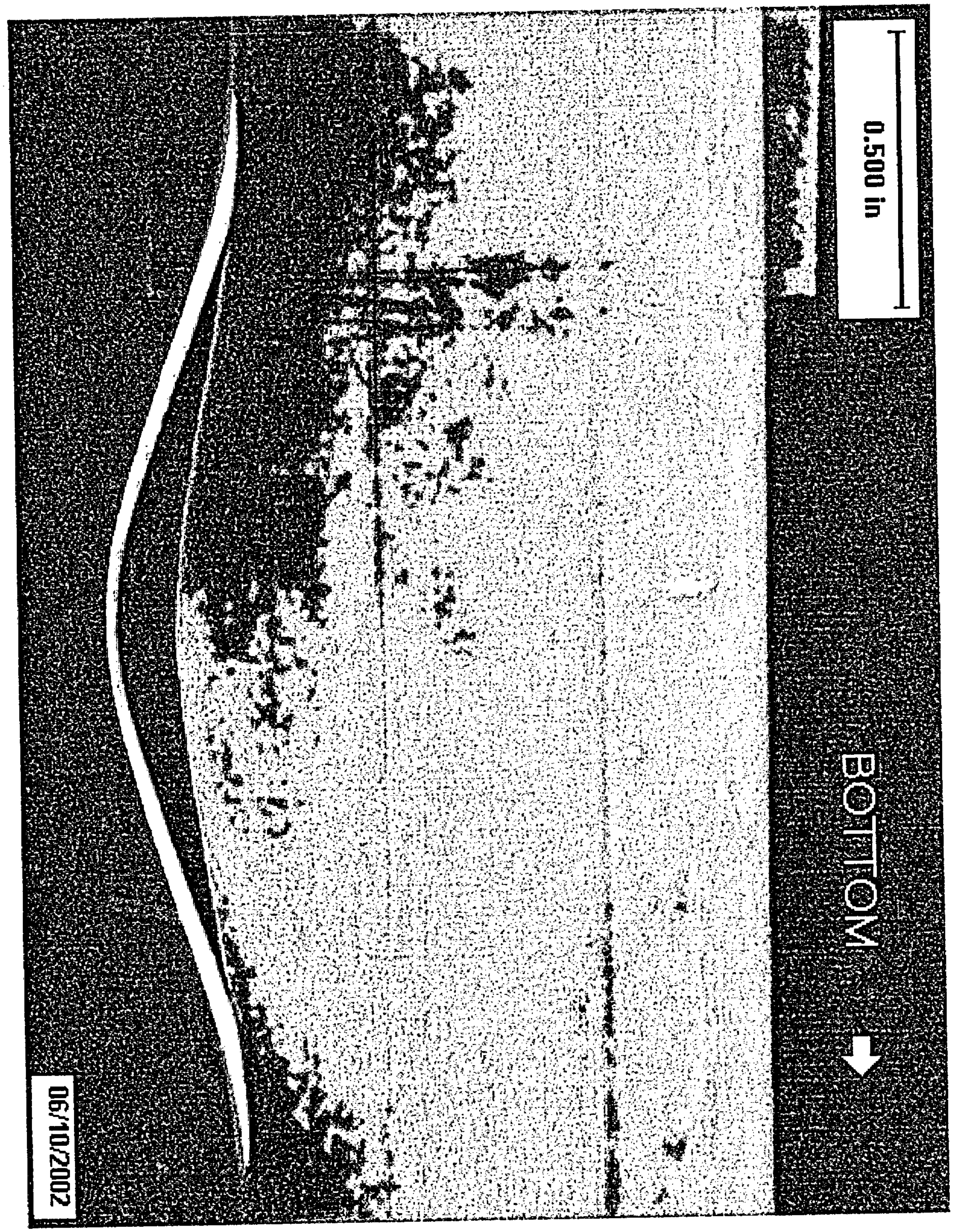


Figure 4-14d. Photograph of Section 5A1 Freespan Burst Area, 180° Face.

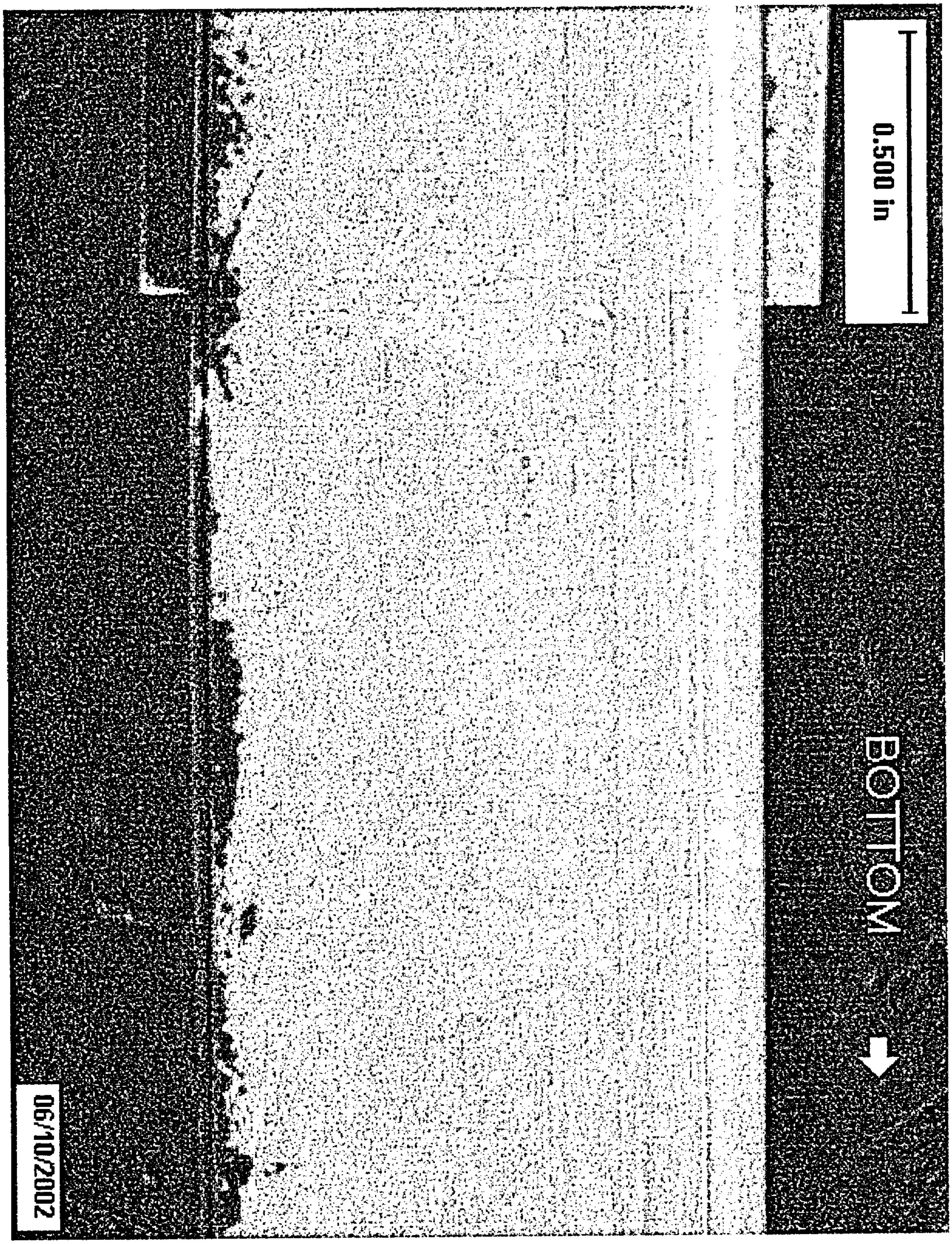


Figure 4-14e. Photograph of Section 5A1 Freespan Burst Area, 270° Face.

# Section 5.0

# FRACTOGRAPHY

## 5.1 Procedure

Following the completion of burst testing, the right face of the burst openings from all three TSP regions were sectioned, to characterize the corrosion by Scanning Electron Microscopy (SEM) and Energy Dispersive Spectrometry (EDS), and to obtain depth profiles of the corrosion by SEM. A depth profile was also obtained from a secondary crack from TSP1.

A longitudinal section was removed from each tube and processed to remove any particulates from the fracture surfaces to minimize charging during the SEM examination. Operation of the SEM/EDS followed the manufacturer's instruction. ASTM has not published procedures for fractography examinations. However, surfaces examined by SEM in accordance with accepted scientific principles and EPRI guidelines can be compared with fractographs presented in various fractography textbooks, such as "Metals Handbook, Volume 12, Fractography", 9th Edition, American Society of Metals, 1985.

Fractographs were taken of the entire fracture surface of each burst opening that had corrosion at approximately 77X. These fractographs were then aligned end to end to complete a photomontage of each crack surface. The depth of degradation was measured at ½ inch increments on each montage using the same steel ruler. These measurements were then divided by the magnification to obtain the defect depth, divided by 0.050 inch (the nominal tube wall thickness) to obtain the fraction throughwall, and then multiplied by 100 to obtain the percent throughwall.

## 5.2 Results

Burst Opening Depth Profiles

Table 5-1 provides a summary of the depth profiles. Tables 5-2 through 5-5 provide the measurements from the depth profile and include the location and size of ligaments of uncorroded metal. Figures 5-1 through 5-4 show plots of the depth profile data, including the location and size of the ligaments.

The TSP1 crack was 100%TW. The secondary crack extended from about 0.275 to 0.55 inches above the bottom of the TSP. This secondary crack was also 100%TW. The longest microcrack (the distance between ligaments) was 0.24 inch.

The TSP2 and TSP3 crack profiles were similar. These depth profiles were relatively uniform and both of these crack extended the full width of the support plate region; however (as was noted during the visual examination) the cracks did not extend outside of the TSP region in any case. The longest microcrack from either of these two support plate regions was 0.21 inch. For TSP3 a 69%TW secondary crack was identified 40 mils to the left of the burst opening by metallography.

TSP1 Burst Opening Fractography

Figure 5-5 presents a fractograph of a part-throughwall portion of the main crack from the TSP1 region. The delineation between the corrosion near the OD surface and the ductile tearing near the ID surface is easily seen. Figure 5-5 shows that this corrosion was OD initiated. Figures 5-6 and 5-7 show closer views of the TSP1 crack surface near the crack mouth. There is a considerable amount of foreign debris on the crack surface. This is typical when a bladder/foil with lubricant is required to perform a burst test. Besides the debris, the grain facets are semi-well defined. The somewhat rounded appearance of the grain facets suggests a thick surface oxide or deposit. The rock candy appearance of the crack surface is indicative of intergranular corrosion.

Figures 5-8 and 5-9 show closer views of the main crack near the crack tip. There is considerably less debris near the tip and the grain facets are better defined than at the mouth. Figure 5-8 also shows some debris on the ductile tearing portion of the burst opening, thus suggesting that the debris was introduced to the crack surface after the burst.

An examination was conducted after an attempt was made to clean the surface of the left burst face with deionized water and acetone. The surface was then lightly carbon coated using a sputtering technique to reduce charging of non-conductive debris. Figure 5-10 shows a part-throughwall area after cleaning. Figures 5-11 and 5-12 show close-ups of the mouth of the crack. Most of the debris was removed, and in comparison to Figure 5-7, the grain facets are better defined. This suggests that much of the deposit/oxide at the mouth is easily removed and thus much of it may have been deposited on the crack surface, such as might happen with the use of a bladder/foil with lubricant during a burst test, rather than grown on the crack surface during operation of the generator.

TSP2 Burst Opening Fractography

Figure 5-13 presents a fractograph of a part-throughwall portion of burst opening crack from the TSP2 region. The delineation between the corrosion near the OD surface and the ductile tearing near the ID surface is easily seen. Figure 5-13 shows that this corrosion was OD initiated. Figures 5-14 and 5-15 show closer views of the TSP2 crack surface near the crack mouth. The rock candy appearance of the crack surface is indicative of intergranular corrosion. The grain facets are semi-well defined. The somewhat rounded appearance of the grain facets suggests a thick surface oxide or deposit.

Figures 5-16 and 5-17 show closer views of the main crack near the crack tip. The crack tip is similar in appearance to the crack mouth.

TSP3 Burst Opening Fractography

Figure 5-18 presents a fractograph of a part-throughwall portion of burst opening crack from the TSP3 region. The delineation between the corrosion near the OD surface and the ductile tearing near the ID surface is easily seen. Figure 5-18 shows that this corrosion was OD initiated. Figures 5-19 and 5-20 show closer views of the TSP3 crack surface near the crack mouth. The rock candy appearance of the crack surface is indicative of intergranular corrosion. In contrast to the surface of the TSP2 region crack, the grain facets from TSP3 are well defined, suggesting a thinner oxide.

Figures 5-21 and 5-22 show closer views of the main crack near the crack tip. The crack tip is similar in appearance to the crack mouth.

TABLE 5-1

SUMMARY OF DEPTHS AND EXTENT OF CRACKING FOR THE BURST OPENINGS

| Support | Maximum Depth (%TW) | Mathematical Average Depth (%TW) | Crack Total Length (in) | Number of Microcracks | Note |
|---|---|---|---|---|---|
| TSP1 (Left Side) | 100.0 | 75.4 | 0.625 | 6 | (a) |
| TSP1 (Right Side) | 100.0 | 74.0 | 0.619 | 6 | (b) |
| TSP2 | 71.4 | 52.2 | 0.750 | 11 | |
| TSP3 | 62.6 | 51.2 | 0.743 | 11 | (c) |

Note (a) – Includes all of the secondary crack plus part of the main crack

Note (b) – Includes only the main crack

Note (c) – Deeper cracks were identified by metallography than the maximum depth by SEM

TABLE 5-2
TUBE R12C45 TSP1 (SECONDARY AND MAIN CRACK) BURST MACROCRACK DEPTH PROFILE

| From TSP Bottom (inch) | Corrosion Depth (%TW) | Ductile Ligament Width (inch) |
|---|---|---|
| 0.018 | 0 | |
| 0.025 | 0 | |
| 0.032 | 0 | |
| 0.038 | 0 | |
| 0.045 | 0 | |
| 0.051 | 0 | |
| 0.058 | 0 | |
| 0.064 | 0 | |
| 0.0675 | 0 | |
| 0.071 | 25 | |
| 0.078 | 22 | L1 / 0.005 |
| 0.084 | 17 | L5 / 0.018 |
| 0.091 | 32 | |
| 0.097 | 45 | |
| 0.104 | 46 | |
| 0.111 | 50 | |
| 0.117 | 53 | |
| 0.124 | 57 | |
| 0.130 | 58 | |
| 0.137 | 58 | |
| 0.143 | 58 | |
| 0.150 | 58 | |
| 0.157 | 57 | |
| 0.163 | 58 | |
| 0.170 | 62 | |
| 0.176 | 63 | |
| 0.183 | 63 | |
| 0.189 | 62 | |
| 0.196 | 61 | |
| 0.203 | 67 | |
| 0.209 | 67 | |
| 0.216 | 69 | |
| 0.222 | 68 | |
| 0.229 | 67 | |
| 0.236 | 69 | |
| 0.242 | 67 | |
| 0.249 | 70 | |
| 0.255 | 72 | |

| From TSP Bottom (inch) | Corrosion Depth (%TW) | Ductile Ligament Width (inch) |
|---|---|---|
| 0.262 | 76 | |
| 0.268 | 78 | |
| 0.275 | 74 | |
| 0.282 | 66 | |
| 0.288 | 22 | L2 / 0.036 |
| 0.295 | 39 | |
| 0.301 | 53 | |
| 0.308 | 63 | |
| 0.314 | 70 | |
| 0.321 | 74 | |
| 0.328 | 76 | |
| 0.334 | 82 | |
| 0.341 | 84 | |
| 0.347 | 88 | |
| 0.354 | 91 | |
| 0.361 | 95 | |
| 0.367 | 100 | |
| 0.374 | 100 | |
| 0.380 | 100 | |
| 0.387 | 100 | |
| 0.393 | 100 | |
| 0.400 | 100 | |
| 0.407 | 100 | |
| 0.413 | 100 | |
| 0.420 | 100 | |
| 0.426 | 100 | |
| 0.433 | 100 | |
| 0.439 | 100 | |
| 0.446 | 100 | |
| 0.453 | 100 | |
| 0.459 | 100 | |
| 0.466 | 100 | |
| 0.472 | 100 | |
| 0.479 | 100 | |
| 0.486 | 100 | |
| 0.492 | 100 | |
| 0.499 | 100 | |

| From TSP Bottom (inch) | Corrosion Depth (%TW) | Ductile Ligament Width (inch) |
|---|---|---|
| 0.505 | 100 | |
| 0.512 | 100 | |
| 0.518 | 100 | |
| 0.525 | 100 | L3 / 0.025 |
| 0.532 | 100 | |
| 0.538 | 100 | |
| 0.545 | 100 | |
| 0.551 | 100 | |
| 0.558 | 100 | |
| 0.564 | 100 | |
| 0.571 | 97 | |
| 0.578 | 95 | |
| 0.584 | 92 | |
| 0.591 | 92 | |
| 0.597 | 92 | |
| 0.604 | 90 | L4 / 0.016 |
| 0.611 | 88 | |
| 0.617 | 84 | |
| 0.624 | 82 | |
| 0.630 | 78 | |
| 0.637 | 70 | |
| 0.643 | 72 | |
| 0.650 | 71 | |
| 0.657 | 62 | |
| 0.663 | 58 | |
| 0.670 | 55 | |
| 0.676 | 51 | |
| 0.683 | 38 | |
| 0.689 | 24 | |
| 0.6925 | 0 | |
| 0.696 | 0 | |
| 0.703 | 0 | |
| 0.709 | 0 | |
| 0.716 | 0 | |
| 0.722 | 0 | |
| 0.729 | 0 | |
| 0.736 | 0 | |
| 0.742 | 0 | |
| 0.749 | 0 | |

TABLE 5-3
TUBE R12C45 TSP1 (MAIN CRACK) BURST MACROCRACK DEPTH PROFILE

| From TSP Bottom (inch) | Corrosion Depth (%TW) | Ductile Ligament Width (inch) |
|---|---|---|
| 0.000 | 0 | |
| 0.006 | 0 | |
| 0.013 | 0 | |
| 0.019 | 0 | |
| 0.026 | 0 | |
| 0.032 | 0 | |
| 0.039 | 0 | |
| 0.045 | 0 | |
| 0.052 | 0 | |
| 0.058 | 0 | |
| 0.065 | 0 | |
| 0.067 | 0 | |
| 0.071 | 25 | |
| 0.077 | 15 | |
| 0.084 | 0 | L4 / 0.020 |
| 0.090 | 41 | |
| 0.097 | 0 | |
| 0.103 | 43 | |
| 0.110 | 45 | |
| 0.116 | 48 | L3 / 0.007 |
| 0.123 | 61 | |
| 0.129 | 63 | |
| 0.135 | 62 | |
| 0.142 | 59 | |
| 0.148 | 62 | |
| 0.155 | 57 | |
| 0.161 | 64 | |
| 0.168 | 64 | |
| 0.174 | 64 | |
| 0.181 | 63 | |
| 0.187 | 65 | |
| 0.194 | 64 | |
| 0.200 | 65 | |
| 0.206 | 67 | |
| 0.213 | 66 | |
| 0.219 | 67 | |
| 0.226 | 69 | |
| 0.232 | 70 | |
| 0.239 | 70 | |
| 0.245 | 73 | |
| 0.252 | 75 | |
| 0.258 | 75 | |
| 0.265 | 77 | |
| 0.271 | 79 | |
| 0.277 | 80 | |
| 0.284 | 80 | |
| 0.290 | 88 | |
| 0.297 | 100 | |
| 0.303 | 100 | |
| 0.310 | 100 | |
| 0.316 | 100 | |
| 0.323 | 100 | |
| 0.329 | 100 | L2 / 0.023 |
| 0.335 | 100 | |
| 0.342 | 100 | |
| 0.348 | 100 | |
| 0.355 | 100 | |
| 0.361 | 100 | |
| 0.368 | 100 | |
| 0.374 | 100 | |
| 0.381 | 100 | |
| 0.387 | 98 | |
| 0.394 | 90 | L5 / 0.004 |
| 0.400 | 88 | |
| 0.406 | 82 | |
| 0.413 | 75 | |
| 0.419 | 65 | |
| 0.426 | 62 | |
| 0.432 | 59 | |
| 0.439 | 59 | |
| 0.445 | 59 | |
| 0.452 | 59 | |
| 0.458 | 58 | |
| 0.465 | 72 | |
| 0.471 | 73 | |
| 0.477 | 75 | |
| 0.484 | 83 | |
| 0.490 | 93 | |
| 0.497 | 100 | |
| 0.503 | 100 | |
| 0.510 | 100 | |
| 0.516 | 100 | |
| 0.523 | 100 | |
| 0.529 | 100 | |
| 0.535 | 100 | |
| 0.542 | 100 | |
| 0.548 | 100 | |
| 0.555 | 100 | |
| 0.561 | 100 | |
| 0.568 | 100 | |
| 0.574 | 94 | |
| 0.581 | 92 | |
| 0.587 | 93 | |
| 0.594 | 90 | |
| 0.600 | 86 | |
| 0.606 | 86 | L1 / 0.018 |
| 0.613 | 85 | |
| 0.619 | 80 | |
| 0.626 | 77 | |
| 0.632 | 72 | |
| 0.639 | 62 | |
| 0.645 | 63 | |
| 0.652 | 63 | |
| 0.658 | 58 | |
| 0.665 | 52 | |
| 0.671 | 48 | |
| 0.677 | 37 | |
| 0.684 | 21 | |
| 0.686 | 0 | |
| 0.690 | 0 | |
| 0.697 | 0 | |
| 0.703 | 0 | |
| 0.710 | 0 | |
| 0.716 | 0 | |
| 0.723 | 0 | |
| 0.729 | 0 | |
| 0.735 | 0 | |
| 0.742 | 0 | |
| 0.748 | 0 | |
| 0.755 | 0 | |

TABLE 5-4

TUBE R12C45 TSP2 BURST MACROCRACK DEPTH PROFILE

| From TSP Bottom (inch) | Corrosion Depth (%TW) | Ductile Ligament Width (inch) |
|---|---|---|
| -0.003 | 0 | |
| 0 | 0 | |
| 0.003 | 21 | |
| 0.009 | 29 | |
| 0.015 | 31 | |
| 0.022 | 33 | |
| 0.028 | 31 | |
| 0.034 | 29 | L6 / 0.011 |
| 0.040 | 32 | |
| 0.046 | 38 | |
| 0.052 | 41 | |
| 0.059 | 45 | |
| 0.065 | 47 | |
| 0.071 | 49 | |
| 0.077 | 49 | |
| 0.083 | 48 | |
| 0.089 | 50 | |
| 0.096 | 51 | |
| 0.102 | 50 | |
| 0.108 | 52 | |
| 0.114 | 55 | |
| 0.120 | 53 | L5 / 0.024 |
| 0.126 | 52 | |
| 0.133 | 50 | |
| 0.139 | 47 | |
| 0.145 | 47 | |
| 0.151 | 45 | |
| 0.157 | 55 | |
| 0.163 | 56 | L7 / 0.017 |
| 0.170 | 56 | |
| 0.176 | 54 | |
| 0.182 | 50 | |
| 0.188 | 52 | |
| 0.194 | 53 | |
| 0.200 | 51 | |
| 0.207 | 52 | |
| 0.213 | 57 | |
| 0.219 | 59 | |
| 0.225 | 61 | |
| 0.231 | 56 | |
| 0.238 | 61 | L8 / 0.017 |
| 0.244 | 60 | |
| 0.250 | 61 | |

| From TSP Bottom (inch) | Corrosion Depth (%TW) | Ductile Ligament Width (inch) |
|---|---|---|
| 0.256 | 64 | |
| 0.262 | 65 | |
| 0.268 | 64 | |
| 0.275 | 62 | |
| 0.281 | 60 | |
| 0.287 | 61 | |
| 0.293 | 61 | |
| 0.299 | 60 | |
| 0.305 | 60 | |
| 0.312 | 57 | |
| 0.318 | 56 | |
| 0.324 | 52 | |
| 0.330 | 52 | |
| 0.336 | 55 | |
| 0.342 | 56 | |
| 0.349 | 53 | L9 / 0.027 |
| 0.355 | 39 | |
| 0.361 | 55 | |
| 0.367 | 49 | |
| 0.373 | 57 | |
| 0.379 | 61 | |
| 0.386 | 61 | |
| 0.392 | 67 | |
| 0.398 | 66 | |
| 0.404 | 66 | |
| 0.410 | 63 | |
| 0.416 | 59 | |
| 0.423 | 57 | |
| 0.429 | 59 | |
| 0.435 | 60 | |
| 0.441 | 62 | |
| 0.447 | 68 | |
| 0.453 | 71 | |
| 0.460 | 70 | L4 / 0.017 |
| 0.466 | 65 | |
| 0.472 | 65 | |
| 0.478 | 66 | |
| 0.484 | 68 | |
| 0.490 | 67 | |
| 0.497 | 65 | |
| 0.503 | 63 | |
| 0.509 | 62 | |

| From TSP Bottom (inch) | Corrosion Depth (%TW) | Ductile Ligament Width (inch) |
|---|---|---|
| 0.515 | 65 | |
| 0.521 | 65 | |
| 0.527 | 65 | |
| 0.534 | 63 | |
| 0.540 | 61 | |
| 0.546 | 61 | |
| 0.552 | 57 | |
| 0.558 | 59 | |
| 0.564 | 56 | |
| 0.571 | 55 | |
| 0.577 | 48 | |
| 0.583 | 44 | L3 / 0.017 |
| 0.589 | 54 | |
| 0.595 | 54 | |
| 0.601 | 58 | |
| 0.608 | 60 | |
| 0.614 | 58 | |
| 0.620 | 58 | |
| 0.626 | 51 | |
| 0.632 | 54 | |
| 0.638 | 52 | |
| 0.645 | 50 | |
| 0.651 | 48 | L2 / 0.014 |
| 0.657 | 49 | |
| 0.663 | 43 | |
| 0.669 | 41 | |
| 0.675 | 39 | L10/ 0.020 |
| 0.682 | 46 | |
| 0.688 | 45 | |
| 0.694 | 43 | |
| 0.700 | 42 | |
| 0.706 | 38 | |
| 0.713 | 35 | |
| 0.719 | 32 | L1 / 0.013 |
| 0.725 | 37 | |
| 0.731 | 37 | |
| 0.737 | 35 | |
| 0.743 | 30 | |
| 0.7495 | 21 | |
| 0.7500 | 0 | |
| 0.756 | 0 | |
| 0.762 | 0 | |

# TABLE 5-5
# TUBE R12C45 TSP3 BURST MACROCRACK DEPTH PROFILE

| From TSP Bottom (inch) | Corrosion Depth (%TW) | Ductile Ligament Width (inch) |
|---|---|---|
| 0.000 | 0 | |
| 0.007 | 0 | |
| 0.013 | 11 | |
| 0.020 | 21 | |
| 0.026 | 21 | |
| 0.033 | 25 | |
| 0.039 | 29 | L6 / 0.007 |
| 0.046 | 42 | |
| 0.052 | 42 | |
| 0.059 | 42 | |
| 0.065 | 48 | |
| 0.072 | 50 | |
| 0.078 | 48 | |
| 0.085 | 49 | |
| 0.091 | 49 | |
| 0.098 | 50 | |
| 0.104 | 45 | L5 / 0.013 |
| 0.111 | 42 | |
| 0.117 | 42 | |
| 0.124 | 42 | |
| 0.130 | 31 | L7 / 0.019 |
| 0.137 | 34 | L4 / 0.007 |
| 0.143 | 45 | |
| 0.150 | 50 | |
| 0.156 | 54 | |
| 0.163 | 56 | |
| 0.169 | 58 | |
| 0.176 | 62 | |
| 0.182 | 63 | |
| 0.189 | 58 | |
| 0.195 | 53 | |
| 0.202 | 59 | |
| 0.208 | 57 | |
| 0.215 | 55 | |
| 0.221 | 55 | |
| 0.228 | 55 | |
| 0.234 | 60 | |
| 0.241 | 58 | |
| 0.248 | 58 | |
| 0.254 | 58 | |
| 0.261 | 58 | |
| 0.267 | 61 | |
| 0.274 | 59 | |
| 0.280 | 57 | |
| 0.287 | 57 | |
| 0.293 | 56 | |
| 0.300 | 56 | |
| 0.306 | 56 | |
| 0.313 | 58 | |
| 0.319 | 57 | |
| 0.326 | 60 | |
| 0.332 | 60 | |
| 0.339 | 57 | |
| 0.345 | 56 | L3 / 0.012 |
| 0.352 | 53 | |
| 0.358 | 57 | |
| 0.365 | 57 | |
| 0.371 | 54 | |
| 0.378 | 52 | |
| 0.384 | 55 | |
| 0.391 | 54 | L2 / 0.010 |
| 0.397 | 47 | |
| 0.404 | 49 | |
| 0.410 | 51 | |
| 0.417 | 57 | |
| 0.423 | 58 | |
| 0.430 | 56 | |
| 0.436 | 55 | |
| 0.443 | 55 | |
| 0.449 | 54 | |
| 0.456 | 53 | |
| 0.462 | 54 | |
| 0.469 | 55 | |
| 0.475 | 57 | |
| 0.482 | 57 | |
| 0.488 | 59 | |
| 0.495 | 60 | |
| 0.502 | 61 | |
| 0.508 | 61 | |
| 0.515 | 62 | |
| 0.521 | 60 | |
| 0.528 | 62 | |
| 0.534 | 62 | |
| 0.541 | 56 | |
| 0.547 | 57 | |
| 0.554 | 56 | |
| 0.560 | 53 | |
| 0.567 | 53 | |
| 0.573 | 53 | |
| 0.580 | 55 | |
| 0.586 | 54 | L8 / 0.007 |
| 0.593 | 53 | L9 / 0.008 |
| 0.599 | 58 | |
| 0.606 | 54 | |
| 0.612 | 58 | |
| 0.619 | 58 | |
| 0.625 | 59 | |
| 0.632 | 58 | |
| 0.638 | 58 | |
| 0.645 | 58 | |
| 0.651 | 58 | |
| 0.658 | 56 | |
| 0.664 | 53 | |
| 0.671 | 54 | |
| 0.677 | 53 | |
| 0.684 | 54 | |
| 0.690 | 54 | |
| 0.697 | 53 | |
| 0.703 | 50 | L10/ 0.024 |
| 0.710 | 47 | L1 / 0.007 |
| 0.716 | 45 | |
| 0.723 | 44 | |
| 0.729 | 40 | |
| 0.736 | 32 | |
| 0.743 | 25 | |
| 0.749 | 9 | |
| 0.750 | 0 | |
| 0.756 | 0 | |
| 0.762 | 0 | |

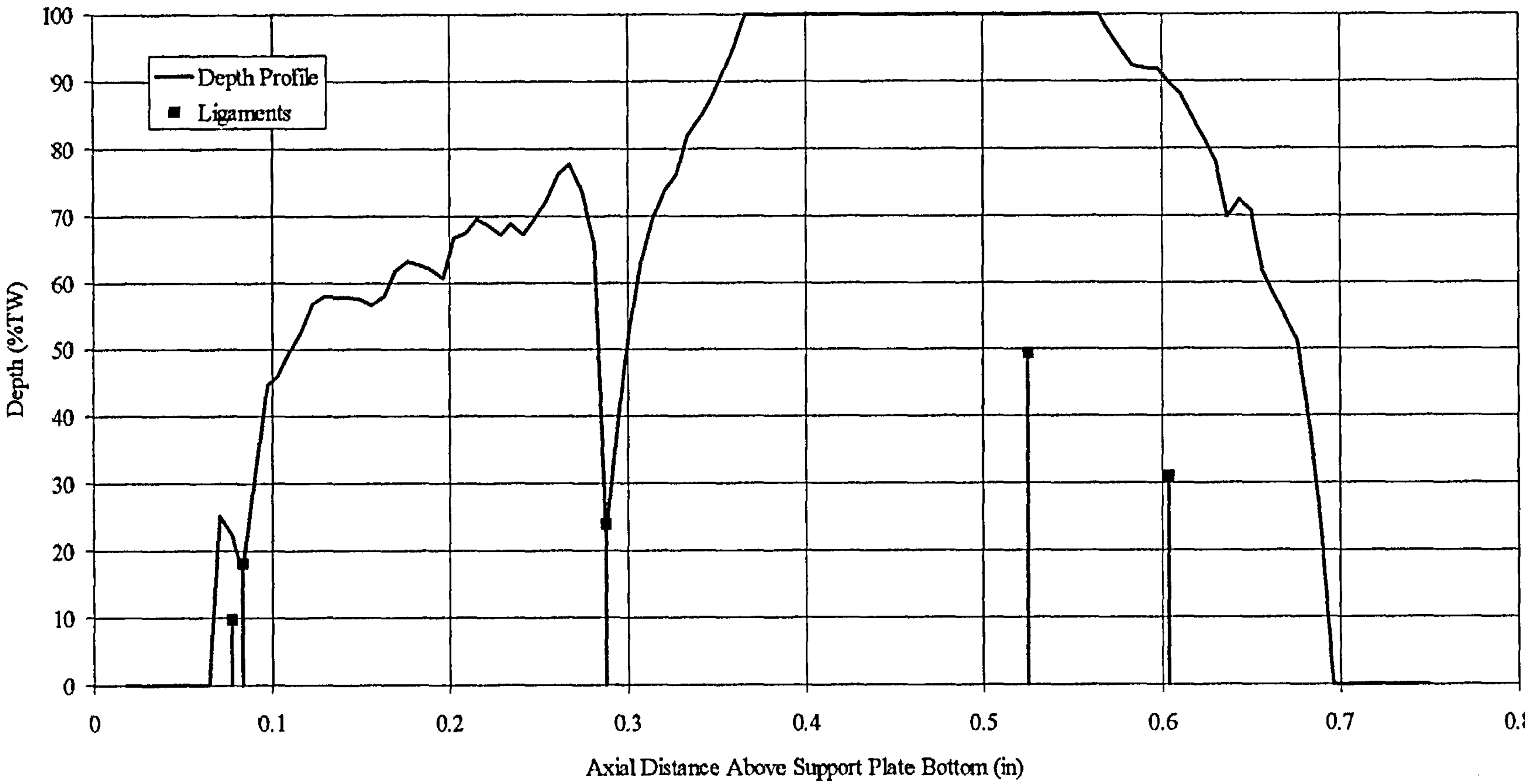


Figure 5-1. TSP1 Left Burst Opening Macrocrack Depth Profile.

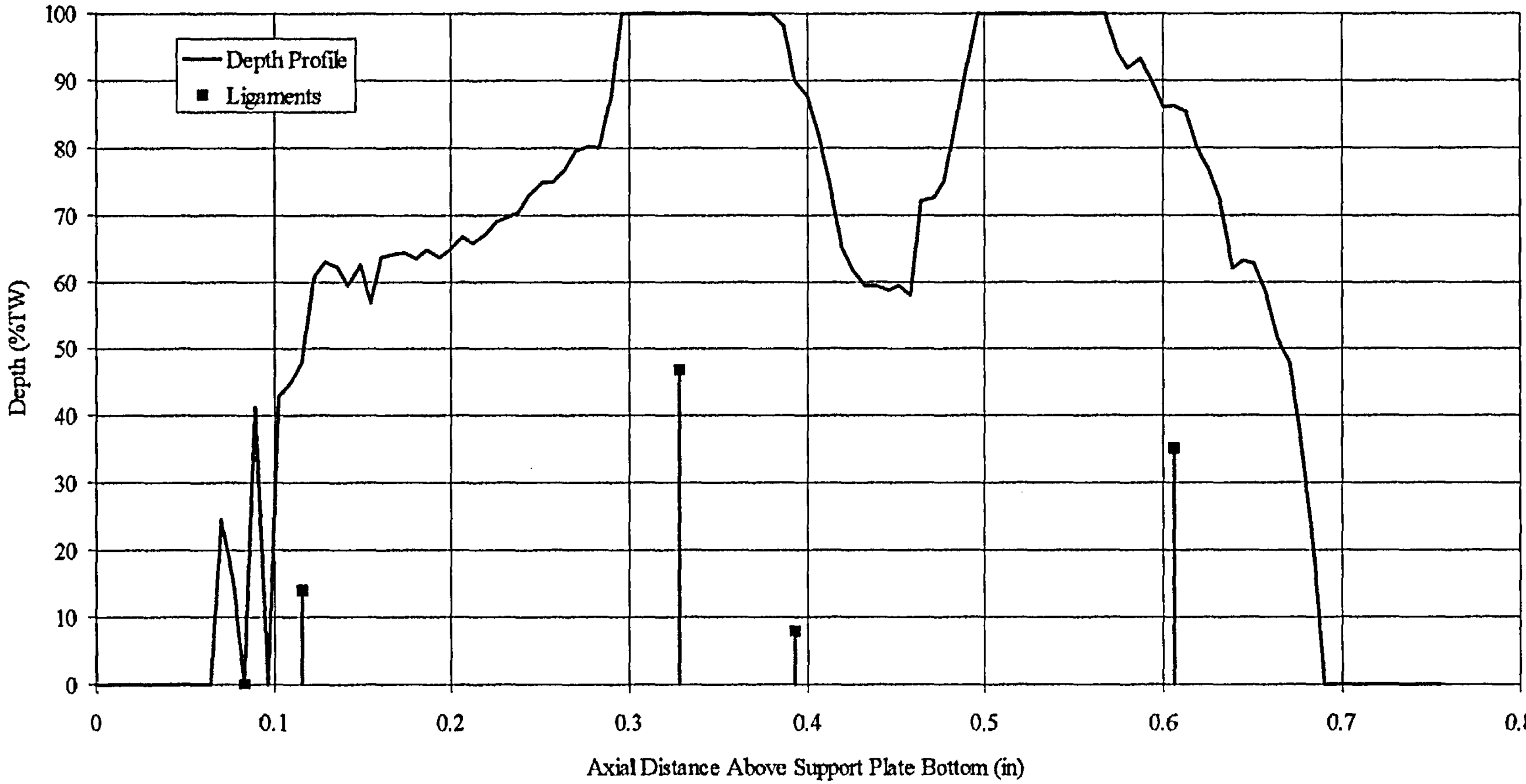


Figure 5-2. TSP1 Right Burst Opening Macrocrack Depth Profile.

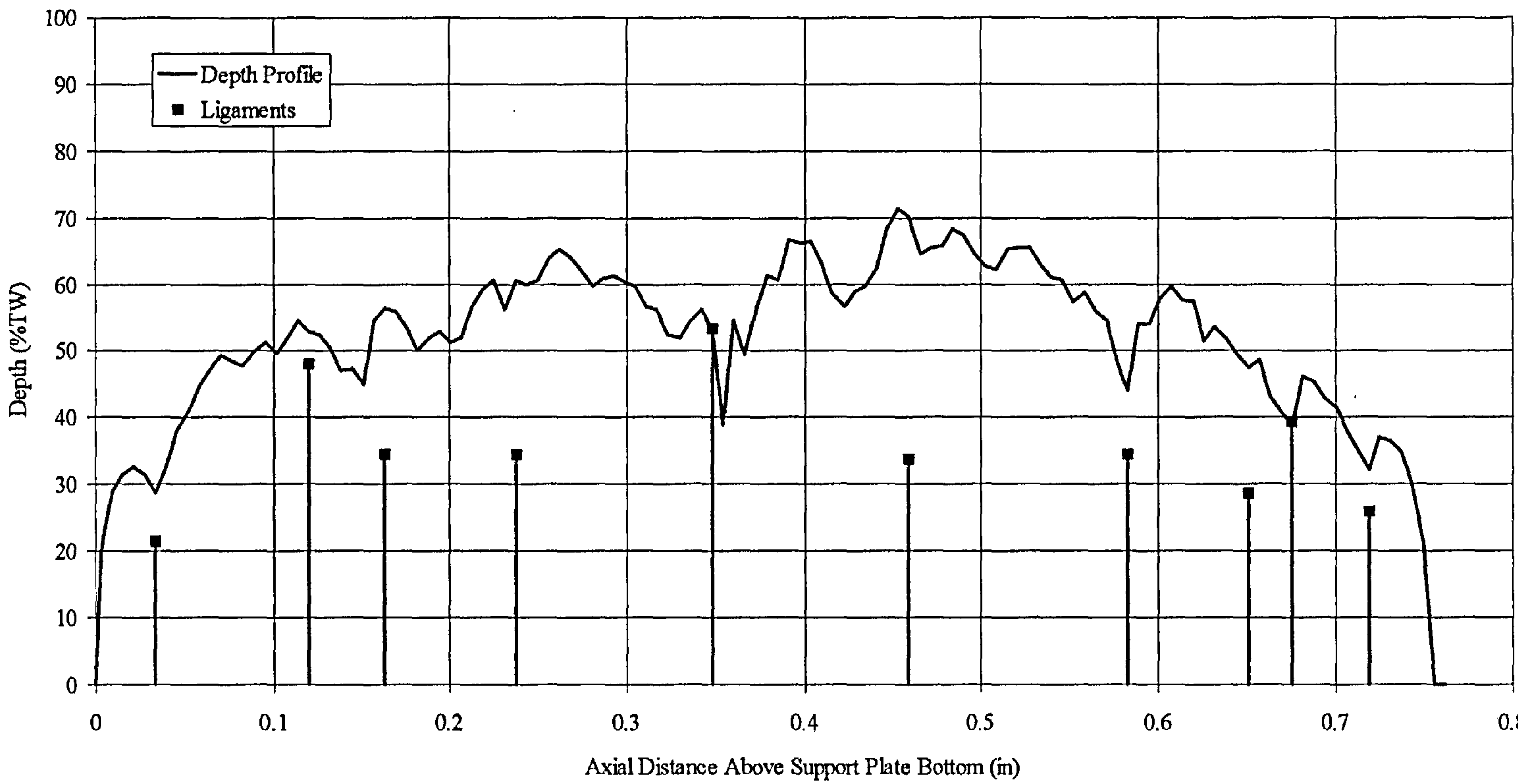


Figure 5-3. TSP2 Burst Opening Macrocrack Depth Profile.

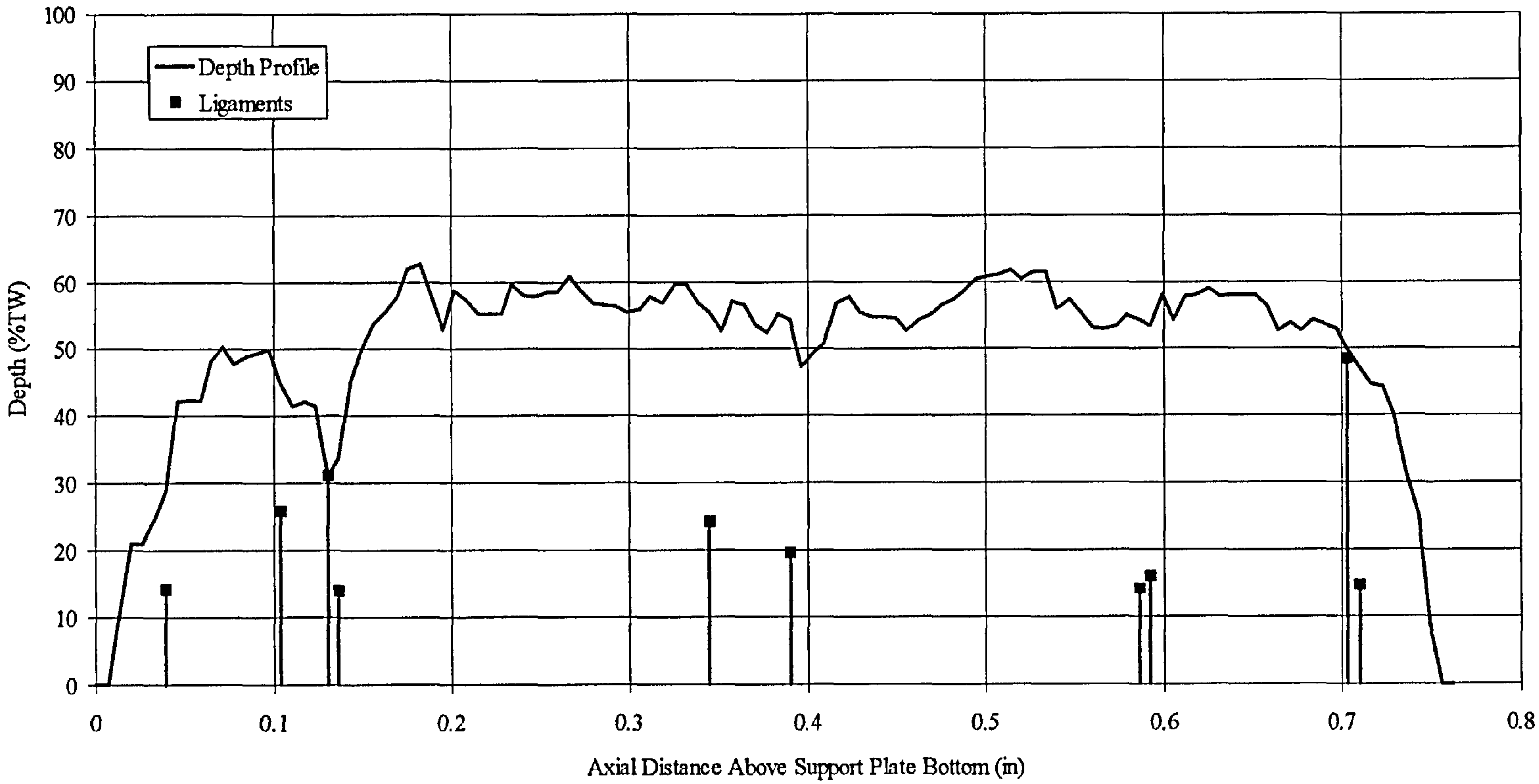


Figure 5-4. TSP3 Burst Opening Macrocrack Depth Profile.

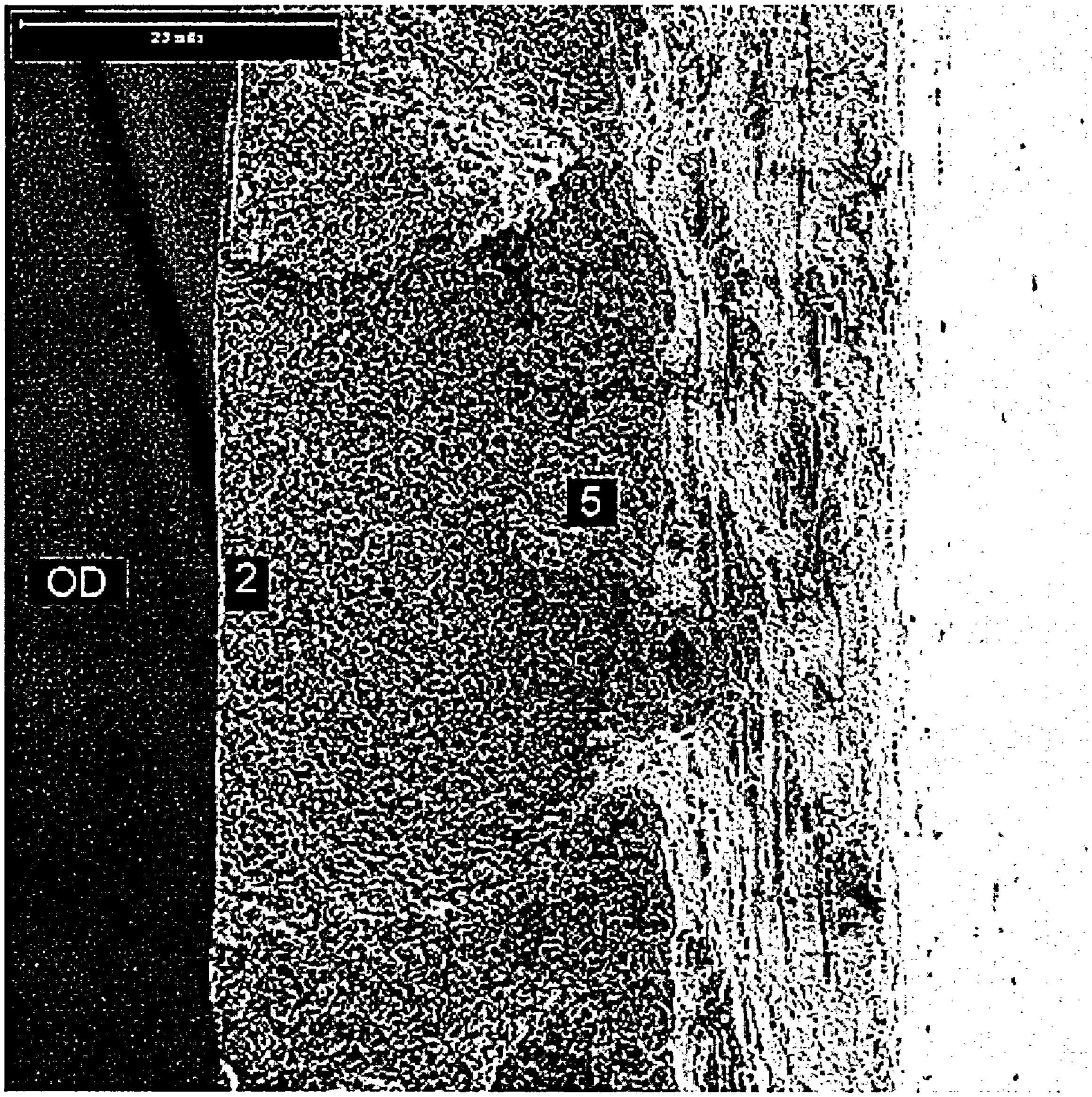

Figure 5-5. TSP1 Burst Opening Fractograph Showing Part Throughwall Corrosion.

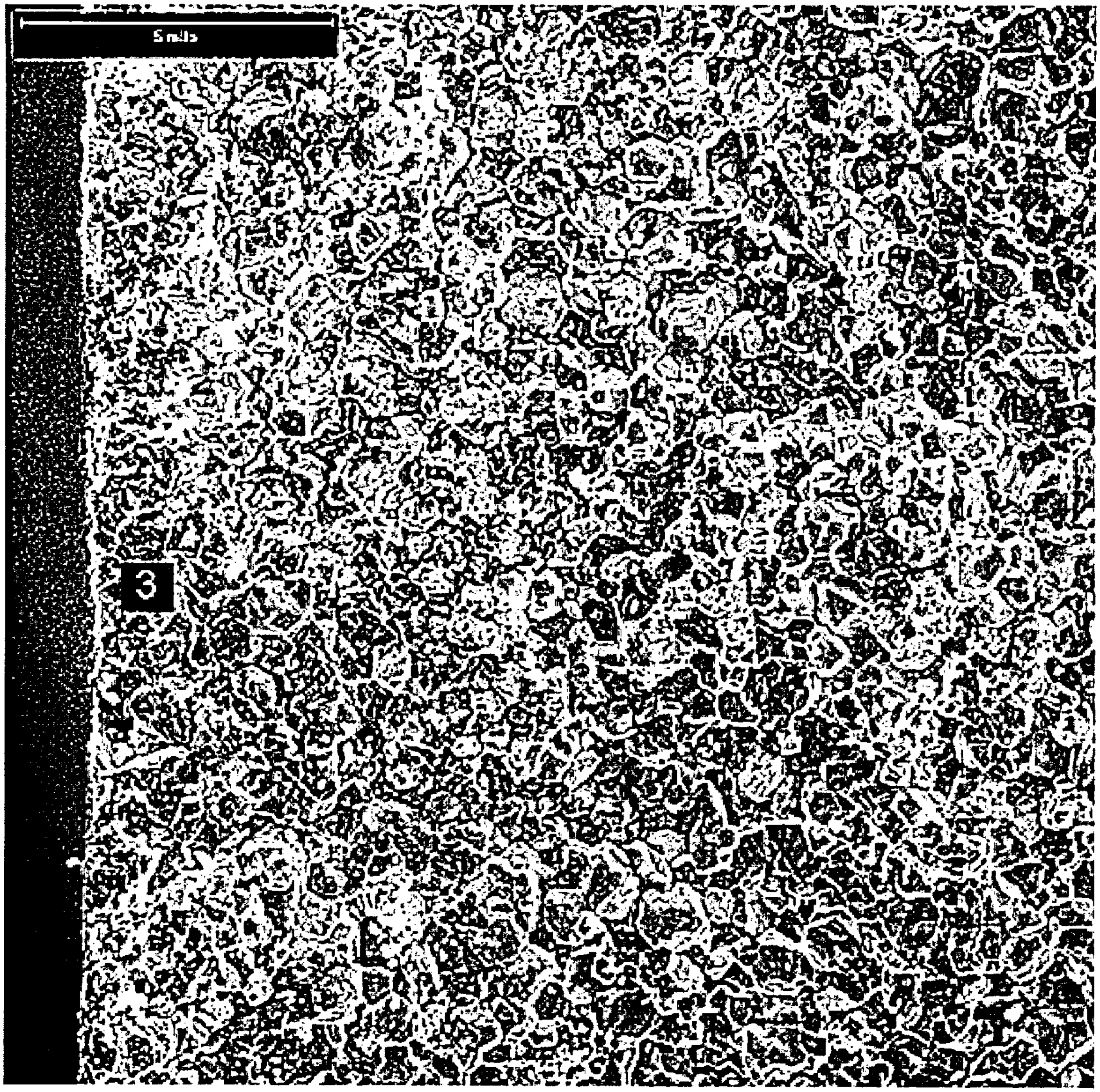


Figure 5-6. TSP1 Burst Opening Fractograph of Crack Mouth.

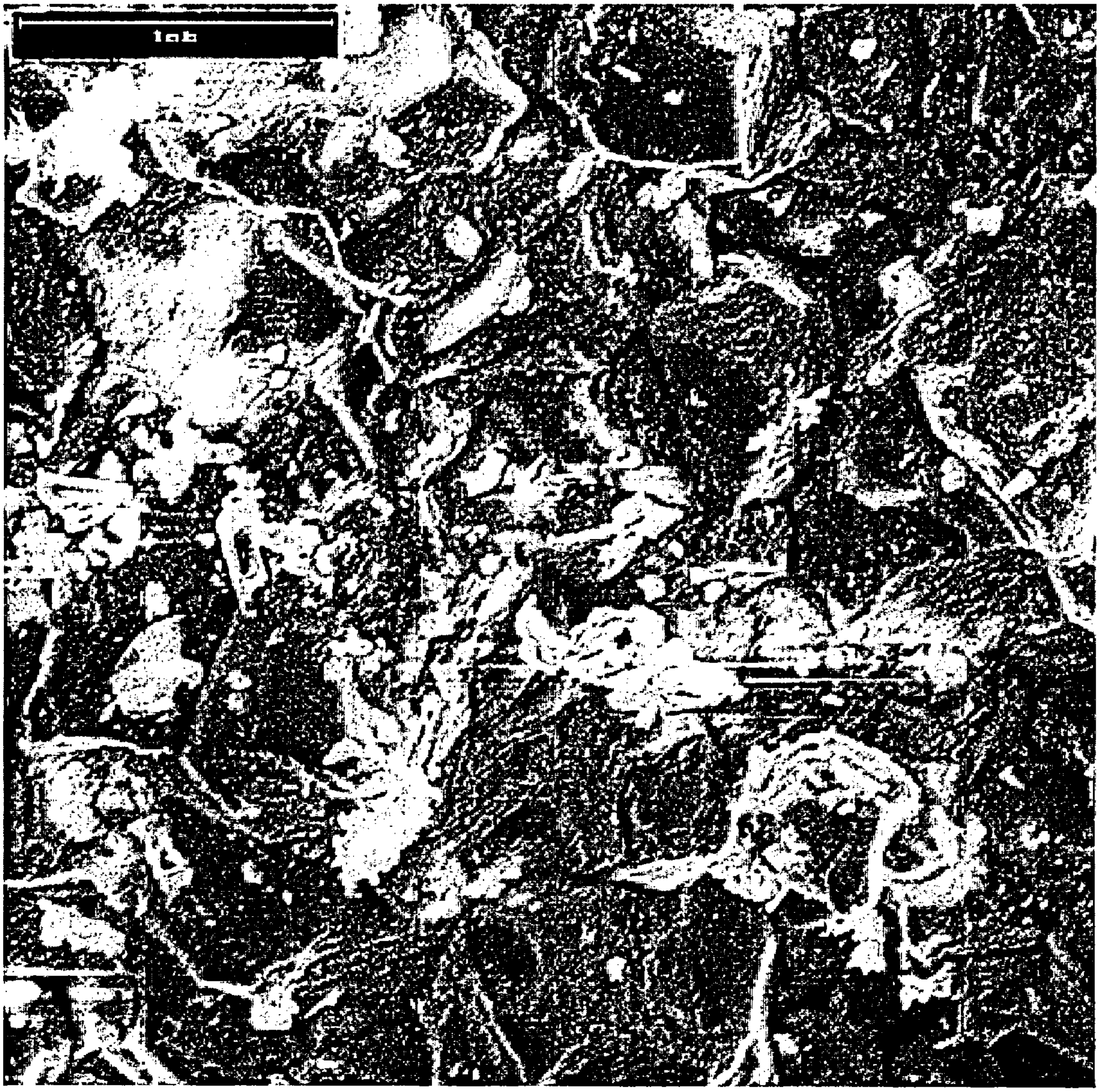

Figure 5-7. Close-Up of TSP1 Crack Mouth.

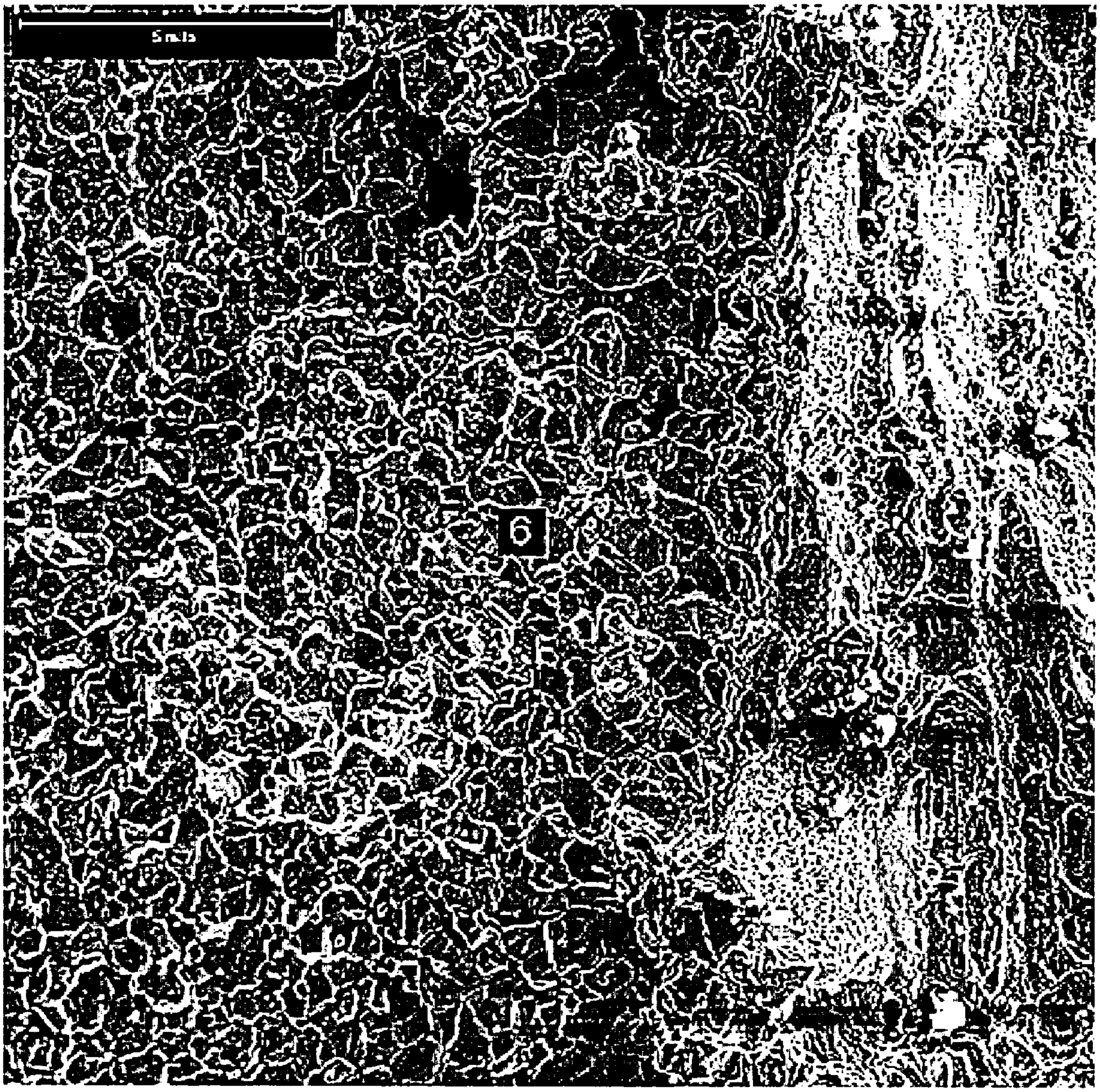


Figure 5-8. TSP1 Burst Opening Fractograph of Crack Tip.

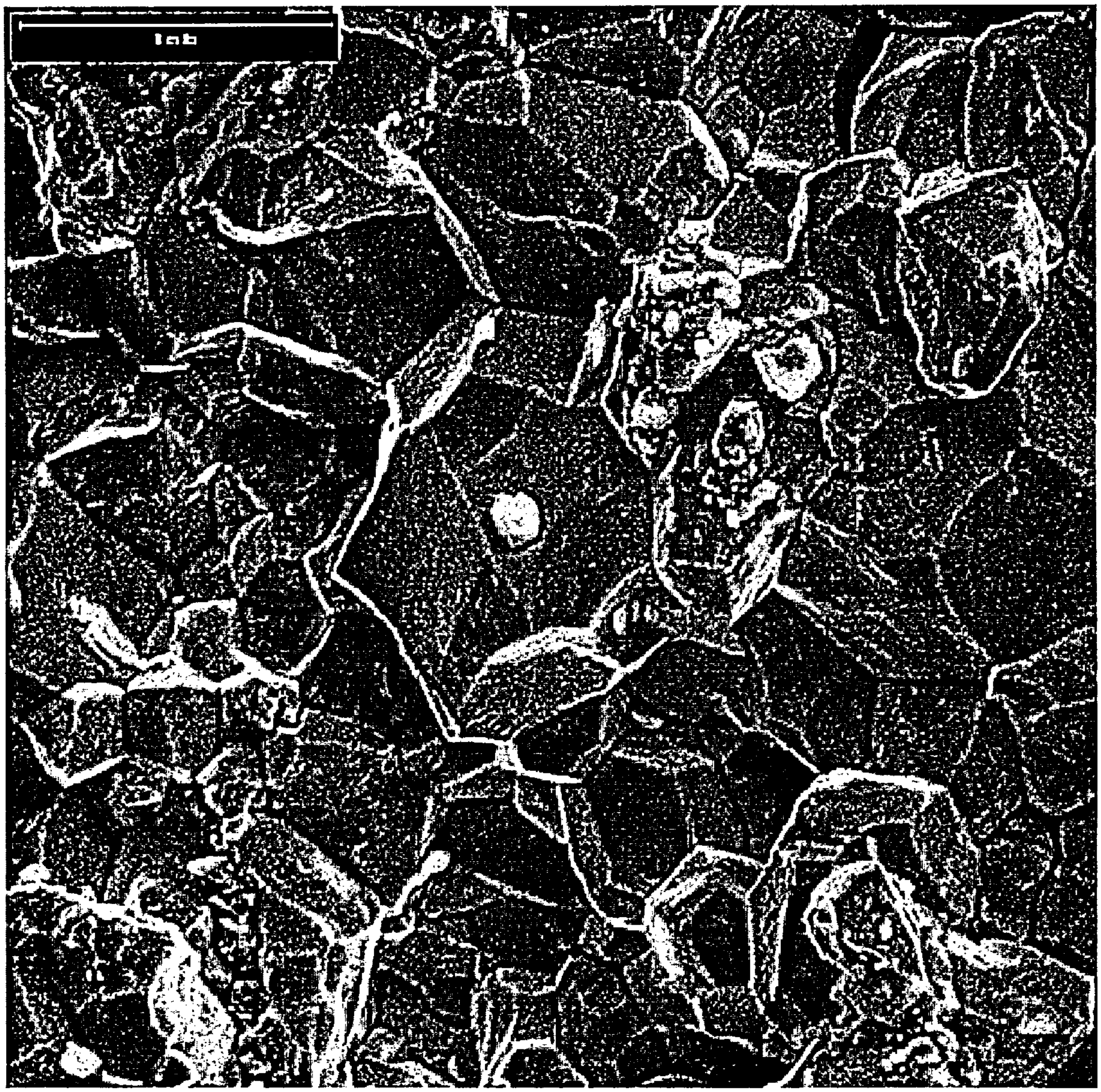

Figure 5-9. Close-Up of TSP1 Crack Tip.

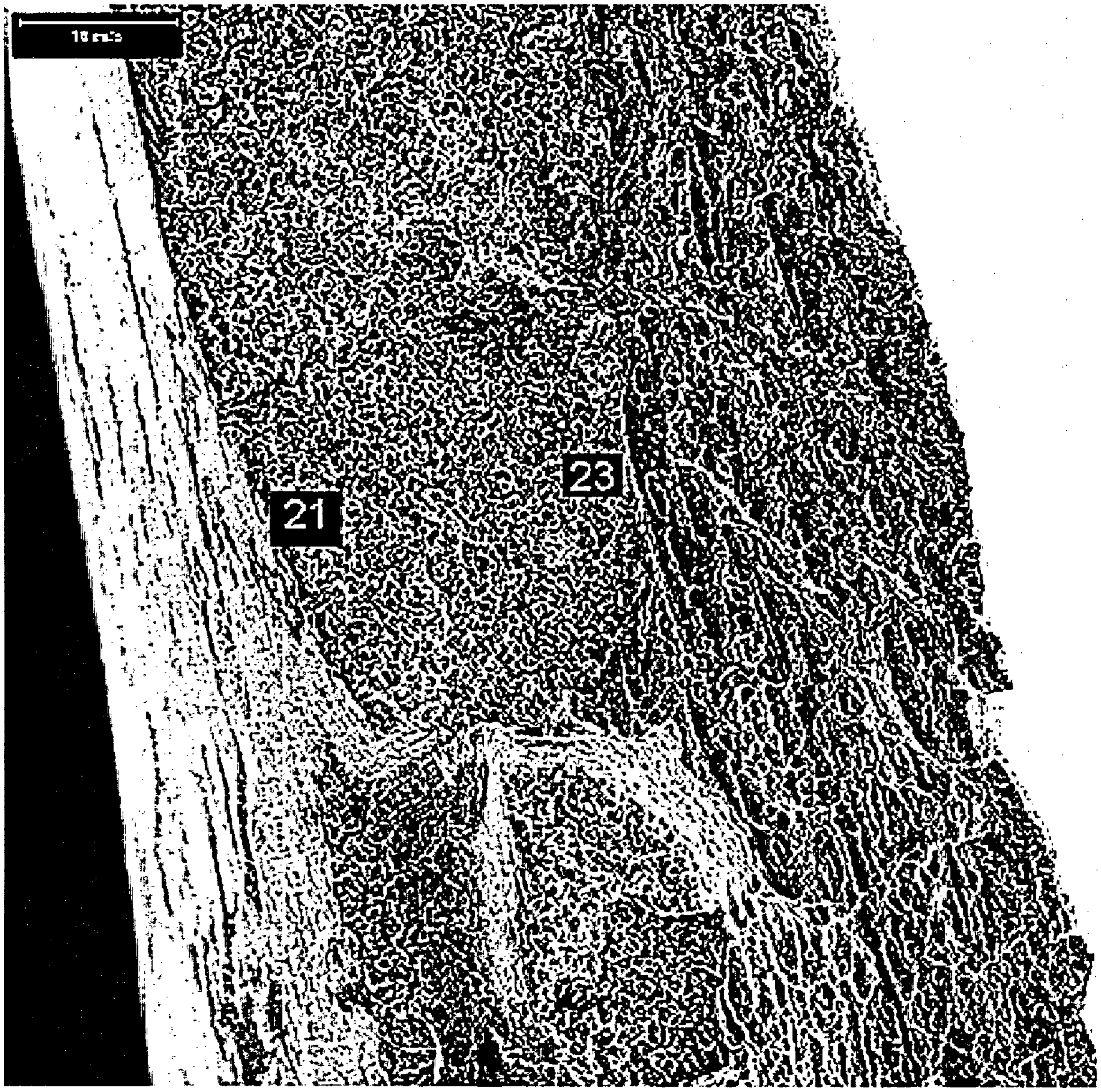


Figure 5-10. TSP1 Burst Opening Fractograph of Part Throughwall Corrosion after Cleaning.

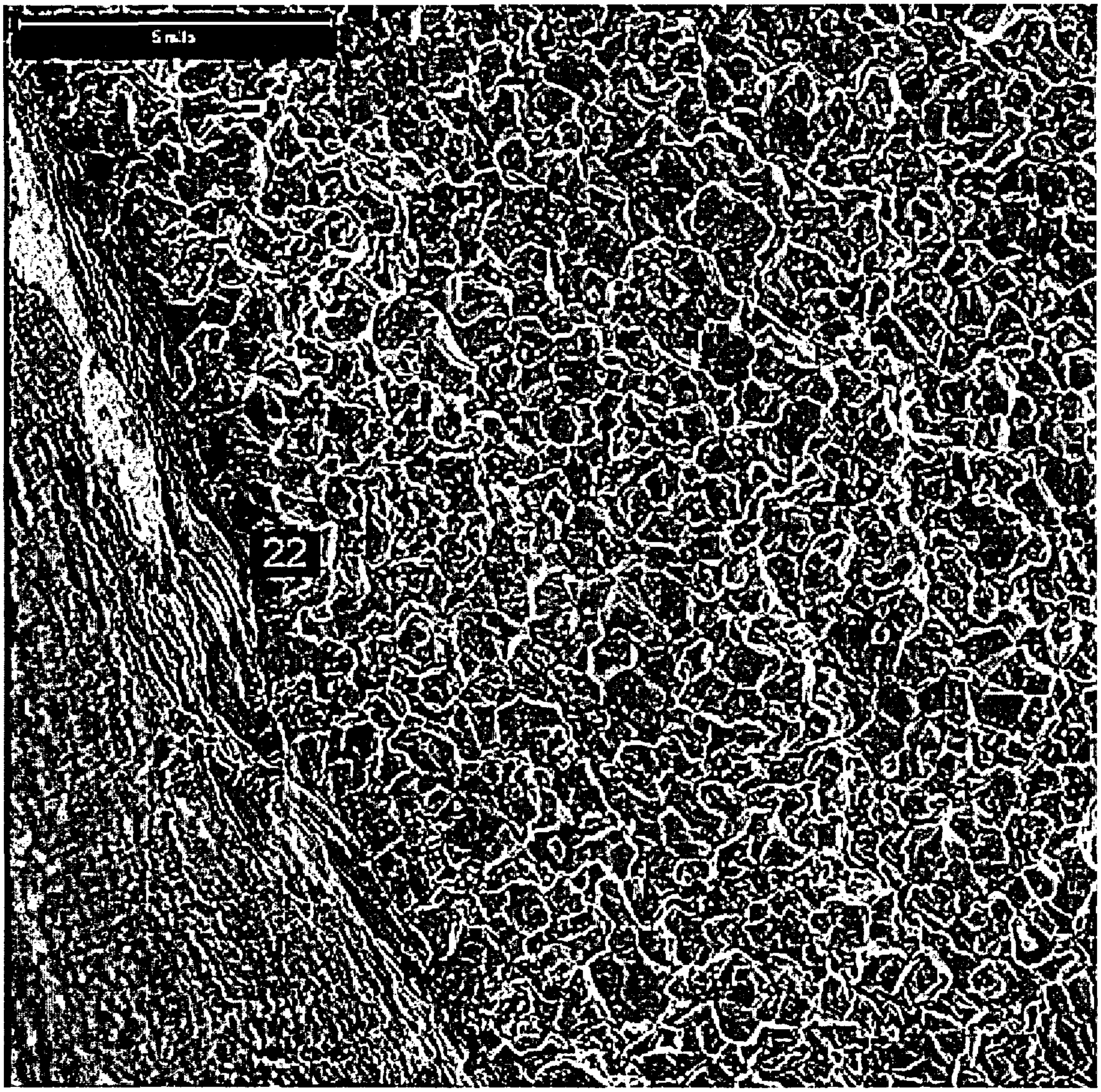


Figure 5-11. TSP1 Burst Opening Fractograph of Crack Mouth after Cleaning.

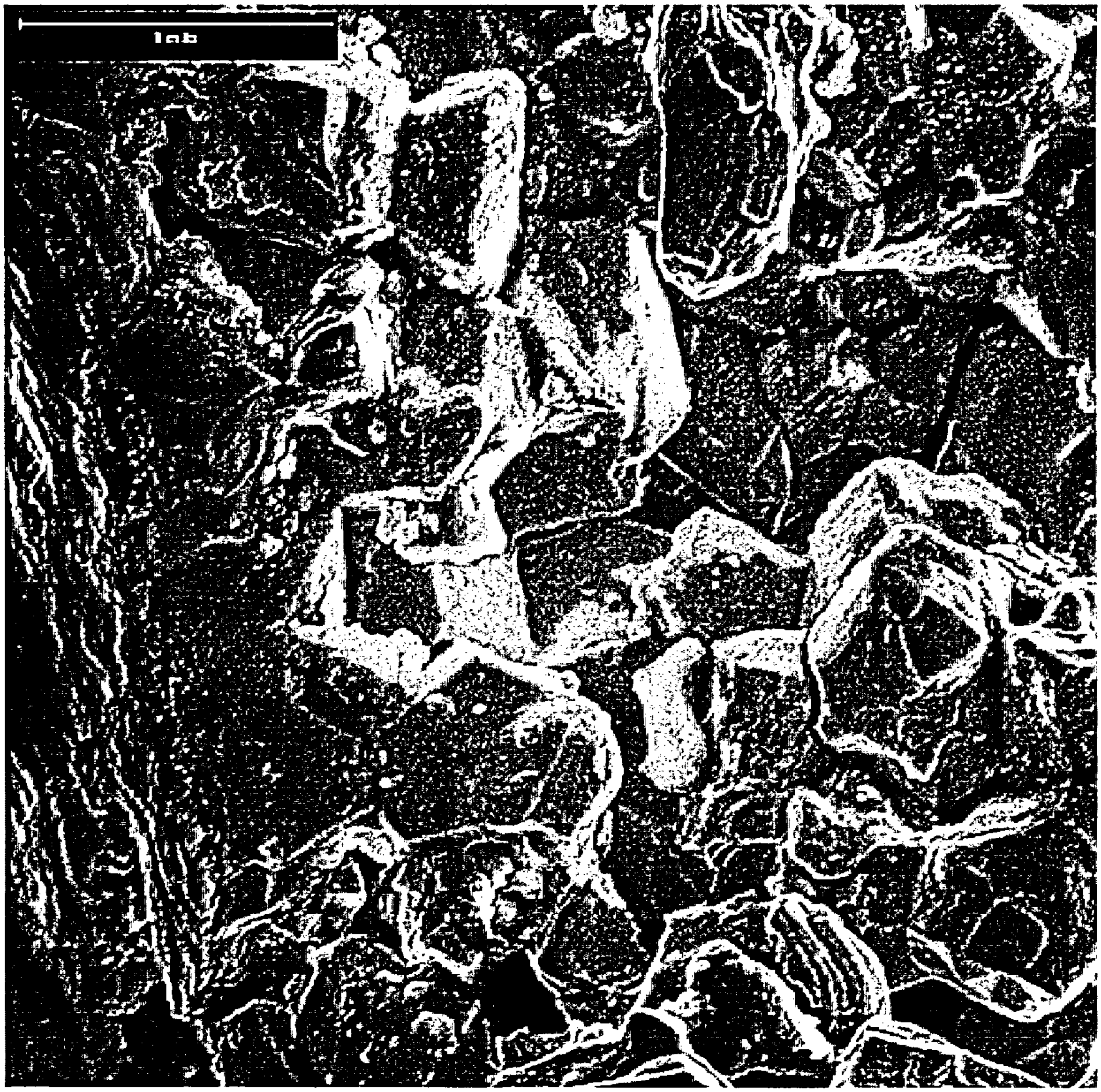

Figure 5-12. Close-Up of TSP1 Crack Mouth after Cleaning.

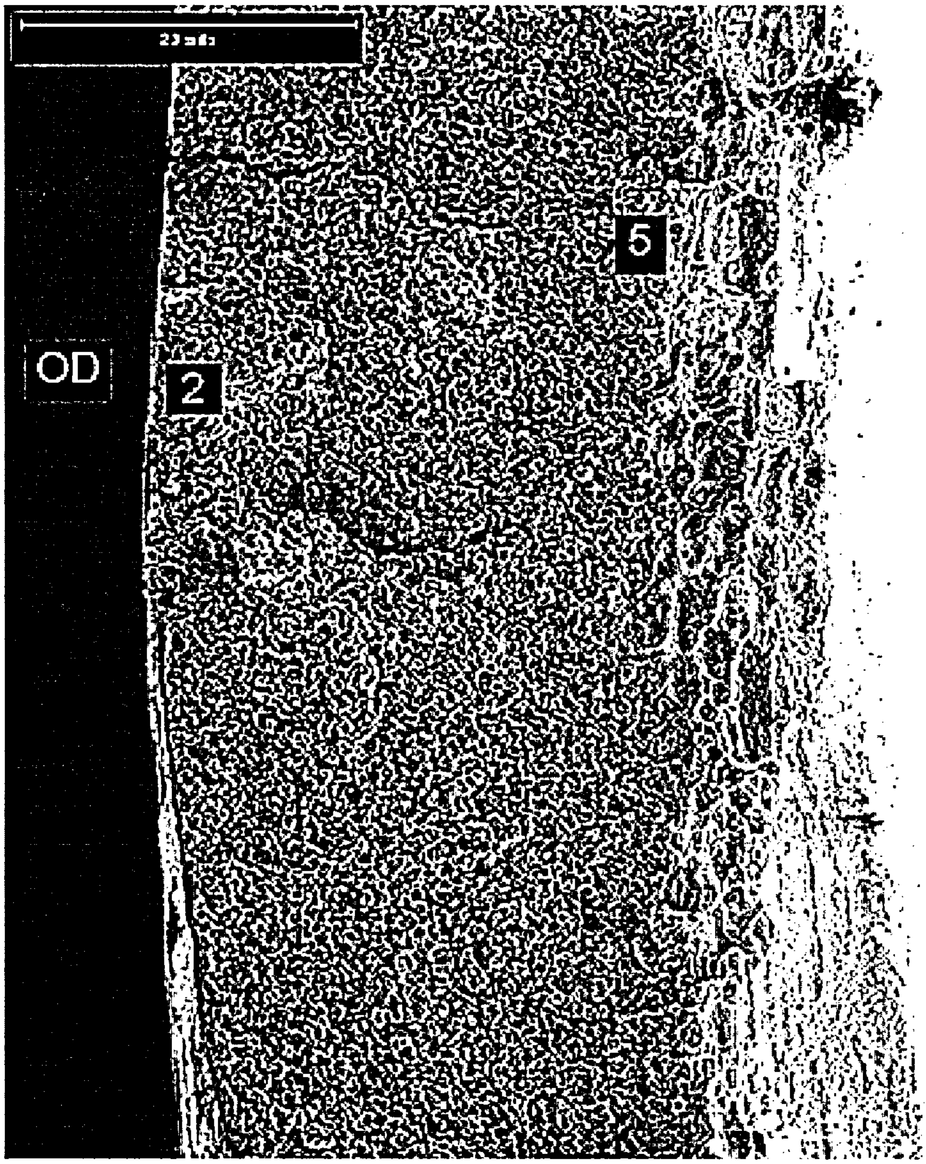


Figure 5-13. TSP2 Burst Opening Fractograph Showing Part Throughwall Corrosion.

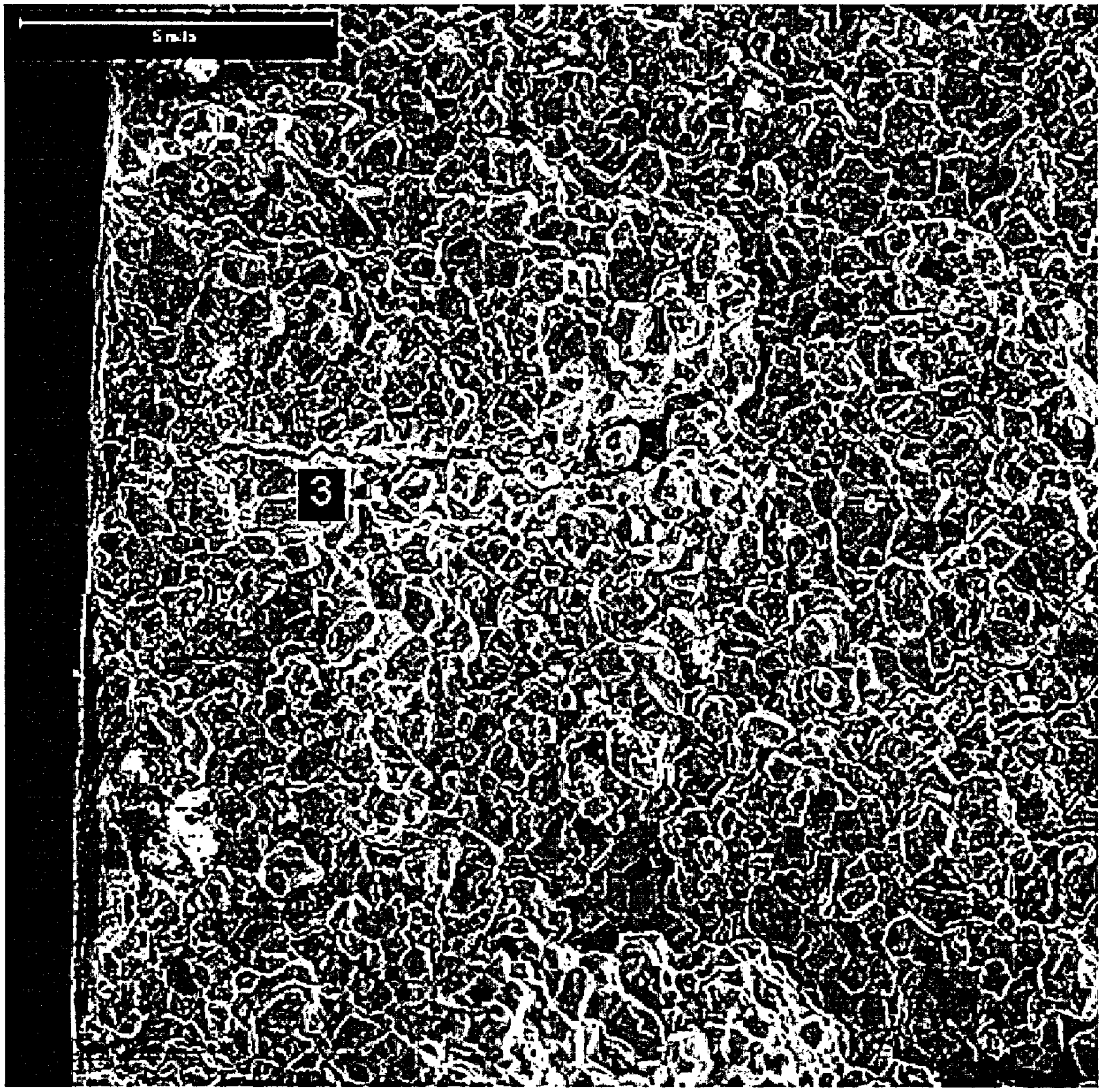


Figure 5-14. TSP2 Burst Opening Fractograph of Crack Mouth.

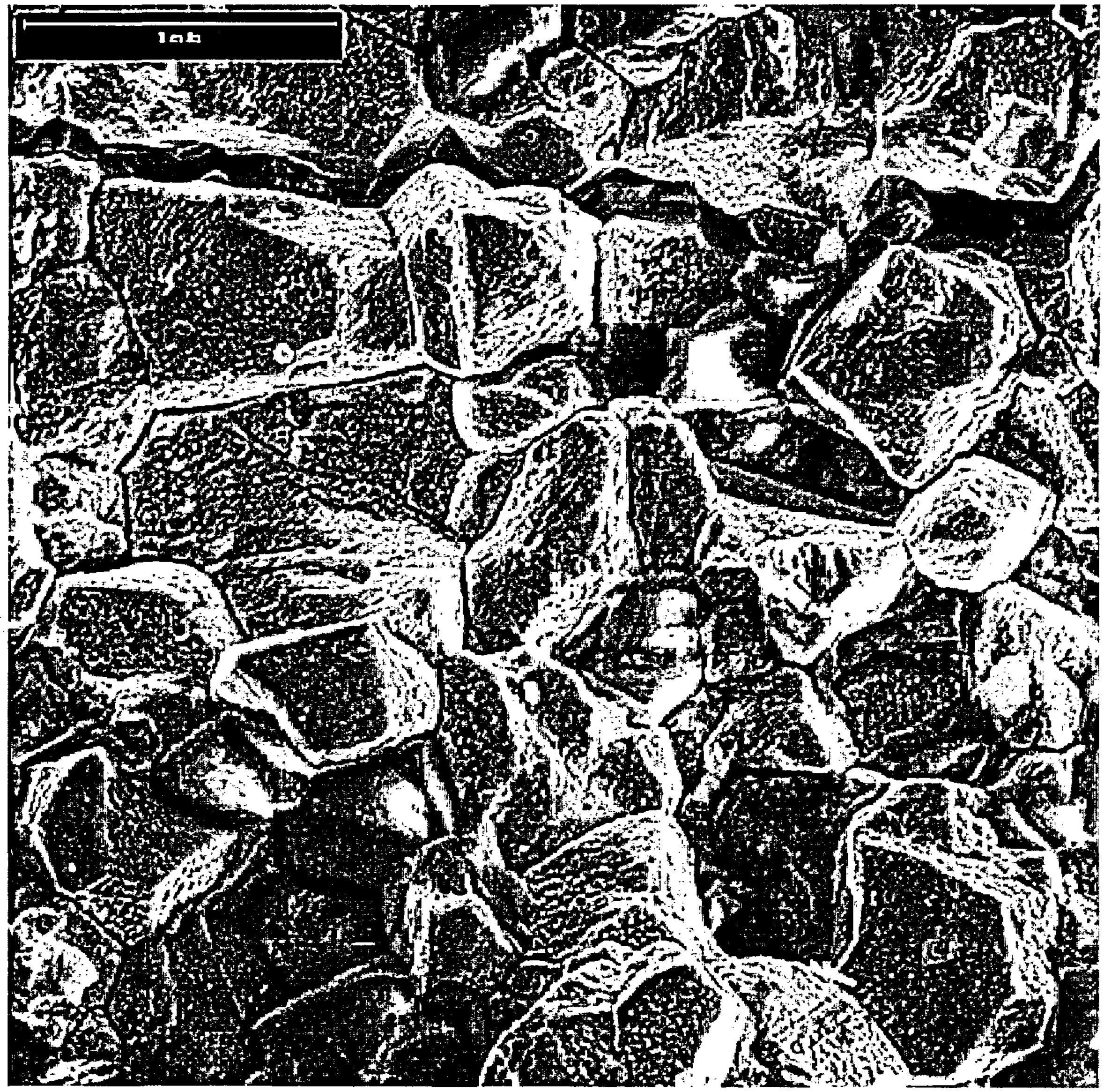


Figure 5-15. Close-Up of TSP2 Crack Mouth.

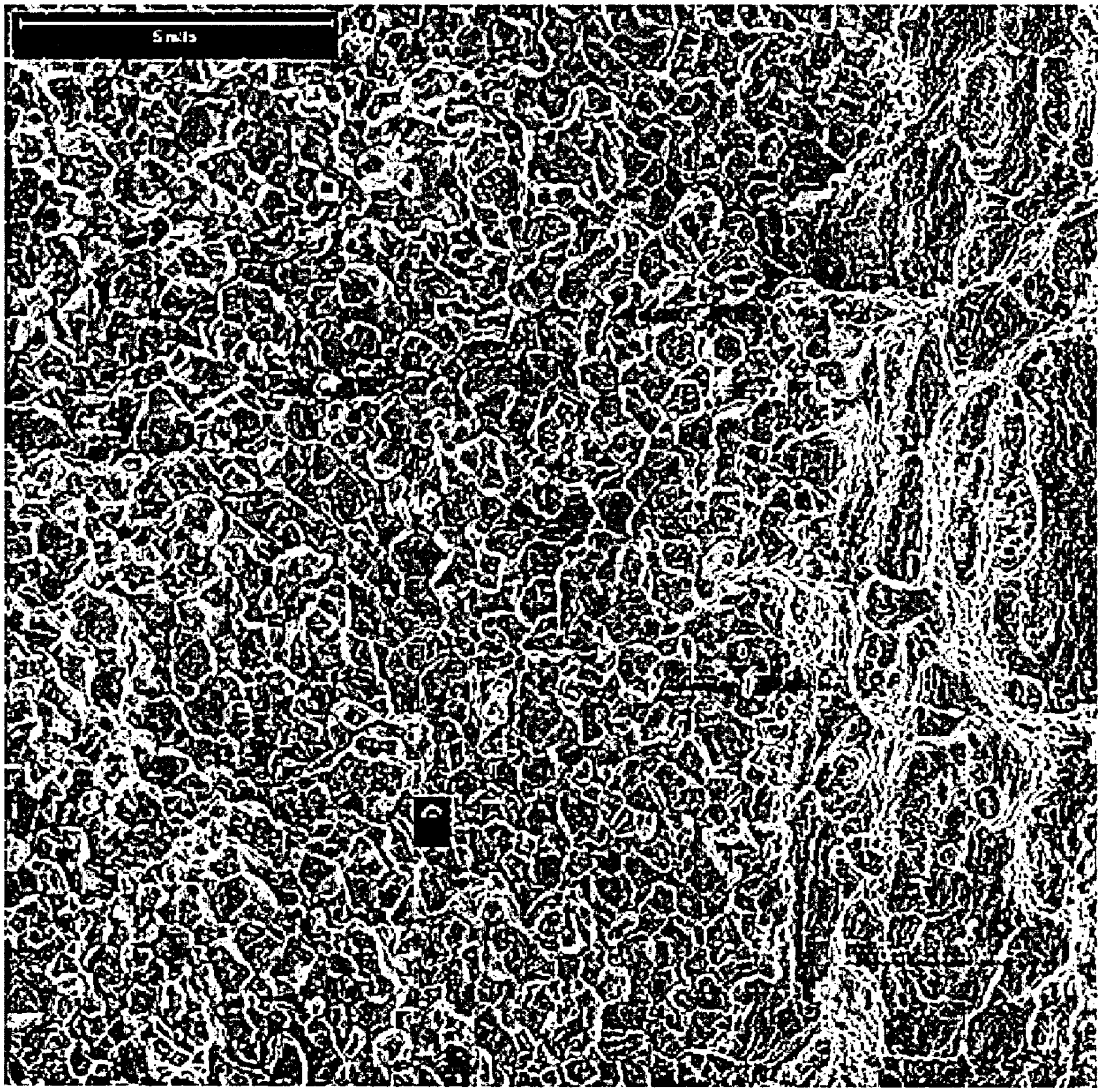


Figure 5-16. TSP2 Burst Opening Fractograph of Crack Tip.

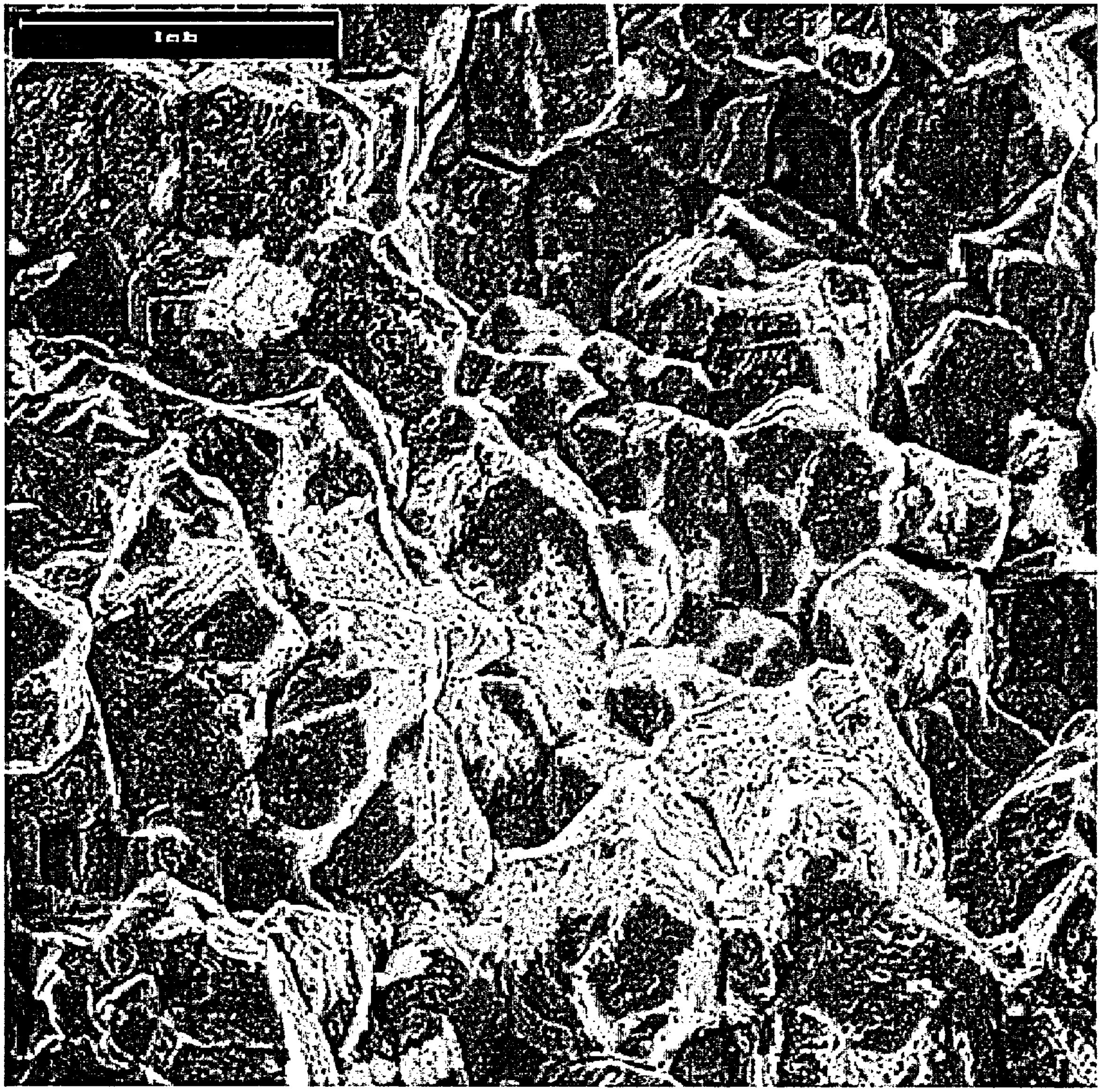

Figure 5-17. Close-Up of TSP2 Crack Tip.

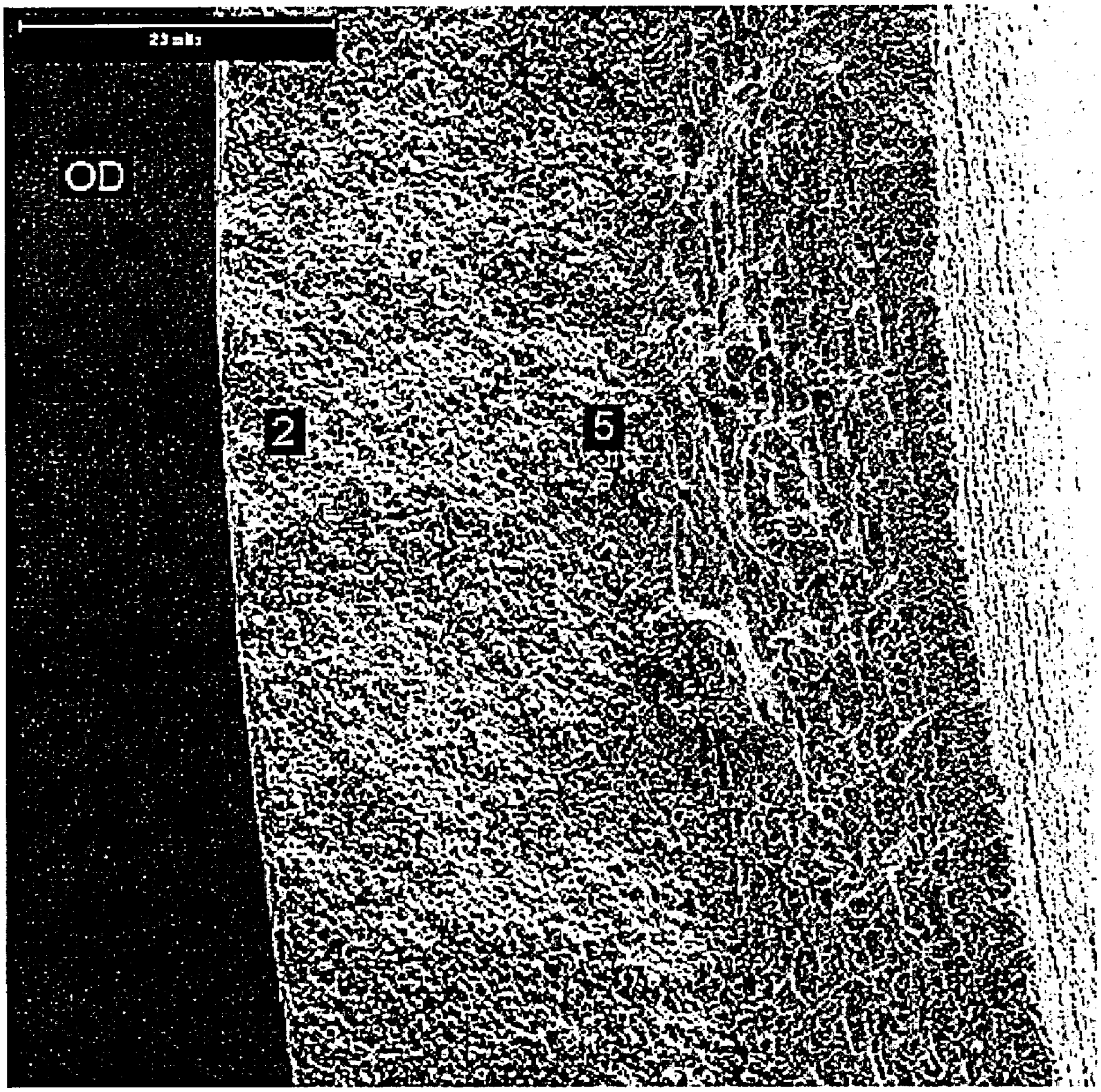


Figure 5-18. TSP3 Burst Opening Fractograph Showing Part Throughwall Corrosion.

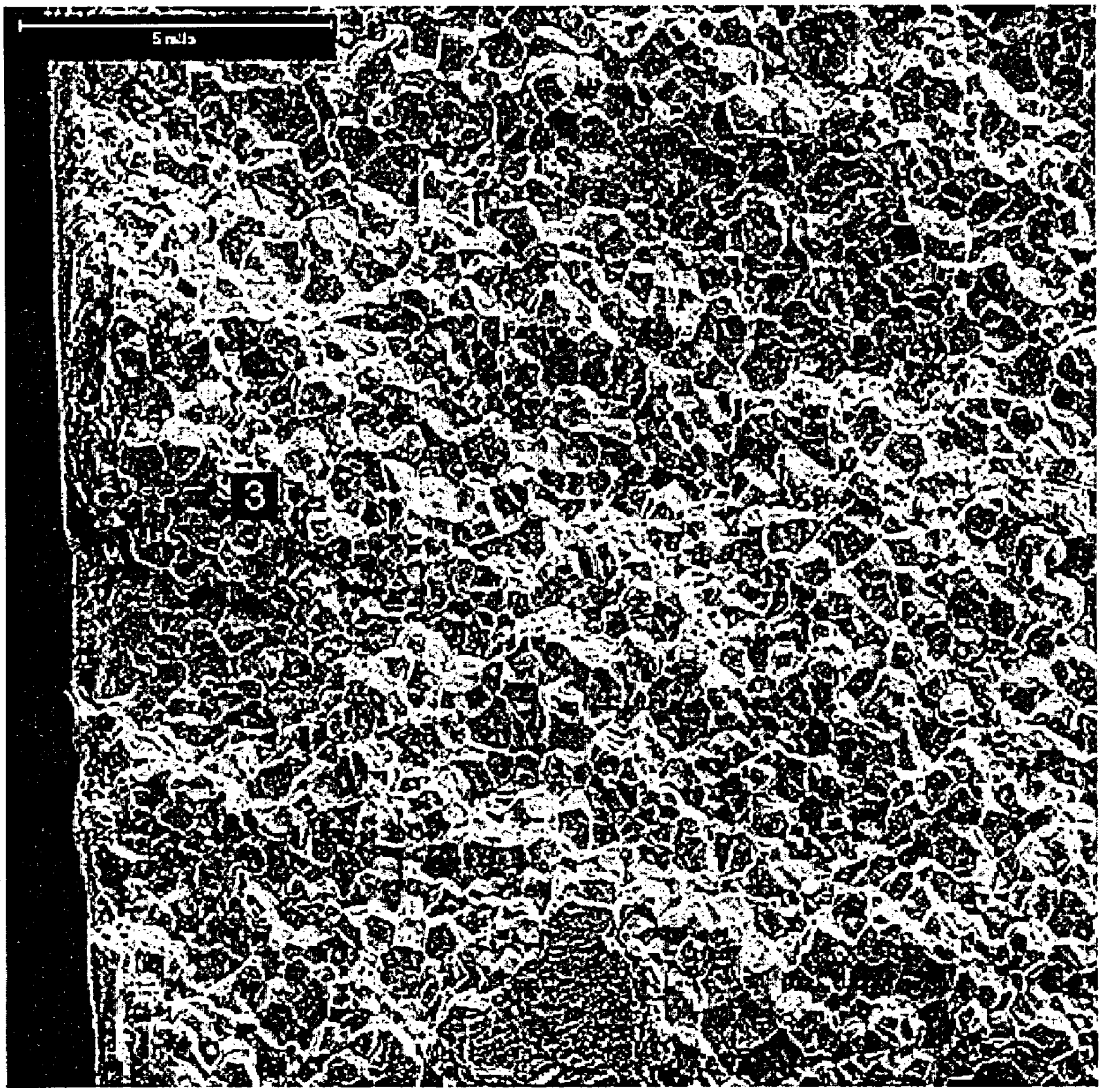


Figure 5-19. TSP3 Burst Opening Fractograph of Crack Mouth.

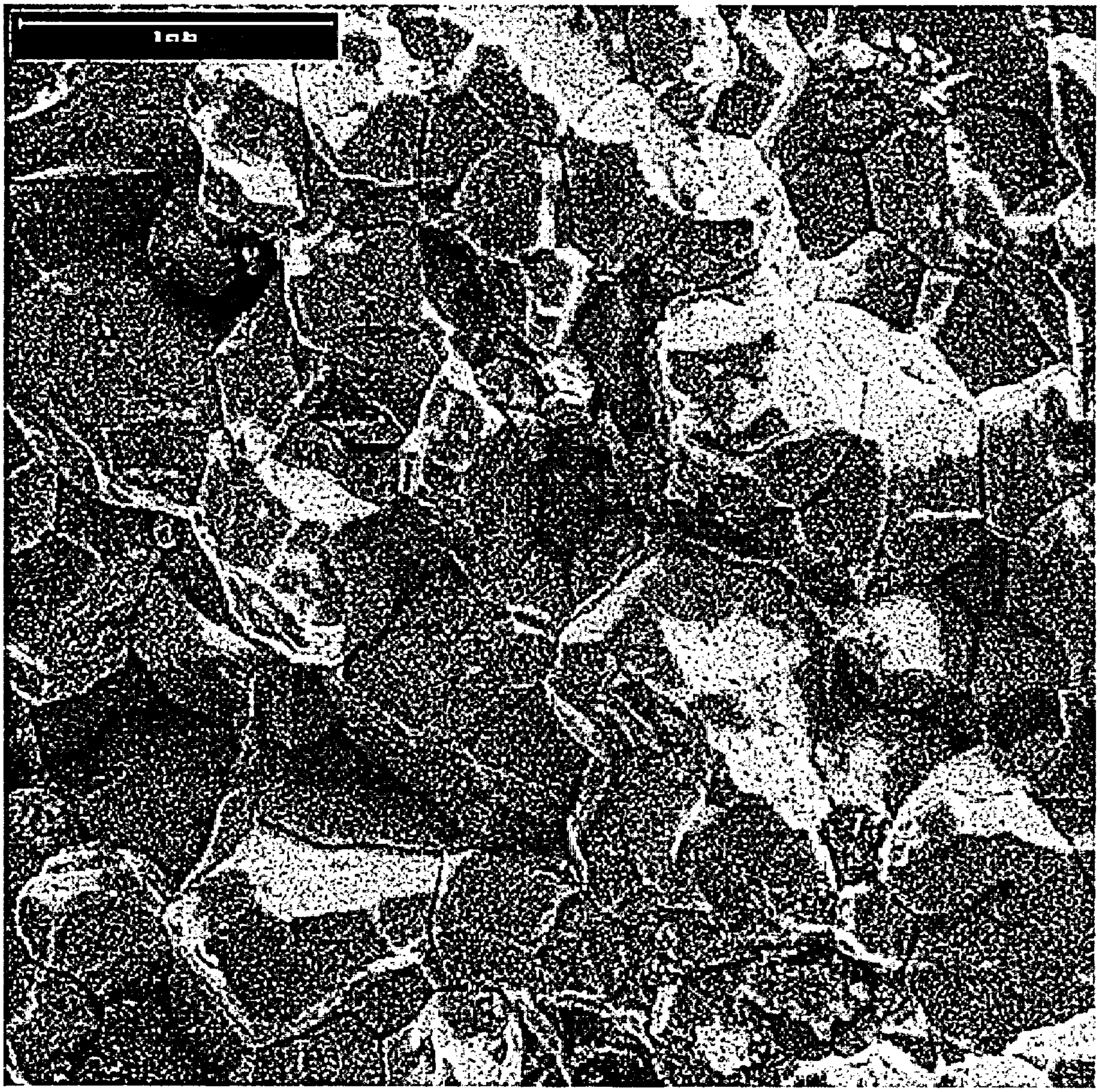

Figure 5-20. Close-Up of TSP3 Crack Mouth.

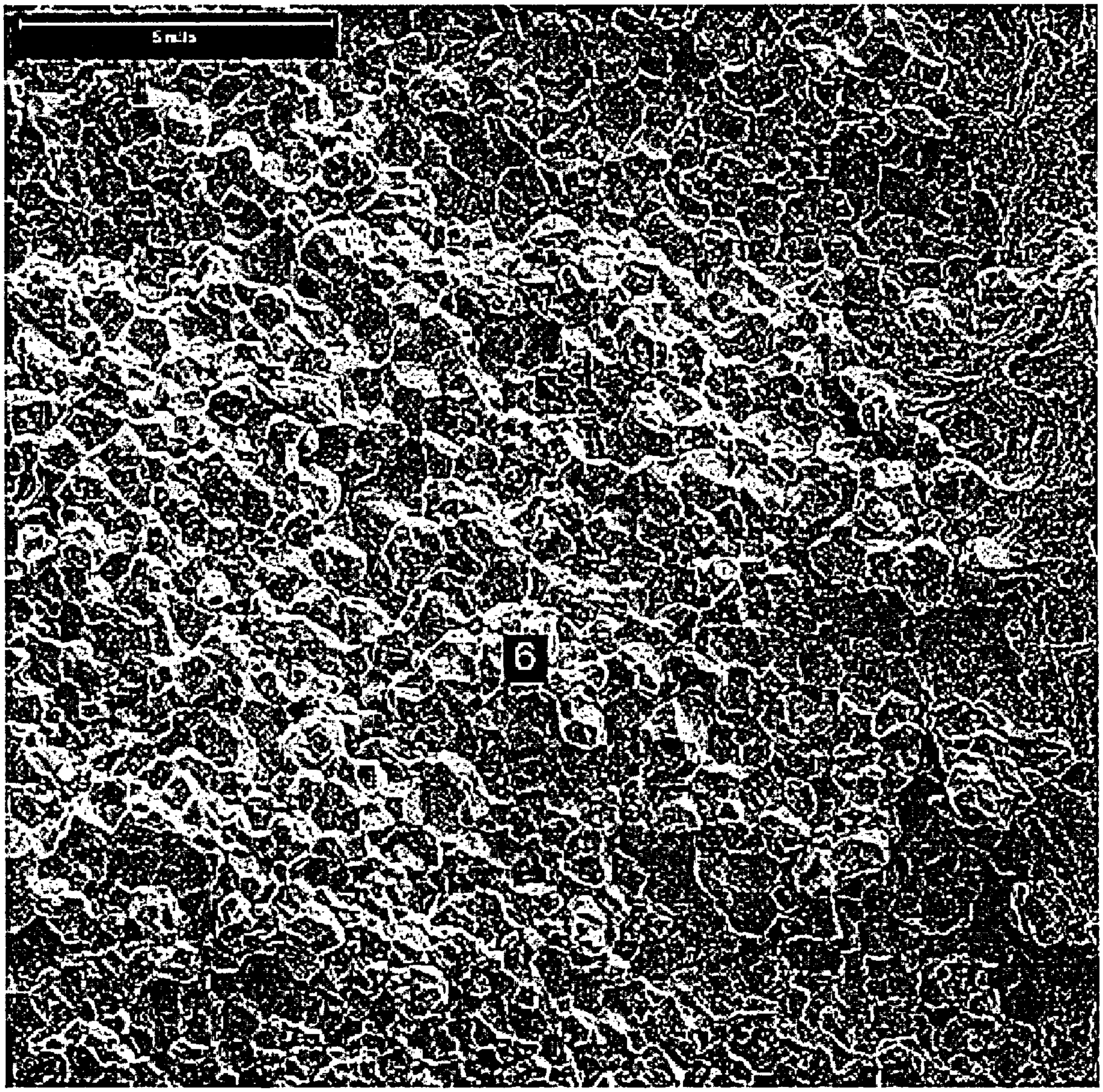


Figure 5-21. TSP3 Burst Opening Fractograph of Crack Tip.

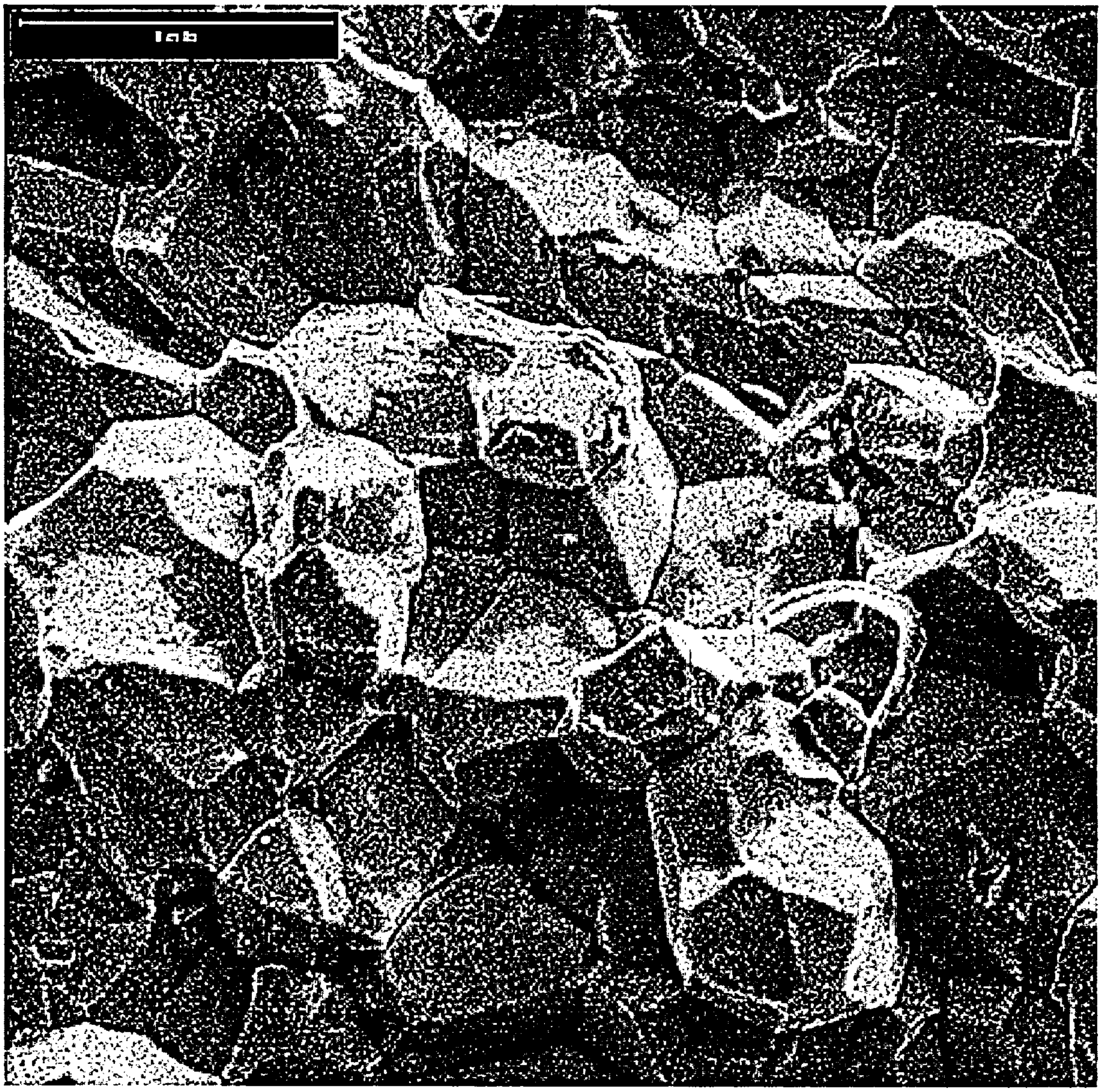

Figure 5-22. Close-Up of TSP3 Crack Tip.

## Section 6.0

## METALLOGRAPHY OF DEFECTS

### 6.1 Procedure

Light optical metallography (LOM) was conducted using transverse samples removed from all three TSP regions. The sample locations are more clearly defined in the sectioning diagrams section (refer to Section 3.0).

The transverse sections were selected to document the mode of cracking (IGA or IGSCC) and to provide depth of degradation information. In addition, the sample from the TTS region was selected to show how multiple OD initiated defects were positioned around the circumference. Also, the sample selected from TSP3 was to characterize the cracks found within installation scratches that were observed after the burst test.

The transverse samples were mounted in the direction shown by the large arrows in the Section 3.0 sectioning diagrams. Each sample was ground with SiC papers, followed by diamond wheels using polishing oil, followed by diamond aerosol sprays, leaving the edge to be examined with a mirror finish. Transverse samples were also examined and photographed in the as-polished condition. Selected defect areas were then examined and photographed after an electrolytic nital etch. The electrolytic nital etch was chosen to highlight the relationship between the cracks and the grain boundaries.

### 6.2 Results

<u>TSP1 Region Axial Cracks</u>

The sample from the TSP1 region (mount number M2534) was cut from an area with deep secondary cracks adjacent to the burst opening. No attempt was made to find the deepest secondary crack; this sample was obtained to characterize the cracks in the TSP1 region.

Figure 6-1 presents the unetched view of the entire sample. The OD initiated cracks were found only next to the burst opening. Three positions were examined; all three positions were similar. Figure 6-2 shows the deepest of the cracks that were found on this sample (taken from position 1 after etching). The deepest crack on this sample was 39%TW. Figure 6-2 shows that the cracks were discrete and had no or few branches. The cracks were intergranular with no IGA between cracks. The transverse section will only show the axial component of cracks; however the visual exam showed that circumferentially oriented cracks were made visible by the burst test. It can therefore be concluded that the cracking at the TSP1 region was cellular corrosion and axial IGSCC. IGA was not observed at the TSP1 region.

TSP2 Region Axial Cracks

The sample from the TSP2 region (mount number M2530) was cut from an area with secondary cracks adjacent to the burst opening. No attempt was made to find the deepest secondary crack; this sample was obtained to characterize the cracks in the TSP2 region.

Figure 6-3 presents the unetched view of the entire sample. The OD initiated cracks were found only next to the burst opening; however there was shallow IGA at all of the other positions examined. Thirteen positions were examined; positions 1 and 2 had IGA at the OD surface with deeper IGSCC; positions 3-13 was mostly shallow IGA. Figure 6-4 shows the deepest of the cracks that were found on this sample (taken from position 2 after etching). The deepest crack on this sample was 43%TW. Figure 6-4 shows that the IGSCC cracks had no or few branches at the deeper locations; however the region around the cracks were surrounded by shallow (~10%TW) IGA. Figure 6-5 presents one region of deeper IGA (position 9, 20%TW); however most of the IGA on this sample was only 3-4 grains deep. The post-burst visual observations characterized this region as having almost nothing but axial cracks but with minor cellular corrosion. It is likely that the cellular corrosion that was observed visually was actually the shallow IGA. The cracking at the TSP2 region can be characterized as relatively shallow IGA with deeper IGSCC penetrations.

TSP3 Region Axial Cracks and Scratch Crack

The sample from the TSP3 region (mount number M2531) was cut from an area with secondary cracks adjacent to the burst opening. No attempt was made to find the deepest secondary crack; this sample was obtained to characterize the cracks in the TSP3 region. It was also cut in a manner to capture the scratch cracks that were located at the 30° orientation.

Figure 6-6 presents the unetched view of the entire sample. The OD initiated cracks were found at each of the seven positions examined. Figure 6-7 shows the deepest of the cracks that were found on this sample (taken from position 1, after etching). The deepest crack on this sample was 69%TW. This is deeper than the maximum depth measured from the SEM depth profile of the burst opening. Figure 6-7 shows that the IGSCC cracks had no or few branches at the deeper locations; however the region around the cracks were surrounded by shallow (~10%TW) IGA. The post-burst visual observations characterized this region as having some patches of cellular corrosion. It is likely that the cellular corrosion that was observed visually was actually the shallow IGA. The cracking at the TSP3 region can be characterized as relatively shallow IGA with deeper IGSCC penetrations.

Figures 6-8 and 6-9 show the scratch cracks located at positions 6 and 7, respectively. The scratch crack at position 6 is 42%TW, the one at position 7 is 24%TW. Figure 6-10 presents a close-up of the position 6 scratch crack at the OD surface. At the OD surface grains, there is possible evidence of elongated grains; however these are less than a typical (non-elongated, Sequoyah-2 tube R12C45) grain deep. Elongated grains would result from an installation scratch and the cold working of the surface may serve as an initiation site for IGSCC.

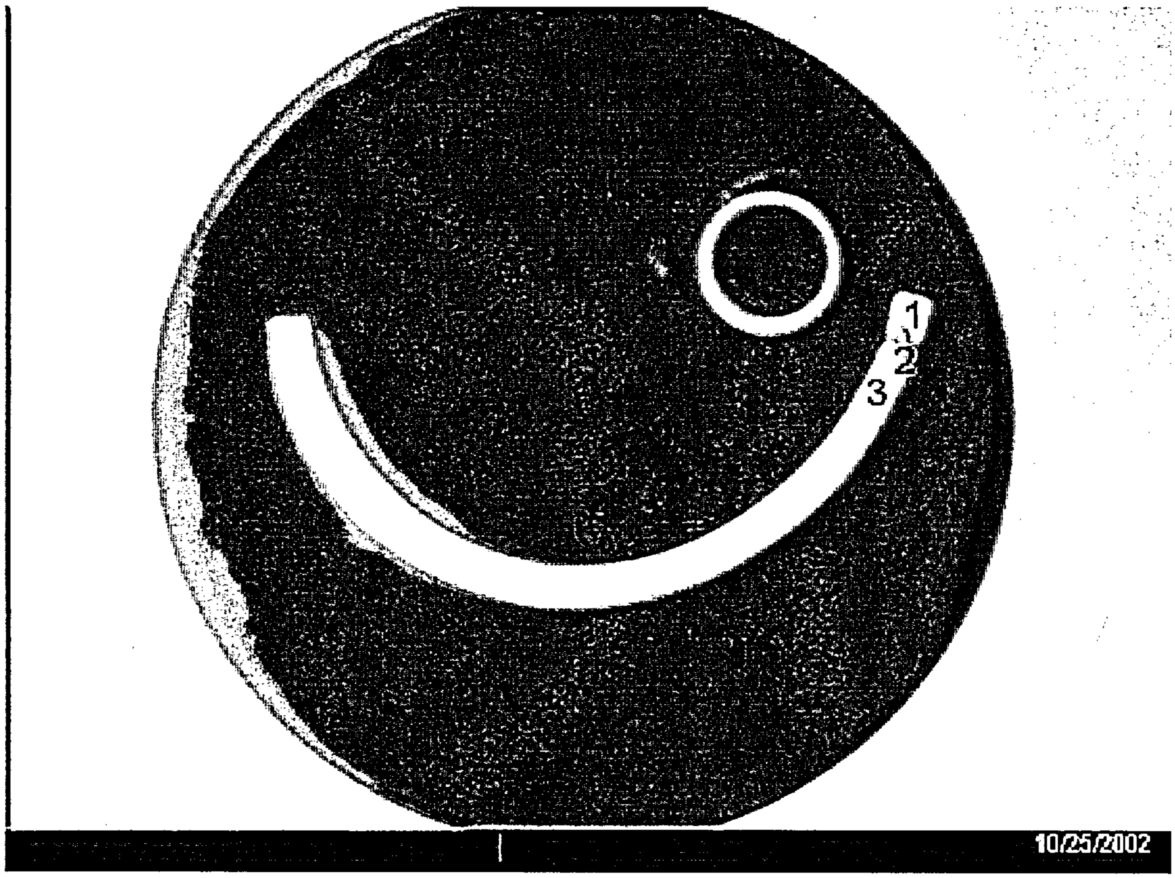


Figure 6-1. Low Magnification View of TSP1 Transverse Section (Unetched).

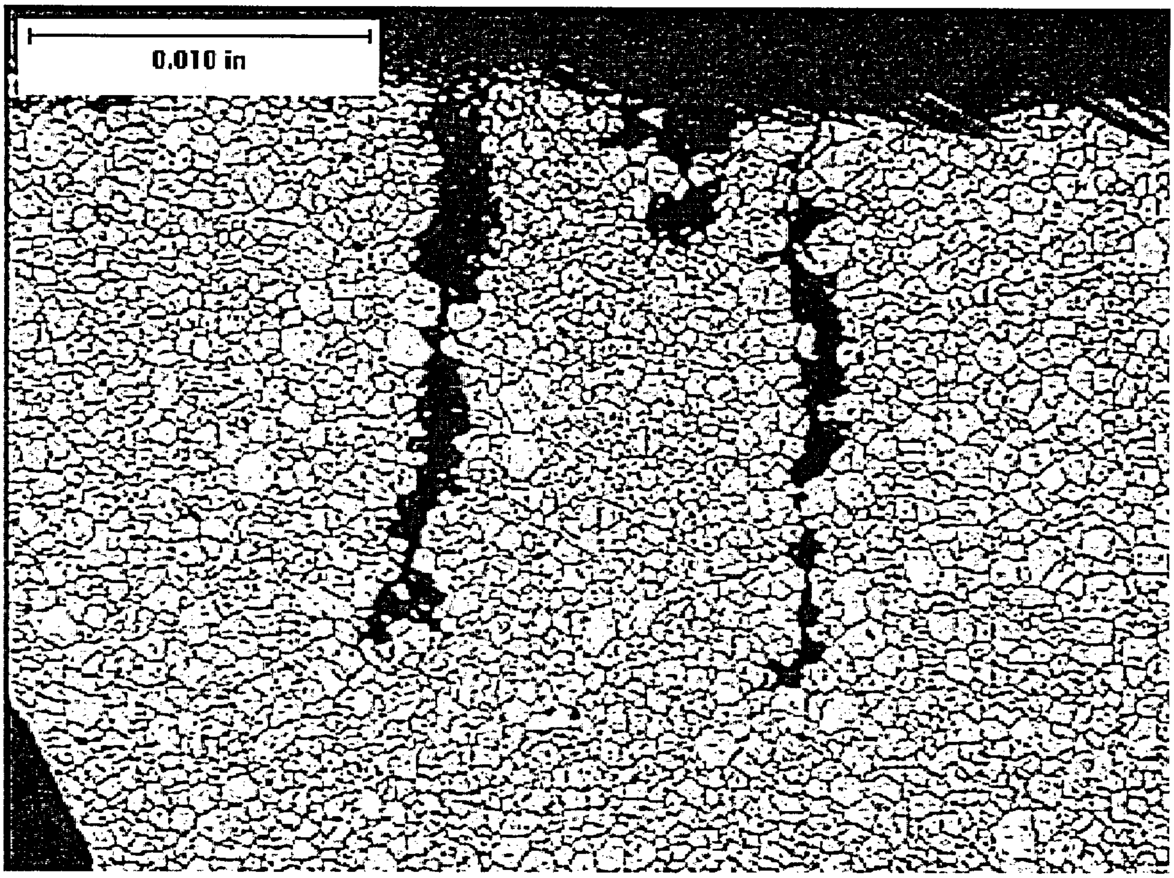

Figure 6-2. Deepest Crack on the TSP1 Transverse Section, Position 1 in Figure 6-1 (Nital Etch).

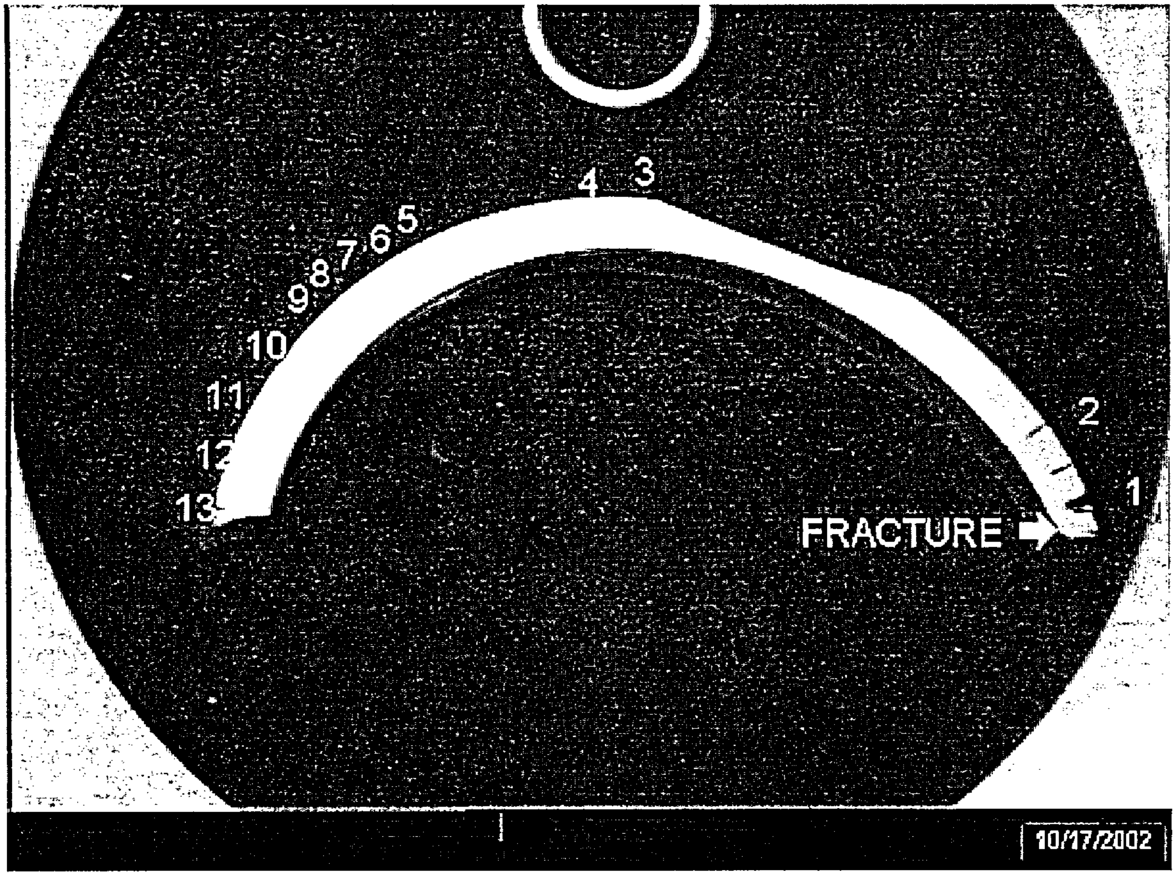


Figure 6-3. Low Magnification View of TSP2 Transverse Section (Unetched).

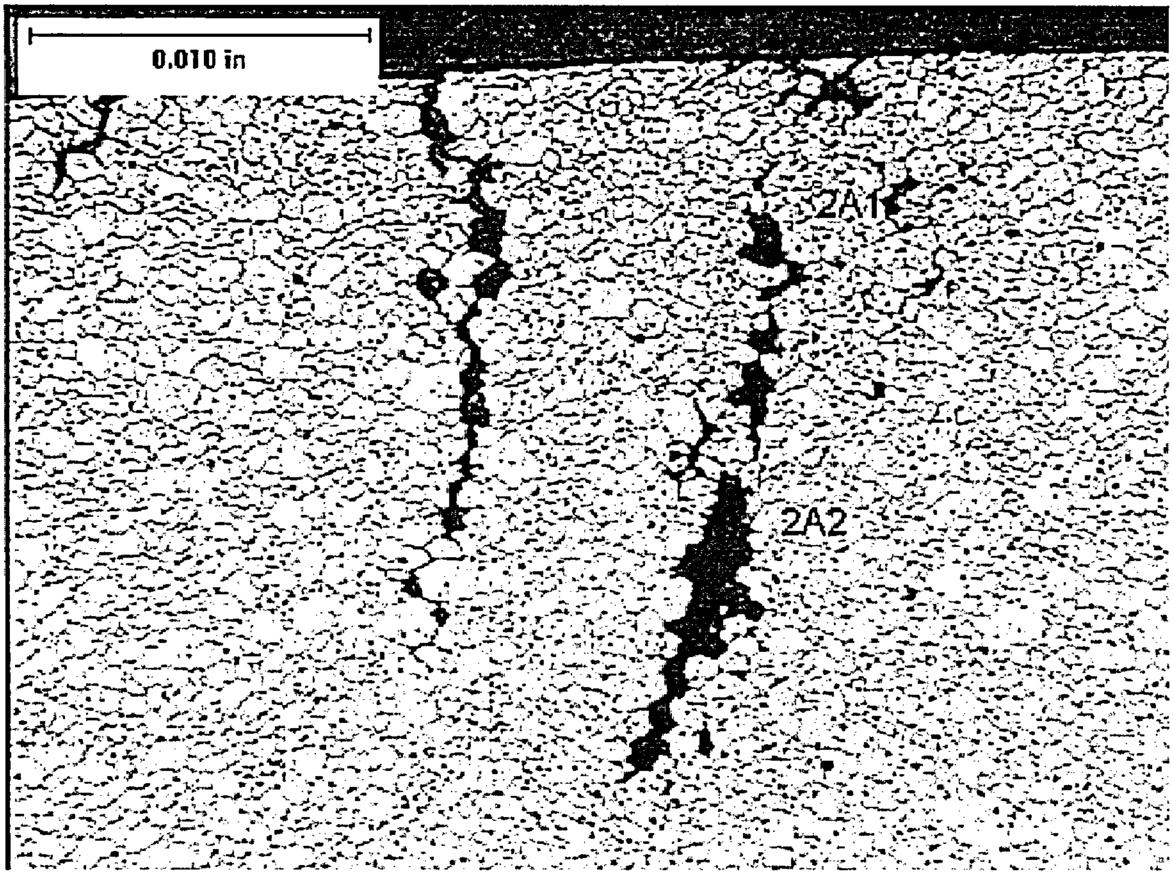


Figure 6-4. Deepest Crack on the TSP2 Transverse Section, Position 2 in Figure 6-3 (Nital Etch).

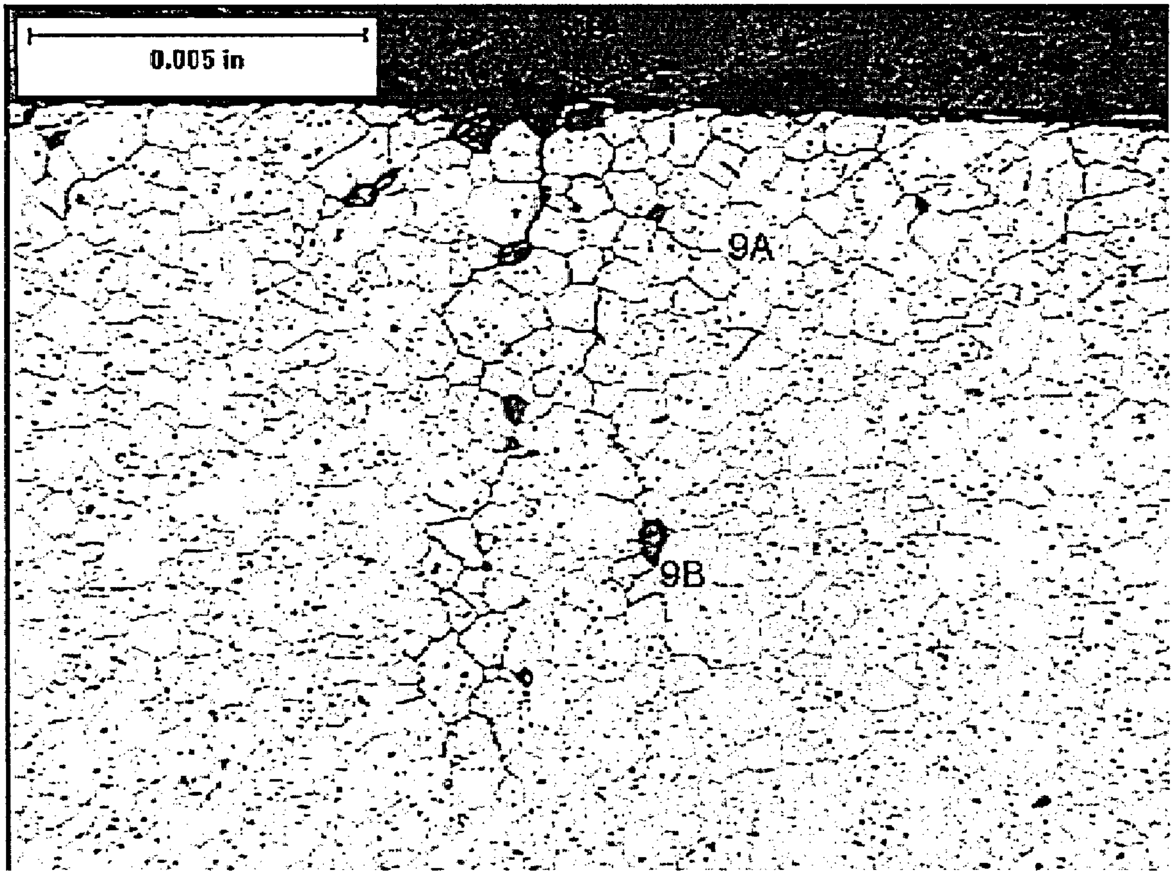


Figure 6-5. Deep IGA on the TSP2 Transverse Section, Position 9 in Figure 6-3 (Nital Etch).

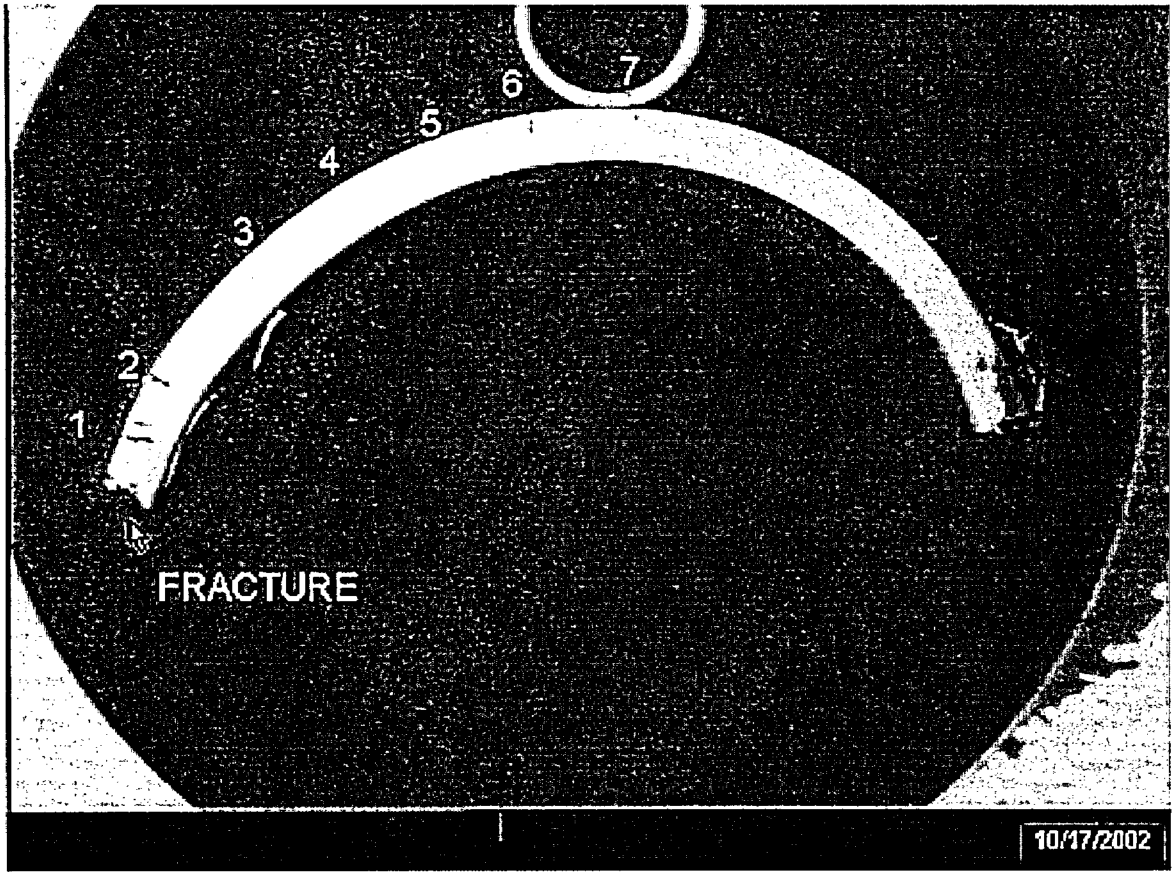


Figure 6-6. Low Magnification View of TSP3 Transverse Section (Unetched).

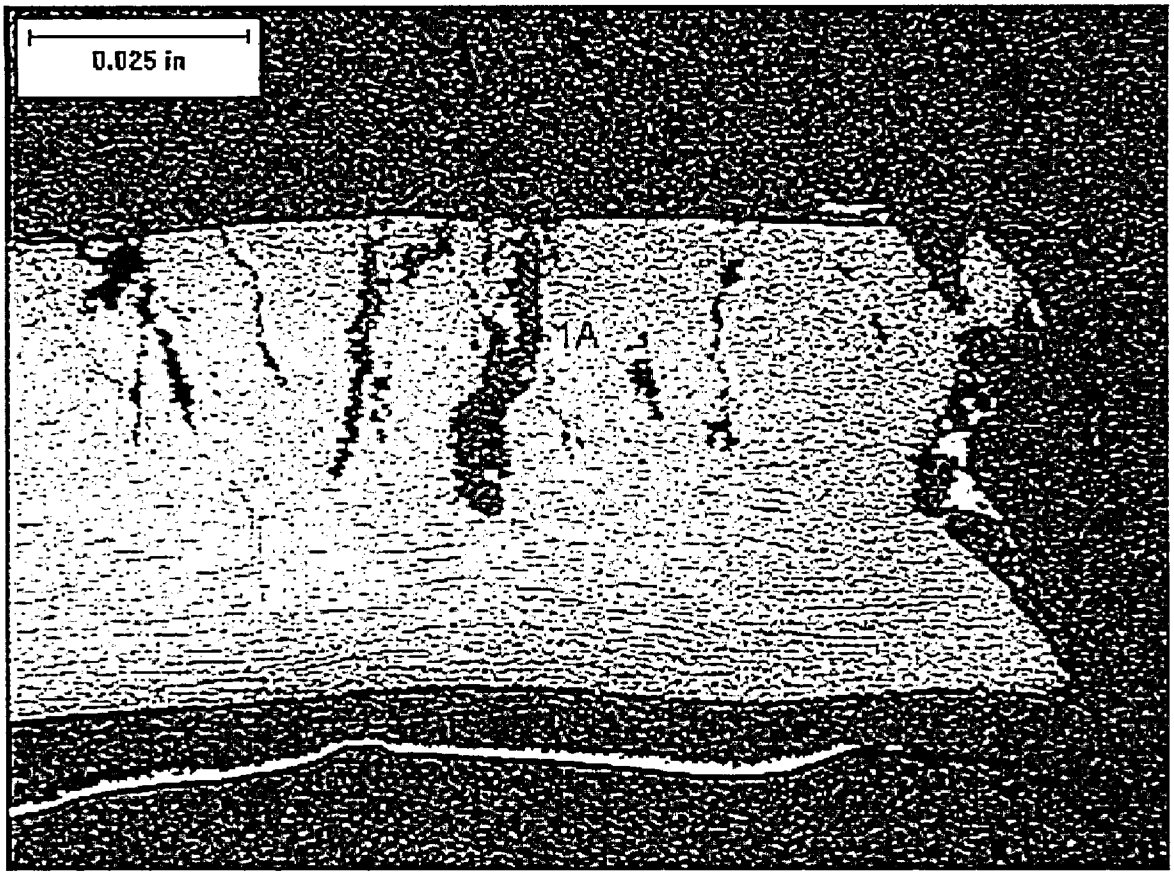


Figure 6-7. Deepest Crack at TSP3, Position 1 in Figure 6-6 (Nital Etch).

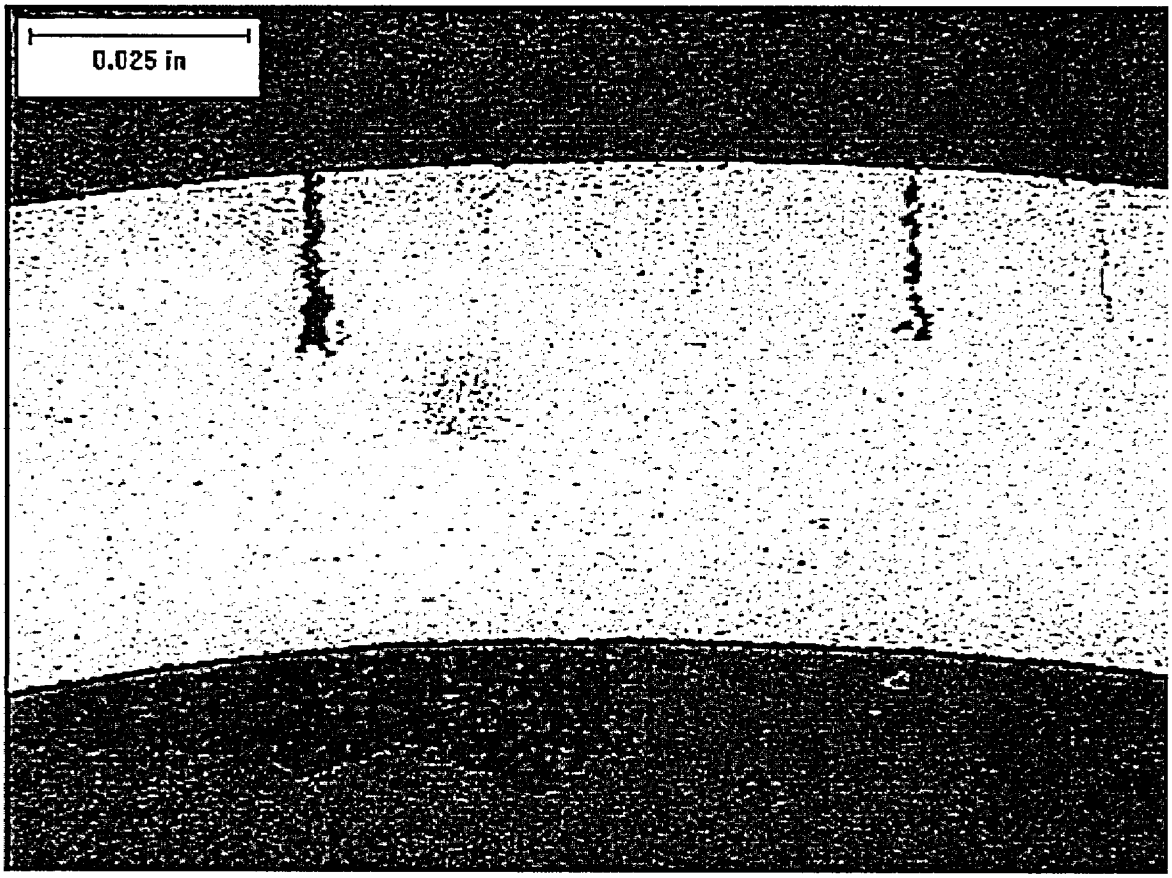


Figure 6-8. Scratch Crack, Position 6 in Figure 6-6 (Nital Etch).

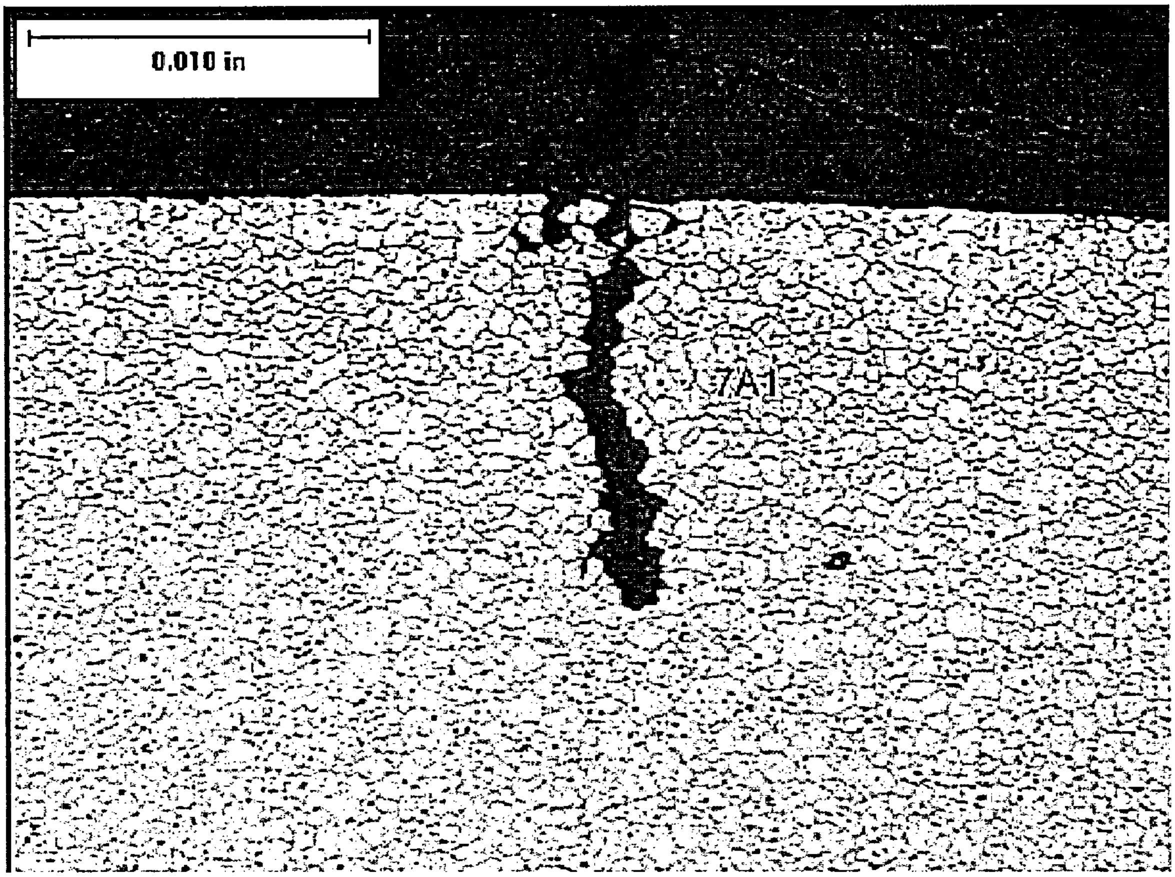


Figure 6-9. Scratch Crack, Position 7 in Figure 6-6 (Nital Etch).

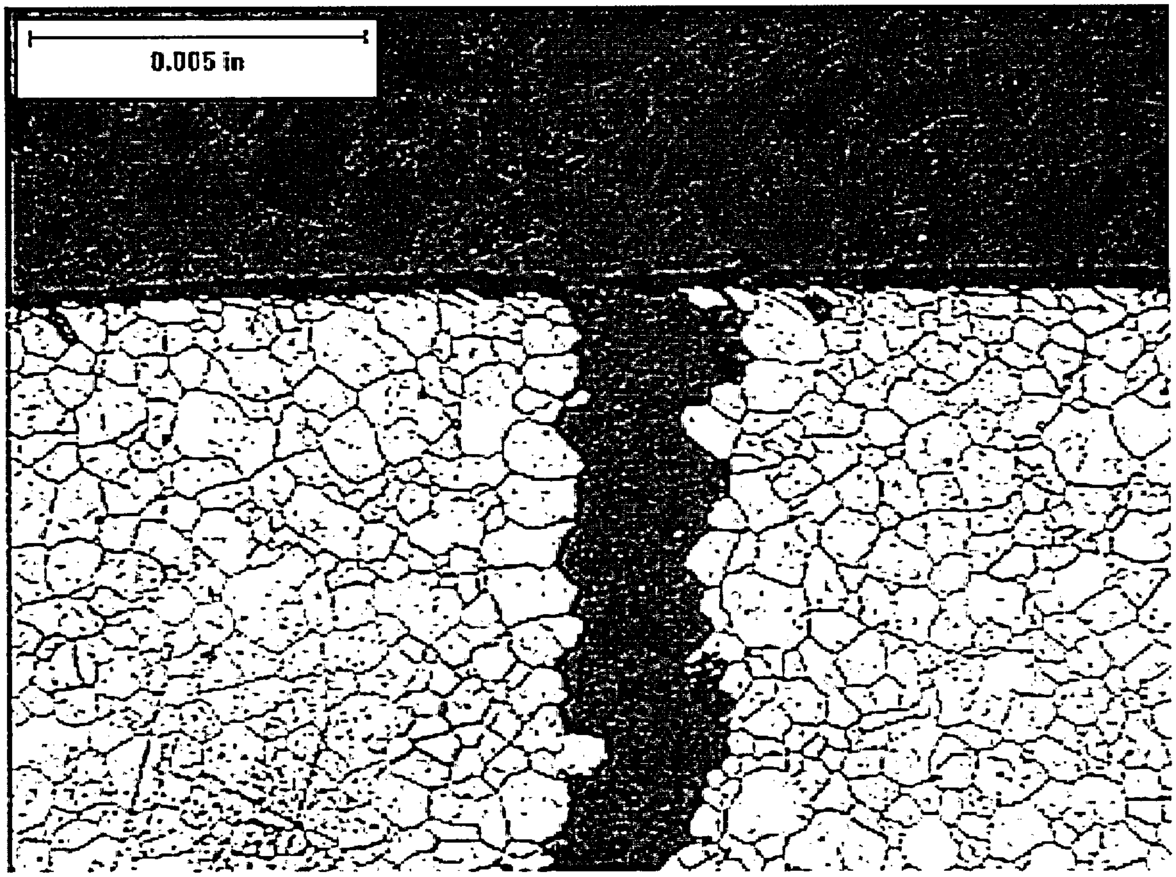


Figure 6-10. Close-Up of Position 6 Scratch Crack (Nital Etch).

# Section 7.0

## TENSILE TESTS

The mechanical properties (i.e., yield strength, ultimate strength, percent elongation) of R12C45 were determined through two room temperature tensile tests of full cross section tubular specimens. The full cross section tubular specimens were fitted with snug fitting stainless steel plugs (mandrels) machined in accordance with ASTM Standard Method E8. A crosshead speed of 0.1 inch/minute was used.

Both tensile test specimens were from freespan regions. The specific pieces tested were 3C1 and 5A2.

Table 7-1 provides the results of the room temperature tensile tests. Figures 7-1 and 7-2 present the stress-strain curves obtained from the tensile tests. The results in Table 7-1 show that the results for the two tensile tests are nearly the same. As was mentioned previously, the pull forces needed to remove the tube from the generator were quite low and well below the yield strength of the material, thus the tube pulling operation did not influence the tensile test results. These results show a relatively high strength material, but a 58 ksi yield strength is typical for this vintage tubing.

TABLE 7-1

TENSILE PROPERTIES

| | Gage Length | Area | Sy, Tensile Yield Strength 0.2% Offset | Su, Ultimate Tensile Strength | Sy+Su |
|---|---|---|---|---|---|
| Sample | in | $in^2$ | ksi | ksi | ksi |
| 3C1 | 6.2 | 0.134451 | 58.6 | 110.8 | 169.4 |
| 5A2 | 5.575 | 0.13526 | 58.4 | 109.5 | 167.9 |
| Average | | | 58.5 | 110.2 | 168.7 |

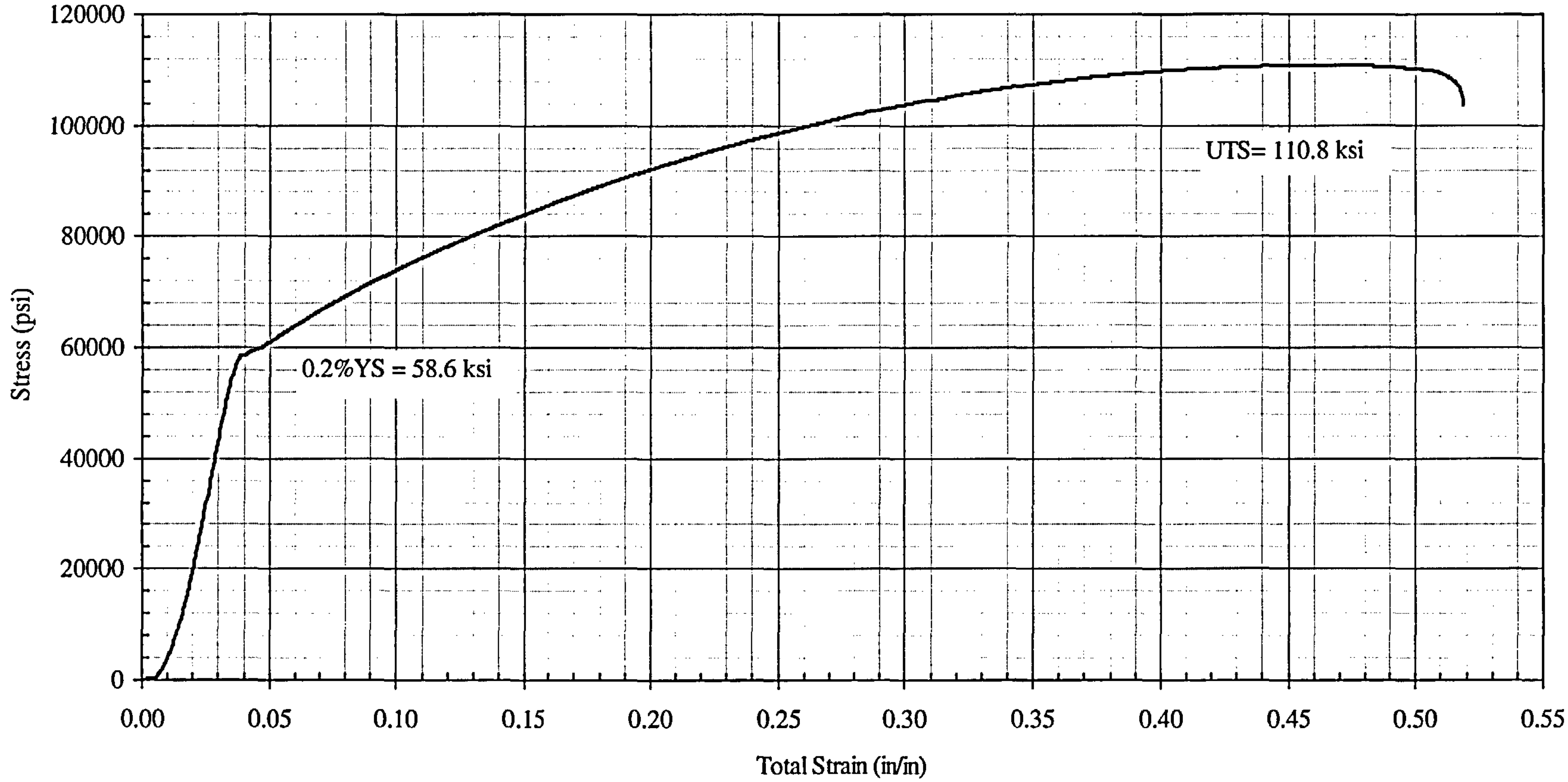


Figure 7-1. Stress-Strain Curve for Specimen 3C1.

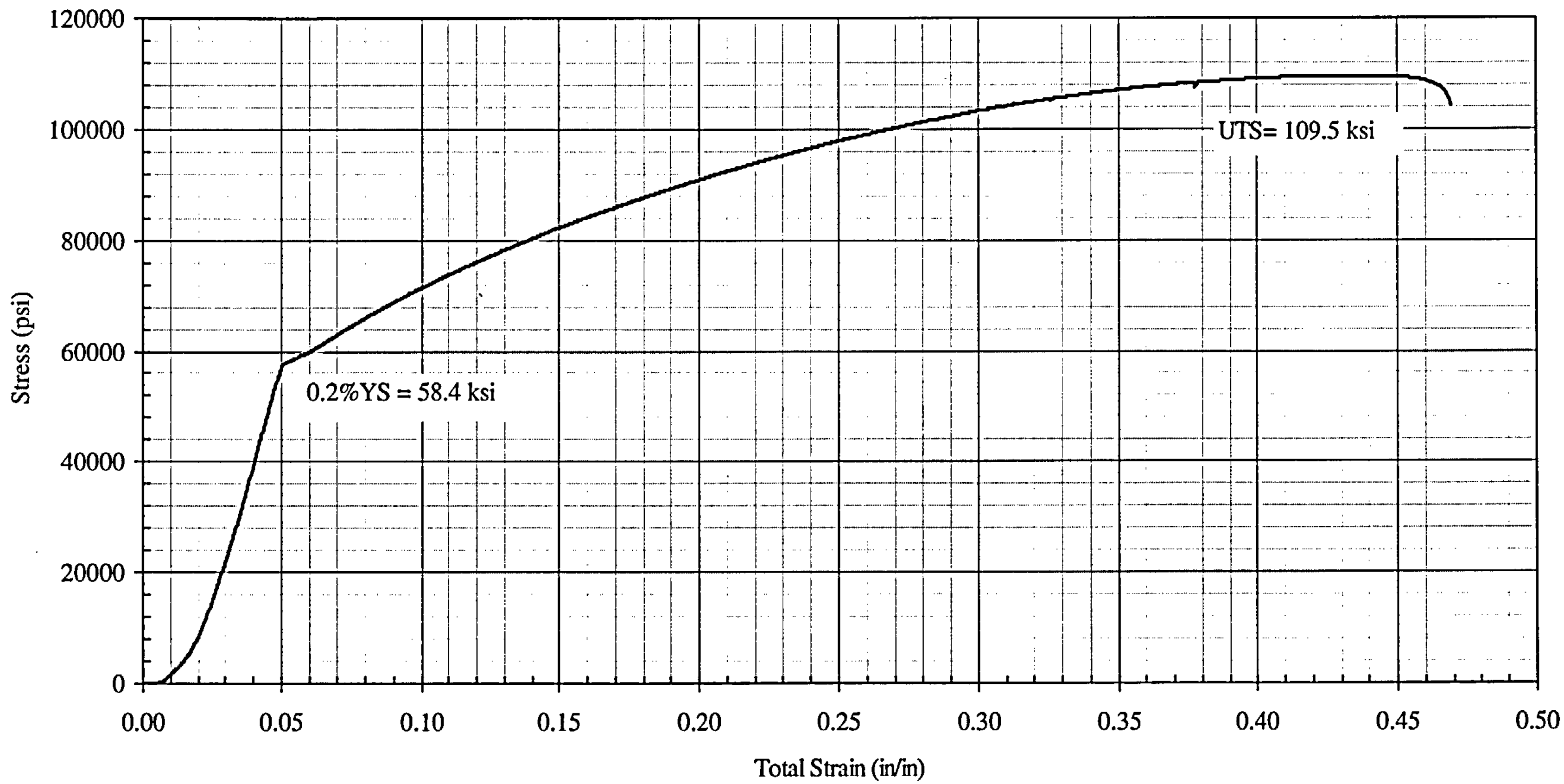


Figure 7-2. Stress-Strain Curve for Specimen 5A2.

## Section 8.0

## DISCUSSION / CONCLUSIONS

The non-destructive and destructive examinations of Sequoyah-2 steam generator tube R12C45 confirmed the presence of OD initiated degradation within the support plate crevices and at the top of the tubesheet.

The corrosion was limited to the support plate crevices and the crevice formed at the TTS by the tubesheet and sludge on the tubesheet. All three support plate regions had axial intergranular ODSCC. The TSP1 region also had cellular corrosion without any evidence of IGA. The TSP2 and TSP3 regions had relatively shallow IGA in addition to the ODSCC.

The maximum depth of corrosion in TSP1 was 100%TW. The maximum depth of corrosion in TSP2 was 71%TW. The maximum depth of corrosion in TSP3 was 69%TW.

The Sequoyah-2 tube was found to have typical tensile and ultimate strengths. This tube had the typical high strength of most early Westinghouse supplied steam generators (usually 58 ksi or greater yield strength is considered high strength).

### Tube Integrity

The TTS region, the freespan tubing and the TSP regions all had burst pressures well in excess of the most limiting Reference 6 requirements of three times the normal operating pressure differential.

Leakage was measured from the TSP1 region only. A leak rate of 0.17 gpm was established for SLB conditions. After leak testing had been completed, TSP1 was tested with bobbin, plus-point and pancake coils. The bobbin voltage increased significantly as a result of leak testing. This is after the bobbin voltage increased from the forces needed to pull the tube out of the generator. The leak rate that was measured in the laboratory is not representative of the leak rate that would have occurred at SLB conditions in the generator; the leak rate is considerably higher as a result of ligaments that were weakened or broken during the tube pull. The TSP1 crack was not truly

axial, but was slanted slightly out of axial towards the circumferential direction. It is likely that the tube pull forces would have damaged some of the ligaments that were present in this crack.

The testing performed on tube R12C45, and the results of the tests, satisfy the Alternative Repair Criteria of Reference 1.

## Section 9.0

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1. "Voltage-Based Repair Criteria for Westinghouse Steam Generator Tubes Affected by Outside Diameter Stress Corrosion Cracking," United States Regulatory Commission Generic Letter 95-05, August 3, 1995.

2. Westinghouse Electric Quality Management System, Revision 5, October 1, 2002.

3. TVA Contract Work Authorization No. N2002-007, Revision 01, June 14, 2002.

4. "Sequoyah Tube Pull," E-Mail from G.T. Estes to T.P. Magee et al., May 3, 2002.

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6. U.S. Nuclear Regulatory Commission Regulatory Guide 1.121, "Basis for Plugging Degraded PWR Steam Generator Tubes", August 1976.

7. "RE: Requests concerning CWA N2002-007 - U2 SG Tube Exam," E-Mail correspondence from E.D. Camp to M.H. Cothron et al., May 21, 2002.

8. "Steam Generator In Situ Pressure Test Guidelines," Revision 1, EPRI Document TR-107620-R1, June 1999.

9. "Steam Generator Tube Integrity, Volume 1: Burst Test Validation of Rupture Criteria (Framatome Data)," EPRI EP-NP-6865-L, Volume 1, June 1991.

10. TVA-02-90, Correspondence from E.A. Dzenis to D.L. Lundy, May 20, 2002.

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