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Westinghouse Energy Systems

WESTINGHOUSE CLASS 3

WCAP-13139

FARLEY UNITS 1 AND 2

STEAM GENERATOR TUBE/ TUBE SUPPORT PLATE ELEVATION ALTERNATE PLUGGING CRITERION SUMMARY

DECEMBER 1991

WESTINGHOUSE ELECTRIC CORPORATION
Nuclear and Advanced Technology Division
P.O. Box 355
Pittsburgh, Pennsylvania 15230

A meeting was held on November 20, 1991 between Southern Nuclear Corporation, Westinghouse, and the NRR staff at the Bank of Maryland Building, Bethesda, Md., to resolve a series of NRR questions related to the implementation of a steam generator tube plugging criterion for tube support plate elevation outer diameter intiated stress corrosion cracking at Farley Units 1 and 2.

The meeting agenda included discussions on:

1. Summary of the Bobbin Probe Signal Amplitude Steam Generator Tube Plugging Criterion.

2. Steam Generator Tube Structural Integrity upon Implementation of the Plugging Criterion.

3. Steam Line Break Primary to Secondary Leakage Considerations.

4. Farley Units 1 and 2 Steam Generator Eddy Current Inspection Results.

5. Pulled Tube Examinations.

All aspects of the proposed criterion with the exception of radiological consequences and systems review were presented to the NRR staff at this meeting.

Farley APC for ODSCC at TSPs
NRC Meeting, November 20, 1991
Discussion Topics

Agenda

Presentation Format

- Approximately Organized by Sections of WCAP-12871, Rev. 1
- Summary of WCAP Section Results
- Summary of NRC Question Responses

Topic	Presenter	Approximate Time
Sections 6, 12, 1, 2	Pitterle	90 minutes
Sections 4, 7, 9.1 to 9.5, 9.8, 10	Begley	60 minutes
Sections 5, 8, App. A	Malinowski	90 minutes
Sections 9.6, 9.7, 11, 12.5	Houtman	60 minutes
Section 11.3	Whiteman	15 minutes

ACRSAPC:11/91

Alternate Plugging Criteria for ODSCC at TSPs

Objectives

Obtain Tube Plugging Criteria that Relate NDE Measurement to Tube Integrity (Burst, Leakage) Criteria of R.G. 1.121

Continue to maintain safety margins and minimal potential for significant operating leakage

Eliminate Need to Assess NDE Measurements Near Threshold of Detectability (40% Depth)

- o Enhanced probes and EC analysis skills have moved detection to limits of detectability
- o Plugging criteria initiated following undetected indication of short crack with 62% maximum depth at Farley-1
- o Need further demonstrated by extended outage at Trojan where tube pulls have demonstrated tube integrity for indications marginally detectable

Extend Operating Period of S/Gs with Limited Tube Plugging and/or Sleeving

General Approach to Plugging Criteria for ODSCC at TSPs

Specifying conservative burst correlations based on free (uncovered) span ODSCC under accident conditions to demonstrate structural integrity.

Conservatively assuming open crevice conditions to maximize leakage potential.

Satisfying the R.G. 1.121 structural guidelines for tube burst margins by establishing a conservative structural limit on voltage amplitude that provides times normal operating pressure differential for tube for times normal operating pressure differential for tube burst capability.

General Approach to Plugging Criteria for ODSCC at TSPs (Cont'd.)

Satisfying the FSAR requirements for allowable leakage under accident conditions by demonstrating that the dose rate associated with potential leakage from tubes remaining in service is a small fraction of 10 CFR 100 limits.

Including considerations for crack growth and NDE uncertainties in both the structural assessment and leakage analysis.

Specifying a requirement to perform 100% BC inspection for all hot leg TSP intersections and all cold leg intersections down to the lowest cold leg TSP where ODSCC indications have been identified.

Table 6.3

Field Experience: Suspected Tube Leakage for ODSCC AT TSPs(1)

Plant	Inspection	Bobbin Coil		Comments
		Volts	Depth	

[ ] g

Notes:

1 Field experience noted is for nominal 0.750" OD tubing with 0.043" wall thickness. No data are known to be available for tubes with 0.875" OD.

2 Reported voltages were adjusted (values given in parentheses) to the normalization in this report of 2.75 volts for 20% ASME flaw and 400/100 kHz mix. The adjustment factor was developed based on voltage ratios measured between a metric calibration standard as used to obtain the original data and the reference ASME standard of this report. This adjustment provides an order of magnitude conversion to make these data roughly comparable to other data in this report. However, any conversion factor is disputable because it depends on the procedural/environmental conditions and thus may vary from case to case.

Potential for TSP Displacement and Tube Burst at SLB Accidents

Potential for TSP Displacement

- SLB Analysis for Model 51 S/G
  - TSP displaced relative to normal operating positions under assumptions of open crevices and zero friction including wedges at TSP to wrapper interface

- TSP displacement prevented by tube denting, TSP corrosion leading to incipient denting or small [ ]b,c tube to TSP gaps
  - Evaluations completed for Farley-1 and [ ]g indicate no TSP displacement which precludes tube burst
  - Expected that analyses could be performed for Farley-2 and other Model 51 S/Gs

Potential for TSP Displacement and Tube Burst at SLB Accidents (Cont'd.)

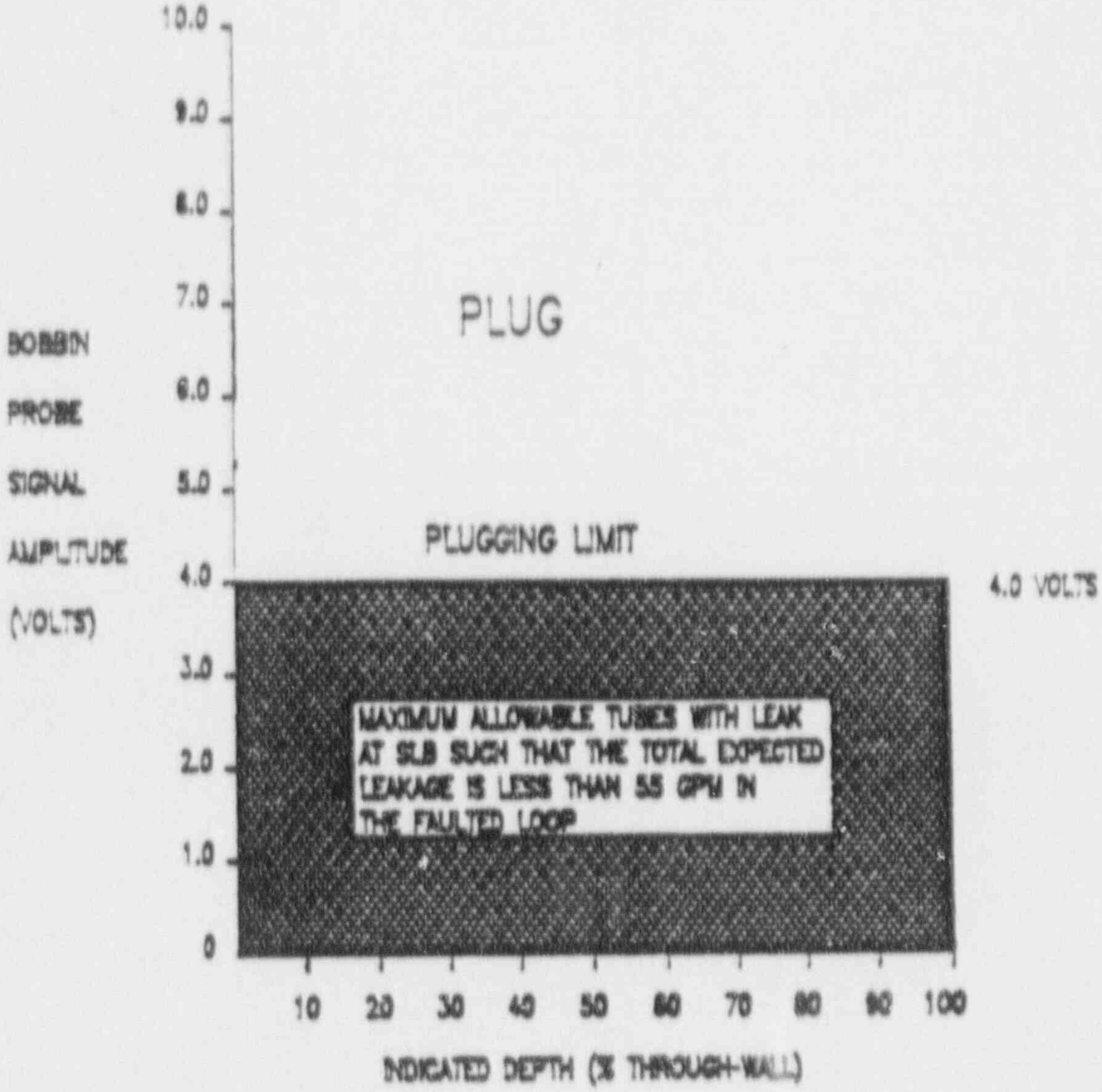
Throughwall Crack Length for Burst at SLB Greater than TSP Thickness

- Tube burst for 2650 psi SLB condition at [ ] b,c
- TSP Thickness = 0.75"
- Tube burst at accident conditions not expected for ODSCC at TSPs

Low Probability (~10^{-6}/cycle) of Crack Growth from 4.0 volt Plugging Limit to Voltage for Burst at SLB conditions

- Conservative Farley S/G growth rates
- Voltage/burst correlation applied for plugging limits

TUBE SUPPORT PLATE ELEVATION
SG TUBE ALTERNATE PLUGGING CRITERION*



* APPLICATION OF ALTERNATE PLUGGING CRITERION LIMITED TO WITHIN THICKNESS OF TUBE SUPPORT PLATES

SGPLIM1

Farley S/G Plugging Criteria for ODSCC at TSPs

Tube Plugging Criterion

- o Tubes with bobbin coil indications exceeding 4.0 volts will be plugged or repaired

SLB Leakage Criterion

- o Predicted SLB leak rates from tubes left in service must be less than 55 gpm for each S/G, including considerations for NDE uncertainties and ODSCC growth rates

Inspection Requirements

- o A 100% bobbin coil inspection shall be performed for all hot leg TSP intersections and all cold leg intersections down to the lowest cold leg TSP with ODSCC indications

- o All tubes with bobbin coil indications >1.5 volts at TSP intersections shall be inspected using RPC probes. The RPC results shall be evaluated to support ODSCC as the dominant degradation mechanism

Farley S/G Plugging Criteria for ODSCC at TSPs (Cont'd.)

Operating Leakage Limits

- Plant shutdown will be implemented if normal operating leakage exceeds 150 gpd per S/G

Exclusions from Tube Plugging Criterion

- Tubes with RPC indications not attributable to ODSCC and circumferential indications shall be evaluated for tube plugging based on a 40% depth limit.

Operating Leakage for ODSCC at TSPs

No operating leakage occurrences in Domestic S/Gs

Three Occurrences Reported in European Units

- o Leak rates not quantifiable for indications at TSPs
  - Leakage at non-TSP locations contributed to leakage
  - Total leak rates of 63-140 gpd

No reported leakage in French Units

- o Operation at higher equivalent indication voltages than proposed for Farley

...ACRSAPC:10/91

Tube Plugging Limits to Satisfy Structural Requirements

Item	Volts	Basis
Maximum Voltage Limit to Satisfy Tube Burst Structural Requirement	[	Burst Pressure vs. Voltage Correlation at -95% confidence level.
Allowance for NDE Uncertainty		10% uncertainty increased to 15% pending field experience with probe wear procedure and conservatively increased to 20% to establish plugging limits.
Allowance for Crack Growth Between Inspections	]	Overall average growth/cycle of 37% and 29% for Units 1 and 2. Allowance increased to 50% of Tube Plugging Limit to provide conservative margin for variations in future cycles.
Tube Plugging Voltage Limit	4.0	

Responses to General Concerns

Burst and Leak Test Data Base (Pages 1-2)

Burst: 41 Points (27 MB, 14 Field)

- Was 13 MB, 4 Field

Leak Rate: 28 Points (24 MB, 4 Field)

- Was 6 MB, 4 Field

Pulled Tubes < 10v

Model Boiler Specimens

- Crack morphologies similar to pulled tubes
- Emphasized > 8 v to define structural limits and leak rates

Extended data base permits use of uncertainty bounds for voltage/burst correlations

- Lower 95% uncertainty band used to define plugging limits
- Eliminates need for "added margins" in defining plugging limits as applied in Rev. 0

Pulled Tube Data Base for APC

31 Pulled Tubes, 58 Intersections to Characterize Voltage Response and Crack Morphology

- ODSCC with Minor or No IGA -37 Intersections
  - 5 from Farley S/Gs of 14 Intersections examined
  - 6 from [ ] [g]
- IGA/SCC or IGA -19 Intersections
  - 3 from [ ] [g]
  - 13 from French Units
  - 2 from non-Westinghouse Units

14 Tube Intersections of 7/8" Diameter with Burst Pressure Tests

- 3 from Farley
- 7 from [ ] [g]

Supplemental Data for APC obtained from laboratory specimens obtained in model boilers under protypic conditions

Table 6.2

Pulled Tube Leak Rate and Burst Pressure Measurements

			Bobbin Coil		Destructive Exam		Leak Rate(l/hr)		Burst
Plant	Row/Col.	TSP	Volts.	Depth	Max Depth	Length(1) (in.)	Normal Oper.	SLB	Pressure (psi)

[ ]g

Notes:

1. Crack network length for burst crack with through wall crack length given in parentheses.
2. Negligible leak rate evaluated as no leakage for this report.
3. Measurements were not made and values are estimated based upon crack morphology obtained from destructive examination.
4. Leakage not detected as pressure increased to indicated burst pressure.
5. Depth not determinable from phase angle.
6. Field measurement using 550/100 kHz mix for 0.75 inch diameter tubing.

VOLTAGE AMPLITUDES FOR PULLED TUBES

AMPLITUDE CORRELATED WITH BURST PRESSURE FOR APC

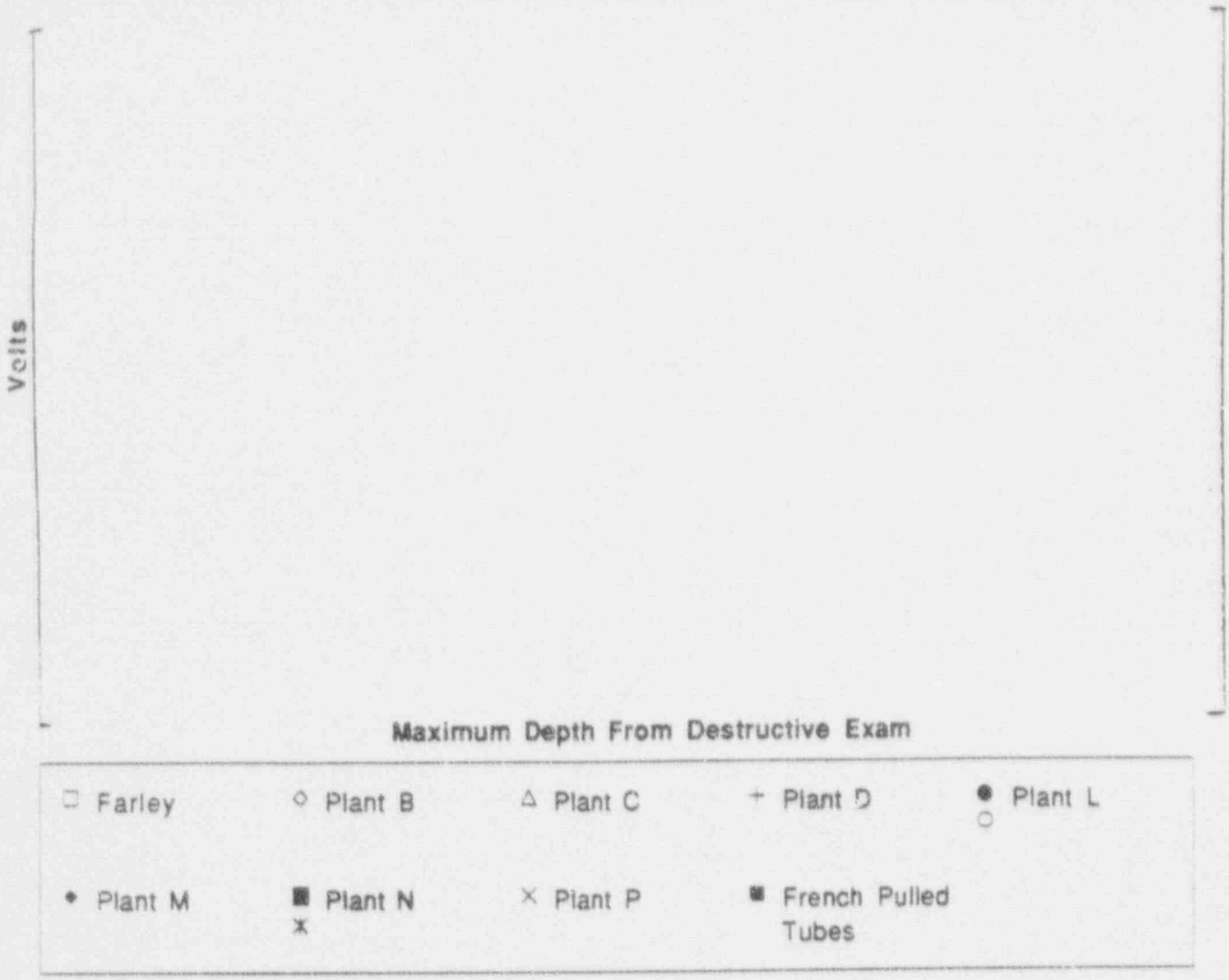
AMPLITUDES FOR IGA/SCC TEND TO BE AS HIGH OR HIGHER THAN FOR SCC ONLY

- IGA INVOLVEMENT TENDS TO INCREASE AMPLITUDE
- IGA/SCC TENDS TO OCCUR WITH MULTIPLE CRACKS OF COMPARABLE DEPTHS WHICH INCREASE AMPLITUDE

EARLY ODSCC DEVELOPMENT OCCURS AS SHORT (0.1-0.2") MICROCRACKS WHICH CAN BE NEAR DETECTION THRESHOLD

- A FEW OCCURRENCES OF INDICATIONS TO 60-70% MICROCRACK DEPTHS NOT DETECTED IN FIELD INSPECTIONS

Pulled Tube Destructive Exam Data Including French Data



Note: Solid symbols represent tubes with IGA/SCC indications.
All other symbols represent tubes with SCC indications only.

Responses to General Concerns
IGA and Circ. ODSCC at TSPs (Page 3)

Circumferential ODSCC Not Found and Not Expected in Farley S/Gs

- Circ. ODSCC associated with significant denting at TSPs
  - Historically, axial PWSCC has been a predecessor to circumferential cracking
- Negligible denting in Farley S/Gs

Significant IGA Not Found in Farley S/Gs

- 8 Tubes, 14 TSP Intersections Over 1986-1990
- Minor IGA involvement found at crack faces
  - Slightly greater (~ 15 mils wide) in previously plugged tube (R21C22) than active tube (6 mils wide in R4C73)

IGA Occurrence at TSPs Dominantly IGA/SCC

- SCC Expected in tubes stressed by operating pressure differentials based on laboratory experience
- Slower growth for IGA than SCC

Available Data Supports Detectability of IGA/SCC

- Voltage Responses as High or Higher than for SCC only

Types of Degradation at TSPs
Crack Indications

ODSCC

- o Initiates as multiple microcracks of ~0.1" to 0.2" length
  - Examples are [ ]^{g} R29C70, R30C64, Farley-2 R38C46 and Farley-1 R20C26
  - Can be near threshold of detectability with a locally deep microcrack of up to 70% depth
  - Typically lower voltages and high burst strength
- o Growth occurs as additional microcracks and corrosion of ligaments between microcracks with increasing depth
  - Examples are Farley-2 R4C73, R21C22
  - Typically no operating leakage and high burst pressures
- o Minor IGA at crack faces seen in some tubes

Responses to NRC Questions
ODSCC Outside TSP Boundaries (p. 4)

No ODSCC Outside TSPs Known to Have Been Detected by NDE

- Mechanism of multiple initiation sites and growth linking initiation sites requires crevice or sludge pile conditions with concentration of chemical contaminants

Identified Cracks Extending Outside TSP are Result of PWSCC in Significantly Dented Tubes

- Conditions not applicable to Farley S/Gs

Farley Pulled Tube R20C26

- Band of microcracks (< 0.1" long) up to 0.27" above TSP
- Depths up to 10%
- Only pulled tube of 58 intersections with ODSCC reported outside TSP

Inspection for Cracks Outside TSPs

- 100% bobbin inspection for detection outside TSP
- Where RPC applied, also assessed for cracks outside TSP
- Indications outside TSP plugged to 40% Tech Spec Limit

Types of Degradation at TSPs
Crack Indications (Cont'd.)

IGA/SCC

- o Typically IGA fingers and SCC with some volumetric IGA patches of varying azimuthal extent

- o Commonly many cracks azimuthally around tube

- o Examples are [ ][9] R12C8 (previously plugged) and French data

- o Limited data on burst (R12C8, TSP #3) but local IGA not expected to strongly influence burst capability

Types of Degradation of TSPs
Volumetric Indications

Corrosion

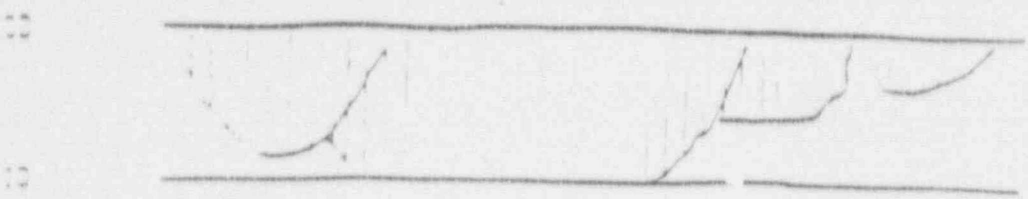
- o Pitting
  - Not found to date at TSPs
- o Cold Leg Thinning
  - Identified at some lower cold leg TSPs, in Model 51 S/Gs
  - Easily detectable (high voltages, RPC characterization) and limited in extent
- o Wastage
  - Insignificant wi.h AVT chemistry

Wear

- o Not found in feedring S/Gs at TSPs

Volumetric Indications Characterized by High Voltages

- o Readily characterized by RPC inspection
- o Indications less than about 2 volts are not a concern for tube integrity
  - RPC characterization required by APC for indications above 1.5 volts



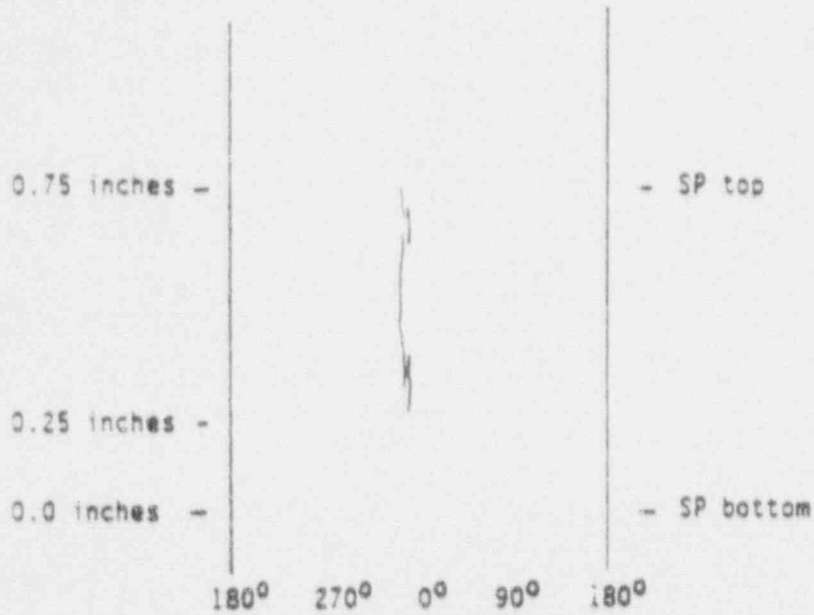
Sketch of Burst Crack

Macrocrack Length = 0.50 inches

Throughwall Length = 0.15 inches

Number of Microcracks = 4 (two ligaments with intergranular features, one with ductile overload features)

Morphology = Intergranular SCC with significant IGA characteristics (width of IGA 0.030 inches)



Sketch of Crack Distribution

Description of OD origin corrosion at the first support plate crevice region of tube R21-C22.

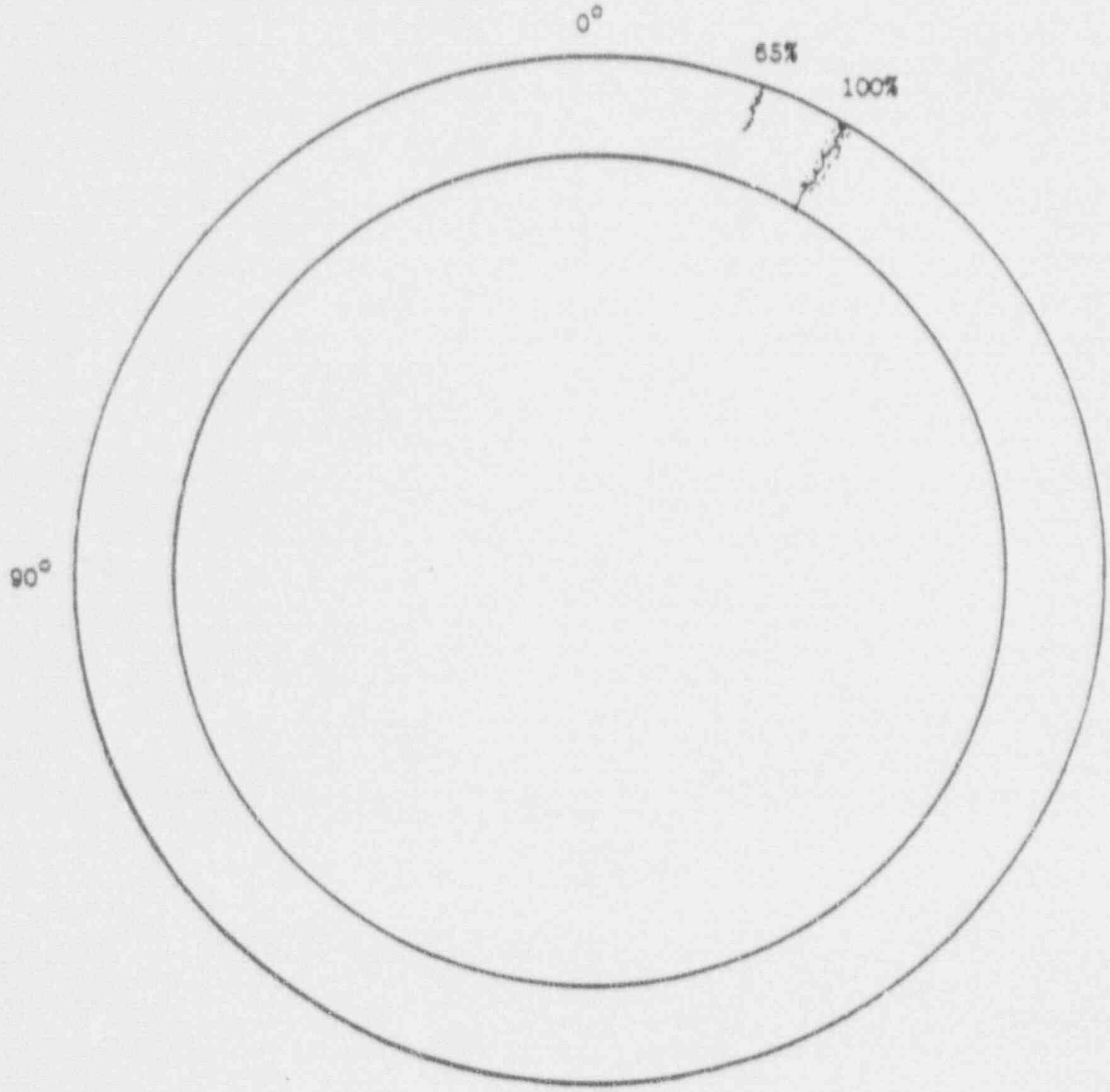
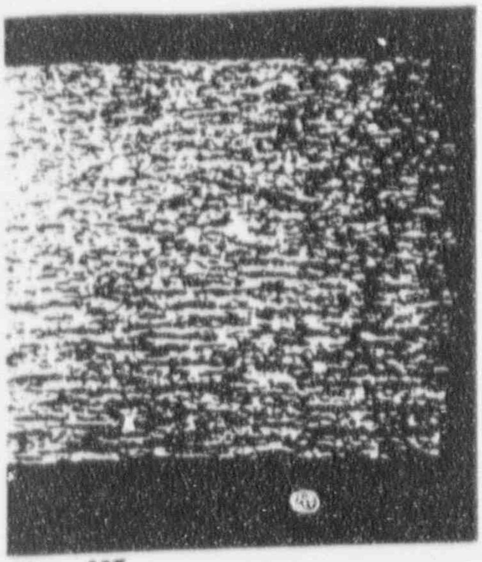
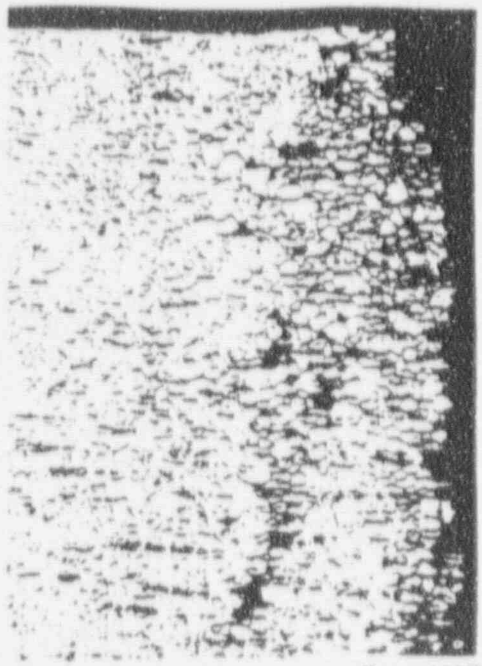


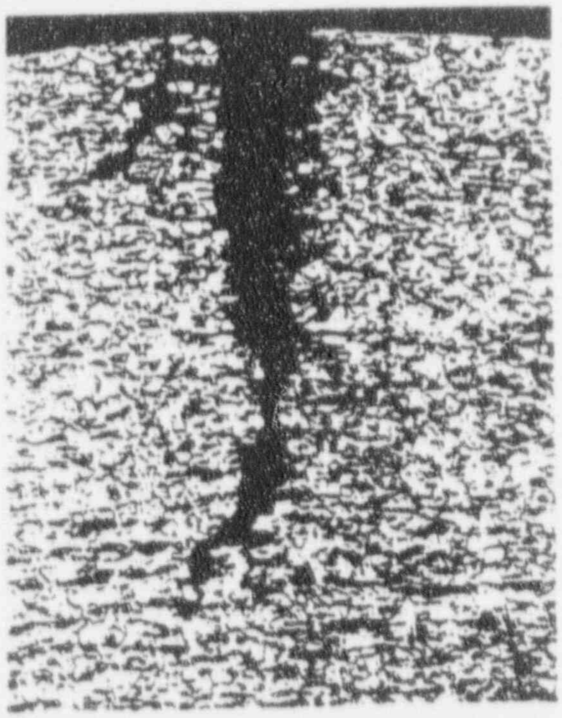
Figure 4-9. Sketch of crack distribution and depth within the first support plate crevice region in tube R21-C22.



Mag. 50X

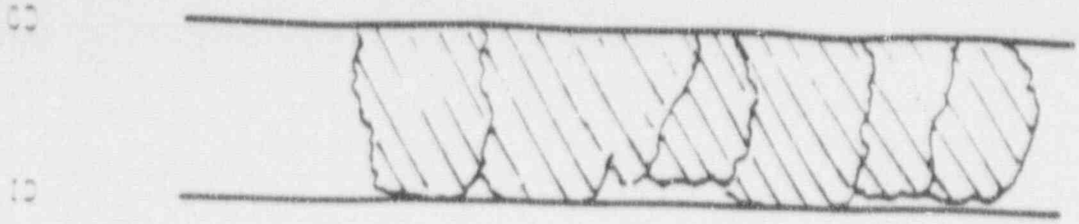


Mag. 100X



Mag. 100X

Top micrographs are from a transverse section through one half of the main burst crack. The morphology is that of IGSCC with significant IGA characteristics (width of IGA is 0.015 inch on one side of the crack). Bottom micrograph is from a transverse section through the only other crack found in the crevice region. Its morphology is more that of IGSCC. (Note: crack has been opened wide by tube deformation).



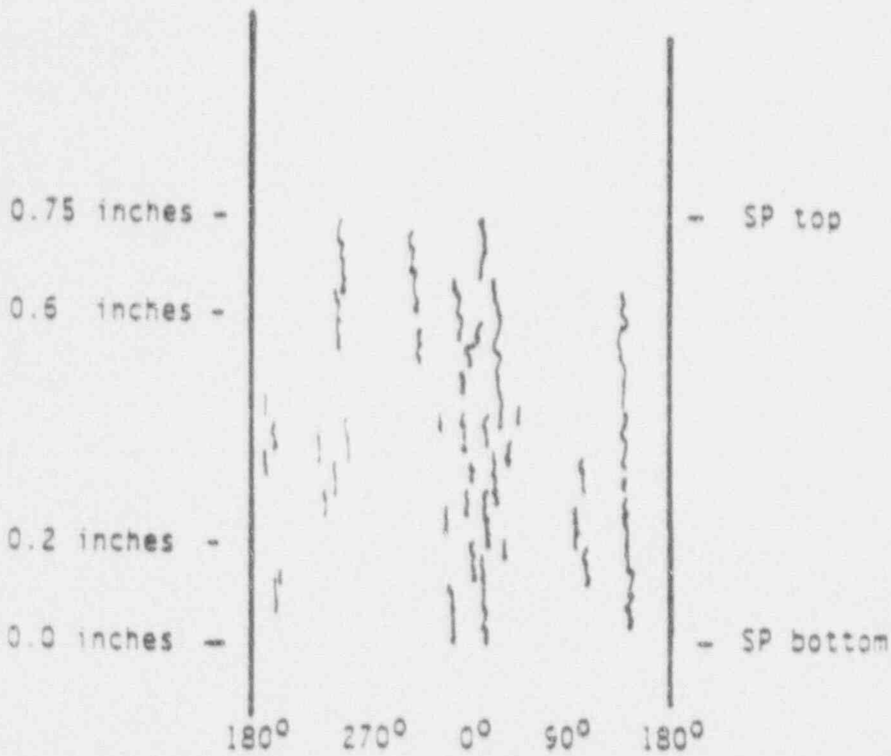
Sketch of Burst Crack

Macrocrack Length = 0.75 inch

Throughwall Length = 0.58 inch (combined through wall length)

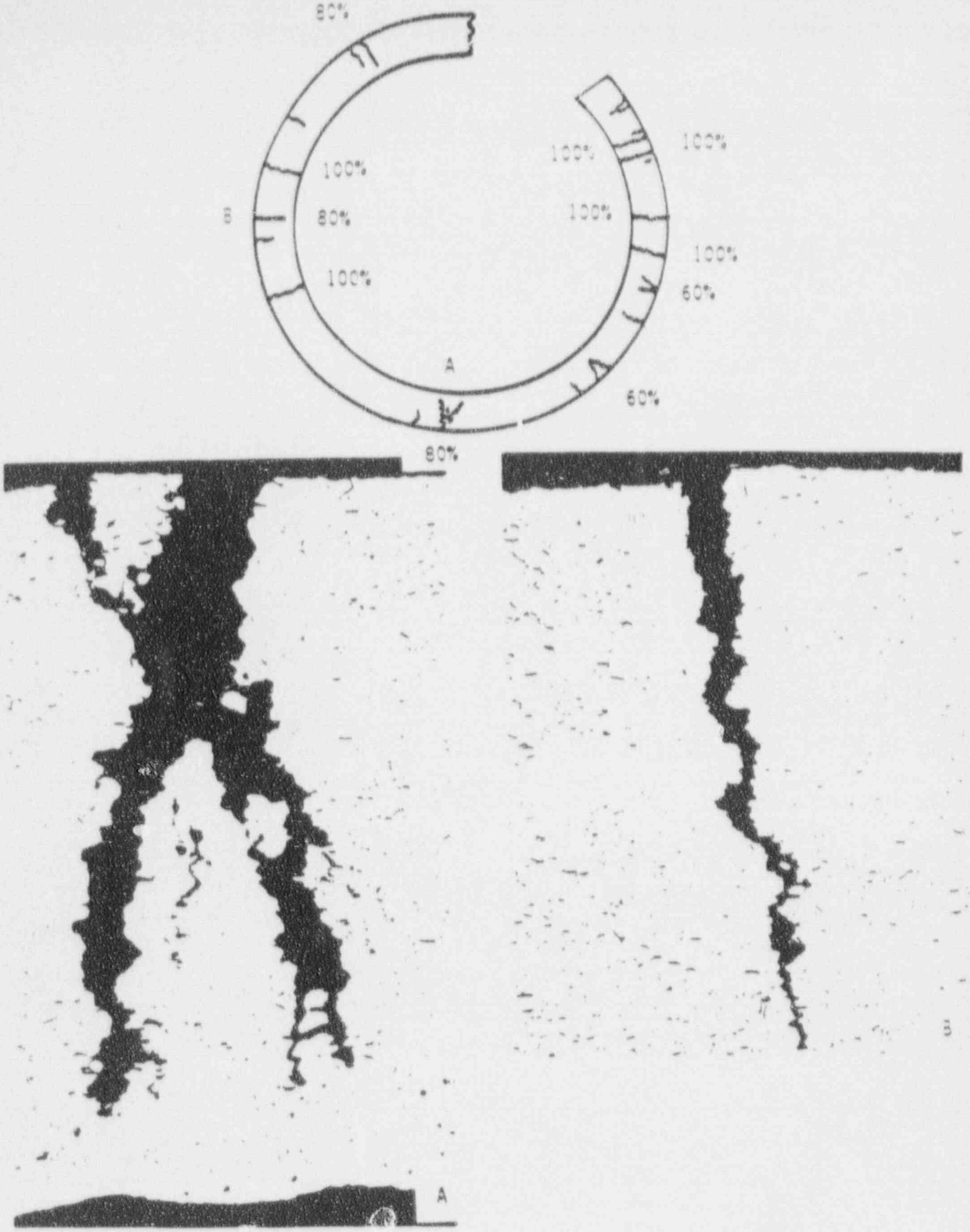
Number of Microcracks = at least 6 (ligaments have mostly intergranular features)

Morphology = IGSCC



Sketch of Crack Distribution

Summary of the burst crack and overall crack distribution in the crevice region of tube 532-2.



Crack distribution as revealed by a metallographic cross section through the center of the crevice of tube 532-2 and photomicrographs of secondary cracks A and B. Mag. 100X

RESPONSES TO NRC QUESTIONS
CRACK GROWTH ALLOWANCE (P. 3)

VOLTAGE GROWTH METHOD MODIFIED FOR REVISION 1

- % GROWTH NOW APPLIED - PREVIOUSLY ABSOLUTE VOLTAGE CHANGE
- CHANGE BASED ON EVALUATING FRENCH DATA AT HIGHER AMPLITUDES THAN DOMESTIC DATA
- CONSERVATIVE ALLOWANCE OF 50% VOLTAGE GROWTH PER CYCLE

AVERAGE GROWTH RATES APPLIED TO MEET $3\triangle P_{N.O.}$ BURST LIMIT

- AVERAGE GROWTH RATES LEAD TO LARGE MARGINS AGAINST BURST AT SLB CONDITIONS
- ESTIMATED PROBABILITY OF BURST AT SLB $< 10^{-6}$

FACTORS CONTRIBUTING TO ODSCC AND CRACK GROWTH

- DOMINANTLY INFLUENCED BY CREVICE CHEMISTRY CONDITIONS
- LOCAL, OPERATING AND RESIDUAL STRESSES OF SECONDARY IMPORTANCE TO CREVICE ENVIRONMENT
  - ODSCC OCCURS IN UNDENTED TSP CREVICES AND SLUDGE PILES
- FARLEY ODSCC INITIATION PRINCIPALLY IN PERIODS OF CHEMICAL IMBALANCE PRIOR TO 1986
  - MODEST GROWTH SINCE 1986
- INCREASES IN TUBE PLUGGING DUE TO ("INSPECTION TRANSIENTS")
  - GREATER KNOWLEDGE ON INTERPRETATION OF BOBBIN SIGNALS
  - CHANGES IN INSPECTION GUIDELINES SUCH AS ELIMINATING 1.75 VOLT CRITERION
  - UTILIZATION OF RPC PROBE

VOLTAGE GROWTH RATES

ALLOWANCE FOR GROWTH INCLUDED IN PLUGGING LIMITS

DEVELOPED FROM FARLEY S/G HISTORICAL INSPECTION RESULTS

CONSERVATIVELY APPLIED % GROWTH INDEPENDENT OF AMPLITUDE

- o ENVELOPES DATA FOUND IN SOME EUROPEAN PLANTS
- o FARLEY DATA SHOWS DECREASING % GROWTH WITH HIGHER INITIAL AMPLITUDE

ALLOWANCE FOR 50% AVERAGE GROWTH IN AMPLITUDE PER CYCLE APPLIED FOR PLUGGING LIMITS

Table 6.4

Comparisons of Voltage Amplitudes Between U.S.-ASME and European Standards

	U. S. - ASME Standard						French 4-hole. 1 mm dia. holes	Belgian 4-hole. 1.25 mm dia. holes	U.S. 4-hole 33 mil dia. holes
Channel	20%	40%	60%	80%	100%	Support Plate	100%	100%	100%
U.S. Calibration Procedure ❑									
400/100 mix	2.75	2.8	5.3	5.6	8.7	<0.6	10.7	18.96	6.4
400 kHz	4.0	3.5	5.5	5.5	7.8	8.2	9.8	17.19	5.4
240 kHz	6.3	5.4	7.9	7.3	9.5	17.4	12.4*	21.15**	7.6
200 kHz	5.9	4.9	7.1	6.3	8.0	17.5	10.9	18.08	-
100 kHz	5.9	2.8	3.6	3.1	3.8	14.5	5.4	8.5	5.2
French Calibration Procedure									
240 kHz	0.66	0.56	0.82	0.76	0.99	1.8	1.3*		
Belgian Calibration Procedure									
240 kHz	0.59	0.51	0.74	0.68	0.90	1.64		2.0**	

❑ U.S. procedure involves setting up the signal for 20% ASME holes at 4 volts for 400 kHz differential channel or 2.75 volts for 400/100 kHz differential mix and then using the "Save/Store" functions of the Zetec DDA-4 software for carrying over the calibration to all other channels.

* When using the U.S. calibration procedures, the French 4-hole standard gives 12.4 volts at 240 kHz and 10.7 volts with the 400/100 kHz mix. It is 1.3 volts for the French calibration. Thus U.S. values at 240 kHz/French values at 240 kHz equals ~9.5. U.S. values at 400/100 mix/French values at 240 kHz equals ~8.2.

** When using the U.S. calibration procedures, the Belgian 4-hole standard gives 21.15 volts at 240 kHz and 18.96 volts with the 400/100 kHz mix. It is 2.0 volts for the Belgian calibration. Thus U.S values at 240 kHz/Belgian values at 240 kHz equals ~10.6. U.S. values at 400/100 kHz mix/Belgian values at 240 kHz equals ~9.5. For general data comparisons, Belgian and French data can be reasonably compared without adjustments or by multiplying the Belgian data by ~0.9 to obtain French volts.

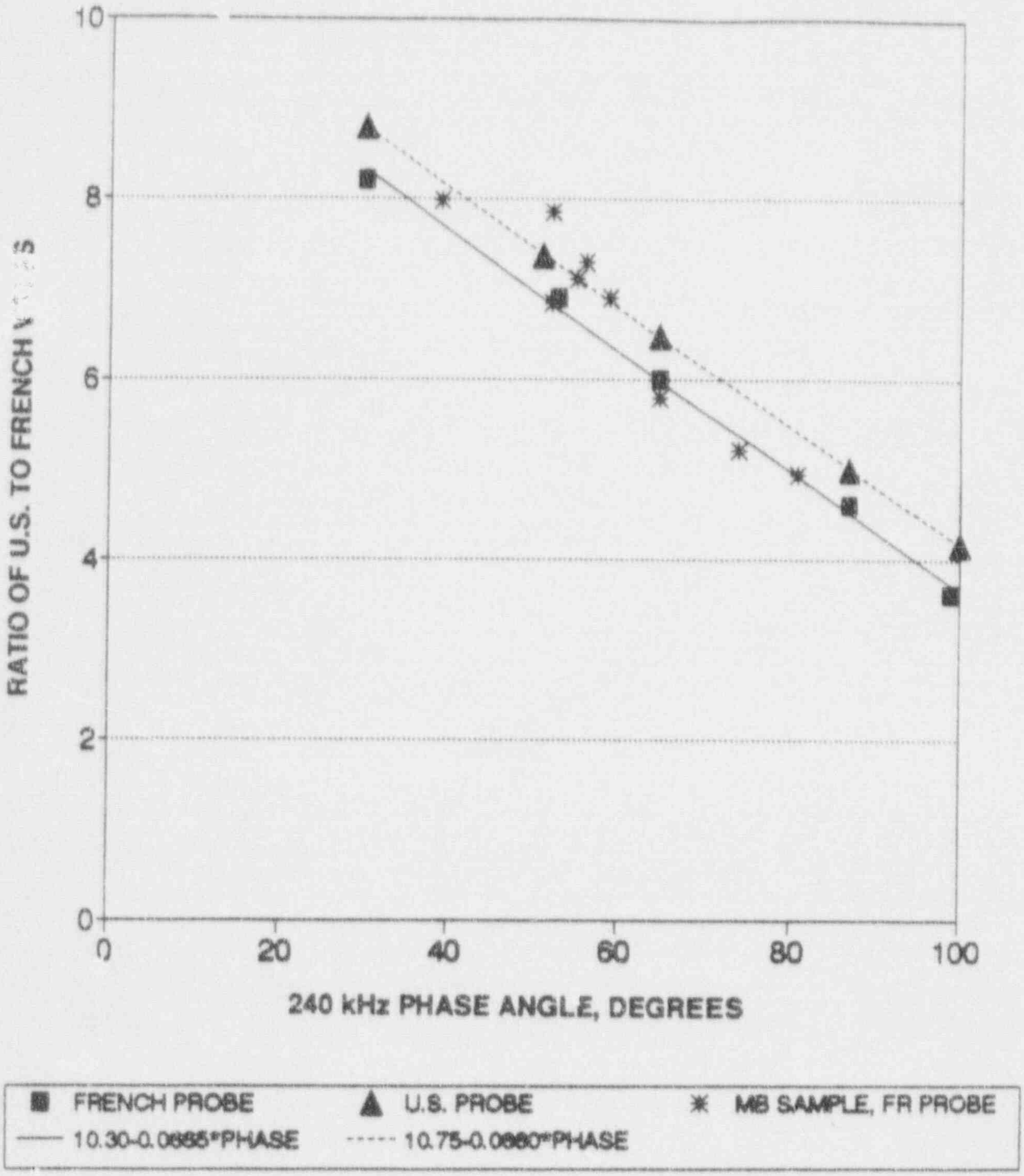
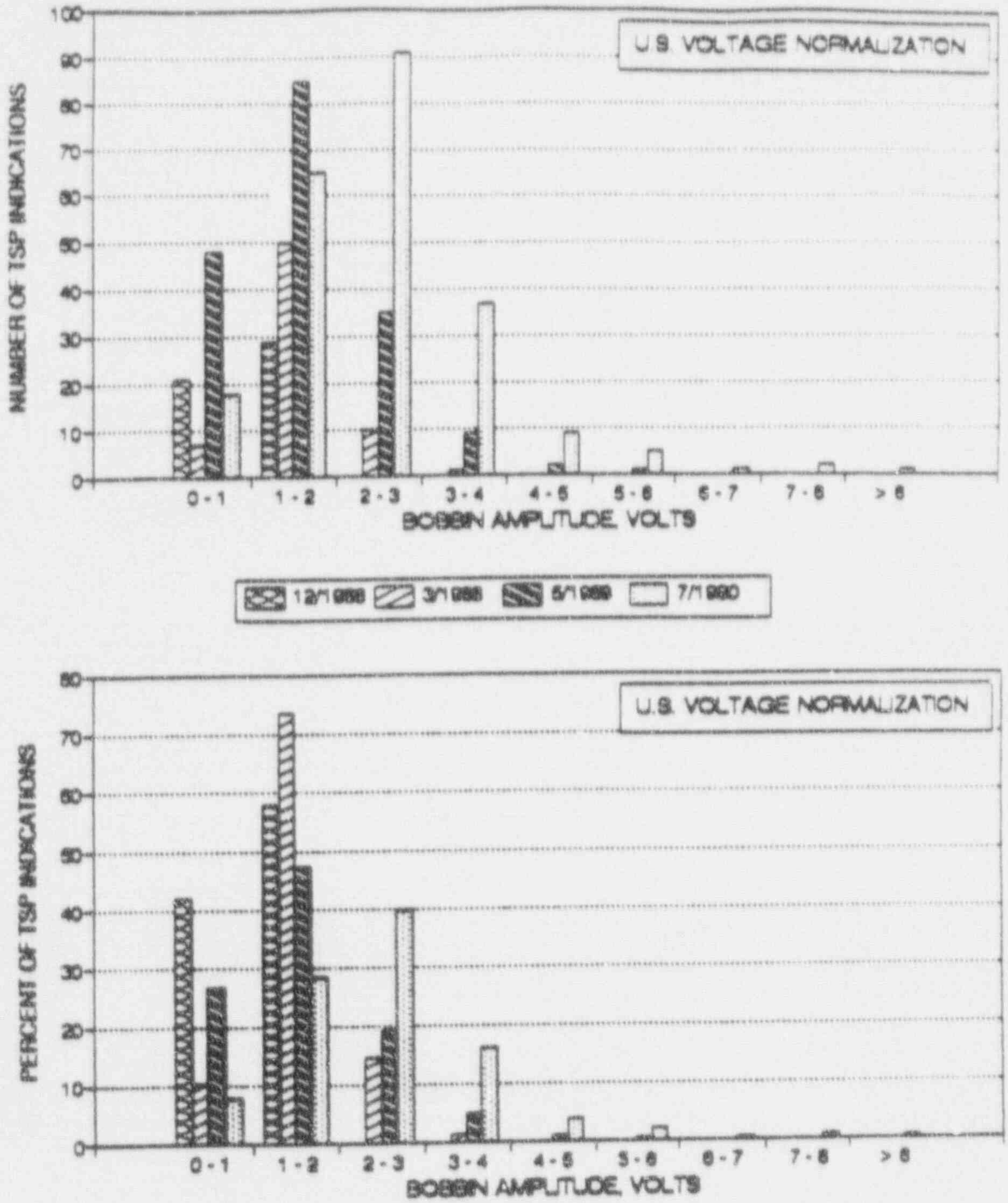
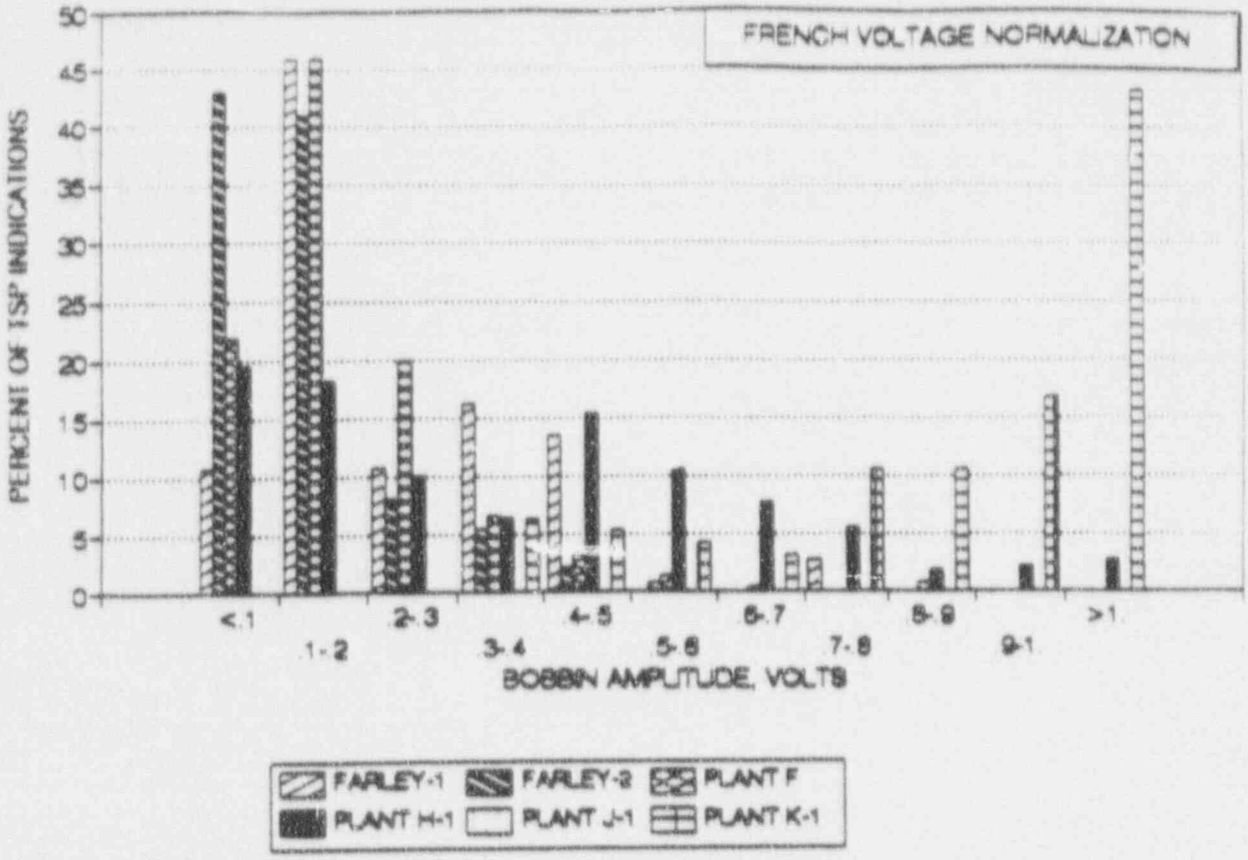


Figure 6-5. Ratio of U.S. to French Volts

Distribution of TSP Indications for Plant H-1 (1986 to 1990)



Comparison of Voltage Indications at TSPs Between U.S. and European Plants



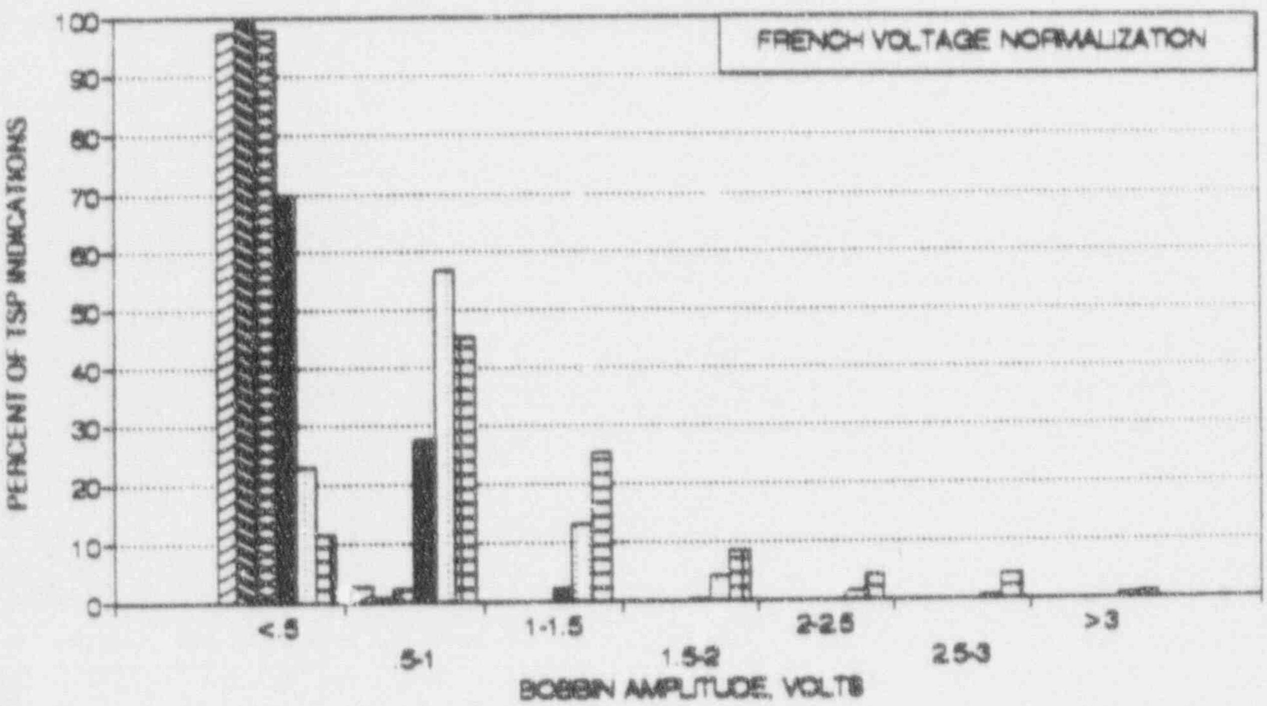
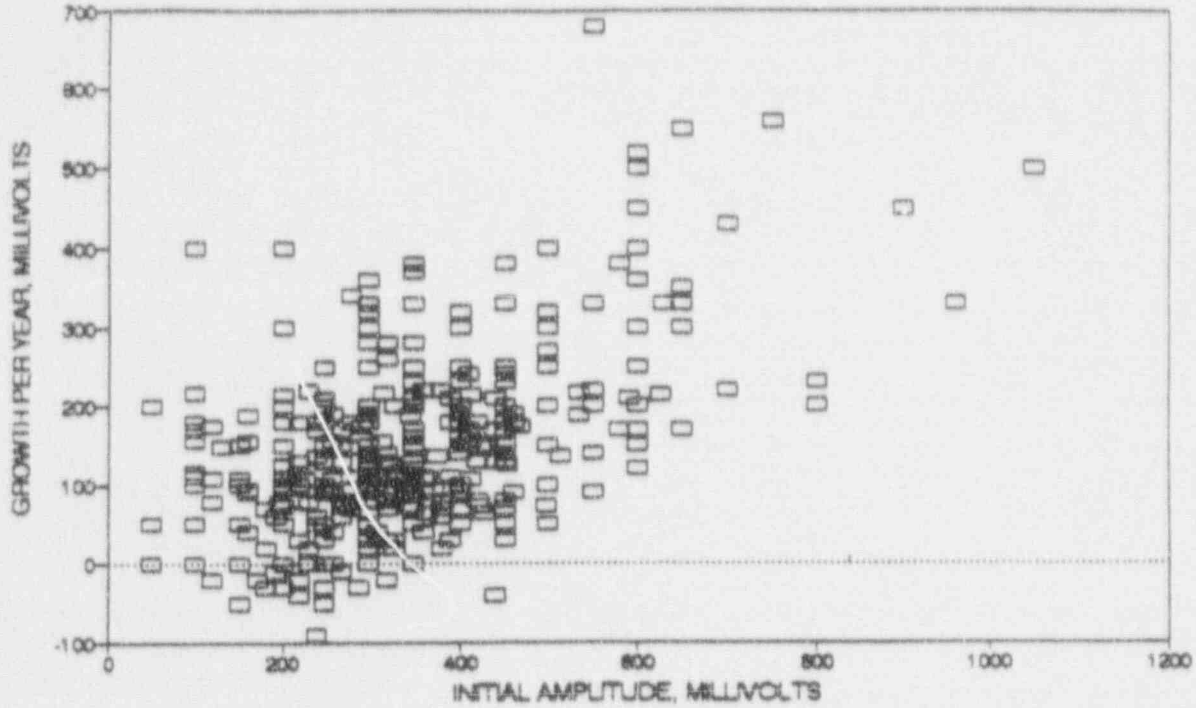


Figure 6-10

TSP Indication Voltage Growth Rates for Plant H-1



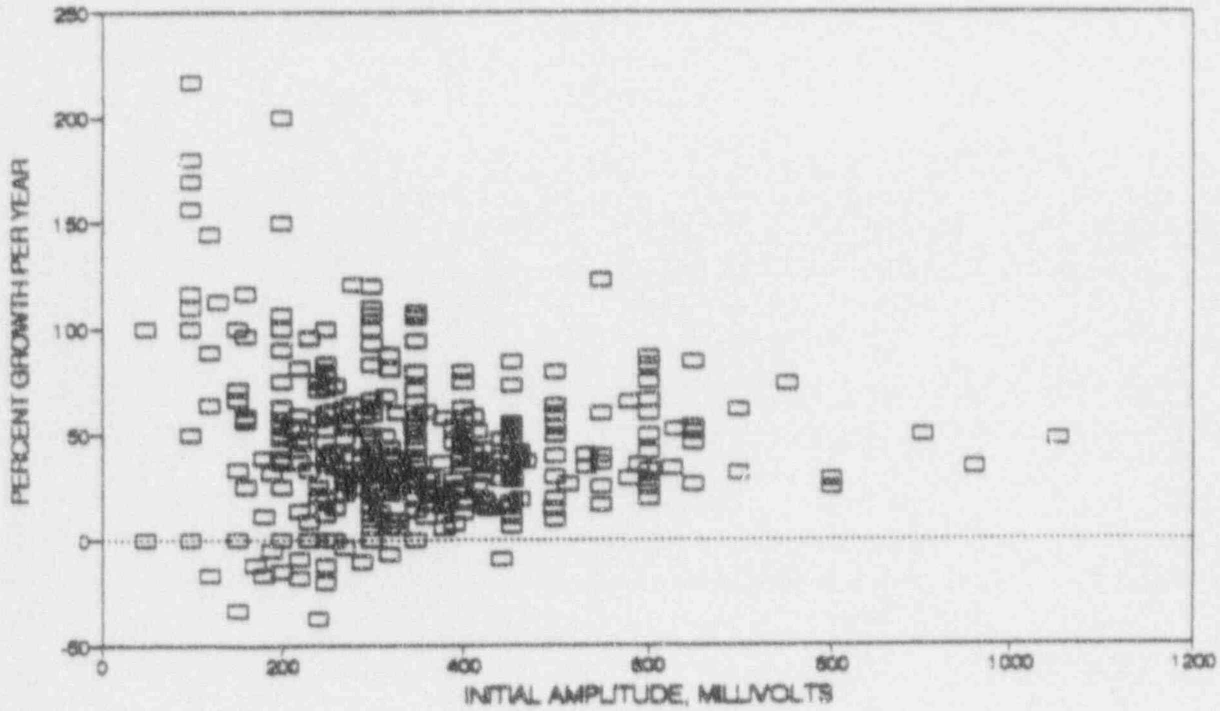
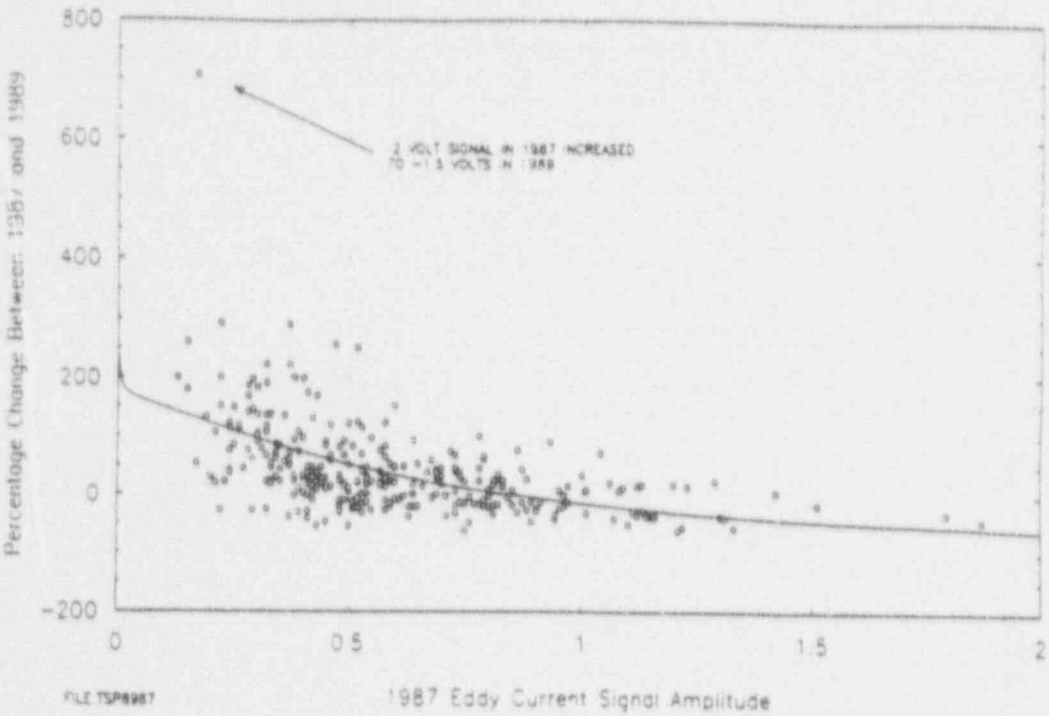
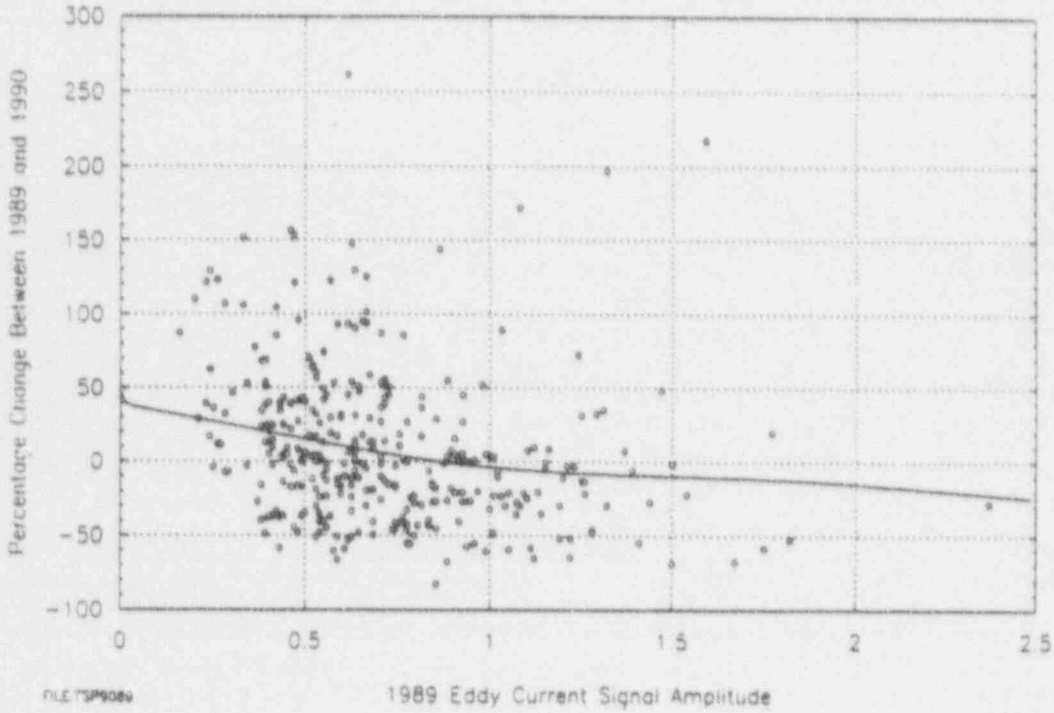
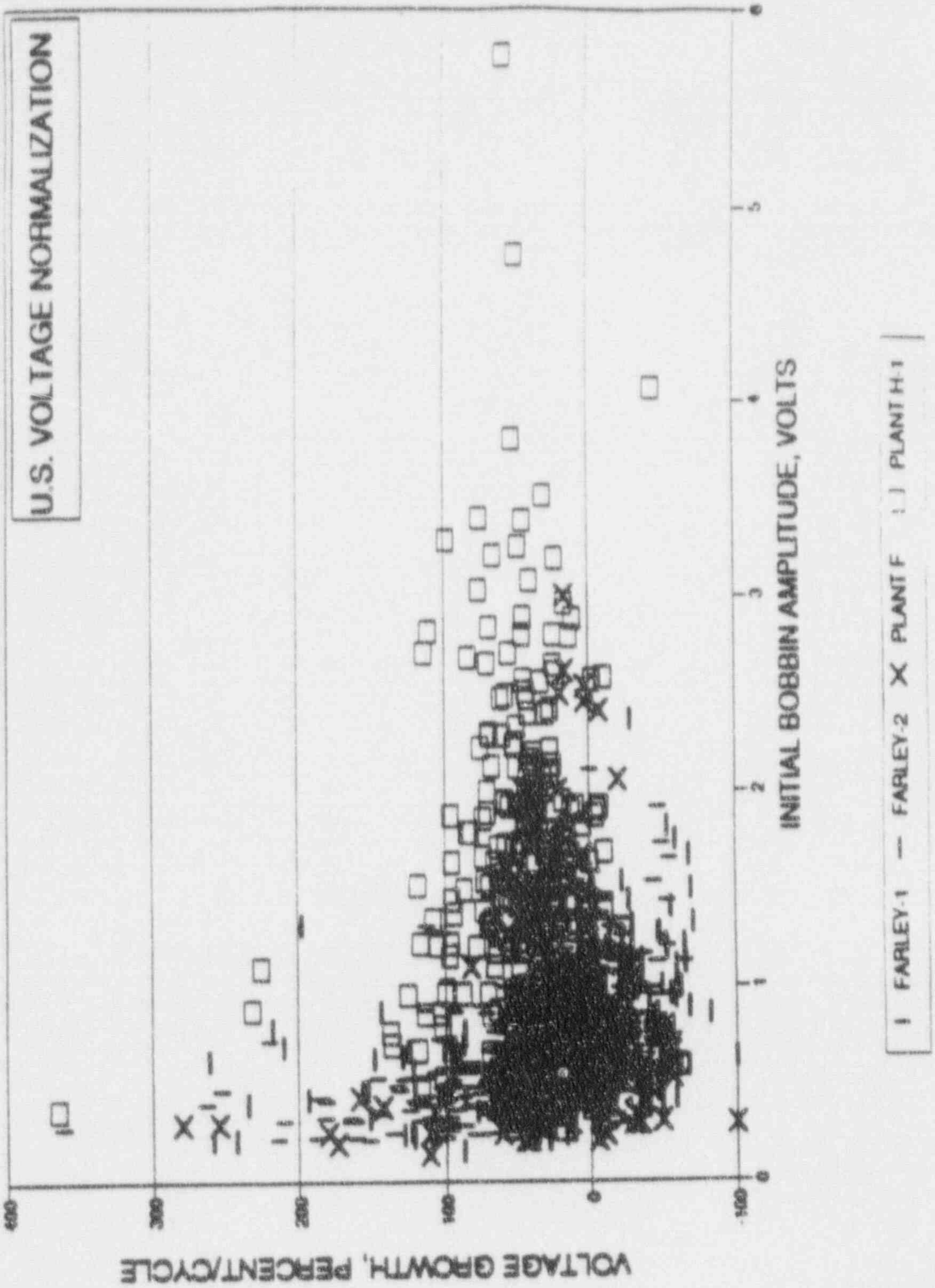


Figure 5-11

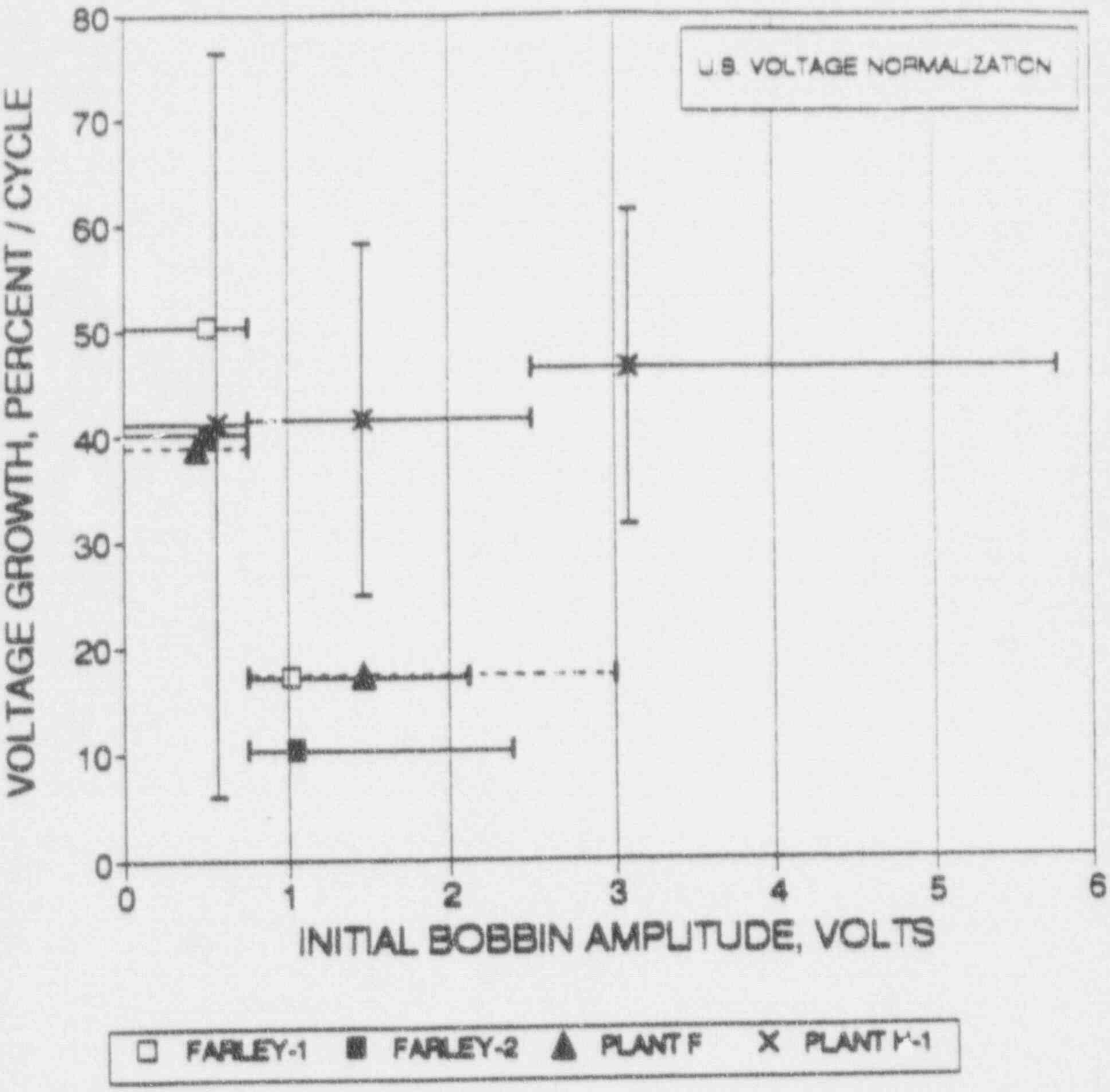
Scatter Plot of Voltage Growth in Farley-2 for Last Two Cycles







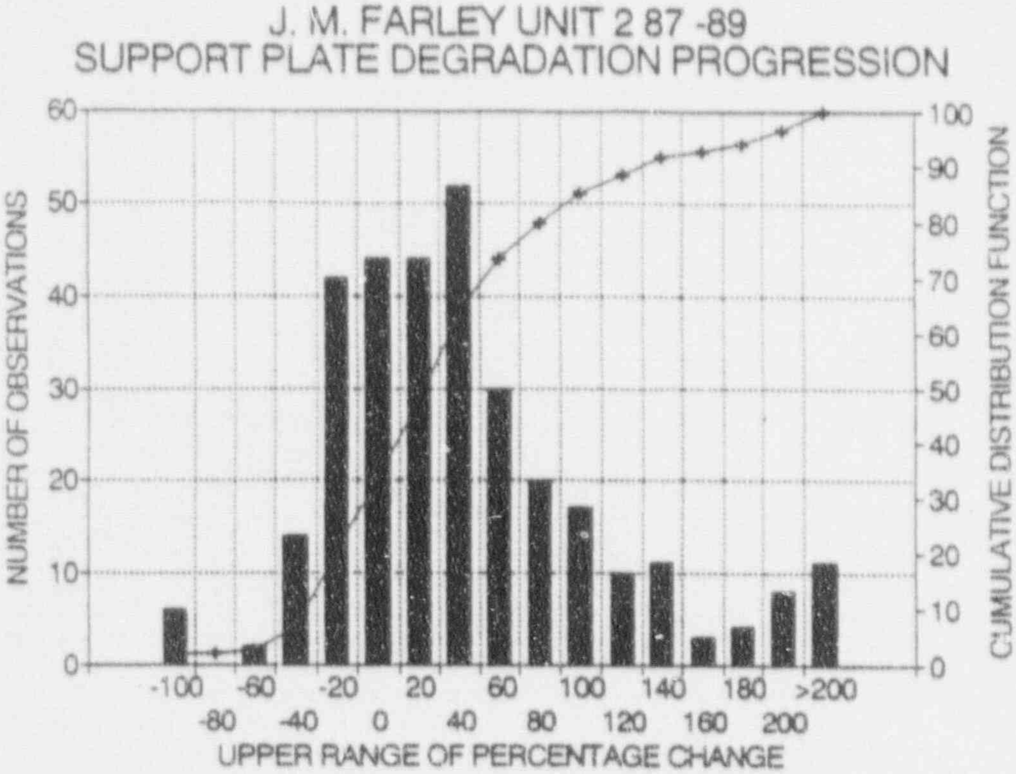
Growth Rate Data for Farley, Plant F and Plant H-1



Average Percent Voltage Growth Rates for Farley, Plant F and Plant H-1

Figure 5-13

Histogram and Cumulative Probability of Voltage Growth in Farley-2 for Last Two Cycles



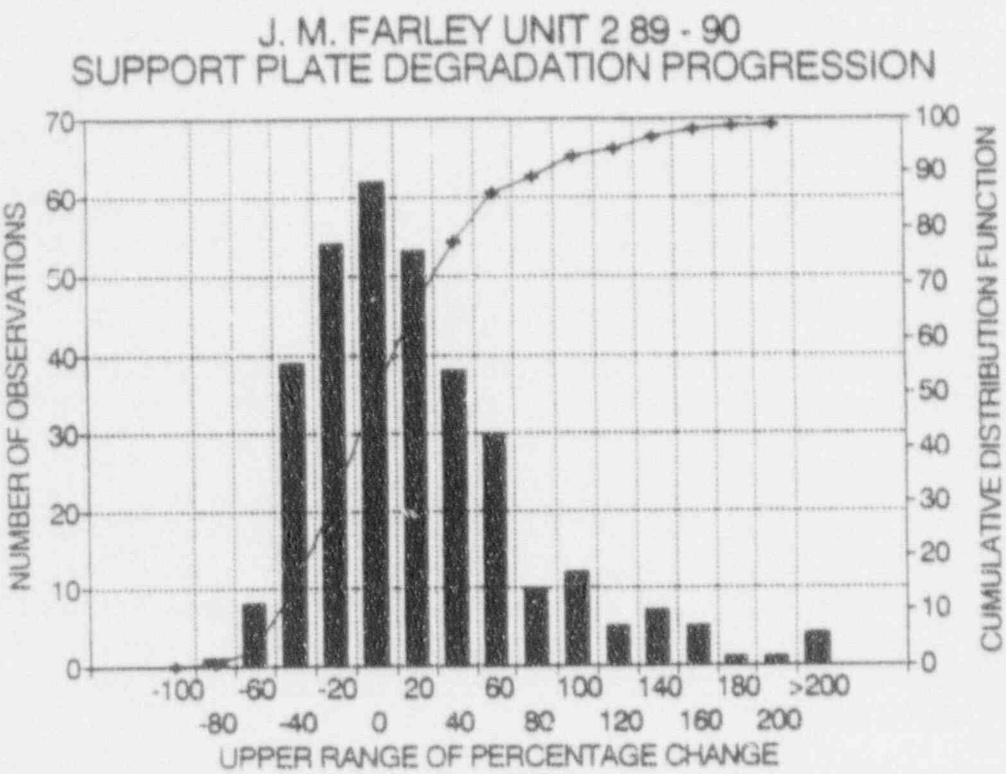


Table 12.3

Estimated Probability of Tube Burst at SLB Conditions

	Farley-1		Farley-2	
	Value	Probability	Value	Probability
Indication at Plugging Limit	4.0V	1.0	4.0V	1.0
Maximum NDE Uncertainty	15%	<0.1(1)	15%	<0.1(1)
Growth/Cycle at 99% Cumulative Probability Based on Last Operating Cycle	180%	0.01	172%	0.01
Maximum EOC Indication(2)	12.9V	$<10^{-3}$	12.5V	$<10^{-3}$
Tube Burst Voltage at Lower 99.7% Limit	12.9V	$3x10^{-3}$	12.9V	$3x10^{-3}$
Estimated Probability of Tube Burst at SLB Conditions		$<3X10^{-6}$/cycle		$<3X10^{-6}$/cycle

Notes:

1. From Figure 8-19, even assuming a worn probe (0.02" wear) the 15% uncertainty corresponds to >1.5 standard deviations or <10% probability.
2. Obtained as product of indication voltage, NDE uncertainty and growth.

Responses to NRC Questions
Circumferential Branching of ODSCC Cracks

Minor Circumferential Branching of ODSCC is Found in Model Boiler and Pulled Tubes

- Acceptable within tube plugging criterion
- Branching can include some IGA effects as well as ODSCC

Branching Has No Significant Influence on Burst Pressures Within Voltage Range of Tube Plugging Criterion

- Burst tests of tubes in >20 volt range are comparable with and without presence of branching
- Burst tests at very high amplitudes (>100 volts for model boiler specimens) indicate branching may result in reduced burst capability

No Circumferential Cracks Have Been Found at Farley

- Extensive RPC performed for resolution of indications at TSPs

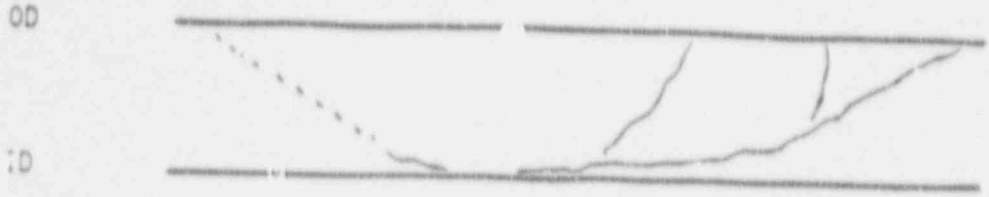
RPC for >1.5v bobbin indications is adequate for Farley to monitor for low likelihood circumferential cracks

- RPC resolution adequate to define clear circumferential cracking
- Initial identification on well defined circumferential indication as contrasted to inadequate RPC resolution

Table 12.4

Examples of Circumferential Branching for ODSCC at TSPs

Plant:Tube	B.C. Voltage	Burst Pressure Pulled Tubes	Destructive Exam Figures	Circumferential Branching Description
		Pulled Tubes		
A-2:R38C46	[	]g	4-11 to 4-13	Numerous microcracks of axial and circumferential orientation
A-2:R31C46			4-1 to 4-2	Minor circumferential branching
B-1:R4C61			4-3 to 4-4	Short circumferential cracks with IGA patches
		Model Boiler Specimens		
528-2			10-18 to 10-21	Burst opening includes circumferentially oriented ligaments
532-1			10-22 to 10-25	Burst opening includes minor circumferential orientation
532-2			10-26 to 10-29	Irregular burst opening involving tearing of interconnecting ligaments
535-1			10-30 to 10-31	Example of minor branching within tube wall
555-3			10-32 to 10-34	Burst involves irregular pattern with turn connecting ledges between cracks



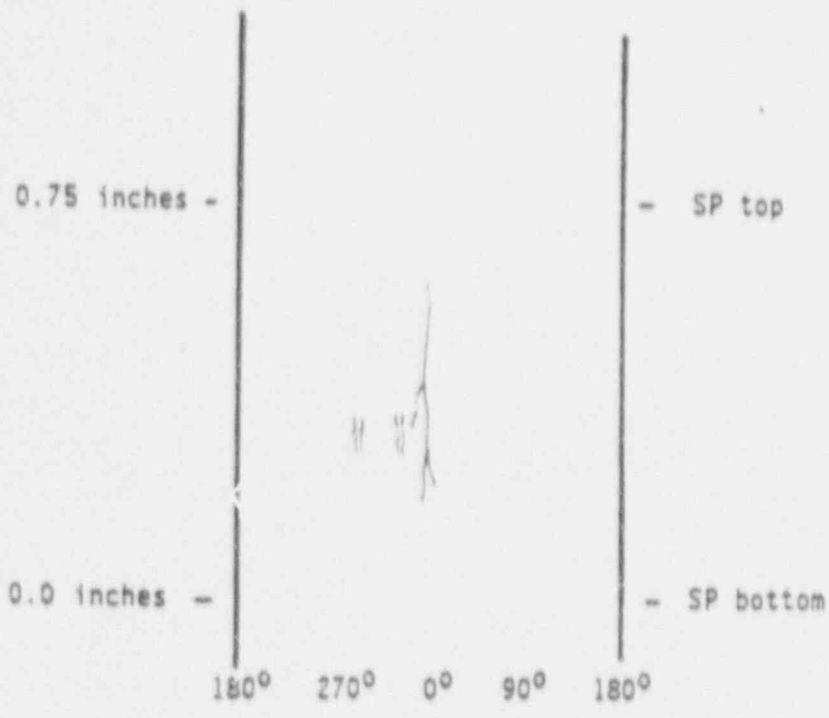
Sketch of Burst Crack

Macrocrack Length = 0.52 inch

Throughwall Length = 0.02 inch

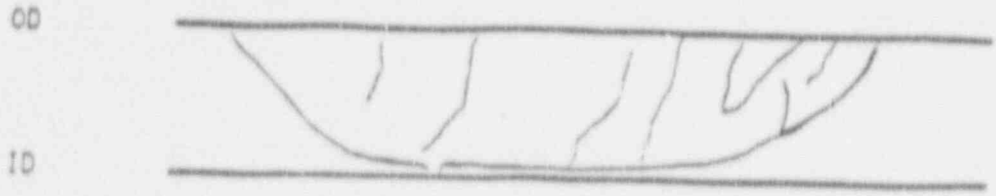
Number of Microcracks = at least 3

Morphology = IGSCC with moderate IGA components



Sketch of Crack Distribution

Figure 4-1. Summary of crack distribution and morphology observed on the first support plate crevice region of tube R31-C46, Farley Unit 2.



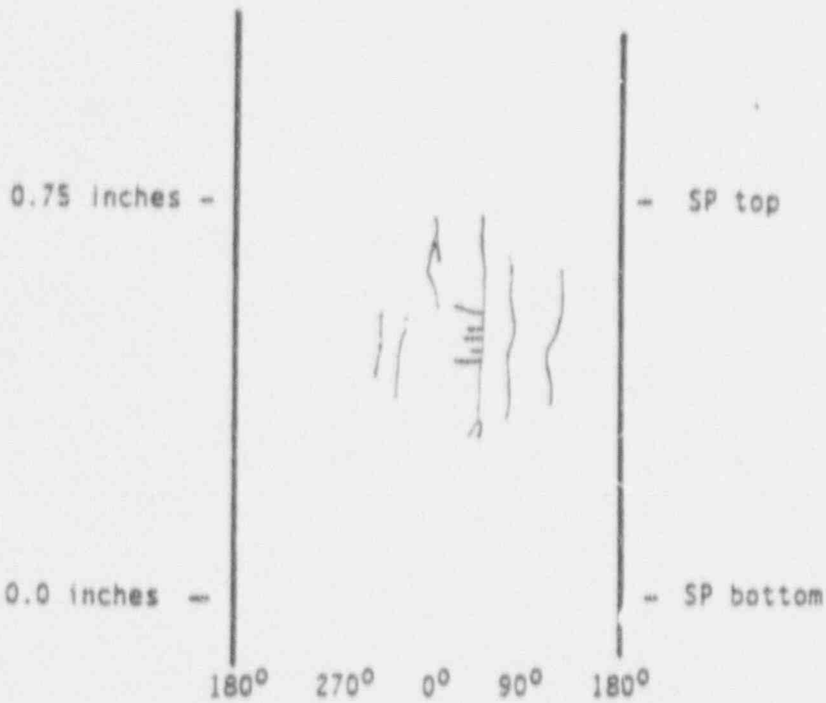
Sketch of Burst Crack

Macrocrack Length = 0.4 inch

Throughwall Length = 0.01 inch

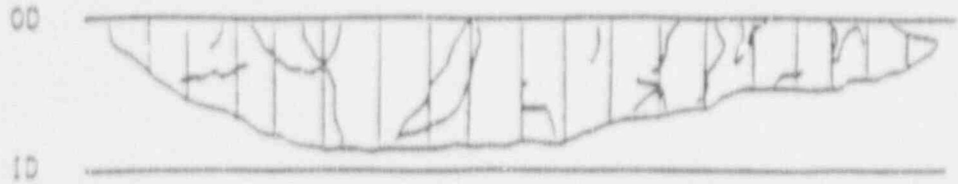
Number of Microcracks = 7 (all ligaments have predominantly intergranular features)

Morphology = IGSCC with some IGA aspects (circumferential cracking has more IGA characteristics)



Sketch of Crack Distribution

Figure 4-3. Description of OD origin corrosion at the fifth support plate crevice region of tube R4-C61, Plant B-1



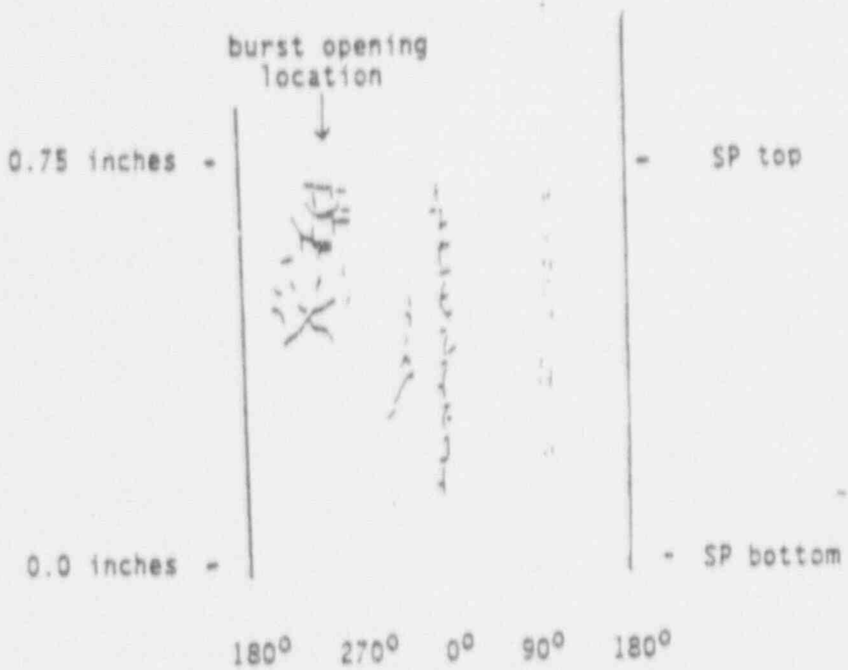
Sketch of Burst Crack

Macrucrack Length = 0.37 inches

Throughwall Length = 0 (78% throughwall)

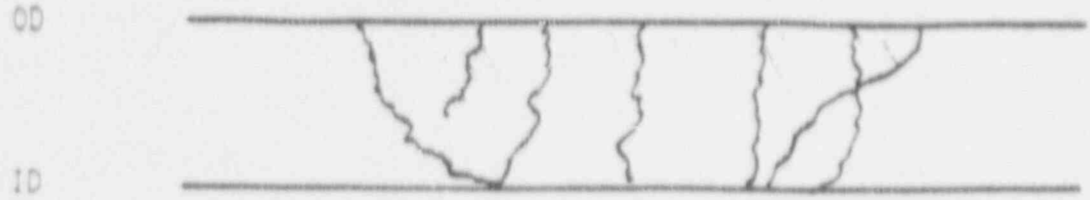
Number of Microcracks = numerous (ligaments have intergranular features)

Morphology = Intergranular SCC with minor IGA features (Unusual spider-shaped crack distribution)



Sketch of Crack Distribution

Figure 4-11. Description of OD origin corrosion at the first support plate crevice region of tube R38-C46.



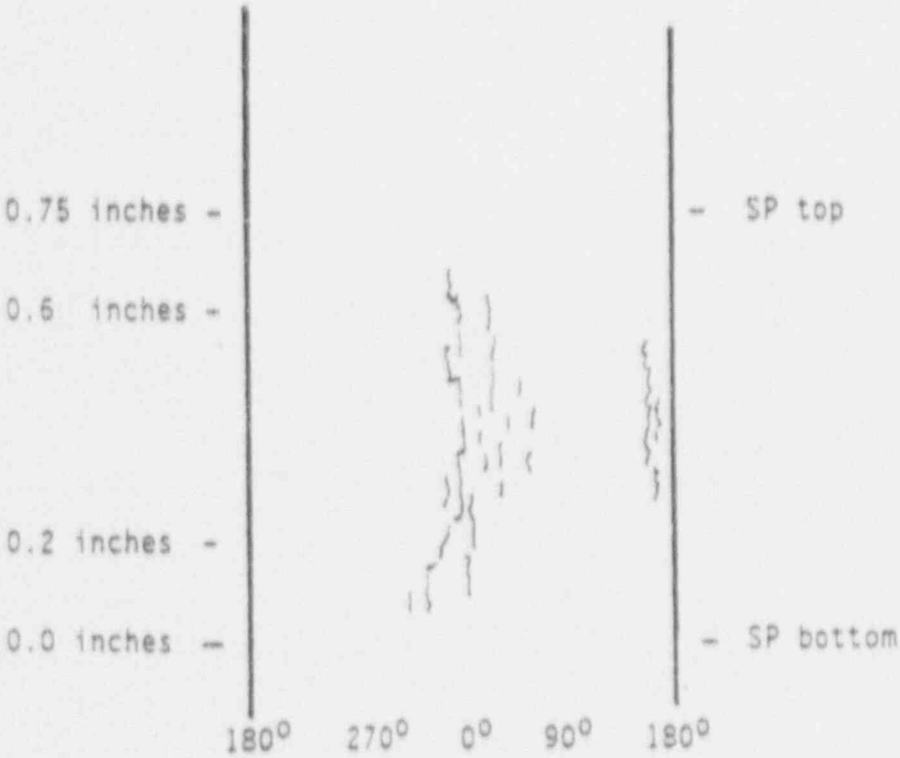
Sketch of Burst Crack

Macrocrack Length = 0.67 inch

Throughwall Length = 0.50 inch

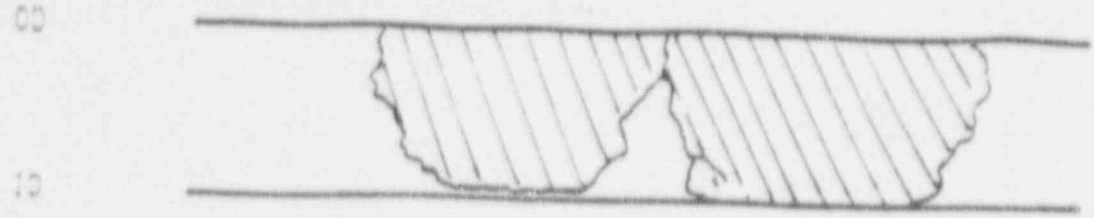
Number of Microcracks = at least 6 (ligaments have intergranular features)

Morphology = IGSCC



Sketch of Crack Distribution

Figure 10-21 Summary of overall crack distribution and morphology observed on tube 528-2.



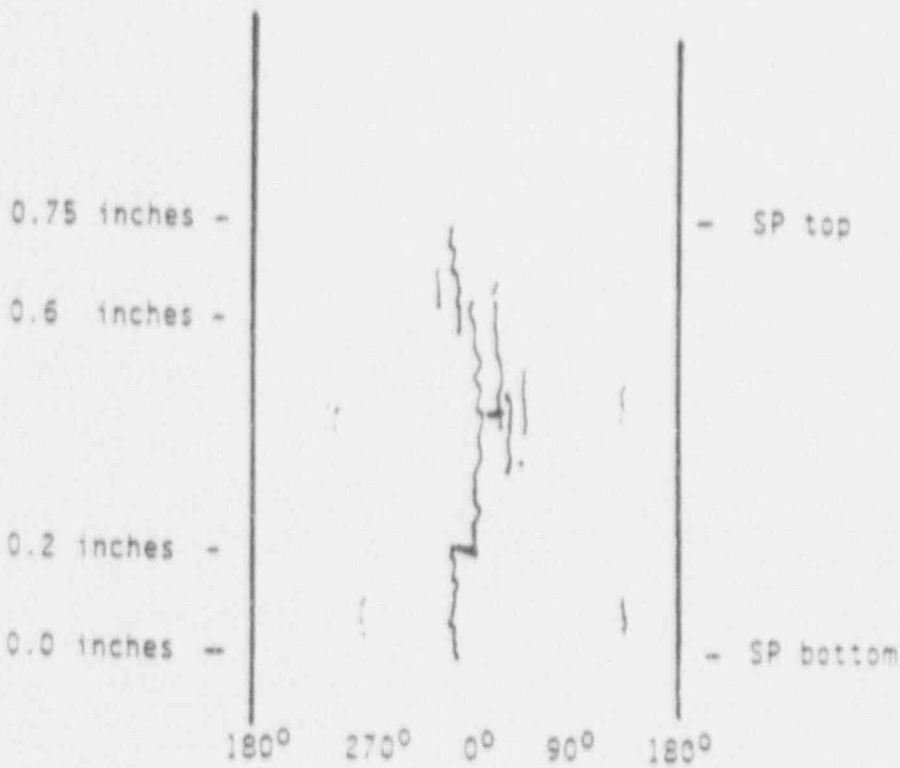
Sketch of Burst Crack

Macrocrack Length = 0.75 inch

Throughwall Length = 0.42 inch

Number of Microcracks = 2 (separated by ductile ligaments)

Morphology = IGSCC



Sketch of Crack Distribution

Figure 10-34 Summary of burst crack observations and the overall crack distribution observed at the crevice region of tube 555-3.

STRUCTURAL INTEGRITY
KEY ISSUES

SATISFY REG. GUIDE 1.121

DEMONSTRATE A FACTOR OF SAFETY OF 3 AGAINST TUBE BURST UNDER NORMAL OPERATING CONDITIONS.

DEMONSTRATE ADEQUATE MARGIN BETWEEN ACCIDENT CONDITION LOADINGS AND THE CRITICAL LOAD TO CAUSE RAPID PROPAGATION TO RUPTURE.

ESTABLISH A LEAKAGE RATE LIMIT DURING NORMAL OPERATION THAT IS LESS THAN THE LEAK RATE OF A TUBE WITH THE LARGEST PERMISSIBLE CRACK.

ESTABLISH LEAKAGE INTEGRITY DURING POSTULATED ACCIDENT CONDITIONS.

MARGINS TO BURST

NORMAL OPERATION

- $3\Delta P$ (4380 PSI) ESTABLISHED AT 95% CONFIDENCE LEVEL TO BE [ ]g.

ACCIDENT CONDITIONS

- SLB (OR FLB) MOST LIMITING FOR BURST (2650 PSI).

- VOLTAGE MARGIN OF 31.0 VOLTS VERSUS 6.85 VOLTS AT END OF CYCLE (EOC) USING CONSERVATIVE AVERAGE GROWTH.

- PROBABILITY OF $3*10^{-6}$/CYCLE ESTABLISHED WITH BURST VERSUS VOLTAGE PROBABILITY OF $3*10^{-3}$ FOR MAXIMUM EOC VOLTAGE OF 12.9 VOLTS.

Burst Pressure - Bobbin Voltage Regression Analysis

Second Order Regression Solution

- Burst pressure versus Log (volts)

- Forty data points from pulled tubes and model boiler samples - room temperature tests

- The mean correlation:

  $$BP = 8.93 - 2.37\,Log(v) - 0.29(Log(v))^2$$

- The -95% confidence prediction interval:

  $$BP_{-95\%} = BP - T_{-95\%} * S * N$$

  Where

  $T_{-95\%}$ = Students T Value

  S = 0.957

  N = Prediction interval factor

- The -95% confidence curve with lower tolerance limit (LTL) strength properties at operating temperature is obtained by scaling by 0.857.

Burst Pressure Versus Bobbin Voltage
(7/8x0.050 Inch Tubing)

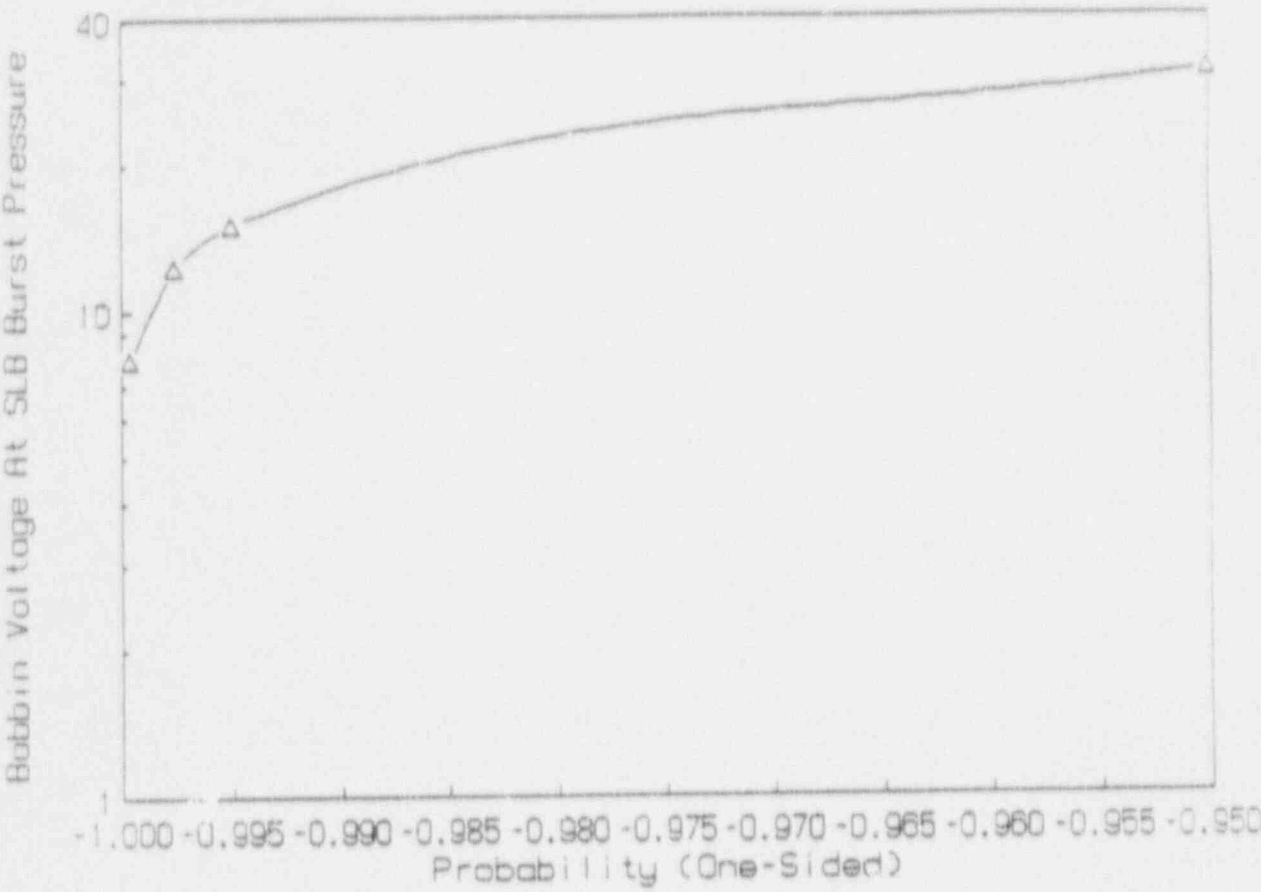
4

Burst Pressure, ksi

Bobbin Voltage, Volts

Bobbin Voltage Versus Probability

For SLB Burst Capability



Burst Pressure Versus Bobbin Voltage
(7/8x0.050 Inch Tubing)

[9]

Burst Pressure, ksi

Bobbin Voltage, Volts

Operating Leakage Rate Limit

Leak Before Break

Assuming 0.1 GPM leak rate limit and Belgian burst capability

Nominal leakage vs crack length

- 3$\triangle$P burst capability is assured; [ ],[g] burst vs leak.

-95% Confidence leakage vs crack length

- SLB burst capability is assured; [ ],[g] burst vs leak.

Normalized Burst Pressure ($\bar{P}$)

Normalized Crack Length (λ)

Comparison of Several Tube Burst Test Correlations Along with Lower Bound Tube Rupture Equation **(Ref. EPRI NP-6864-L)**

BURST PRESSURE VERSUS CRACK LENGTH

7/8X0.050 INCH TUBING

9

BURST PRESSURE, KSI

AXIAL CRACK LENGTH, INCH

Leakage Rate Calculation

Uncertainty Analysis

Measured versus predicted values (M vs. P) are fit by linear regression and a standard deviation (SD) determined

- The linear regression fit is on a log-log plot of the values
- It therefore results in a factor to be applied to the predicted value

Normal Operation

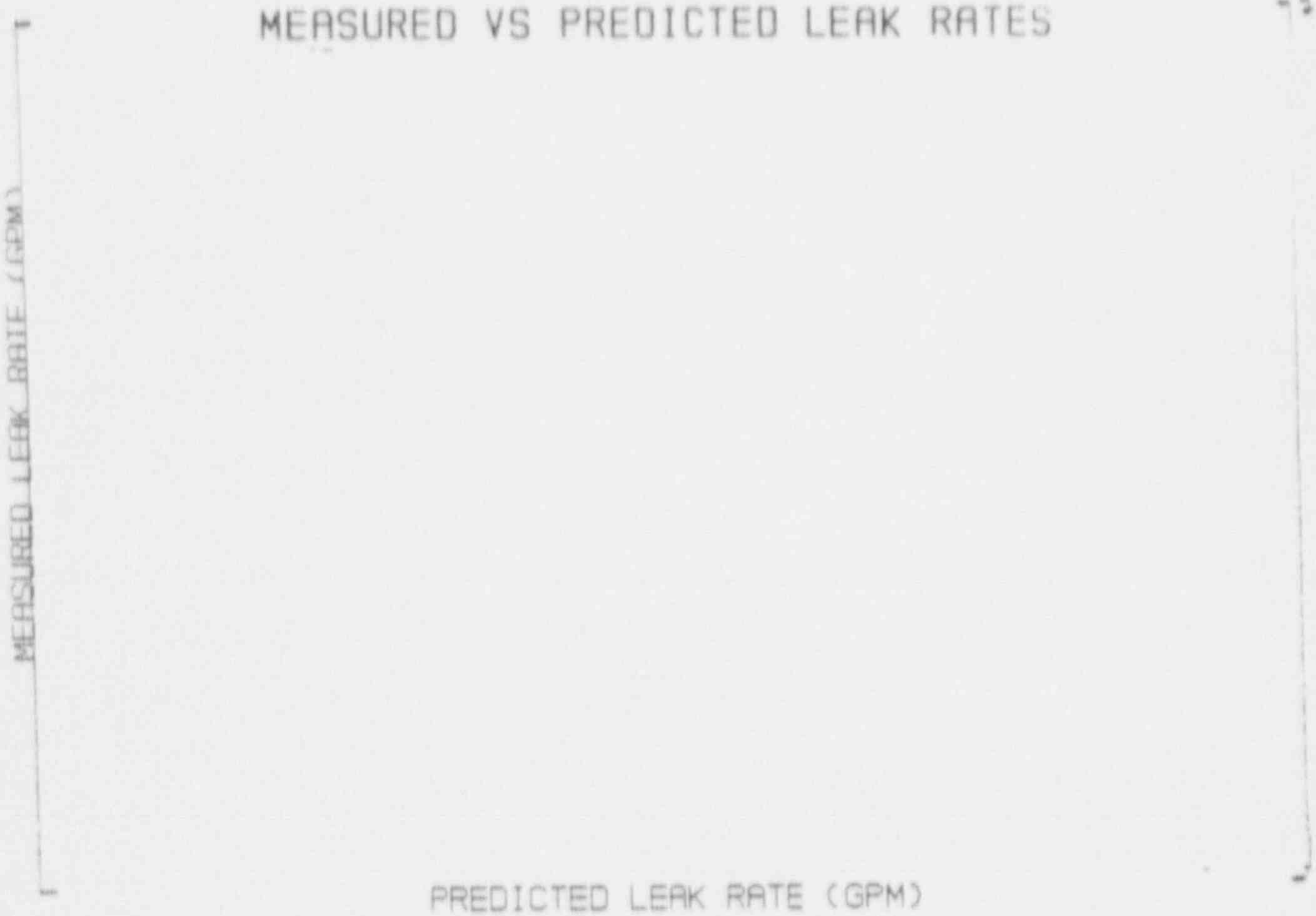
- Log-log SD = 0.4614
- M (or actual) = $P * 10^{N*0.4614*T}$

Where

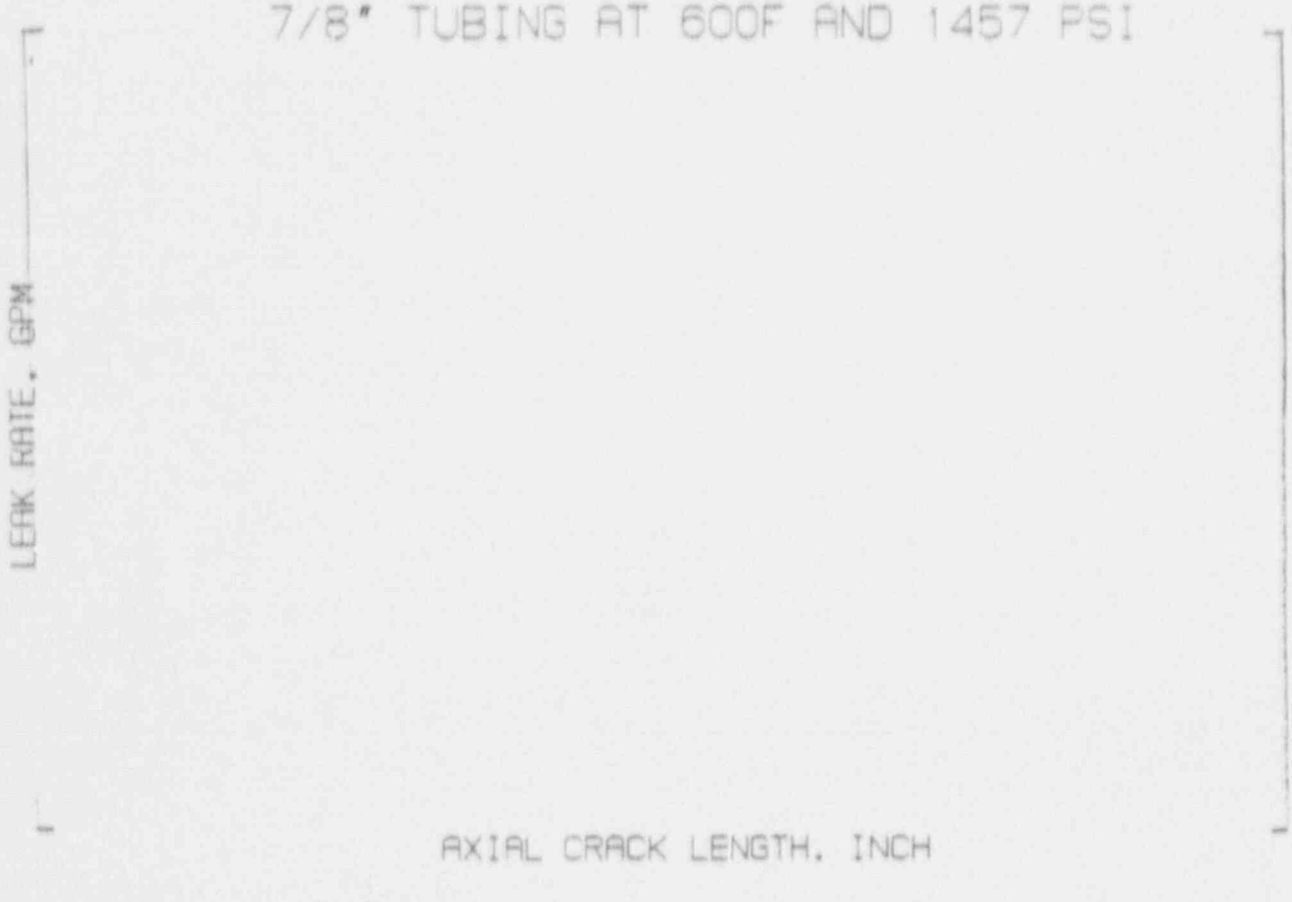
T = Students T value at specified confidence level (95%)

N = Prediction interval factor

CRACKFLO CODE ERROR ANALYSIS
MEASURED VS PREDICTED LEAK RATES



NORMAL OPERATING CONDITIONS
LEAK RATE VS AXIAL CRACK LENGTH
7/8" TUBING AT 600F AND 1457 PSI



Allowable Axial Crack Length

Combined Accident Evaluation

- SSE plus SLB/FLB

Primary Stress at Top TSP

- Pressure Differential
  - Normal Operation (1457 PSI)
  - SLB/FLB (2650 PSI After Blowdown)

- Cross-Section Bending Stress
  - SSE + SLB/FLB (± 19800 PSI)

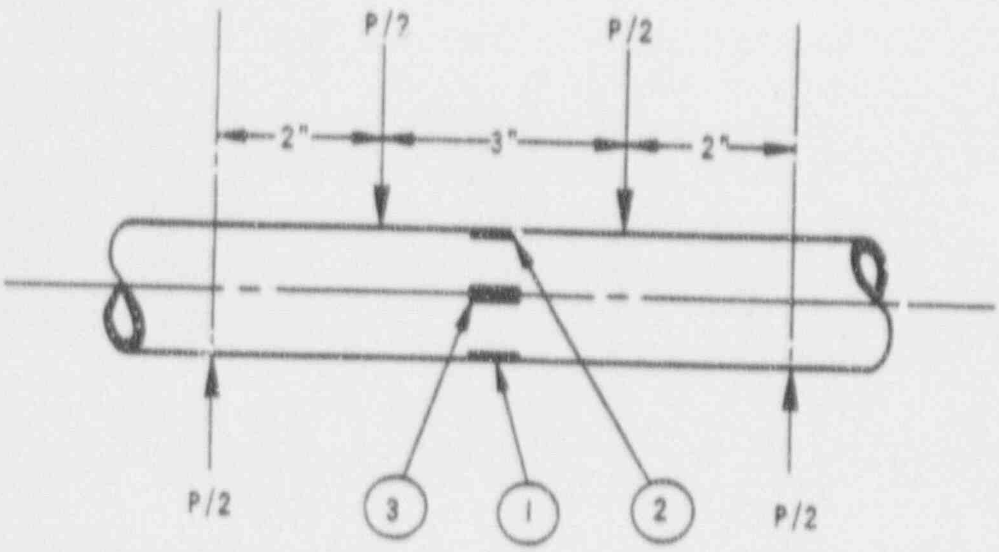
Cross-section bending stress is well below the magnitude required to have an effect on burst pressure (WCAP 7832-A)

- 19800 PSI versus yield strength (35500 PSI)

Allowable axial crack length determined on the basis of internal pressure only is justified

COMBINED BENDING AND INTERNAL PRESSURE BURST TESTS ON TUBES WITH THROUGH WALL SLOTS

b,c



Externally Applied Bending Load and Locations of Through Wall Penetrations

CALCULATION OF POTENTIAL LEAKAGE DURING A POSTULATED SLB

PROBABILISTIC METHODOLOGY

THE LEAK RATE VERSUS BOBBIN VOLTAGE CORRELATION AND POPULATION OF VOLTAGE SIGNALS AT TSP INTERSECTIONS TO BE LEFT IN SERVICE ARE EVALUATED USING MONTE CARLO TECHNIQUES ACCOUNTING FOR VARIATIONS IN THE FOLLOWING PARAMETERS:

- BOBBIN VOLTAGE UNCERTAINTY
- GROWTH ALLOWANCE UNCERTAINTY
- LEAK RATE-VOLTAGE VARIATION WITHIN THE PREDICTION INTERVAL

THUS, AN END OF CYCLE VOLTAGE DISTRIBUTION IS ASSESSED FOR ITS POTENTIAL FOR LEAKAGE DURING A POSTULATED SLB.

- THE METHOD HAS BEEN APPLIED TO THE FARLEY 2 VOLTAGE DISTRIBUTION IN 1990 FOR EACH STEAM GENERATOR.
- THE MAXIMUM CALCULATED LEAK RATE IS 0.34 GPM PER STEAM GENERATOR.

SLB Leak Rate - Bobbin Voltage Regression Analysis

First Order Regression

[ ]g

SLB Leak Rate Versus Bobbin Voltage

(7/8X0.050 Inch Tubing)

Bobbin Voltage, Volts

COMBINED LOCA + SSE ACCIDENT CONDITION ANALYSIS

COMBINED ACCIDENT HAS POTENTIAL IMPACT ON USE OF ALTERNATE CRITERIA

- Yielding of TSP Adjacent to Wedge Groups
- Deformation of Tubes
- Loss of Flow Area
- Opening of Pre-Existing Cracks/Propagation of Existing Cracks Through Wall With Subsequent In-Leakage Which Can Effect Core PCT

ANALYSIS RESULTS

- No Tubes Would Reach Collapse △D Threshold
- No Tubes With Significant Deformation
- No Tubes Excluded From Alternate Plugging Criteria

COMBINED LOCA + SSE ACCIDENT CONDITION ANALYSIS
ANALYSIS METHOD

SSE Analysis

[ ]a,c

LOCA Analysis

[ ]a,c

a,c,e

Series 51 Seismic Finite Element Model Geometry

a,c,e

Finite Element Models for
Structural LOCA Time History Analysis

DISK 82-POR04-10/3/91

a,c,e

For TSP 1, Wedge Groups Rotated 36° From Positions Shown Above

TSP 1-6: Wedge Group Width = 6 in.
TSP 7: Wedge Group Width = 10 in.

WEDGE GROUP ORIENTATION
LOOKING DOWN ON TSP

DISK 82-POR04-10/3/91

COMB NED LOCA + SSE ACCIDENT CONDITION ANALYSIS
ANALYSIS METHOD (CONT'D.)

- FORMATION/COLLAPSE
  - D TO CAUSE COLLAPSE BASED ON COLLARED TUBE TS
  - D RESULTING FROM TSP LOADS BASED ON RECENTLY MPLETED CRUSH TESTS FOR SERIES 51 PLATES
    - FOUR PLATE GEOMETRIES TESTED
    - THREE WEDGE ORIENTATIONS/TWO WEDGE WIDTHS
    - TESTS MEASURED FORCE VERSUS DEFLECTION & △D VERSUS LOAD

ALLOWABLE COLLAPSE PRESSURE VS ID DEFORMATION

WCAP 8429 DATA (COLLAR A)

b,c

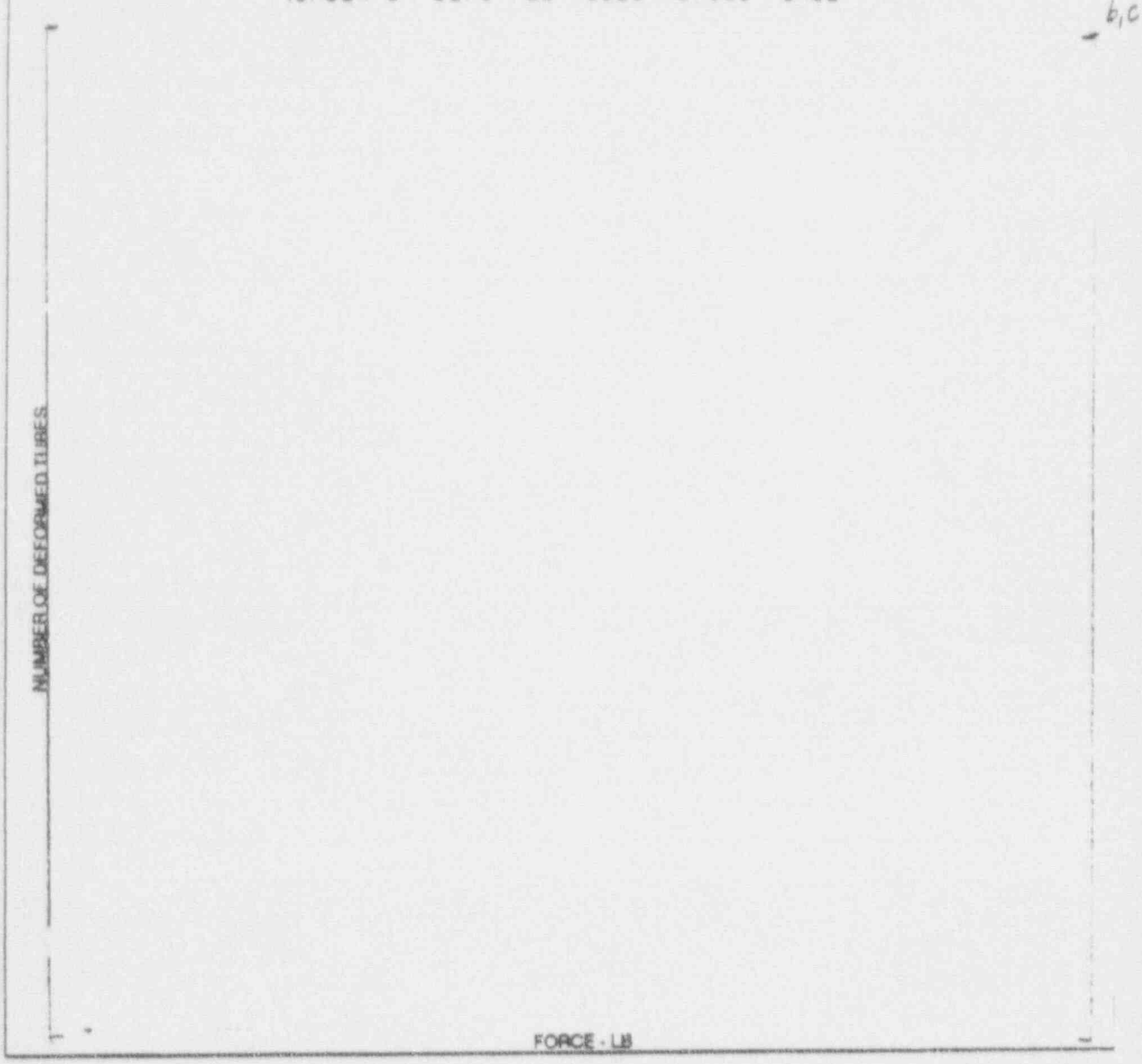
ALLOWABLE COLLAPSE PRESSURE, KSI

CHANGE IN ID, INCH

SERIES 51 CRUSH TEST RESULTS
FORCE VERSUS DEFLECTION

b,c

SERIES 51 CRUSH TEST RESULTS
NUMBER OF DEFORMED TUBES VERSUS FORCE



Summary of Wedge Loads
Combined LOCA + SSE Loadings
Steam Generator Inlet Break

b,c

Loading Condition	Angle (DEG)	Load Factor	TSP 1 (KIPS)	TSP 2-6 (KIPS)	TSP 7 (KIPS)
LOCA Rarefaction					
LOCA Shaking					
Combined LOCA					
Seismic					
Combined LOCA + Seismic					
Wedge Load					
a. LOCA					
b. Seismic					
a. LOCA + Seismic					
Wedge Load					
a. LOCA					
b. Seismic					
a. LOCA + Seismic					
Wedge Load					
a. LOCA					
b. Seismic					
a. LOCA + Seismic					

* Angles for TSP 1

SUMMARY OF WEDGE LOADS
COMBINED LOCA + SSE LOADINGS
ACCUMULATOR LINE BREAK

LOADING CONDITION	ANGLE (DEG)	LOAD FACTOR	TSP 1 (KIPS)	TSP 2-6 (KIPS)	TSP 7 (KIPS)
LOCA Rarefaction					b,c
LOCA Shaking					
Combined LOCA					
Seismic					
Combined LOCA + Seismic					
Wedge Load					
a. LOCA					
b. Seismic					
a. LOCA + Seismic					
Wedge Load					
a. LOCA					
b. Seismic					
a. LOCA + Seismic					
Wedge Load					
a. LOCA					
b. Seismic					
a. LOCA + Seismic					

* ANGLES FOR TSP 1

Number of Deformed Tubes as a Function of Load
Series 51 Steam Generator

6" WEDGE GROUP
[ ]a,c,e ORIENTATION

b,c

Leakage Rate Calculation

LOCA In-Leakage

Assuming 0.1 GPM Normal Operating Limit

- In-leakage from secondary to primary ΔP during LOCA is less than 0.1 GPM
  - Secondary to primary ΔP is steam pressure minus ambient (778 PSI)
  - Secondary to primary ΔP causes much less leakage than primary to secondary ΔP of same magnitude (WCAP-9659)

FARLEY 1 AND 2
STEAM GENERATOR
INSPECTION RESULTS

November 20, 1991

Table 5.1

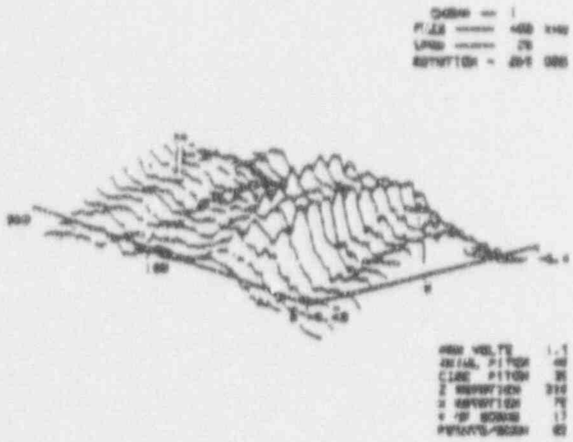
Summary of EC Indications in Last Inspection of Farley SGs

	SG-A		SG-B		SG-C	
	HL	CL	HL	CL	HL	CL
			UNIT 1 (MARCH 1991)			
Bobbin Signals						
<20% Depth	0	0	0	1	0	0
20-29%	0	0	0	2	0	1
30-39%	0	0	0	0	0	1
40-49%	0	0	0	0	0	0
50-59%	2	0	2	0	0	0
60-69%	2	0	1	0	1	0
70-79%	2	0	2	0	1	0
80-89%	4	0	0	0	0	0
90-100%	0	0	0	0	0	0
Distorted	180	0	126	0	208	0
RPC Results						
Degradation Verified	72	0	24	0	20	0
Tubes Plugged for ODSCC Indication	55		24		18	
			UNIT 2 (OCTOBER 1990)			
Bobbin Signals						
<20% Depth	3	2	2	4	1	0
20-29%	7	2	0	2	1	1
30-39%	3	2	5	0	4	1
40-49%	1	0	1	0	6	0
50-59%	1	0	4	0	11	0
60-69%	1	0	8	0	17	0
70-79%	4	0	9	0	23	0
80-89%	1	0	4	0	8	0
90-100%	0	0	0	0	0	0
Distorted	40	0	54	2	114	0
RPC Results						
Indications Probed	48	0	81	2	179	0
Degradation Verified	31	0	66	0	151	0
Tubes Plugged for ODSCC Indication	29		64		147	

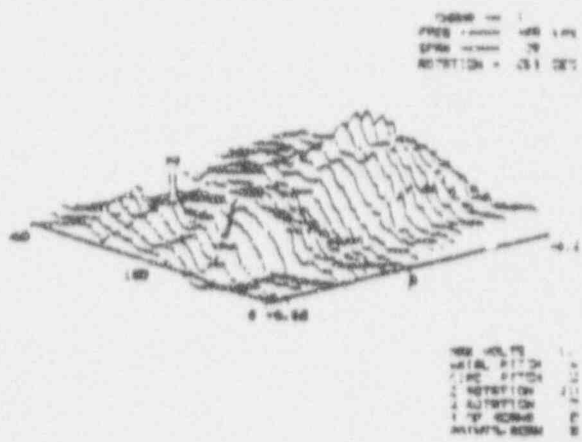
Figure 5-8

Farley-1 RPC Characterization (November 1989)

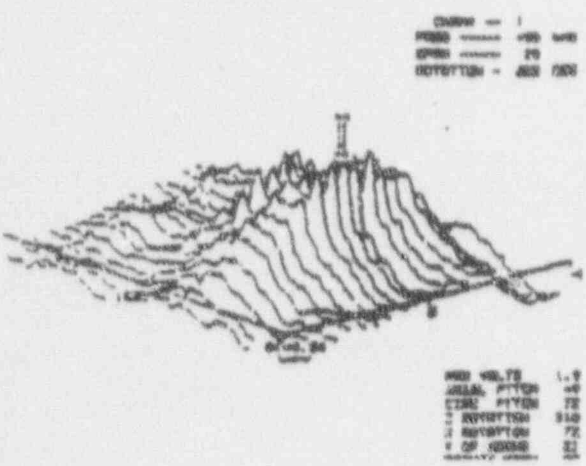
R12C3 2H S/G 21



R12C3 5H S/G 21



R31C50 2H S/G 21



R20C23 1H

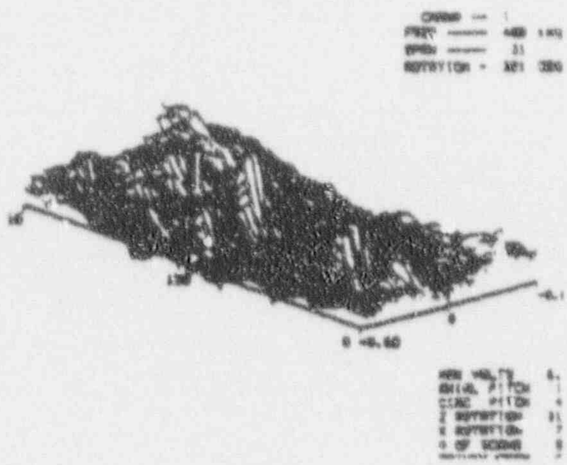


Figure 5-9

Farley-2 RPC Characterization (November 1990)

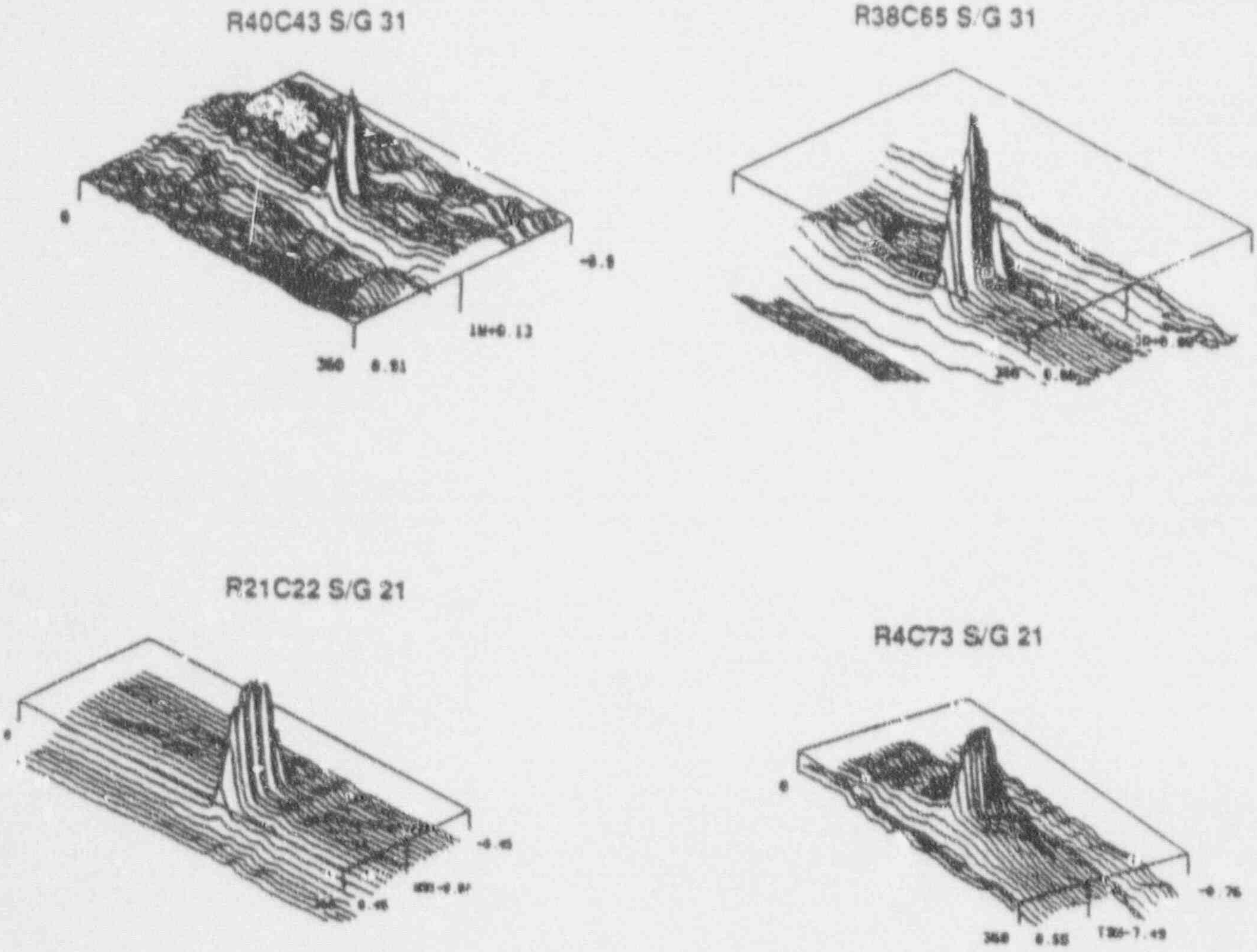


Figure 5-1

Distorted Indication Signal Amplitudes in Farley-1 S/Gs (March 1991)

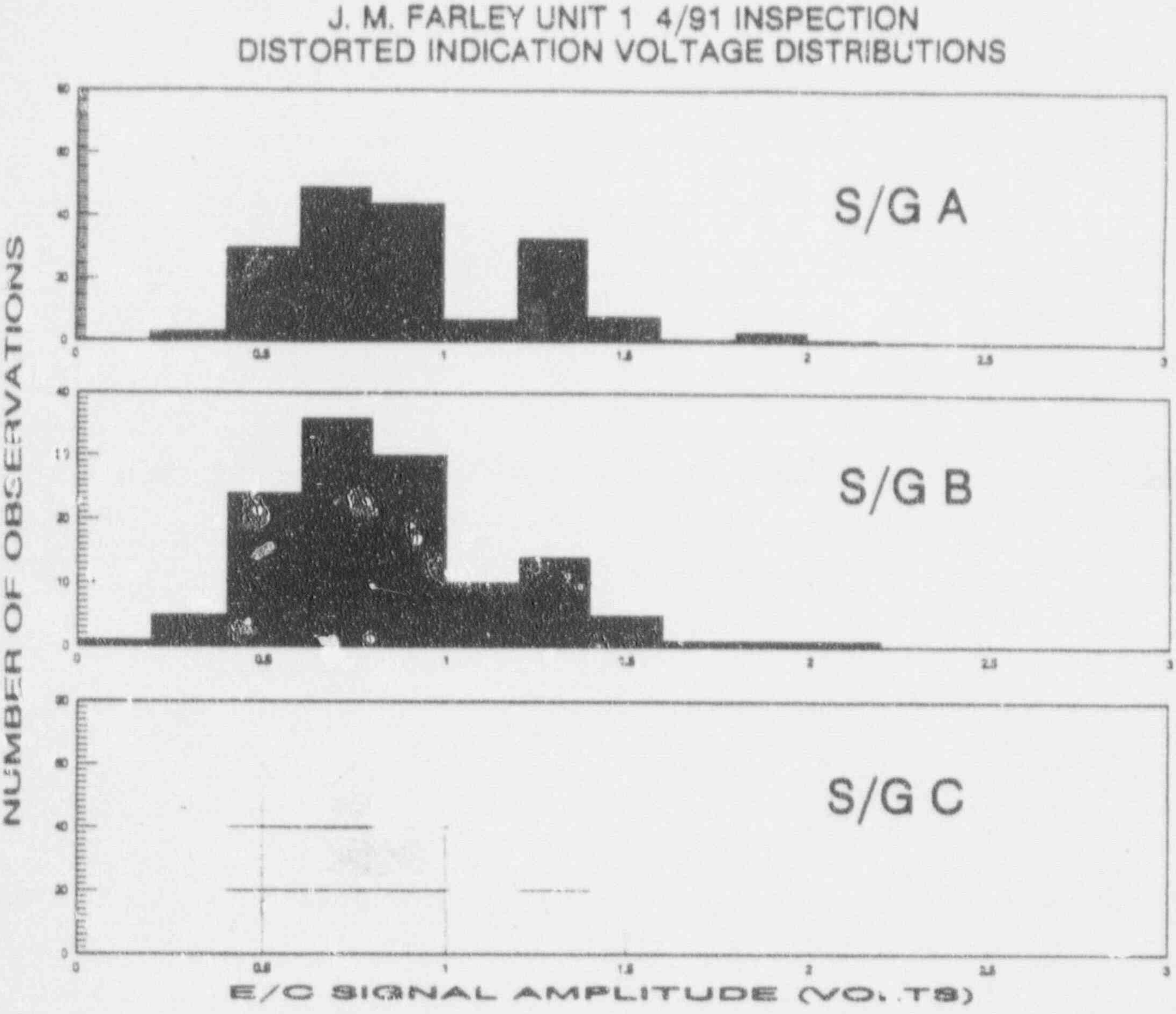


Figure 5-2

Axial Distribution of Distorted Indication Signals in Farley-1 S/Gs (March 1991)

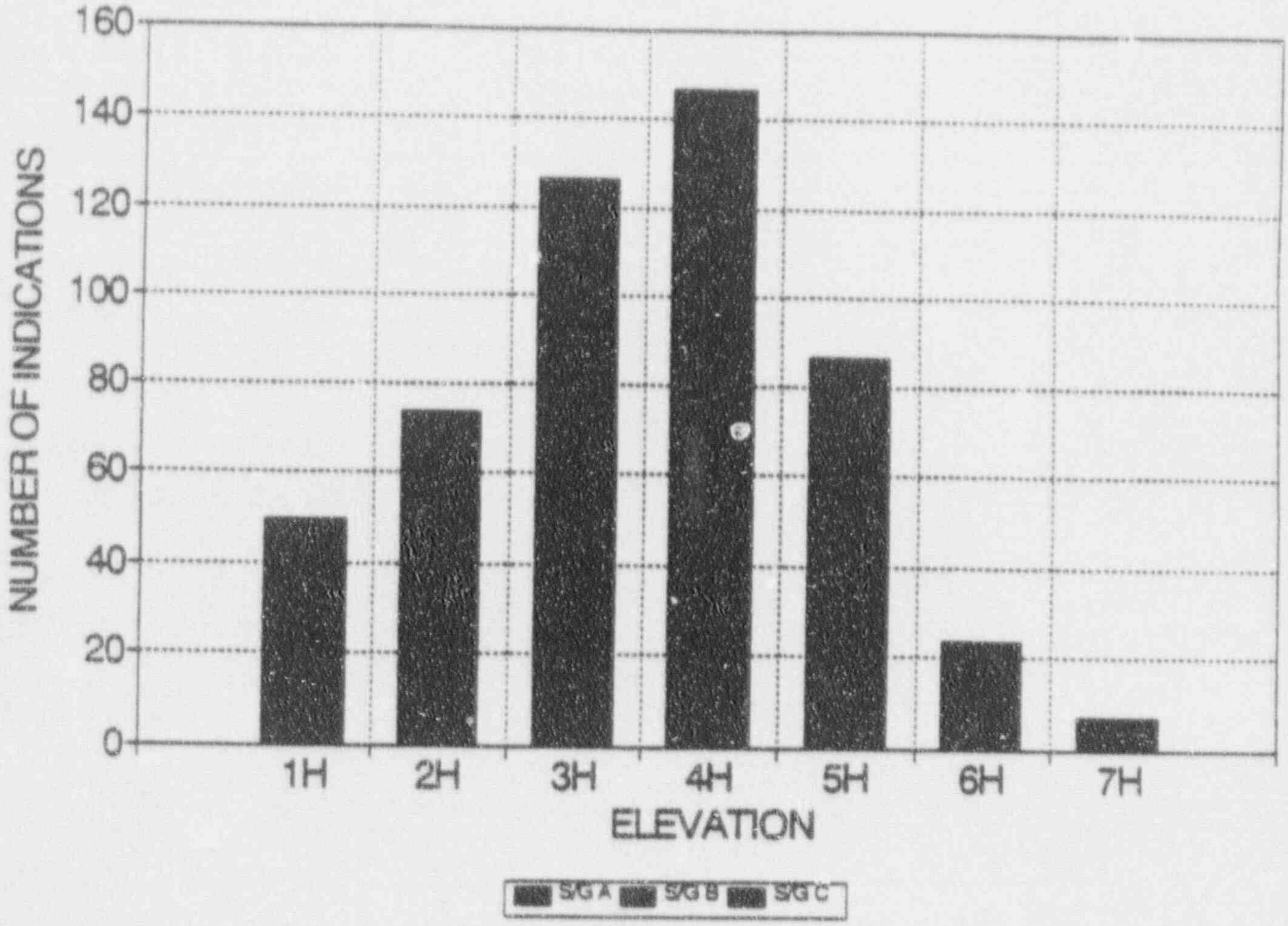


Figure 5-4

Axial Distribution of TSP Indications in Farley-2 S/Gs (October 1990)

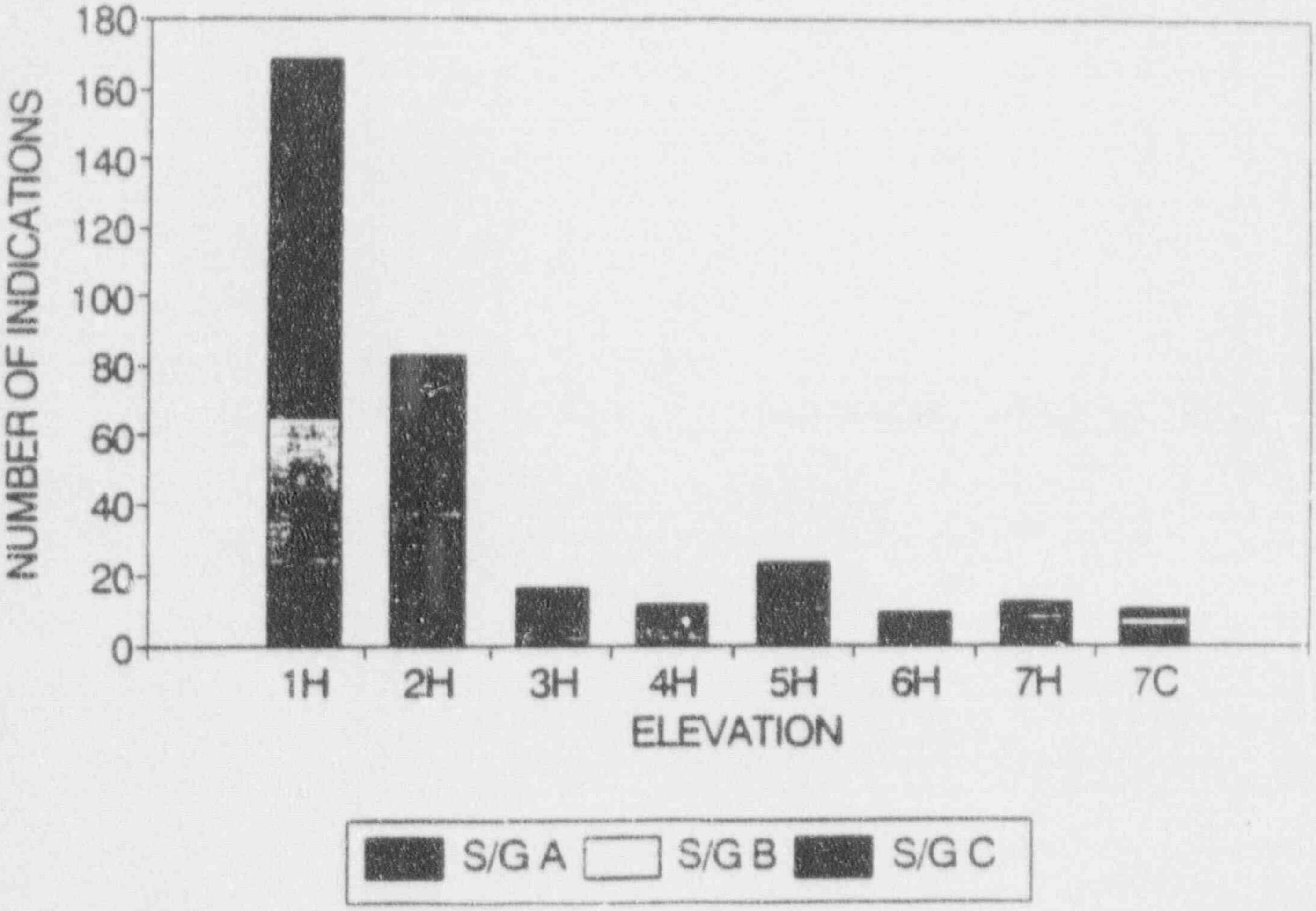


Figure 5-5

Distribution of TSP Indication Amplitudes in Farley-2 S/Gs (October 1990)

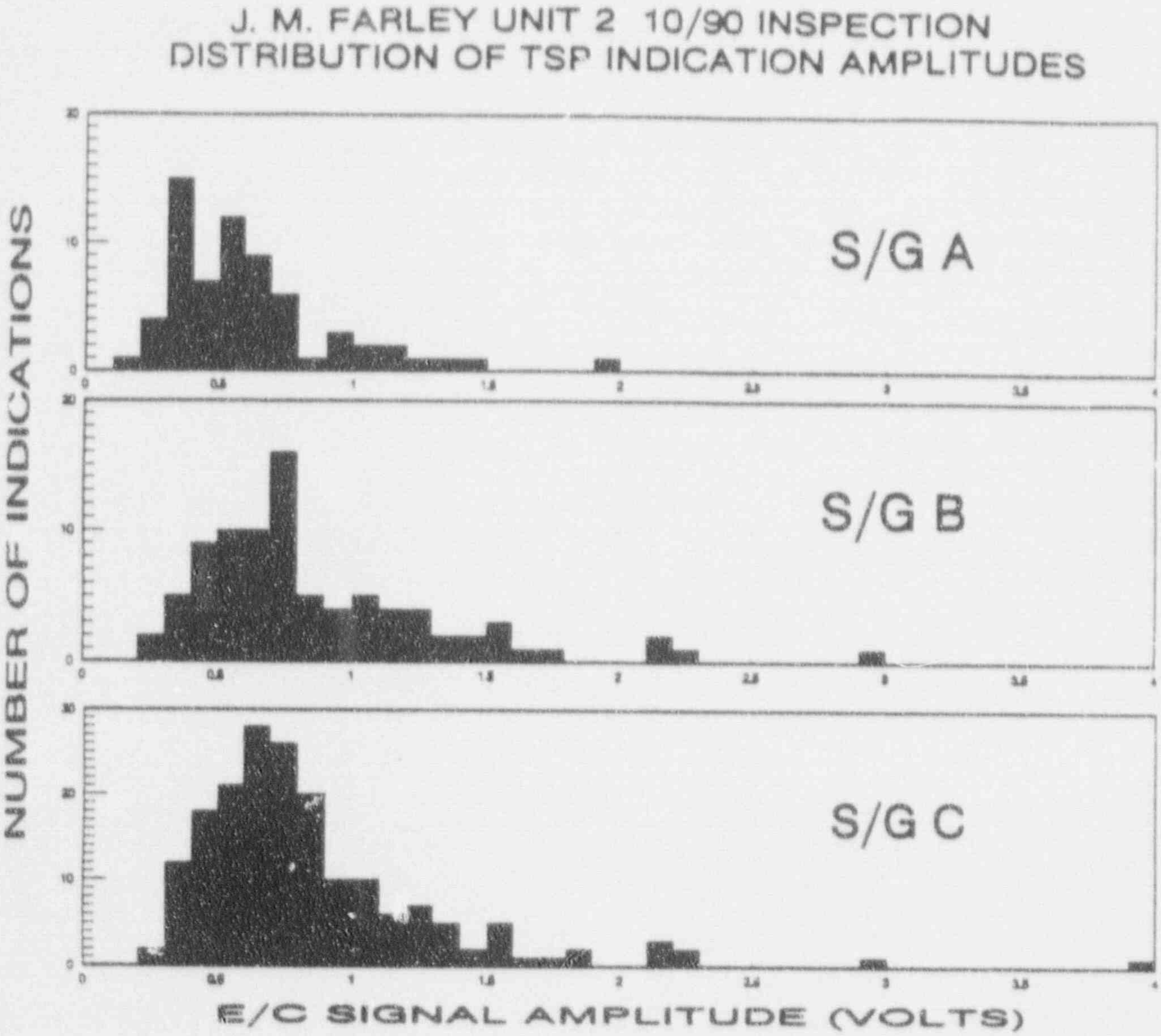


Figure 5-6

Support Plate Indication Progression in Farley-2 SGs

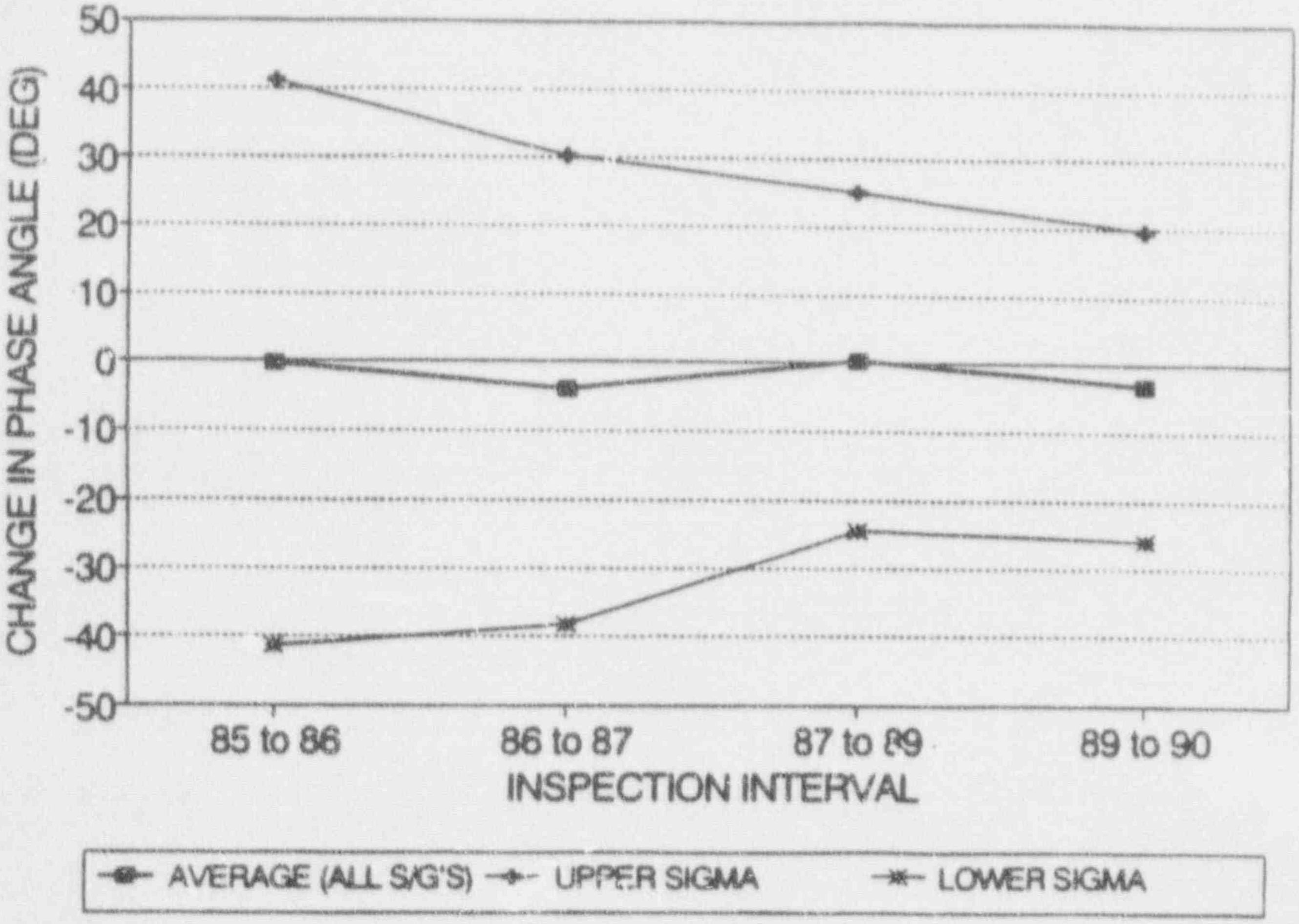


Figure 5-3

Average Growth in Depth for Farley-1 S/Gs Over Last 2 Cycles

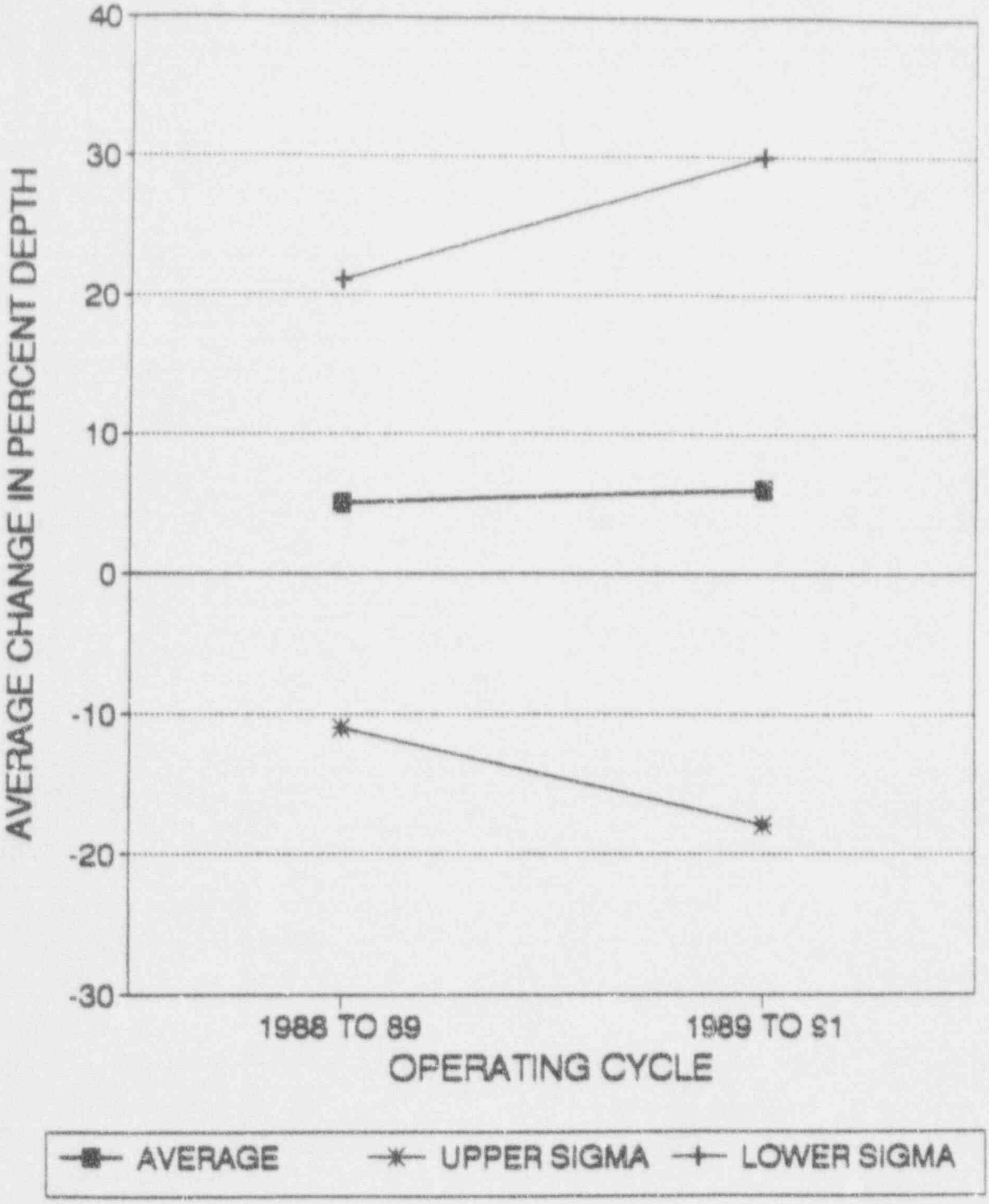
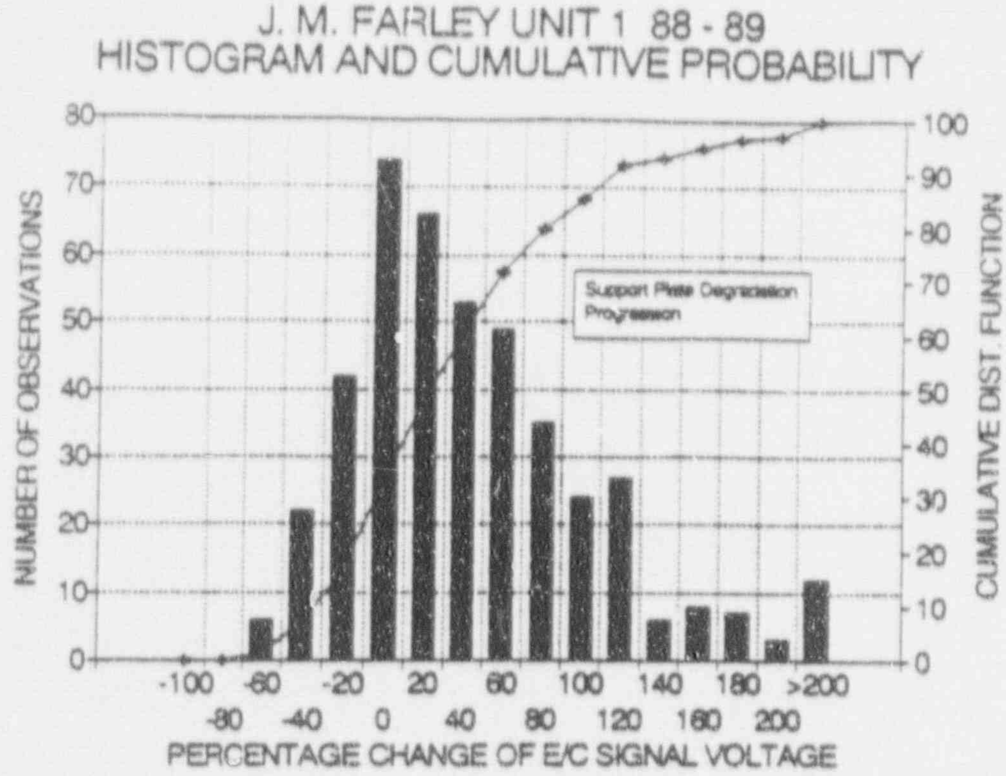


Figure 5-12

Histogram and Cumulative Probability of Voltage Growth in Farley-1 for Last Two Cycles



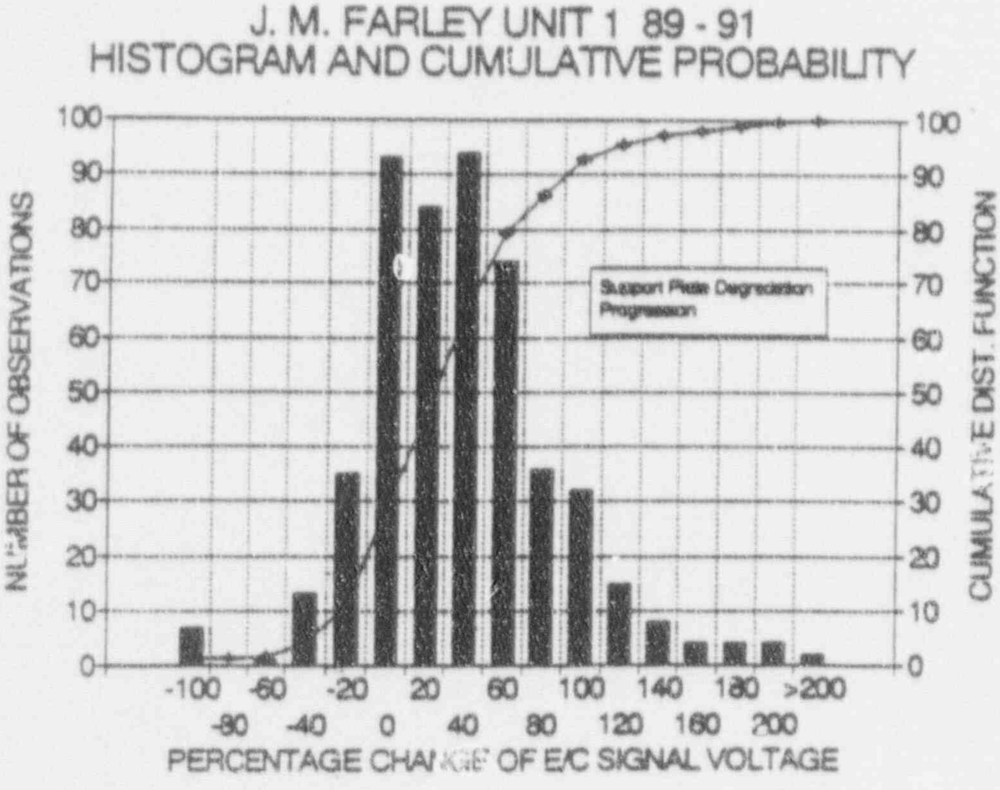
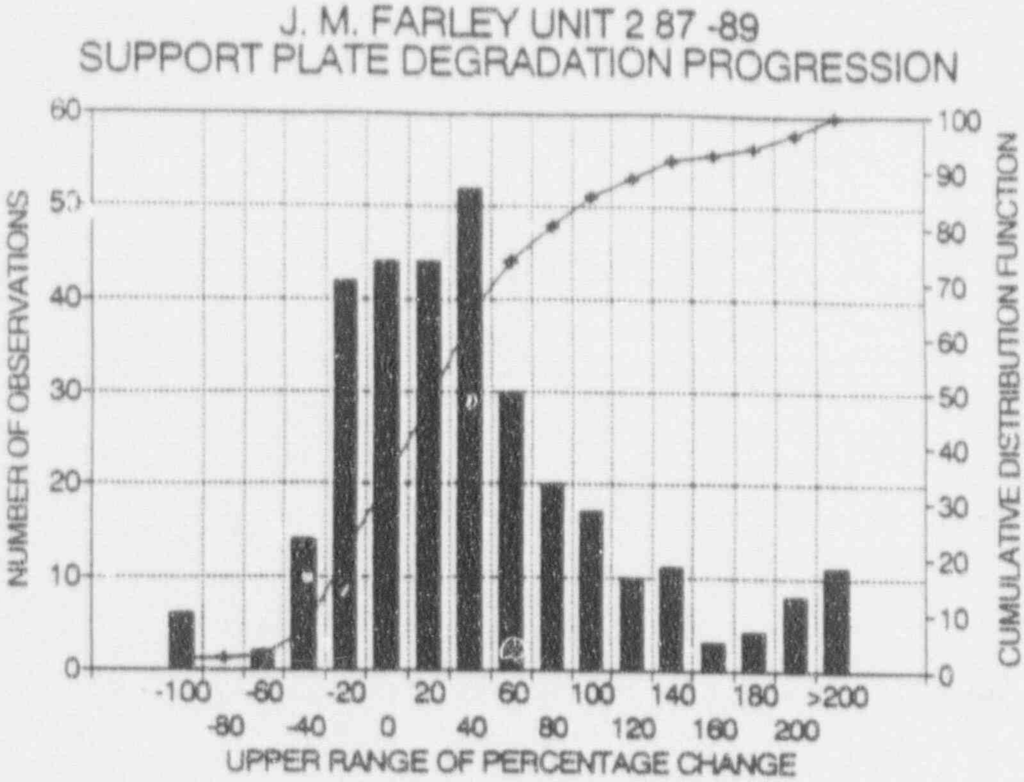


Figure 5-13

Histogram and Cumulative Probability of Voltage Growth in Farley-2 for Last Tv o Cycles



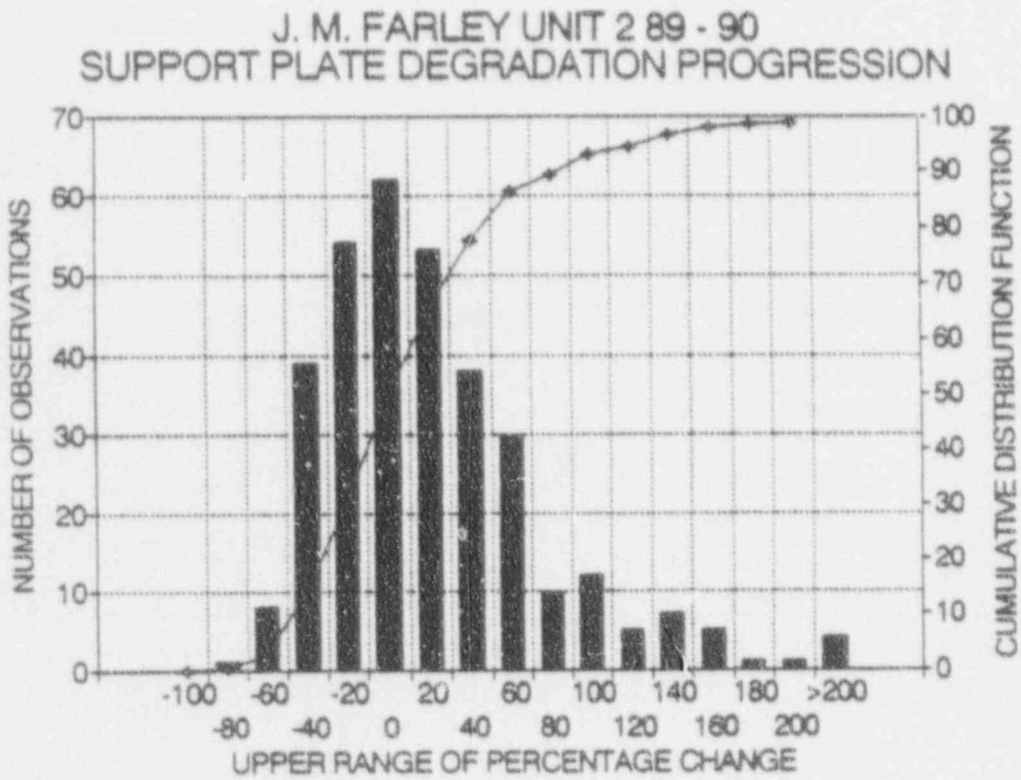
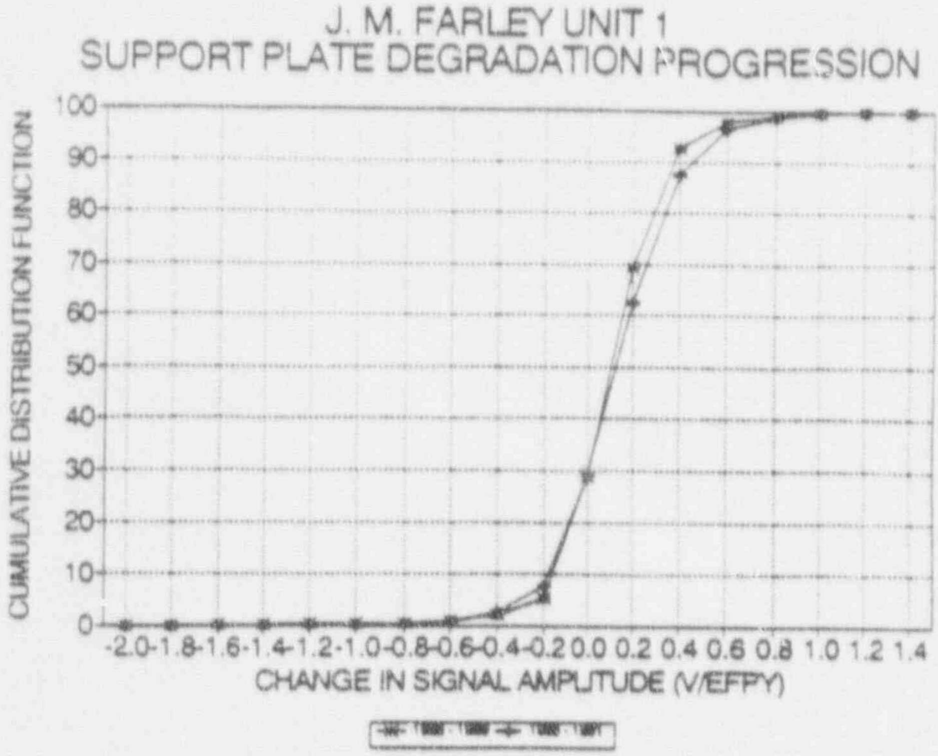


Figure 5-14

Cumulative Probability of Voltage Growth per EFPY for Farley Units 1 and 2



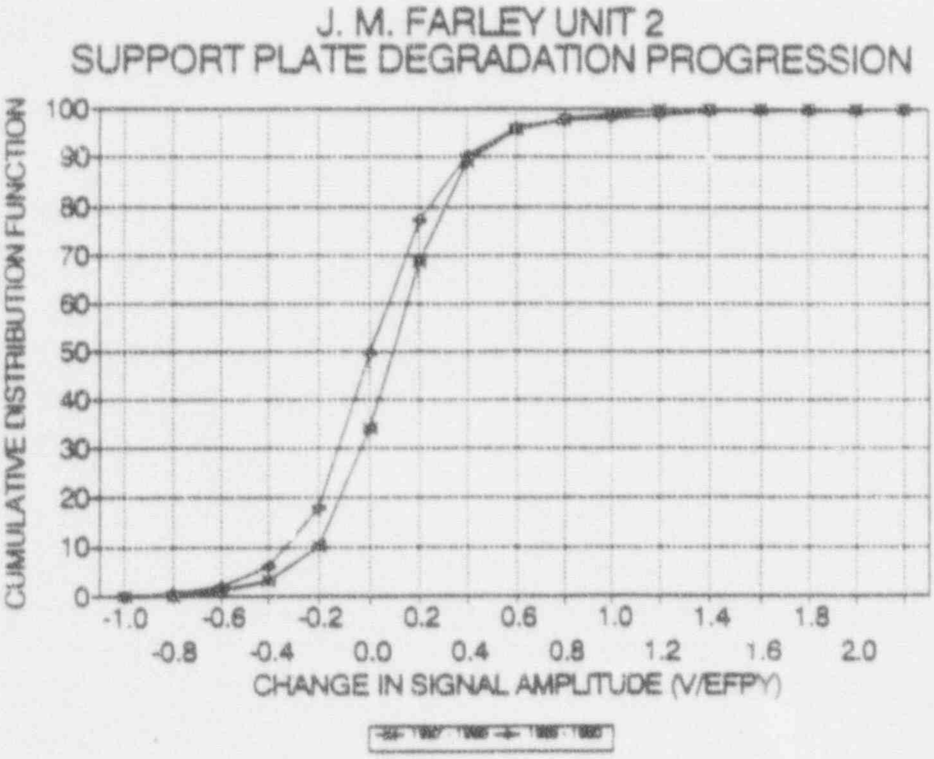


Figure 5-15

Historical Average Voltage Growth Trends in Farley SGs

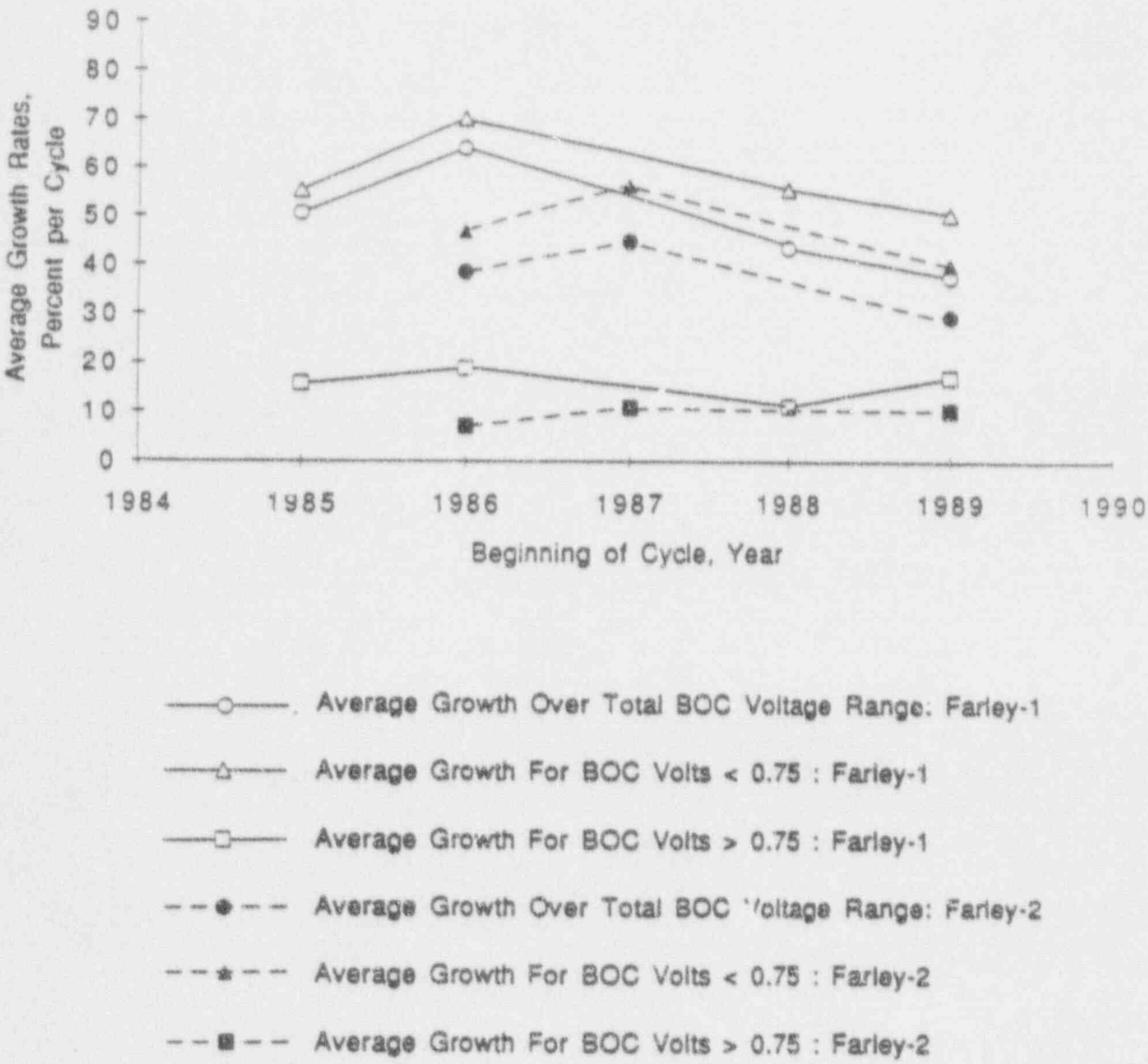
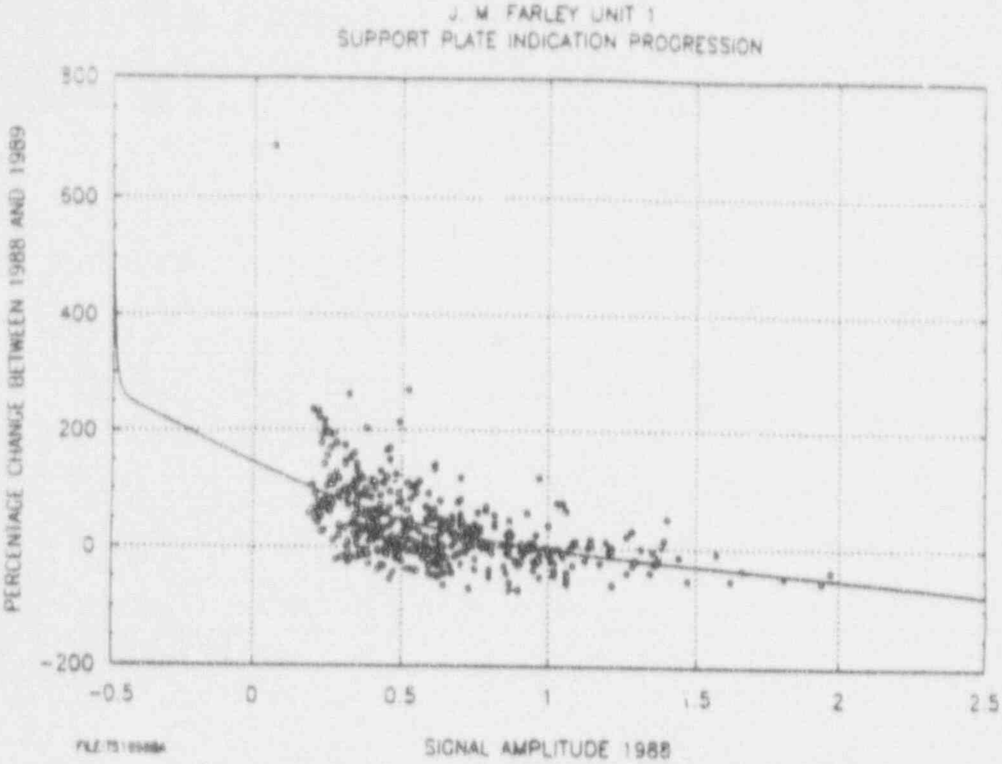


Figure 5-10

Scatter Plot of Voltage Growth in Farley-1 for Last Two Cycles



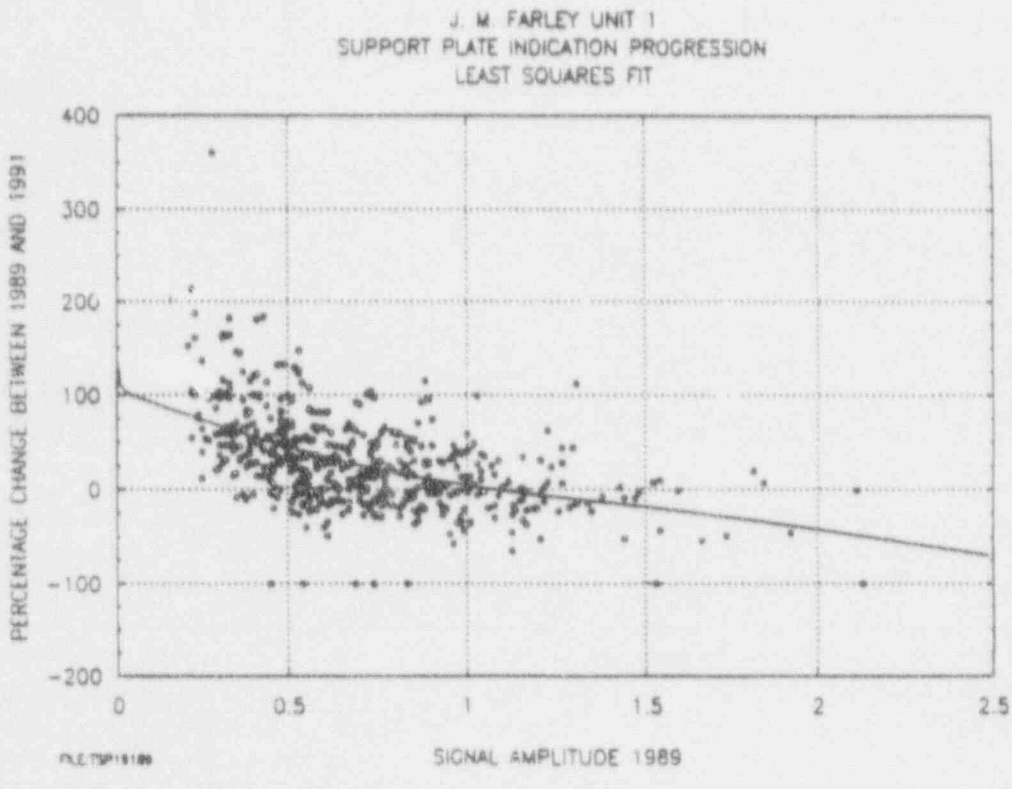
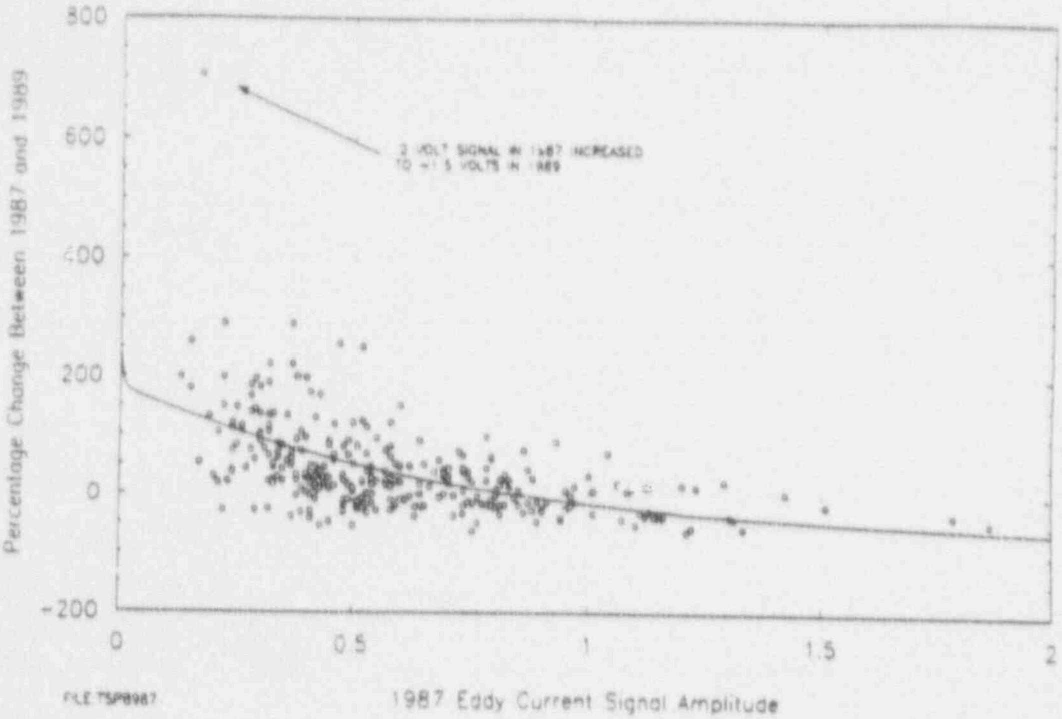
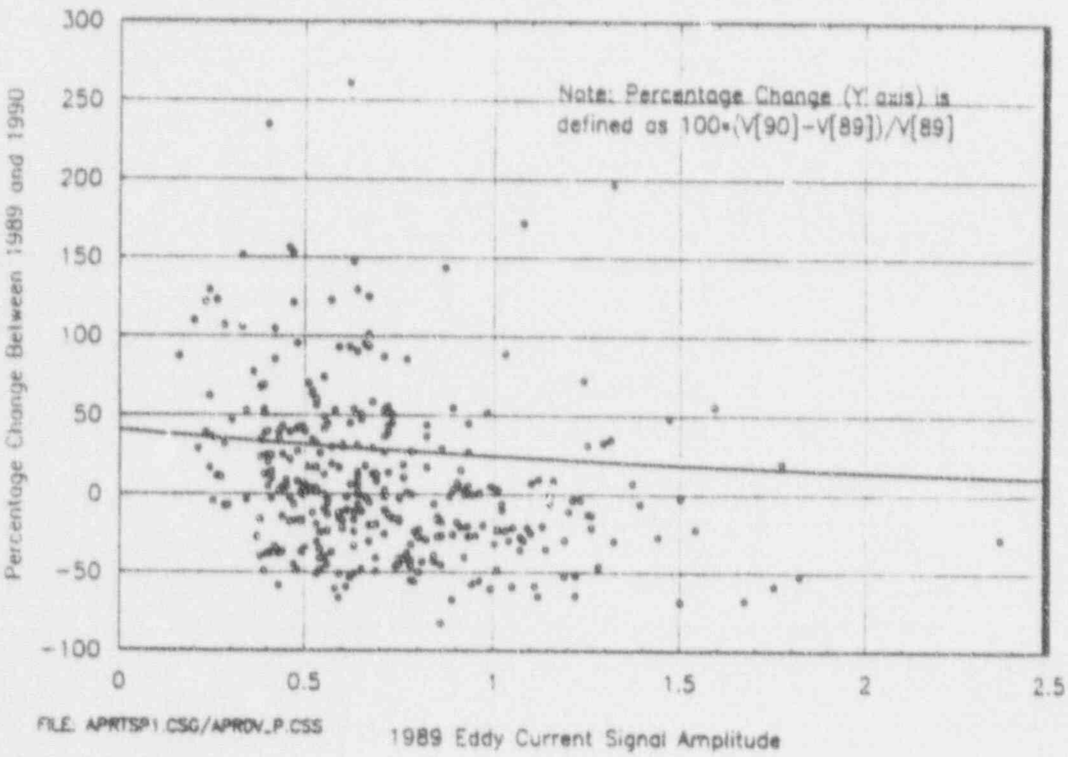


Figure 5-11

Scatter Plot of Voltage Growth in Farley-2 for Last Two Cycles





NDE EVALUATION
OF
TUBE SUPPORT PLATE ODSCC

November 20, 1991

1

IMAGE EVALUATION TEST TARGET (MT-3)

150mm

6"

1

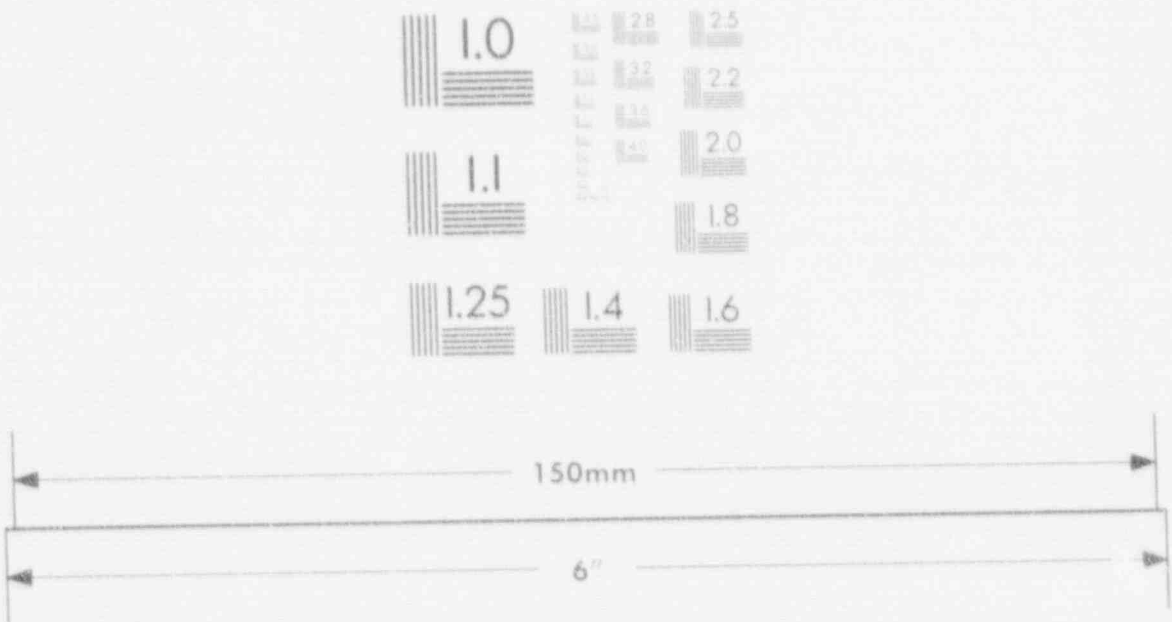
IMAGE EVALUATION
TEST TARGET (MT-3)

150mm

6"

1

IMAGE EVALUATION TEST TARGET (MT-3)



NDE EVALUATION OF TSP ODSCC
MAJOR CONSIDERATIONS

1 Bobbin probe voltage sensitive to crack length, crack depth, presence of ligaments, multiple parallel cracks, oxide coating on crack face

2 Variation of response from different probes from different manufacturers

3 Influence of TSP crevice condition on bobbin response. Possible conditions are open crevices, packed crevices, incipient denting, and fully developed denting.

4 Sensitivity of probe response to probe wear during inspections.

5 Variability among calibration standards, and normalization to frequency mix.

6 Use of RPC to augment bobbin probe inspections.

NDE CONSIDERATIONS

Identification of ODSCC Eddy Current Indications

Bobbin Coil Testing Guidelines

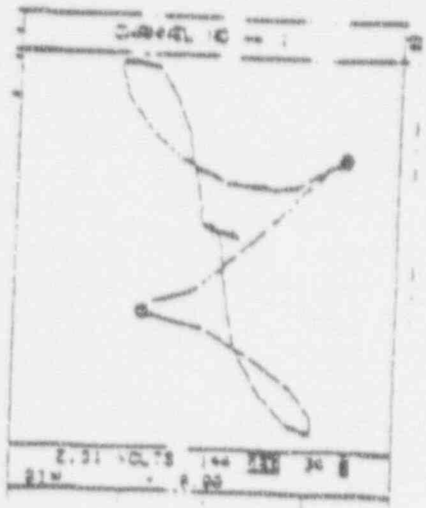
- Four (4) frequency testing for 7/8" 0.050" tubing
  - 400 kHz - prime test frequency
  - 200 kHz - enhanced detection frequency
  - 100 kHz - support plate mixing frequency
  - 10 kHz - Sludge and support plate characterization

- Support plate suppression mix
  - 400 kHz/100 kHz
  - eliminates carbon steel, magnetite, much of copper interference but not tube deformation

- Calibration
  - Field ASME standard with drilled holes lab-tested with standard used for EPRI Alternate Repair Limits program
  - 4 Flat-bottomed 20% holes give 2.75 volts
4 Through-wall drilled holes give 6.4 volts

- Amplitude Measurement
  - Flaw-like signal voltage determined from peak-to-peak displacement including multiple crack segments

400 kHz Primary Analysis Channel



(400/100) kHz Mix Analysis Channel

Figure A-1. ODSCC at TSP - Bobbin Coil Amplitude Analysis

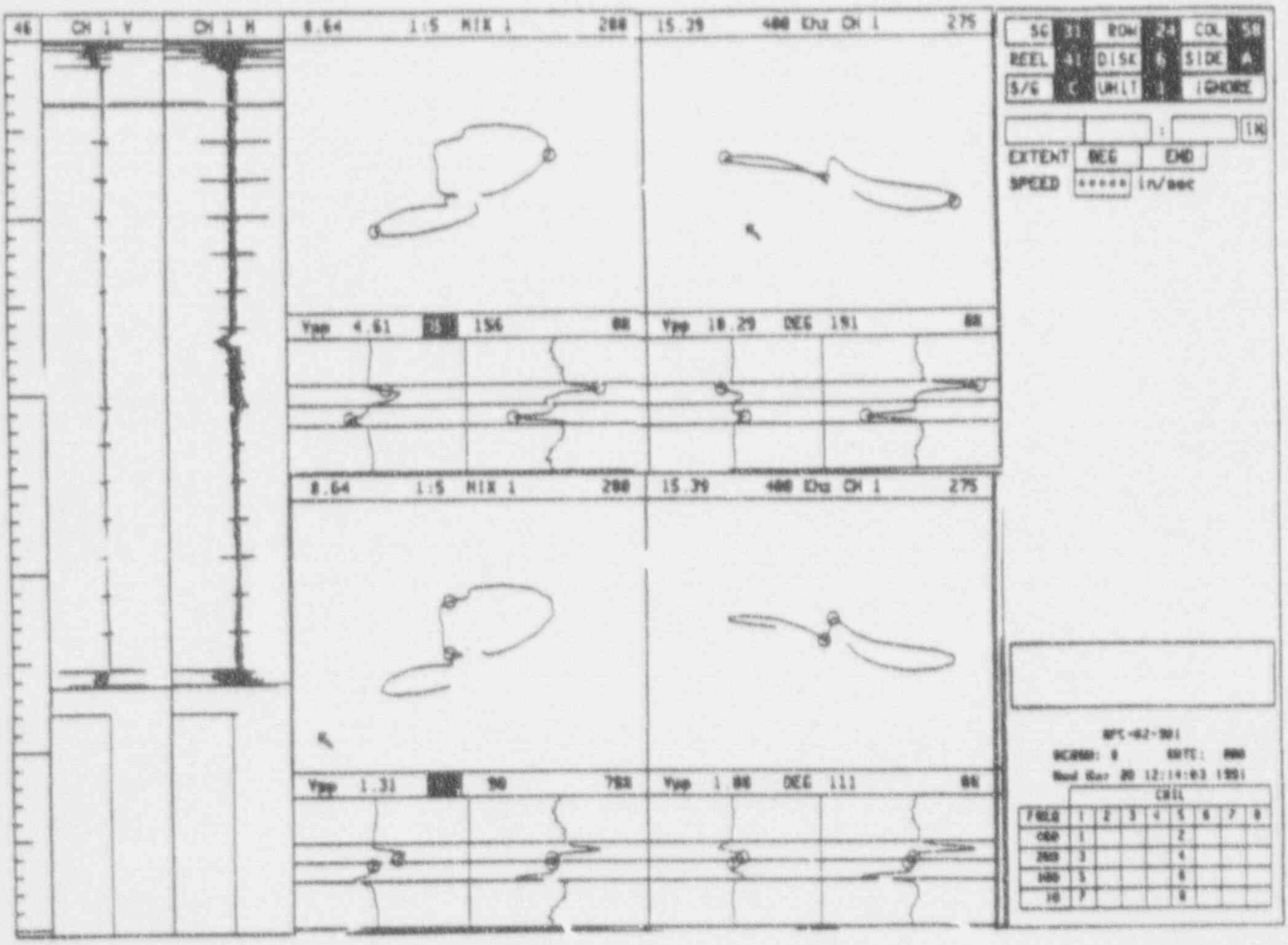


Figure A-6. Example of Bobbin Coil Field Data - Flaw Signals for ODSCC at Dented TSP Intersection

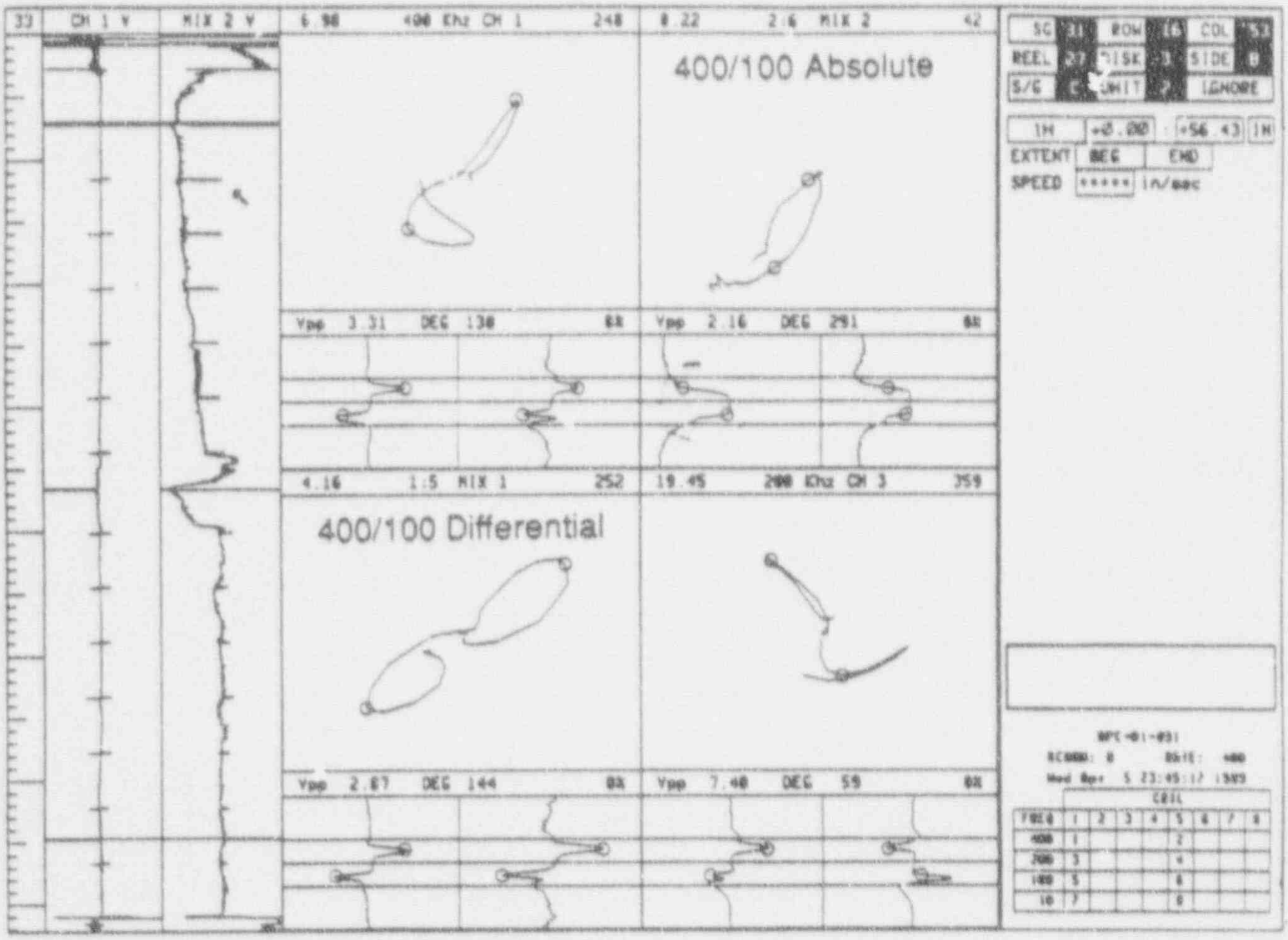


Figure A-4. Example of Bobbin Coil Field Data

RPC CHARACTERIZATION

- Indications identified with bobbin coil as exhibiting significant amplitude (e.g., ≥1.5 volts) will be examined with RFC to characterize degradation.

- Contour plots which contain axially-oriented linear arrays suggestive of ODSCC without circumferential, linear elements will be regarded as confirmatory of the mechanism.

- Crack signals not confined to the support plate dimensions and signals resulting from pitting, thinning or wear will be disposed of in accordance with existing Tech. Specs.

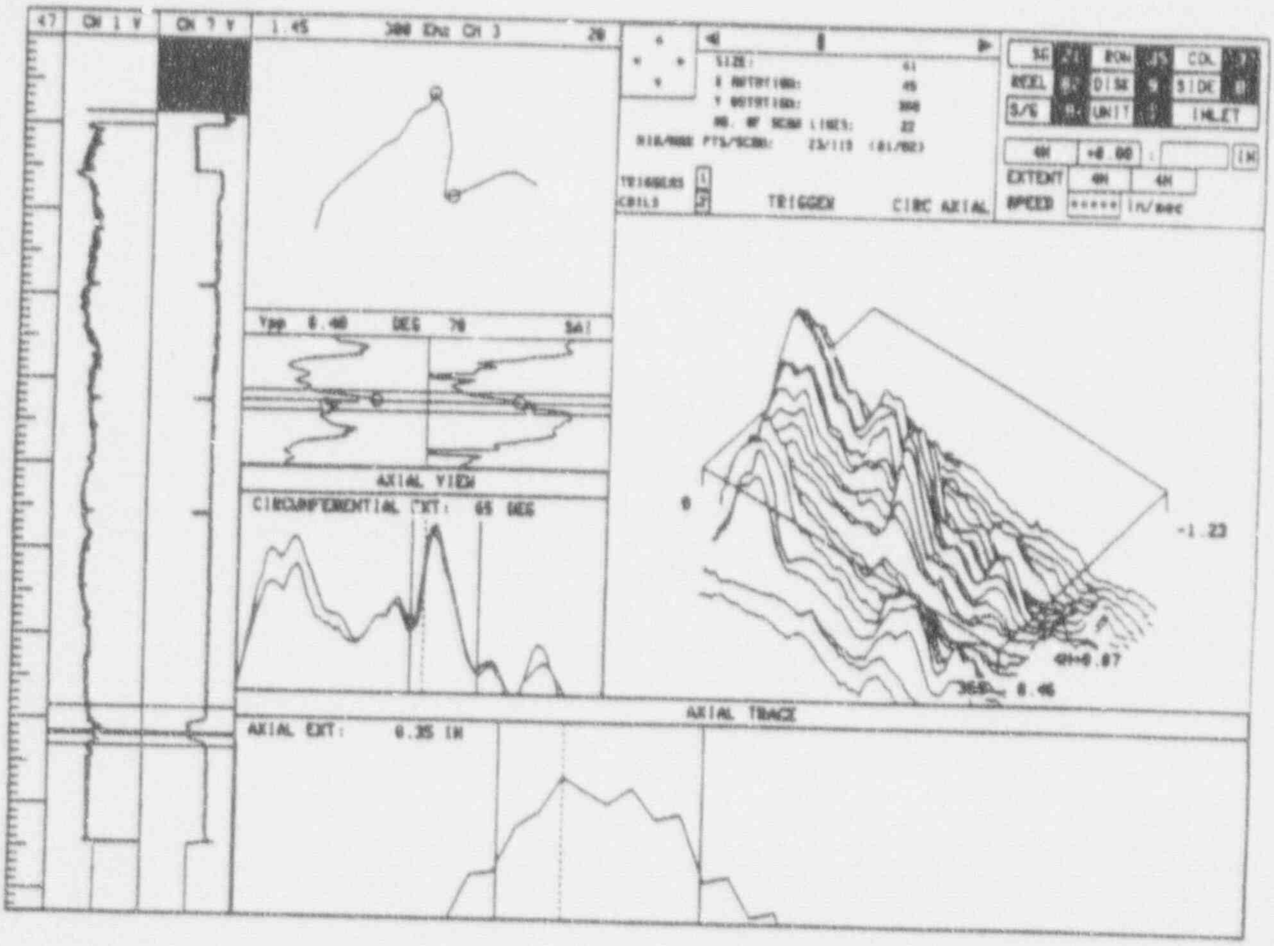
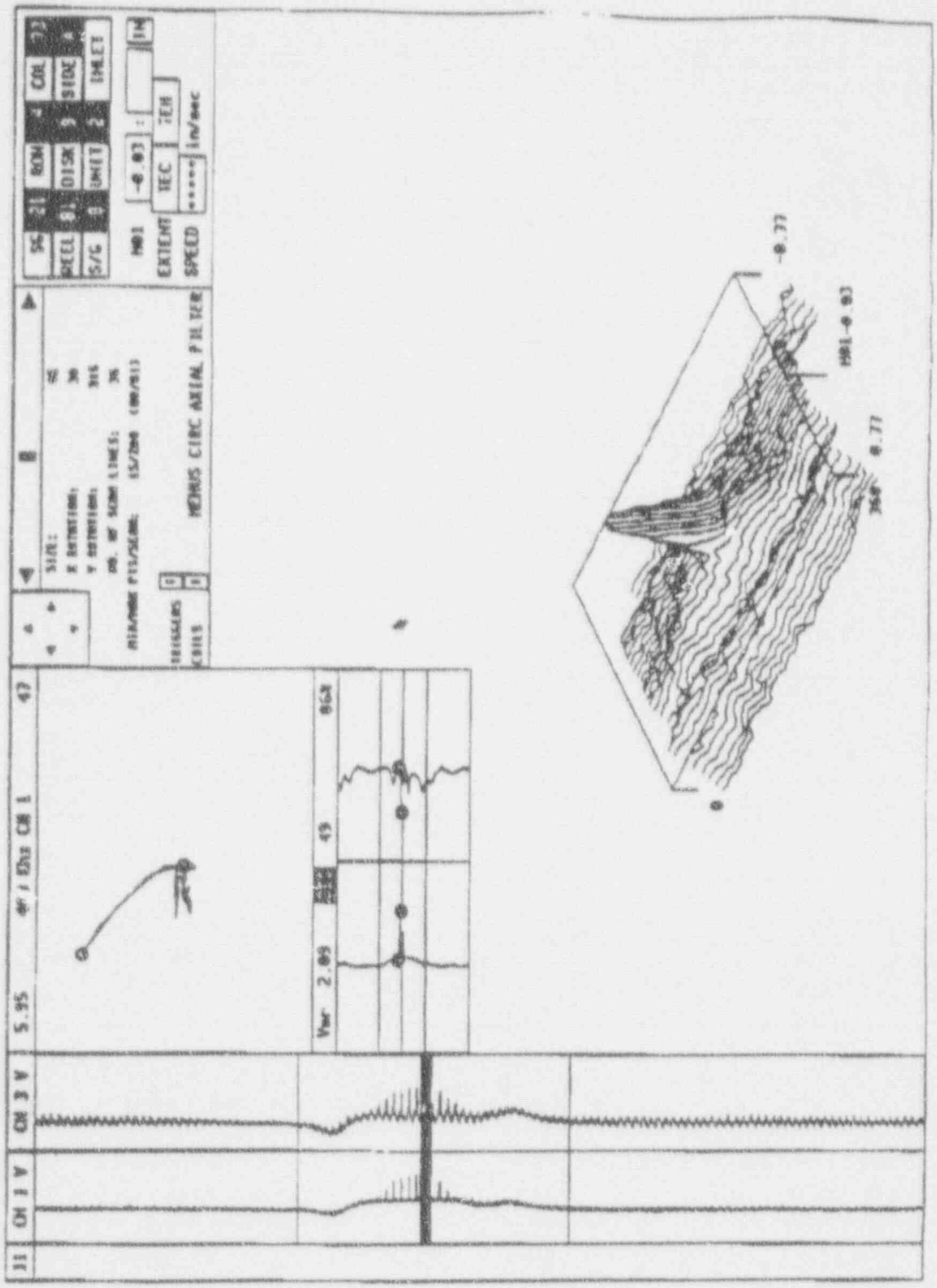


Figure A-14. Axial ODSCC Indications (MAI) at TSP - Farley Unit 1

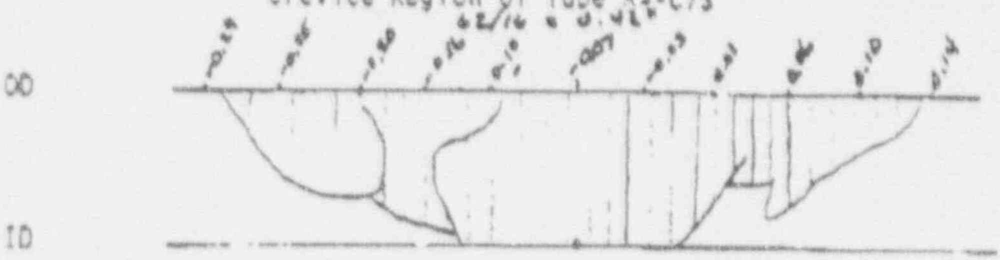
J.M.FARLEY 11/01/90 INLET UNIT: 02 SG: B REEL: _81_ PRI



AUG 2 '91 14:04

Figure 4-1

Description of OD Origin Corrosion at the First Support Plate Crevice Region of Tube R1-C73



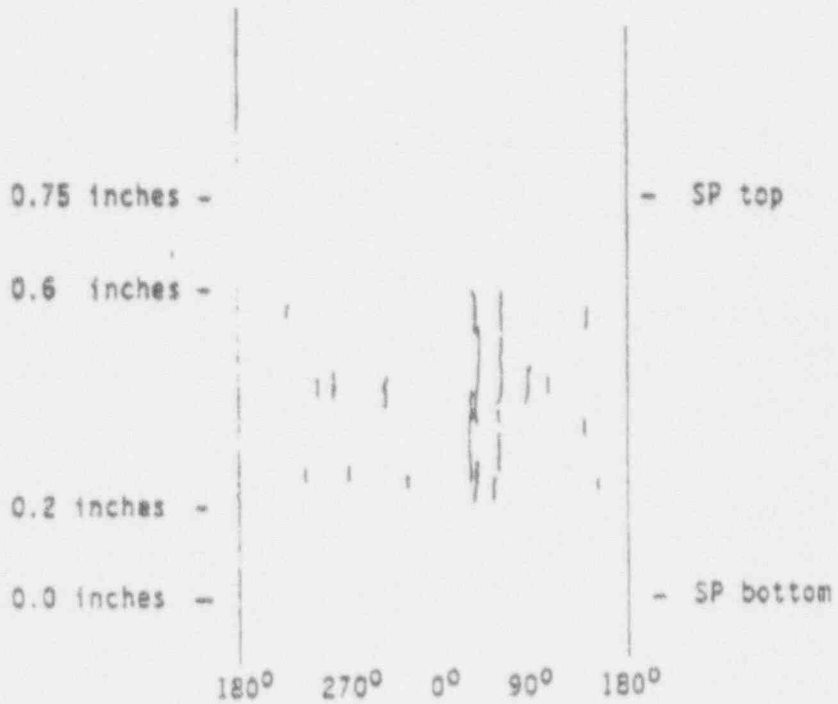
Sketch of Burst Crack

Macrocrack Length = 0.42 inches

Throughwall Length = 0.18 inches

Number of Microcracks = 4 (all ligaments with intergranular features)

Morphology = Intergranular SCC with some IGA characteristics (width of IGA 0.012 inches)



Sketch of Crack Distribution

NDE EVALUATION OF TSP ODSCC TYPICAL EDDY CURRENT SIGNAL AMPLITUDES

Type of Degradation	Voltage Examples
Wastage Characterized by machined rectangular flaws	4.5 to 7.5 V @ 60% depth
Fretting Characterized by machined tapered flaws	~10 V @ 60% depth
Pitting Single drilled hole simulation	~7.5 volts for 60 mil dia., 100% deep ~5.3V for 109 dia., 60% deep ~2V for 30 mil dia., 100% deep
Pitting Multiple pits	~2V multiple indications for multiple pits up to 60 mils dia., and 64% deep

NDE EVALUATION OF TSP ODSCC AXIAL SLOT TEST DATA

1. Both bobbin and RPC voltage amplitudes increase sharply with axial crack length to ~ one inch, 100% deep slots
2. Voltage increase is much smaller for partial depth OD axial slots. Voltage does not increase significantly with length for slots >1/4" long.
3. Signal amplitude dominated by 100% deep portion of slot
4. Bobbin coil voltage function of spatial separation of parallel axial slots. Closely spaced slots show insignificant voltage increase over single slot
5. Correlation exists between RPC and bobbin voltages for single slots. However, bobbin voltage increases with multiple slots; RPC voltages can be isolated on single slots
6. Presence of ligament between axial slots reduces signal voltage
7. Signal amplitude responses to degradation, on the order of the voltage plugging limits, are not significantly dependent upon location of crack within TSP
8. Slot data represents upper bound on signals expected from cracks of similar length and depth.

Figure 8-1

Voltage Sensitivity to Crack Network Morphology

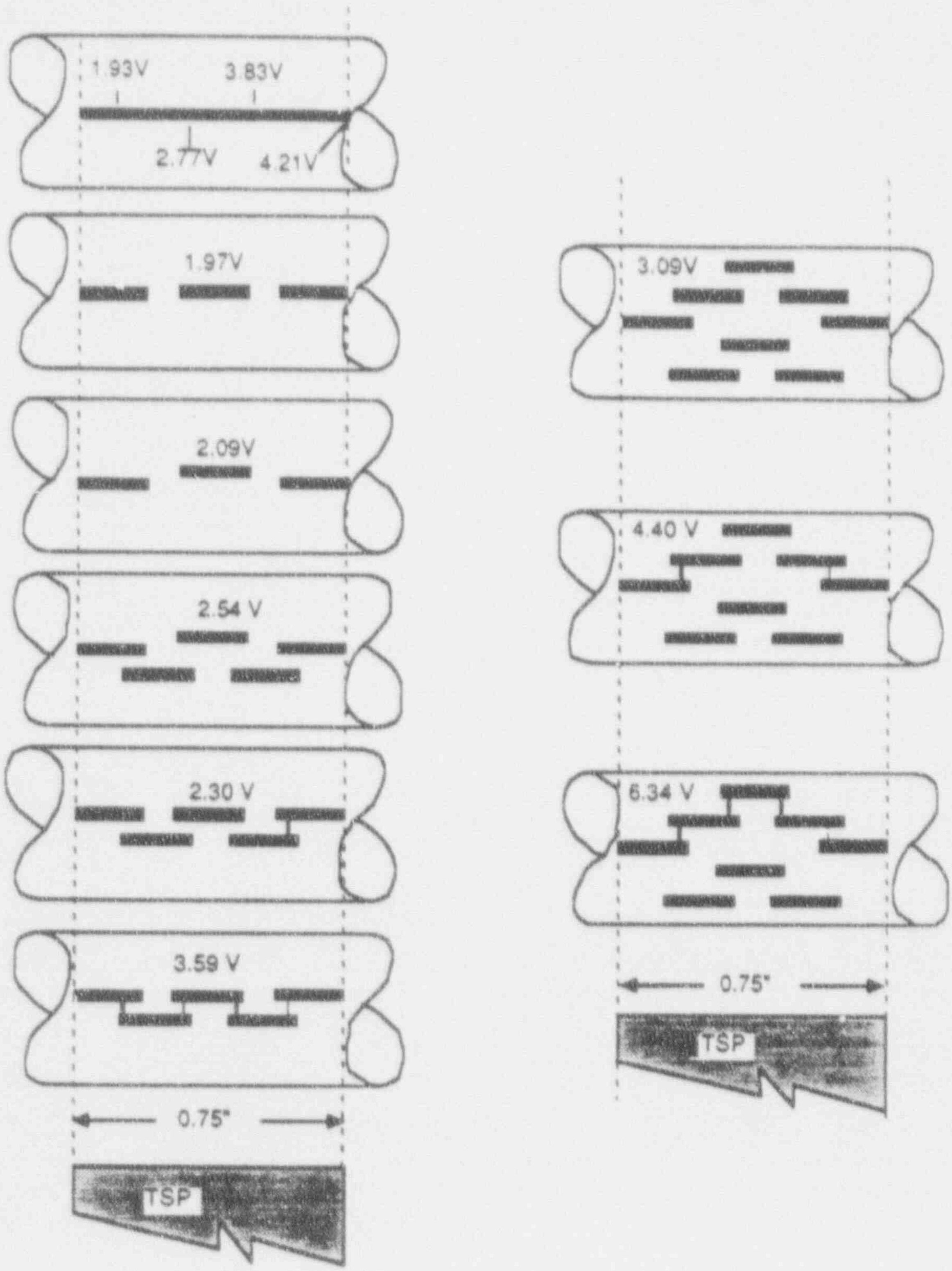


Figure 8-2

Bobbin Coil Voltage Dependence on Slot Length and Depth

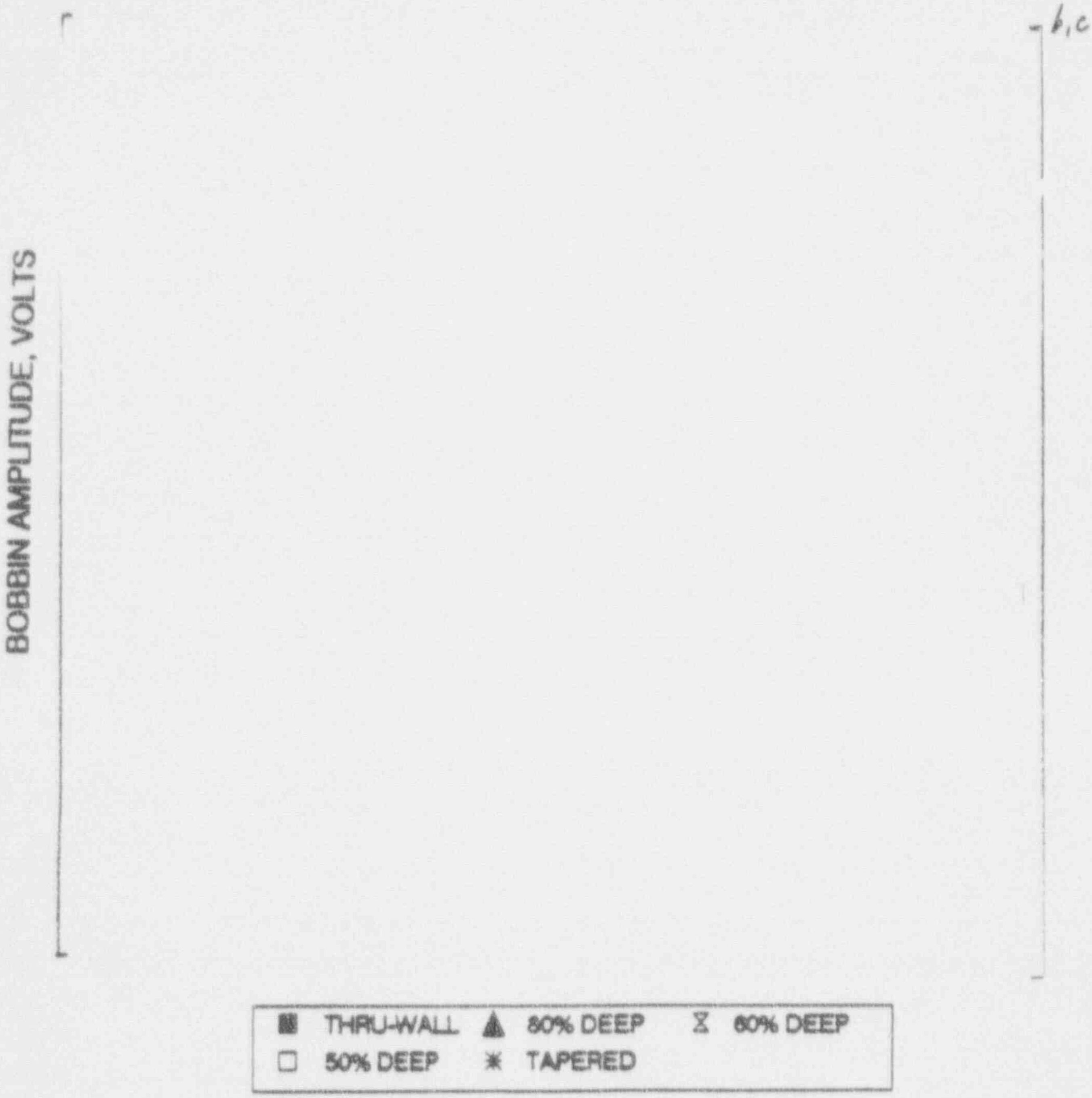


Figure 8-3

Bobbin Coil Voltage Increase due to Tapers at Ends of Through Wall Axial Slots

b,c

% INCREASE OF TAPERED OVER THRU WALL

THROUGH WALL SLOT LENGTH, INCH

Figure 8-6

Voltage Dependence on Ligament Size Between Axial Slots

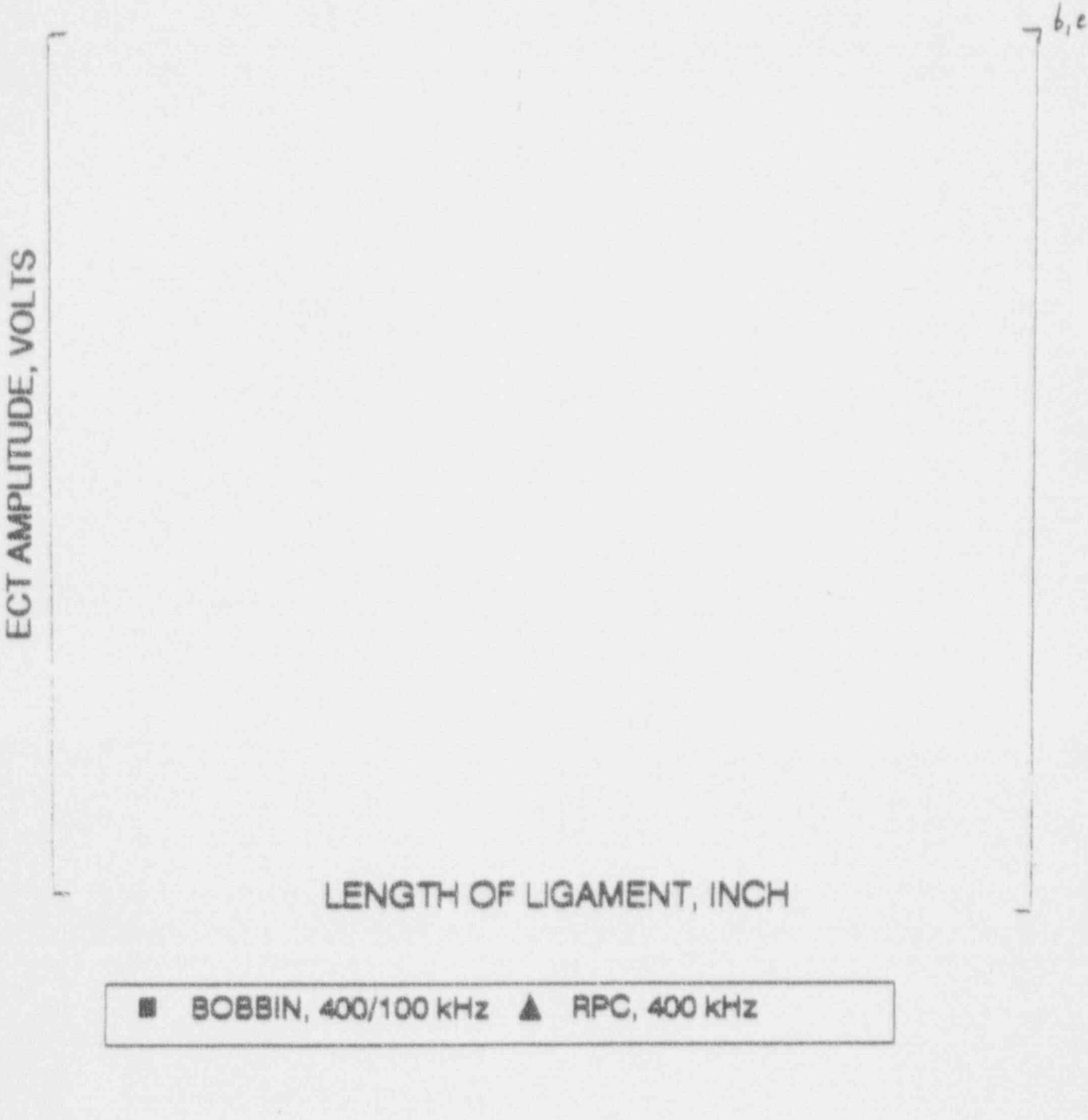


Figure 8-7

Bobbin Coil Voltage Dependence on Circumferential Spacing Between Axial Slots

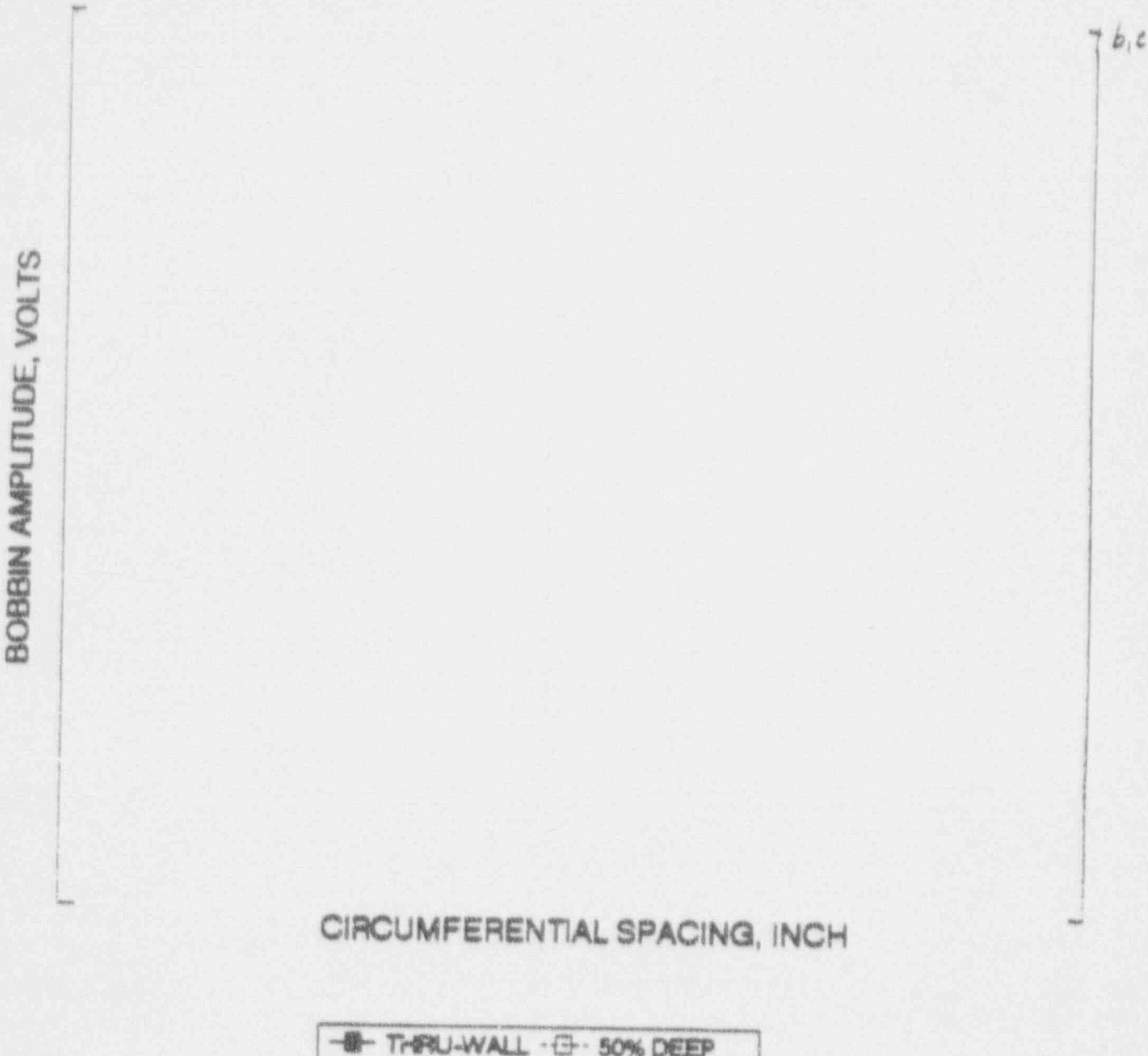
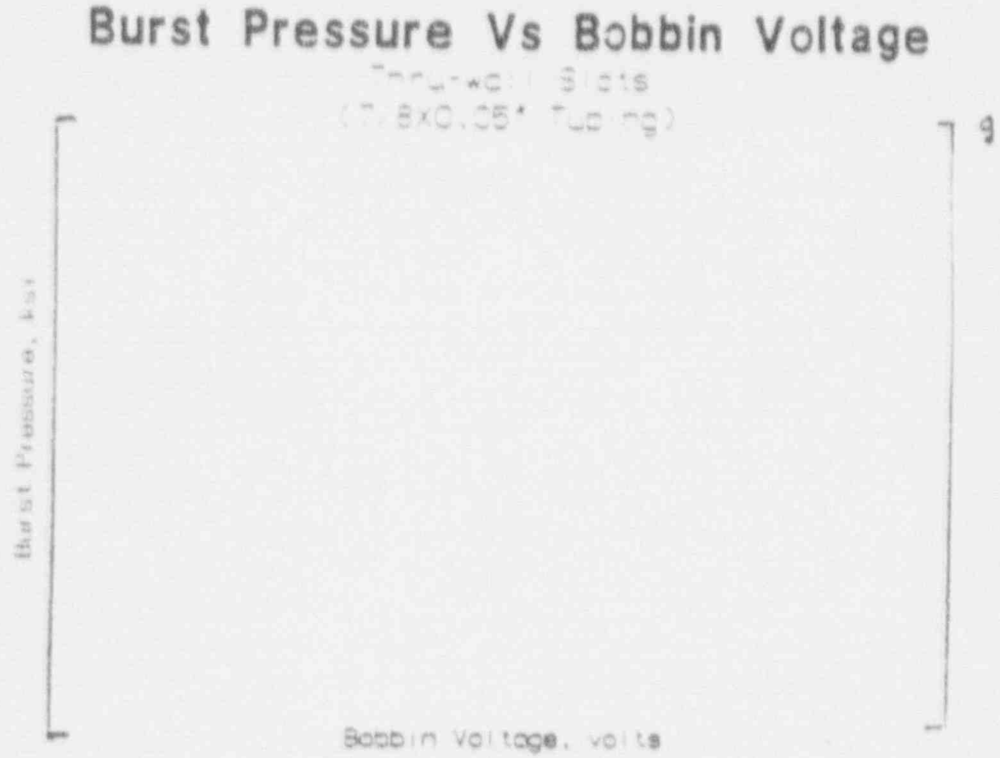


Figure 8-8

Burst Pressure vs. Voltage for EDM Slots



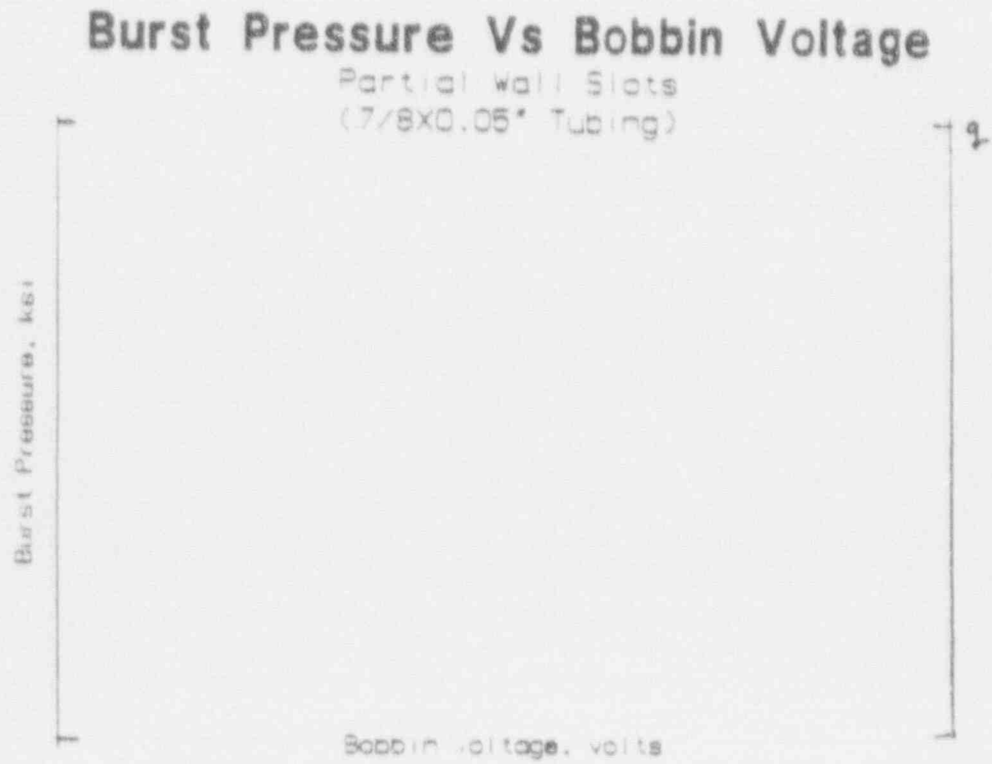


Figure 8-9

Typical Bobbin Coil Voltage vs Depth for Simulated Volumetric Tube Degradation

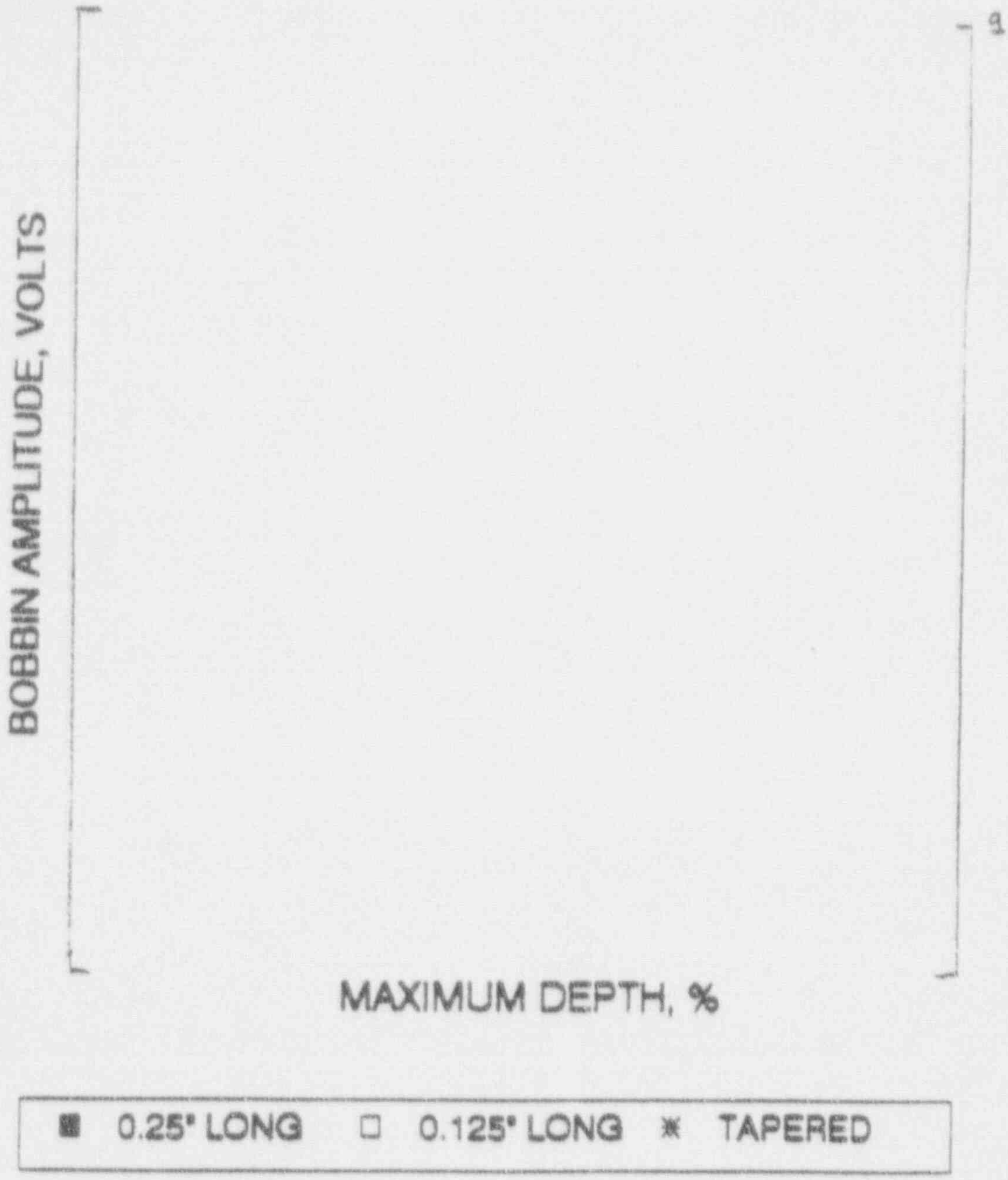


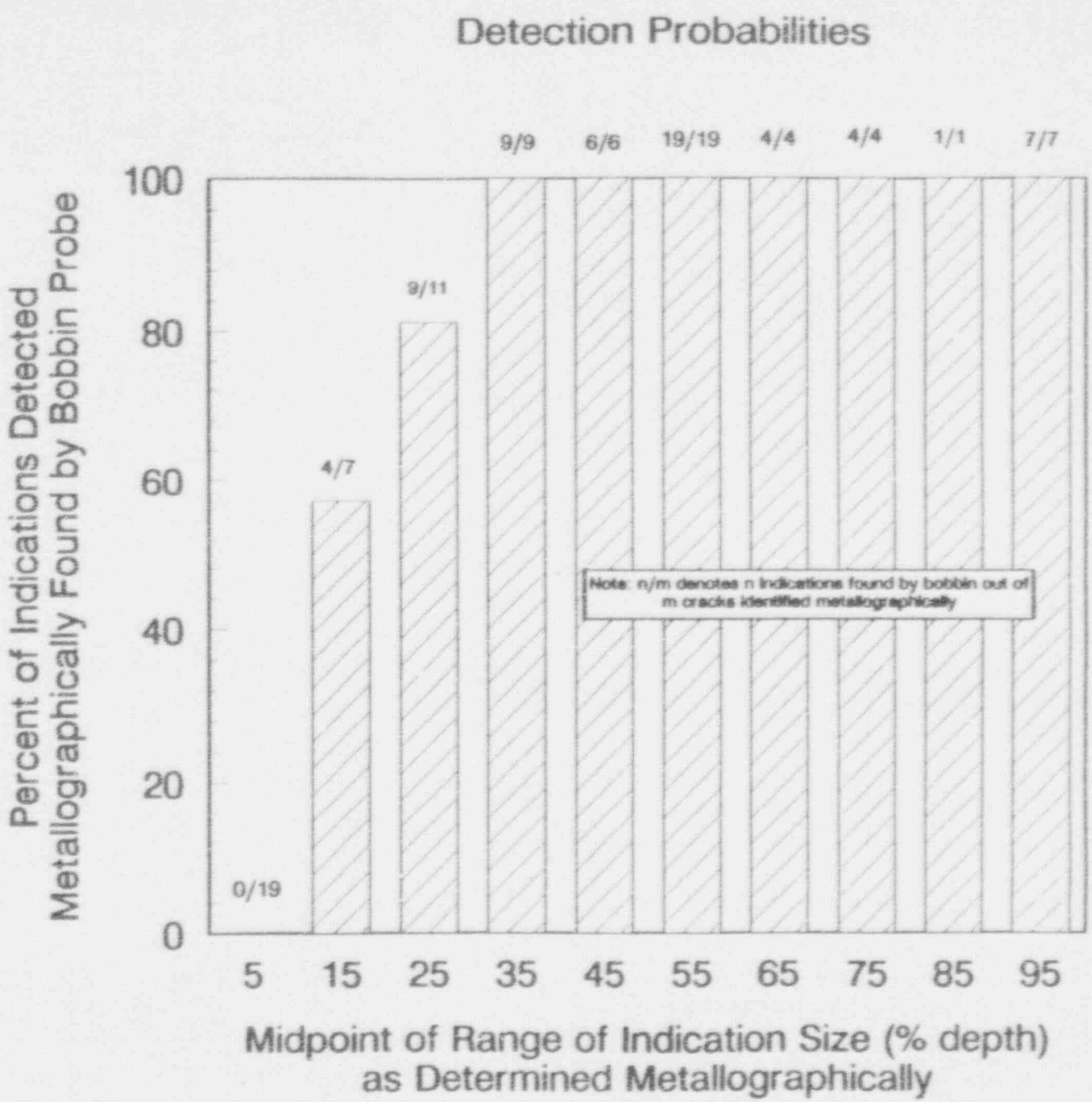
Figure 8-10

Bobbin Coil Voltage Dependence on Diameter of Through Wall Holes

b,c

BOBBIN AMPLITUDE, VOLTS

HOLE DIAMETER, INCH



Detection Probabilities
9/9
6/6
19/19
4/4
4/4
1/1
7/7
9/11
4/7
0/19
100
80
60
40
20
0
Percent of Indications Detected
Metallographically Found by Bobbin Probe
Note: n/m denotes n indications found by bobbin out of m cracks identified metallographically
5
15
25
35
45
55
65
75
85
95
Midpoint of Range of Indication Size (% depth)
as Determined Metallographically

Figure 8-4

RPC Voltage Dependence on Slot Length and Depth

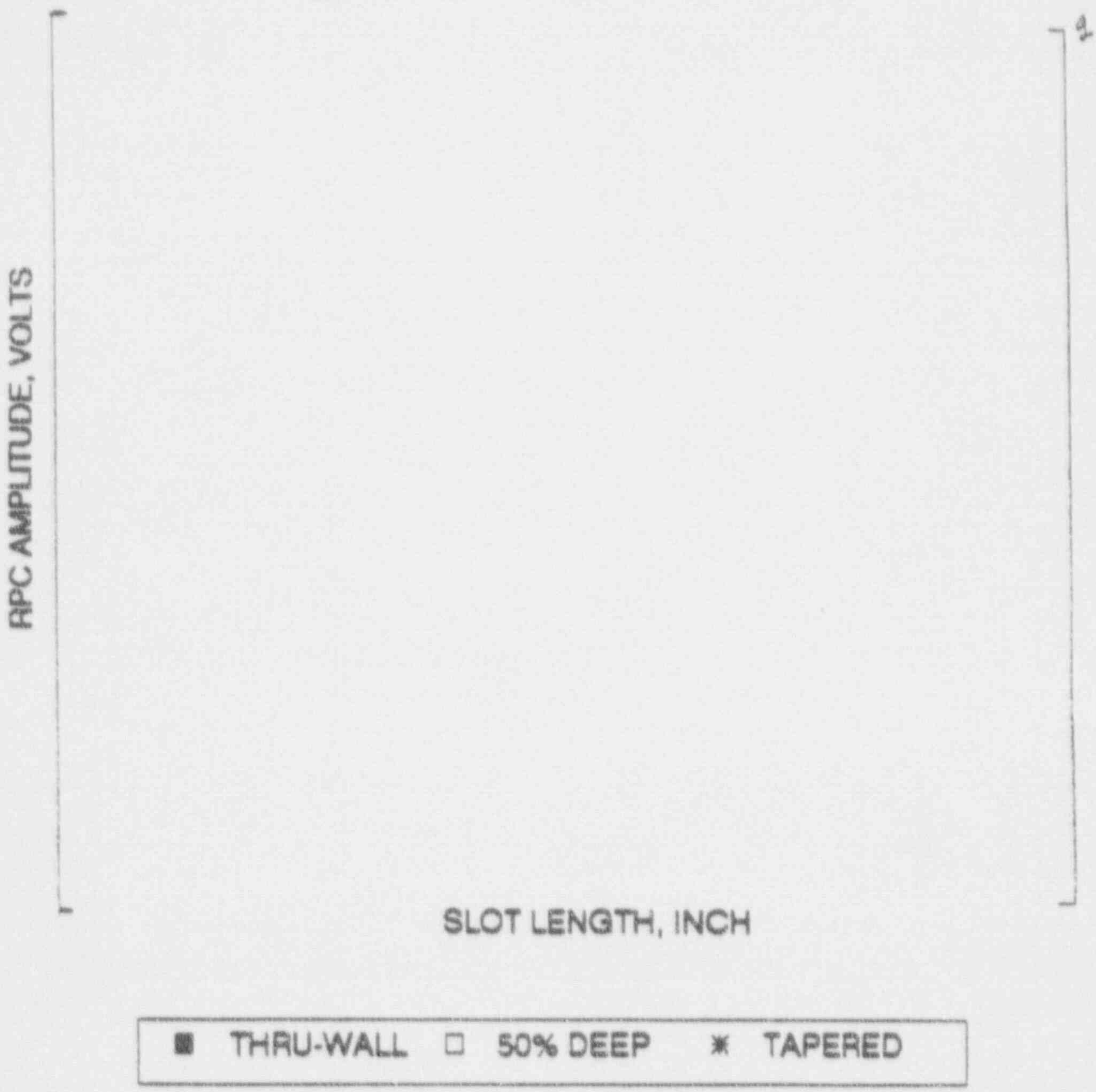
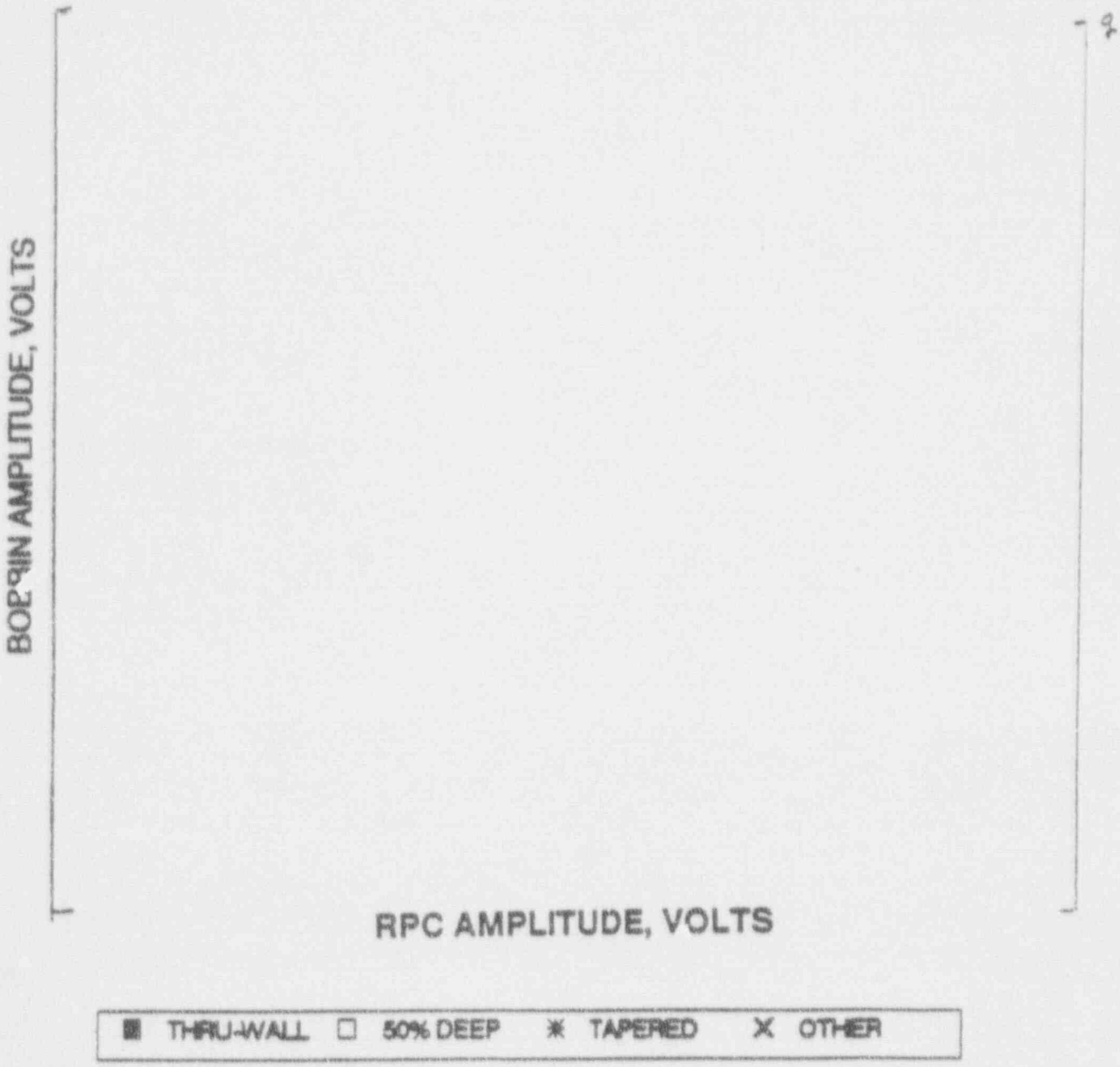
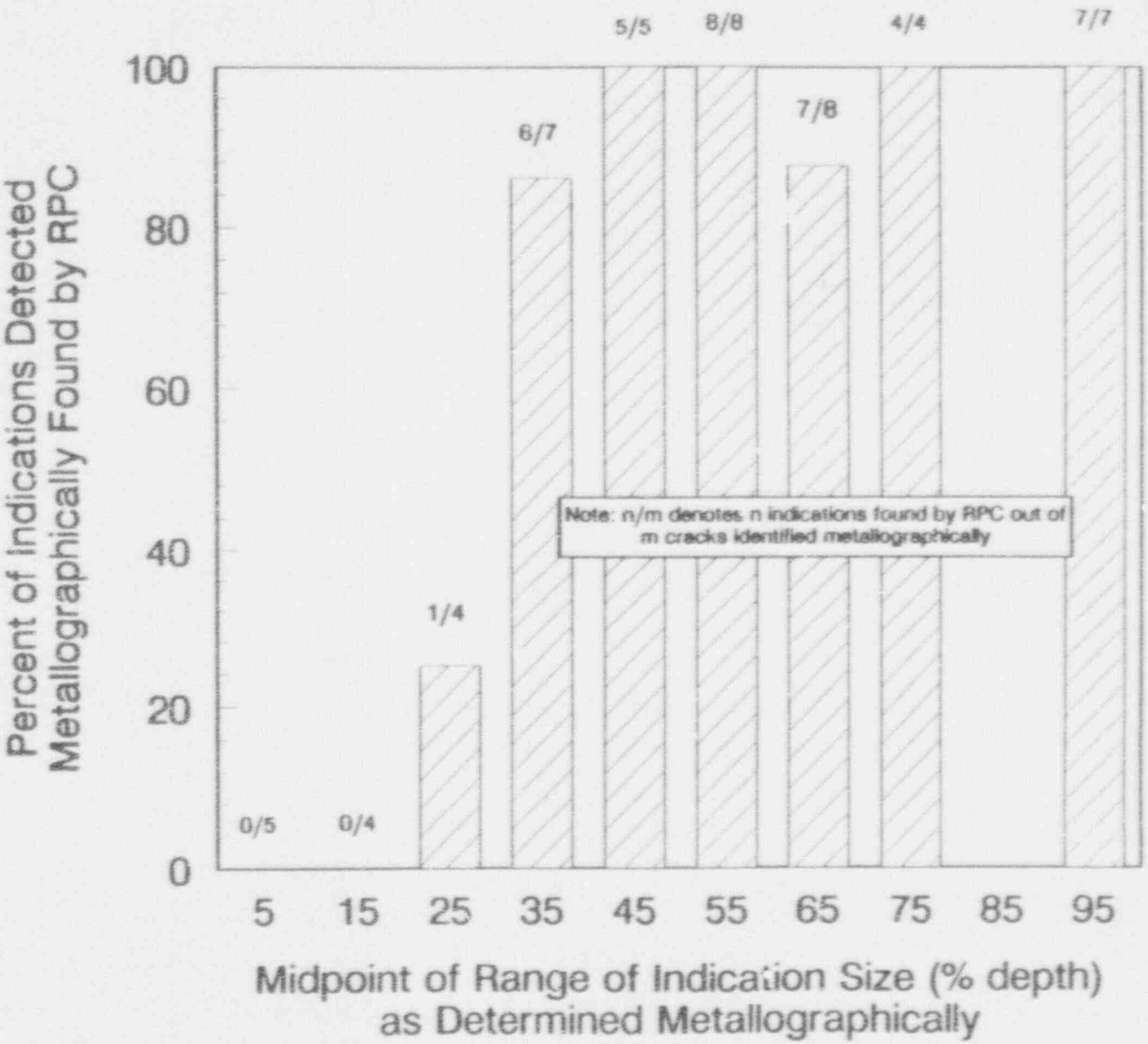


Figure 8-5

Correlation of Bobbin Coil to RPC Voltage



Detection Probabilities



IGA DETECTION - HISTORICAL

- IGA was first noted by tube pull in the tubesheet crevice of [ ][9] tubes.
    - Deep IGA was found in the entire tubesheet crevice
- It was not reported in the field by E.C. inspection.
    - A review of the 100 kHz absolute data produce "drift" indicative of IGA along the entire tubesheet crevice.
- At [ ][9] IGA detection at the top of the tubesheet was complicated because of presence of dent at the top of tubesheet.
    - A review of 100 kHz absolute data showed indications of tube degradation at the top of tubesheet future tubes.
- Detection of IGA in the tubesheet crevices at [ ][9] plant is routinely performed using the absolute bobbin mode.

IGA DETECTABILITY

- Field and Lab. experience shows that the threshold of detectability of volumetric IGA in the support plate intersection using bobbin probe is in the range of 20% depth.

  Examples:
  [ ][g] - detected at ~25% depth
  [ ][g] - detected at ~15% depth

- The 400/100 diff. mix channel was used for this detection although 400 kHz differential channel alone was enough for the case of [ ][g] which has egg crate supports.

- In cases where both SCC and volumetric IGA are present, SCC is often found to extend beyond the IGA--and the SCC signal may dominate.

- Work on samples with Lab. induced IGA confirms that the detection threshold in ~20% depth.
  - The Lab. samples had ~4" long sections with uniform IGA and one had to use absolute mode for this work.
  - The absolute mode data is easily convertible to differential mode data for comparison purposes.

Figure 8-12a

Bobbin Data and Typical Metallographic Sections of Simulated IGA Specimens Using Sensitized Alloy 600MA Tubing

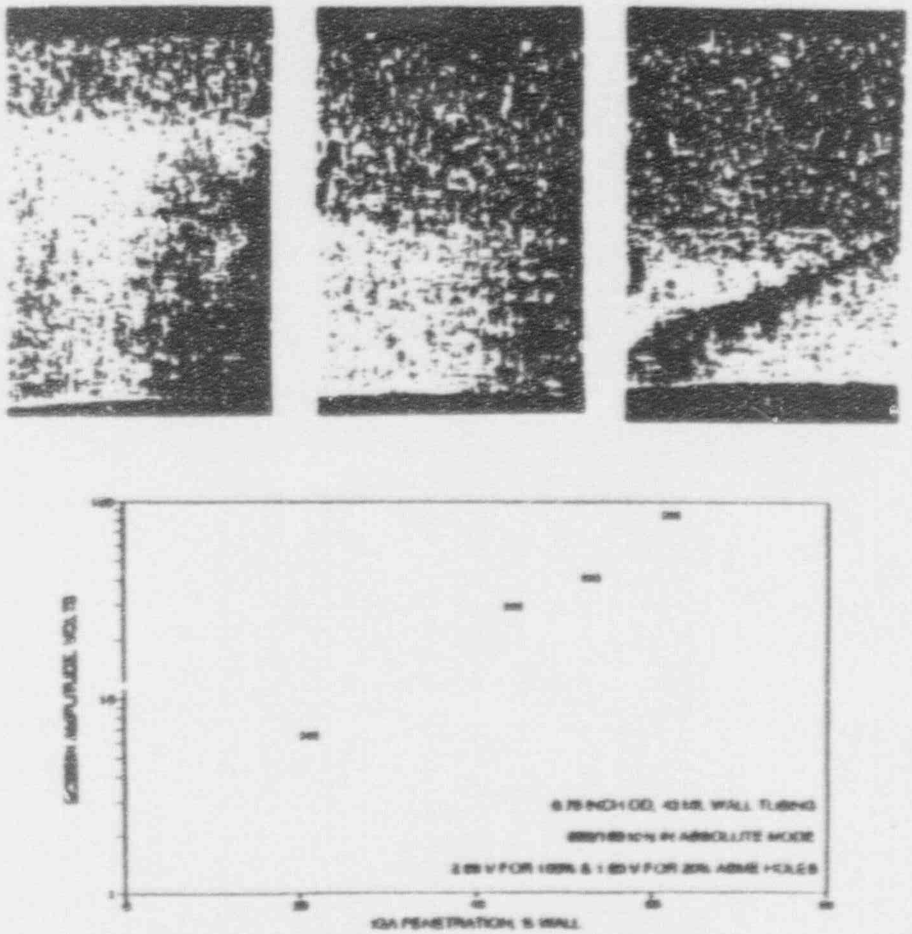


Figure 8-12b

Bobbin Data from Simulated IGA Specimens Using Non-Sensitized Alloy 600MA Tubing

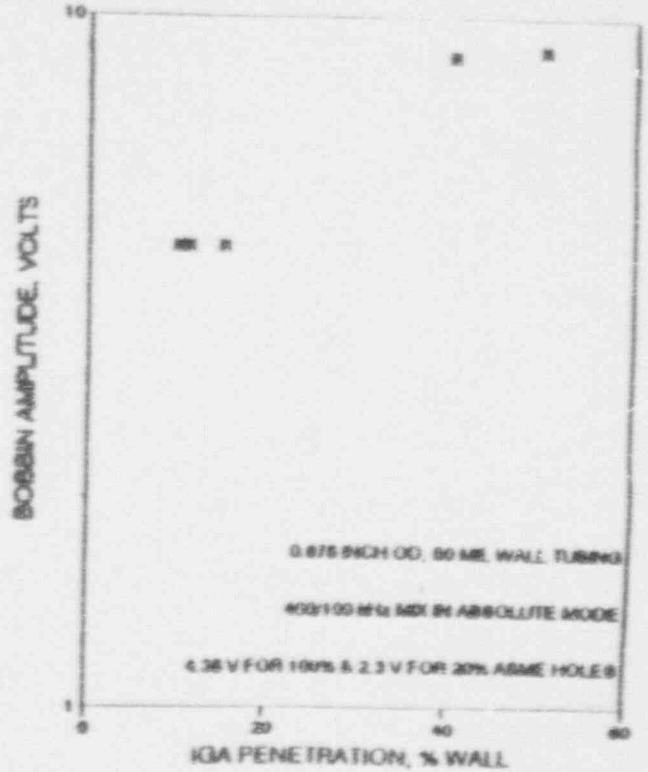


Figure 8-12. Bobbin Coil Results for Laboratory IGA Specimens

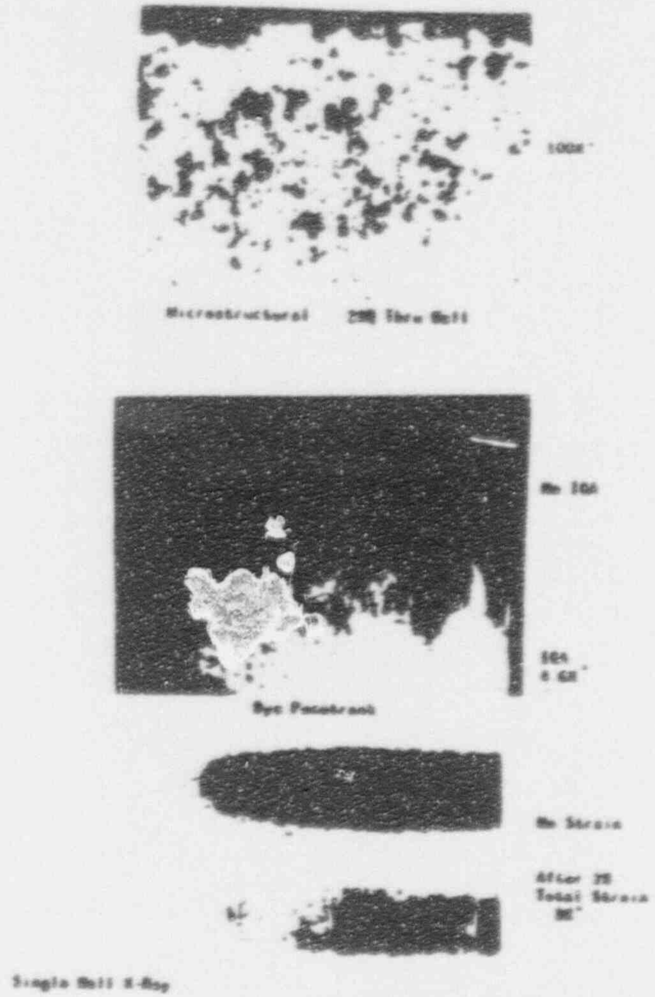


Figure 8- 13a. NDE Results for a Type 1 (IGA) Sample (Dye Penetrant and X-Ray)

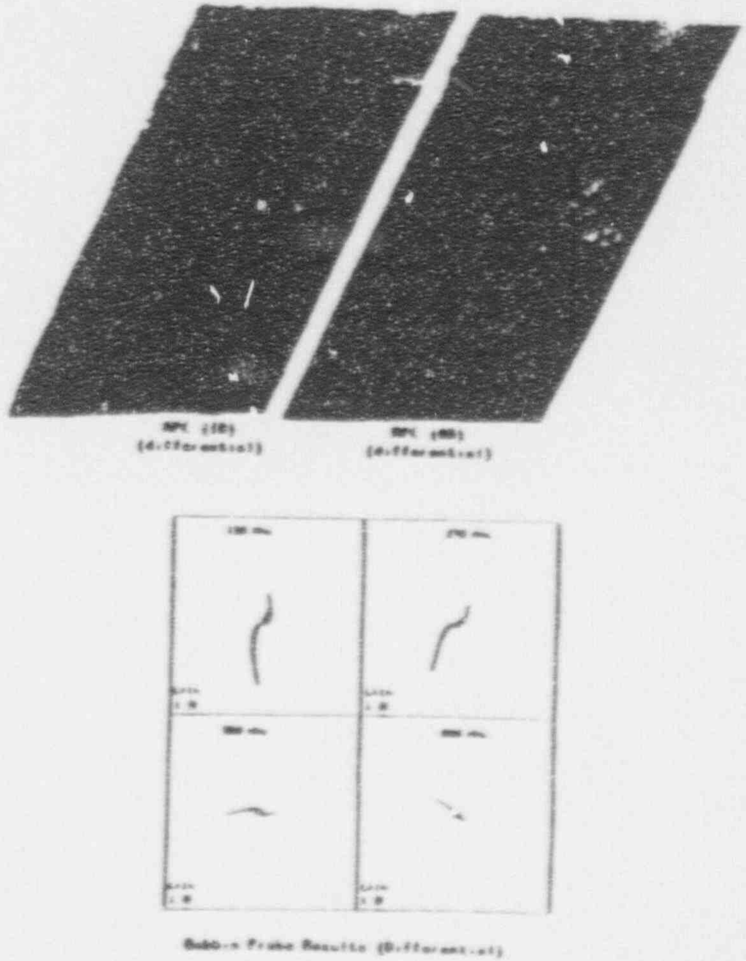


Figure 8 13b. NDE REsults for Type 1 (IGA) Damage (Eddy Current)

Figure 8- 13. Inspection Results for Laboratory IGA Samples from EPRI Program

Pulled Tubes With IGA

Plant	Tube Number	Location	400/100 Mix (Diff.)	Destructive Examination	Remarks
[ ]	R29C46	1C	1.8V/26%	26%	Volumetric IGA 360° around 3/4" long section
	L59R95	1H (Crate)	0.4V/66%	52% Max. Depth 20% IGA Depth	Volumetric IGA with figures/SCC 0.3" 0.7" 
		2H (Crate)	0.6V/29%	13%	Volumetric IGA <0.3" 0.7" 

Lab IGA Samples

Mill Annealed Tubes	400/100 (abs) mix		
	4.5 volt	20%	Uniform IGA 360° around the 4" long section
	9 volt	40%	Uniform IGA 360° around the 4" long section

Figure 8-14

Voltage Comparison of Indications Found With Two Eddy Current Probes
(400/100 kHz Mix)

PROBE 1 VOLTAGE VERSUS PROBE 2 VOLTAGE

PROBE 1 VOLTAGE, VOLTS

PROBE 2 VOLTAGE, VOLTS

Figure 8-15

Comparison of 400/100 kHz Mix Amplitude Response from Two Probes (Model Boiler Sample)

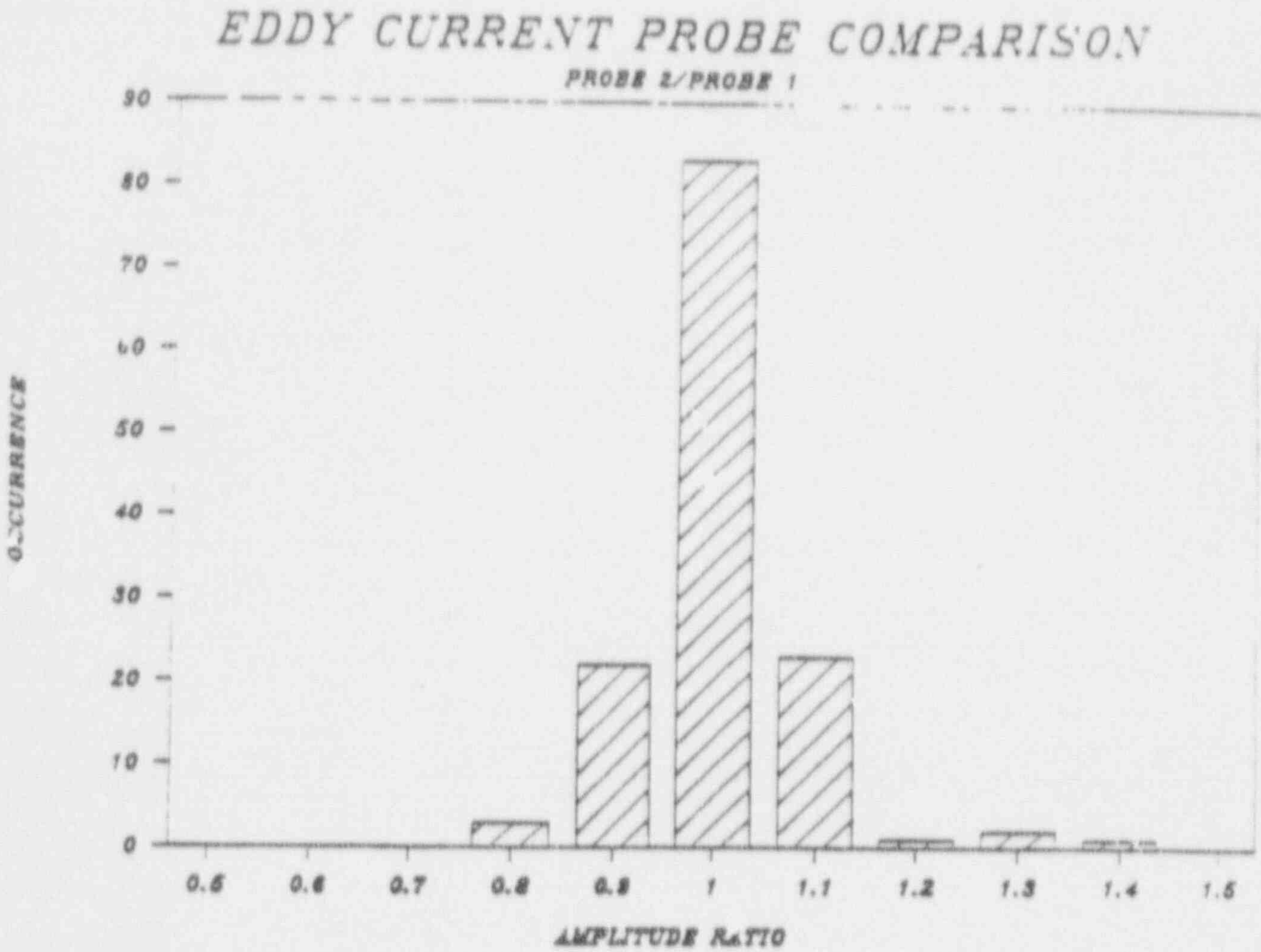


Figure 6-16

Comparison of 400/100 kHz Mix Phase Response form Two Probes (Model Boiler Sample)

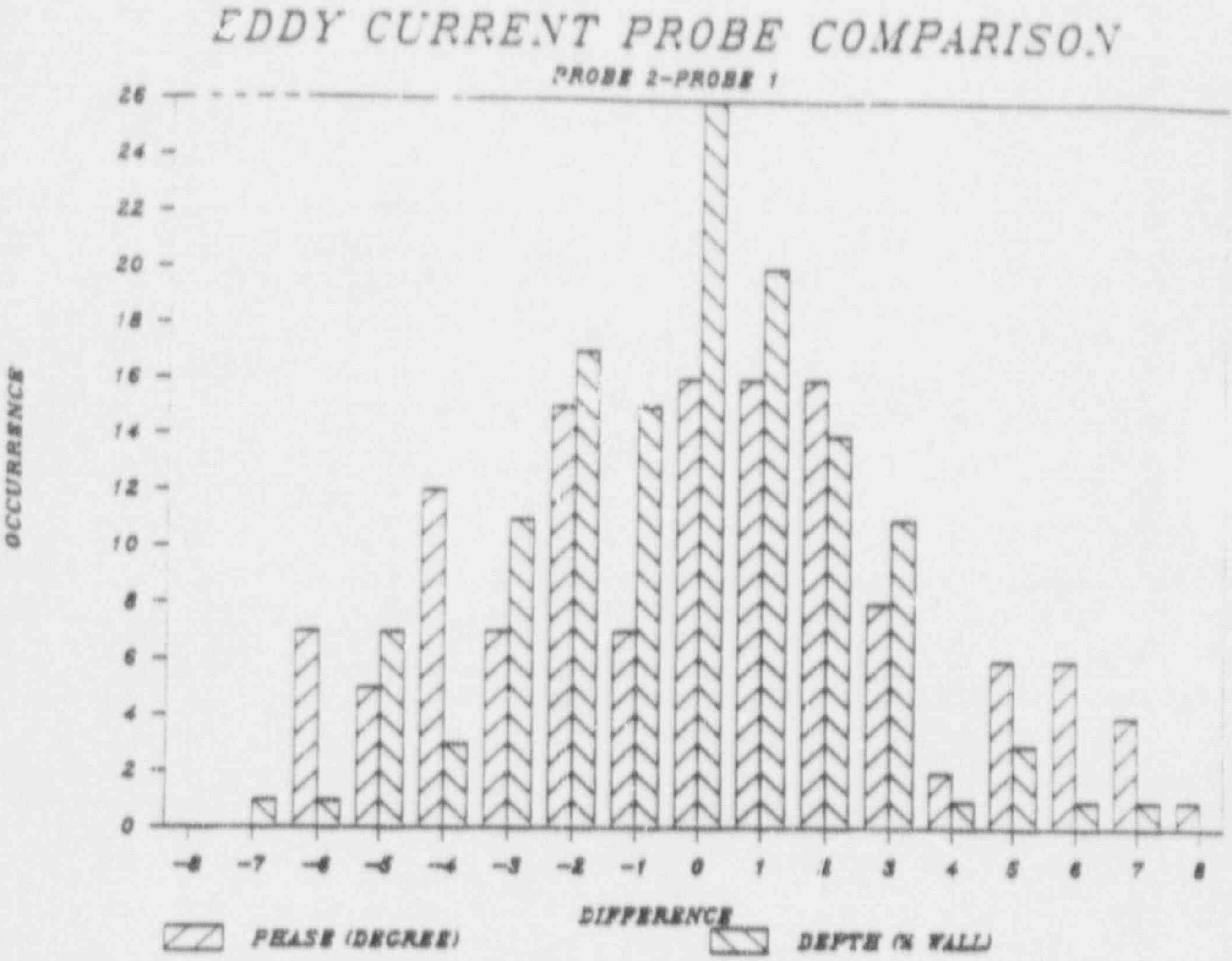


Figure 8-17

Comparison of Tight and Open Crevice Indication Response

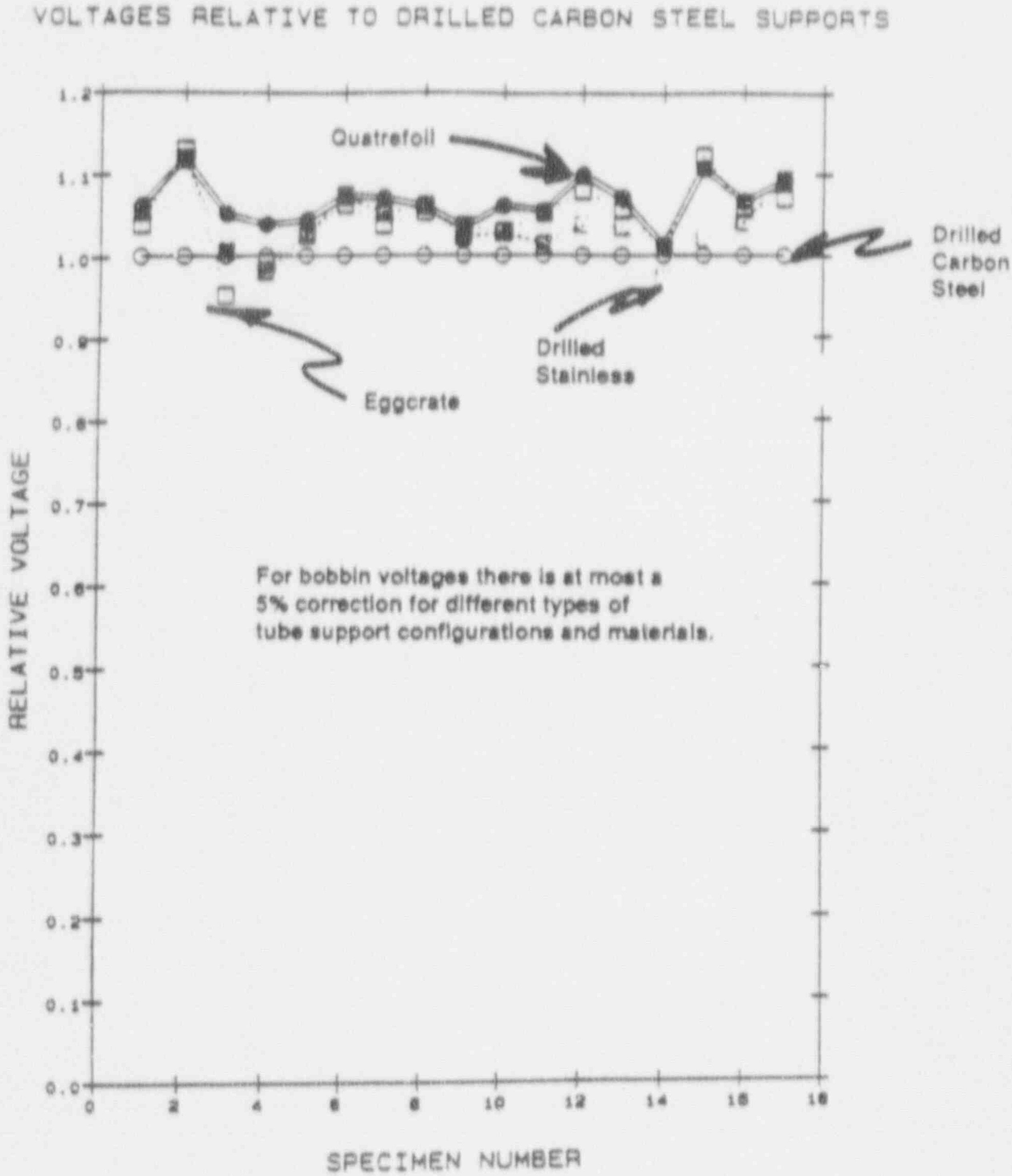
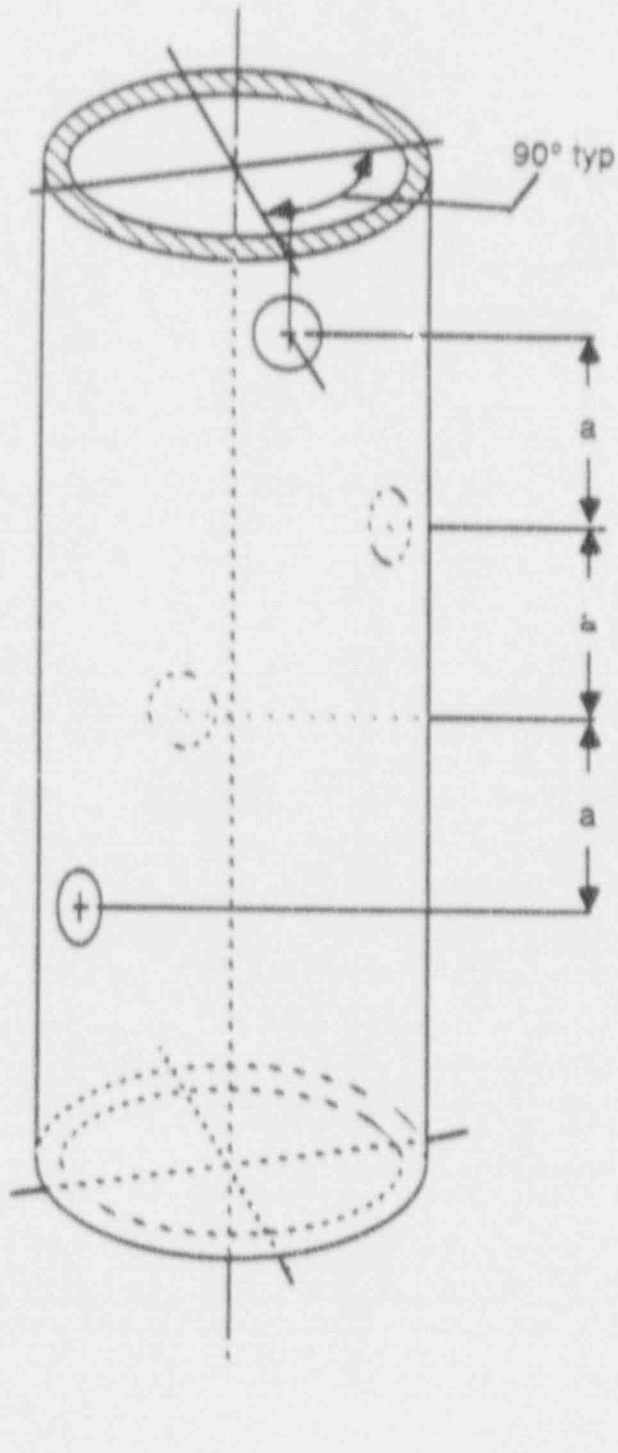
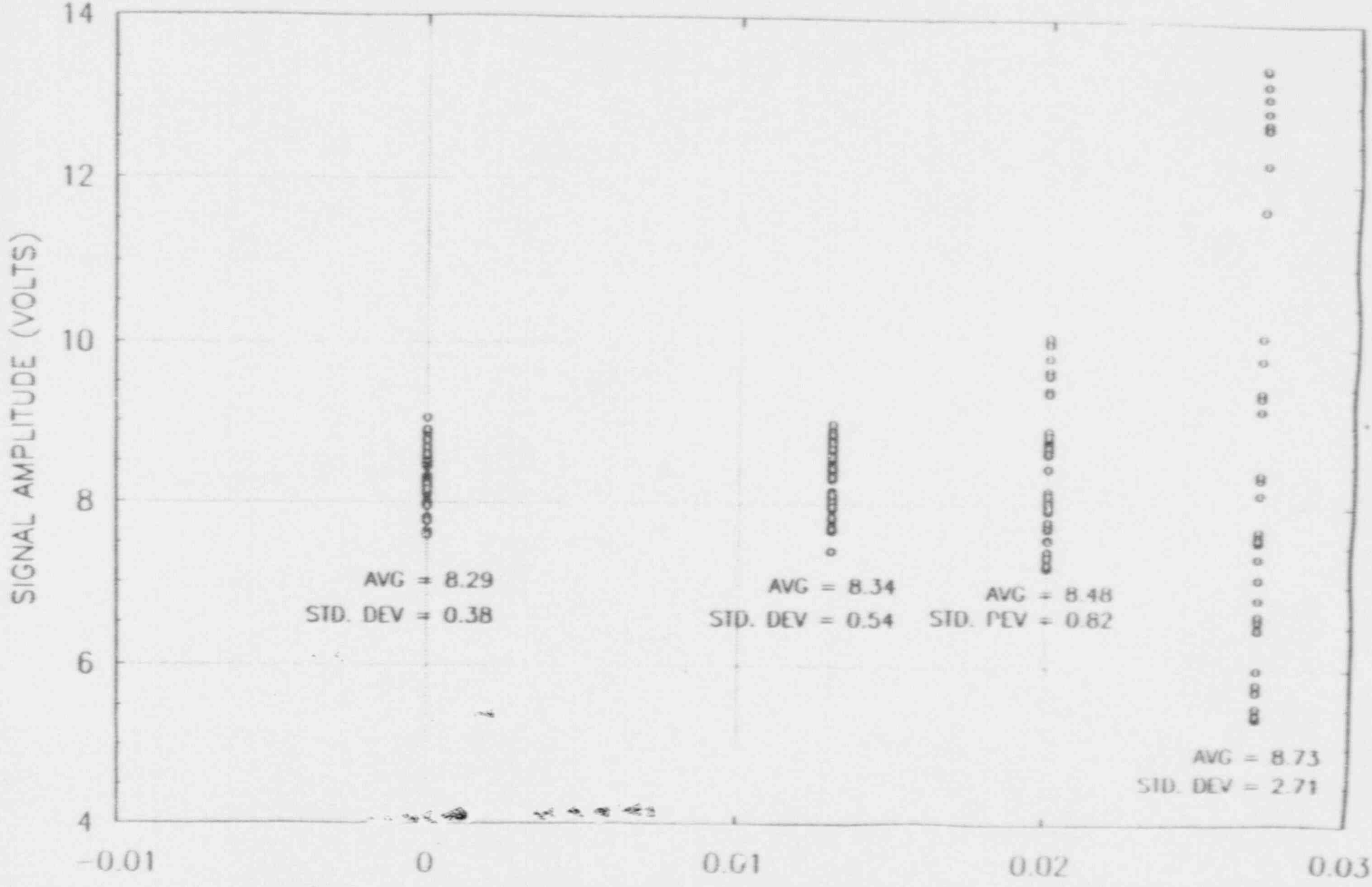


Figure 8-18

Probe Wear Calibration Standard



EDDY CURRENT SIGNAL DEGRADATION
DUE TO PROBE WEAR



PROBE WEAR

Figure 8-21

Signal Amplitude (Arbitrary Units) vs. Center-to-Center Coil Spacing

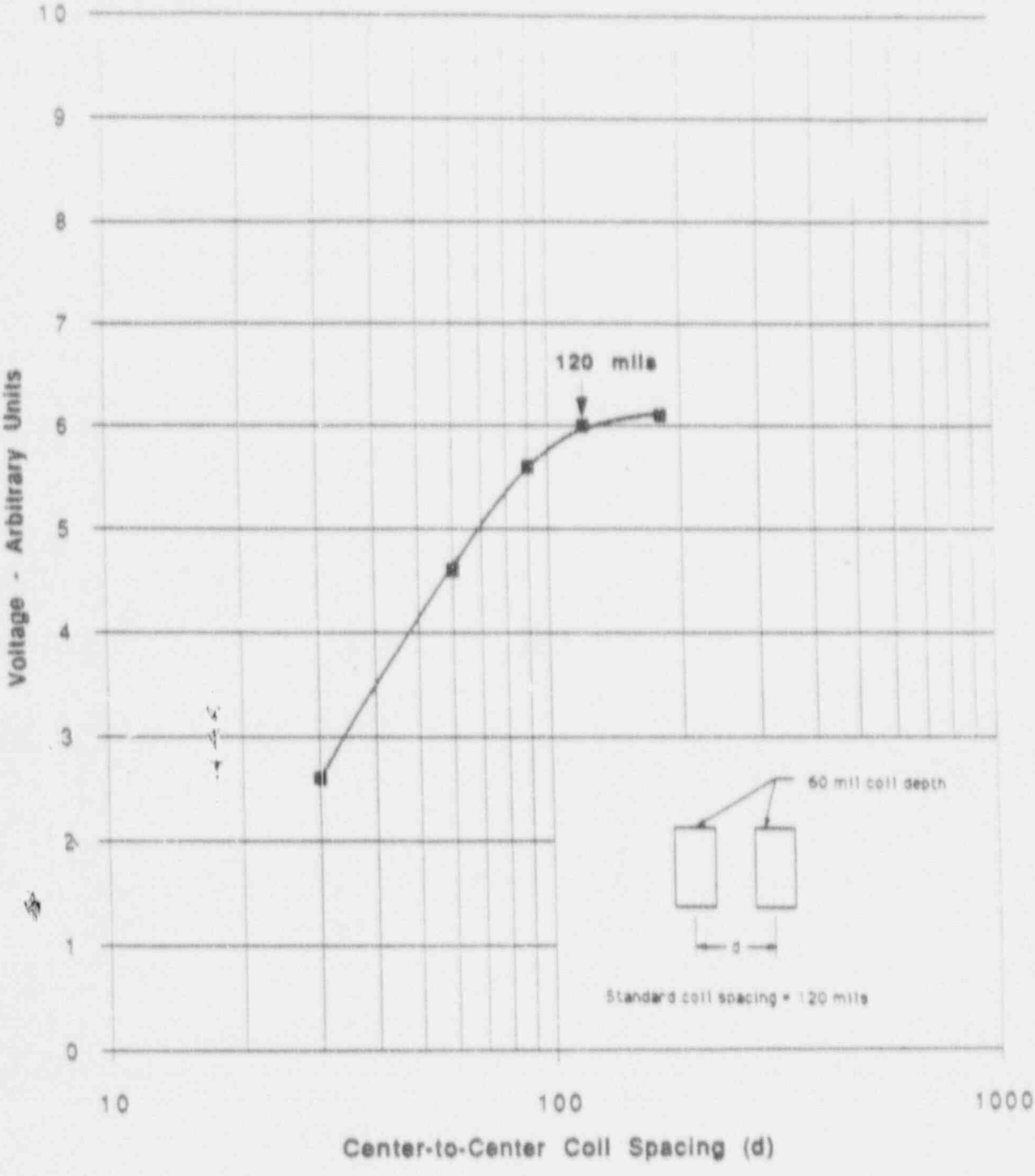


Chart Amp vs Coil Spacing 10/10/91

NDE EVALUATION OF TSP ODSCC GUIDELINES - FIELD CONSIDERATIONS

1 4-hole ASME standard with .033 inch dia. holes place 90 deg apart should be used for field voltage normalizations. Hole diametral tolerance should be .001 inch rather than .003.

2 Additional standard should be used in line with ASME standard to limit effect of probe wear (i.e. probe centering) on field data. This standard will highlight data uncertainties from probe wear, identifying when variation exceeds acceptable limits for tube plugging criteria, requiring use of new probe

3 Calibration should be normalized to 6.4V for 400/100KHz mix for 100% 4 hole ASME standard to eliminate depth uncertainties in the standards, calibration to 4V for 400KHz channel, and carrying over conversion factors to mix channels.

4 WCAP-12871 Rev. 1, Appendix A data acquisition/analysis guidelines implemented to enhance consistency and repeatability of inspection data.

Table 8.9

Variables Influencing NDE Voltage and Burst Correlation Uncertainties

NDE Voltage Uncertainties (Voltage Repeatability)

- o Probe centering: probe diameter and wear considerations(1)
- o Calibration standards: dimensional tolerances(2)
- o Probe design differences(3)

Burst Correlation Uncertainties

- o Crack morphology (length, depth, ligaments, multiple cracks, IGA involvement) variability for same voltage amplitude
- o Tubing dimensional tolerances(4)
- o Human factors affecting voltage repeatability that are not adequately controlled by data analysis guidelines
- o Variations in field crevice conditions (open, packed, deposits, TSP corrosion, small dents, etc.)(5)
- o Effects of tube pull forces on crack morphology and associated burst pressures(6)
- o Utilization of voltage measurements for pulled tubes obtained prior to implementing voltage measurement standards of this report(7)

Notes:

1. Minimized in the field during APC implementation by use of a 4-hole probe wear standard.

2. The influence of dimensional tolerances of the calibration standards on voltage normalization is eliminated by calibrating the field standards to the laboratory reference standard.

3. Uncertainty minimized by specifying coil to coil spacing (coil centers are separated by 120 mils).

4. The influence of tubing dimensional tolerances as they affect burst pressure are inherently included in the spread of burst pressures from pulled tubes and laboratory specimens.

5. The influence of field crevice conditions as they affect burst pressure are inherently included in the spread of burst pressures from pulled tubes.

6. Results as pre-pull field measured voltages rather than post-pull voltages are used in burst correlation.

7. The use of field voltage measurements for pulled tubes obtained prior to implementing the voltage calibration requirements contributes to the spread or uncertainty contained in the burst correlation.

NDE EVALUATION OF TSP ODSCC CONCLUSIONS

1. No difference observed between Zetec and Echoram probes on data acquisition for tube plugging criteria
2. Presence of support plate causes only small changes in indication response (for responses > 2V) for ODSCC specimens.
3. Small indications, with amplitude of response approaching size of mix residual, can be influenced by presence of support plate
4. Packed TSP crevice has little influence on eddy current response
5. Large amplitude cracks, with oxide coating on crack surfaces, are detectable by ECT in presence of minor denting; small amplitude cracks, and oxide-free cracks are masked by dent signal.
6. Probe centering characteristics, related to probe wear, can contribute to uncertainty of eddy current signal.
7. Use of ASME standard for voltage calibration, and calibration of 400/100 KHz channel are recommended for tube plugging criteria. Calibration at mix frequency recommended to minimize effects of variation of frequency responses between probes
8. NDE uncertainties contribute to uncertainty in voltage vs. burst pressure, and tend to lower structural limit for tube burst, which is based on lower 95% confidence bound.

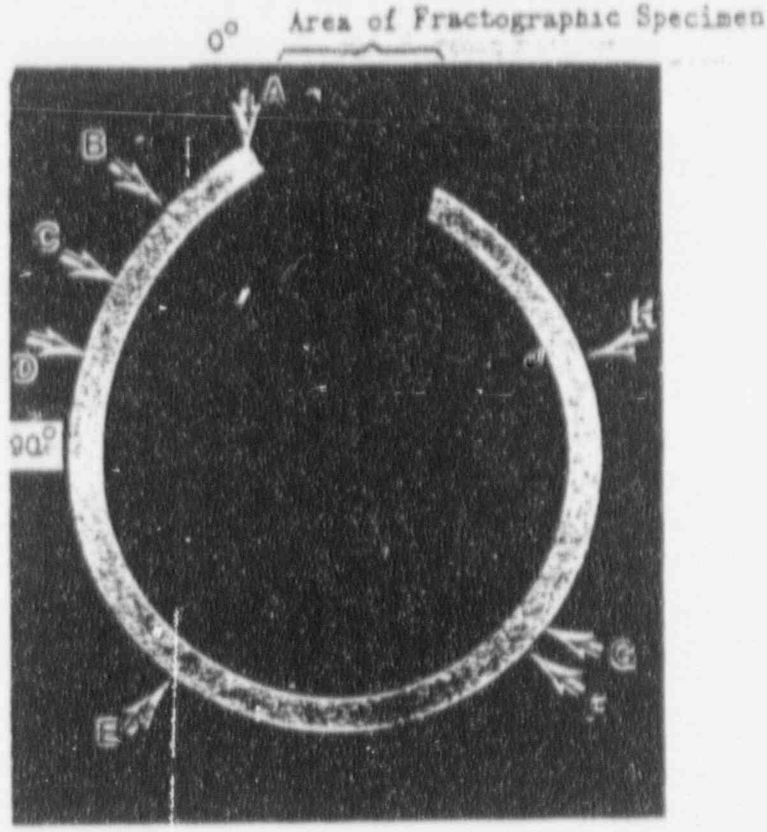
SUMMARY OF WCAP-12871

SECTIONS 4,7,9/2,10

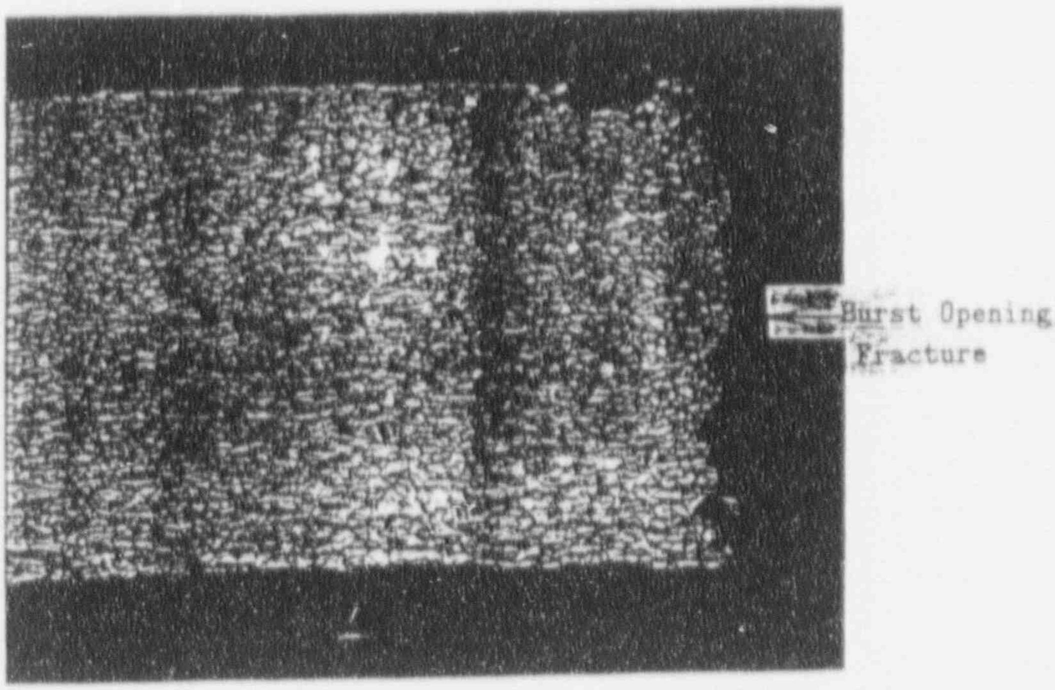
PULLED TUBE EXAMINATIONS

LABORATORY SPECIMEN PREPARATION

LEAK AND BURST TESTING



Mag. 3.25X



Area A

Mag. 50X

Figure 4-5. Metallographic cross section through center of the first support plate intersection of Tube R4-C73. Locations examined are indicated by Area A through H. Area A is shown in the lower photomicrograph.

RM-2648

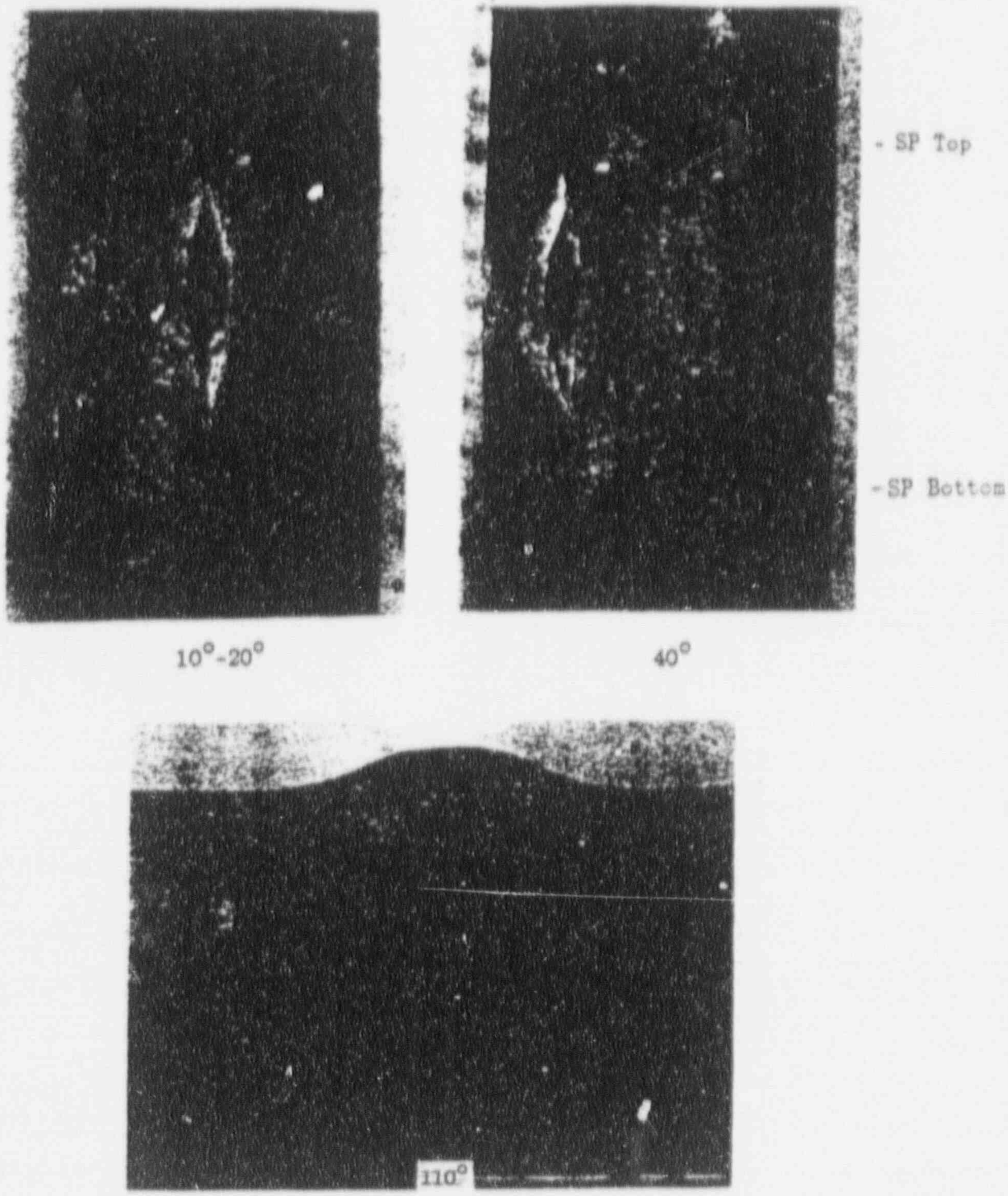


Figure 3-1. Appearance of the burst opening in Tube R4-C73 at the first support plate region; mag. 3.25X

RM-26474

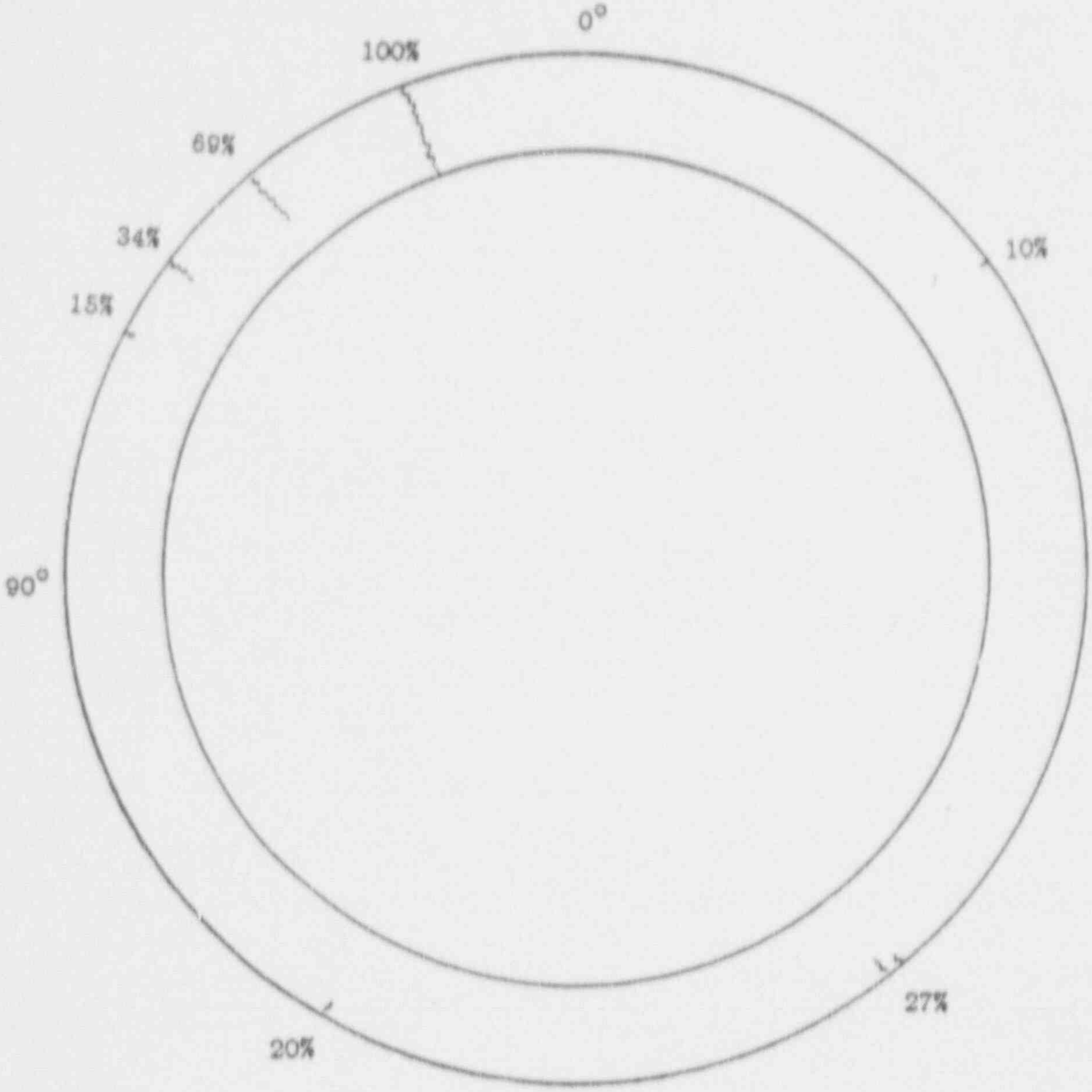
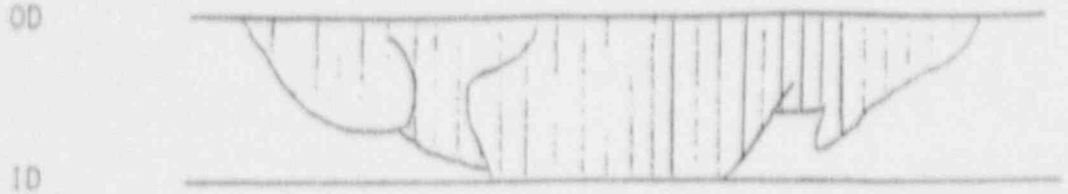


Figure 4-16. Sketch of crack distribution and depth within the center of the first support plate intersection in Tube R4-73.



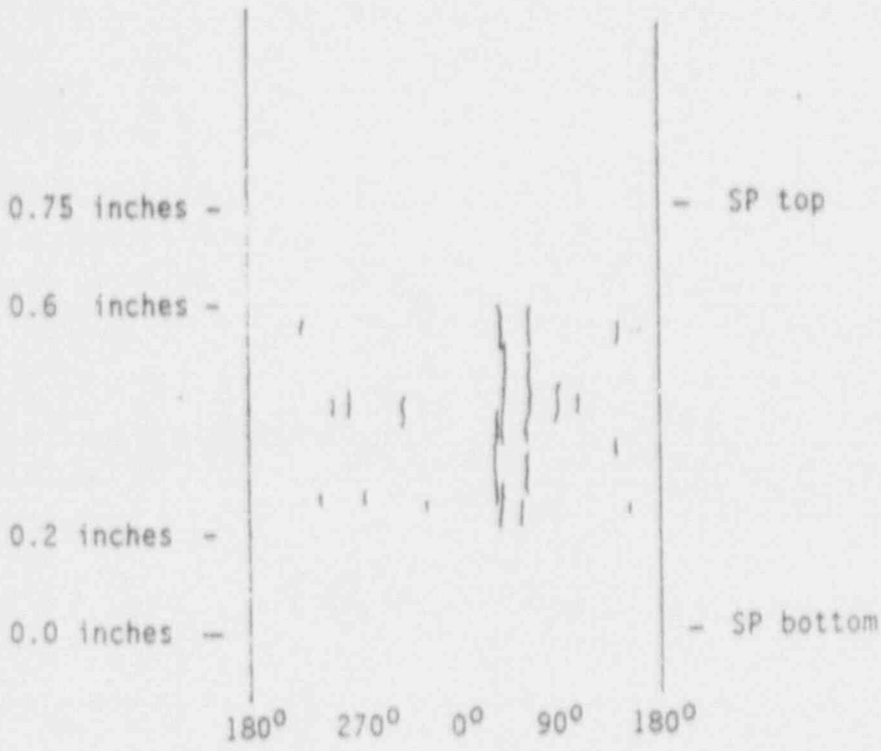
Sketch of Burst Crack

Macrocrack Length = 0.42 inches

Throughwall Length = 0.18 inches

Number of Microcracks = 4 (all ligaments with intergranular features)

Morphology = Intergranular SCC with some IGA characteristics (width of IGA 0.012 inches)



Sketch of Crack Distribution

Figure 4-4. Description of OD origin corrosion at the first support plate crevice region of Tube R4-C73.

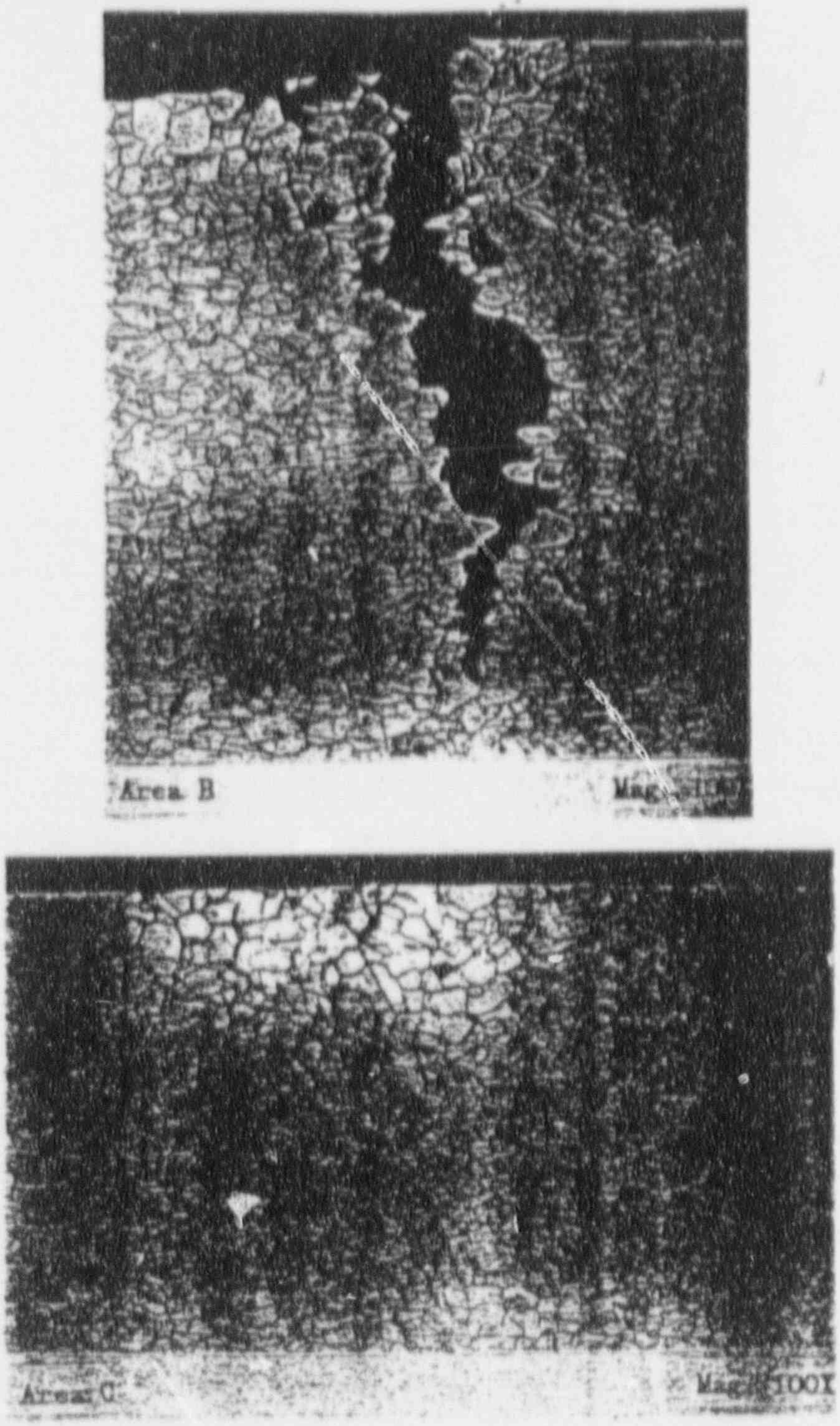


Figure 4-6. Metallographic details seen in Areas B and C (Figure 4-5).

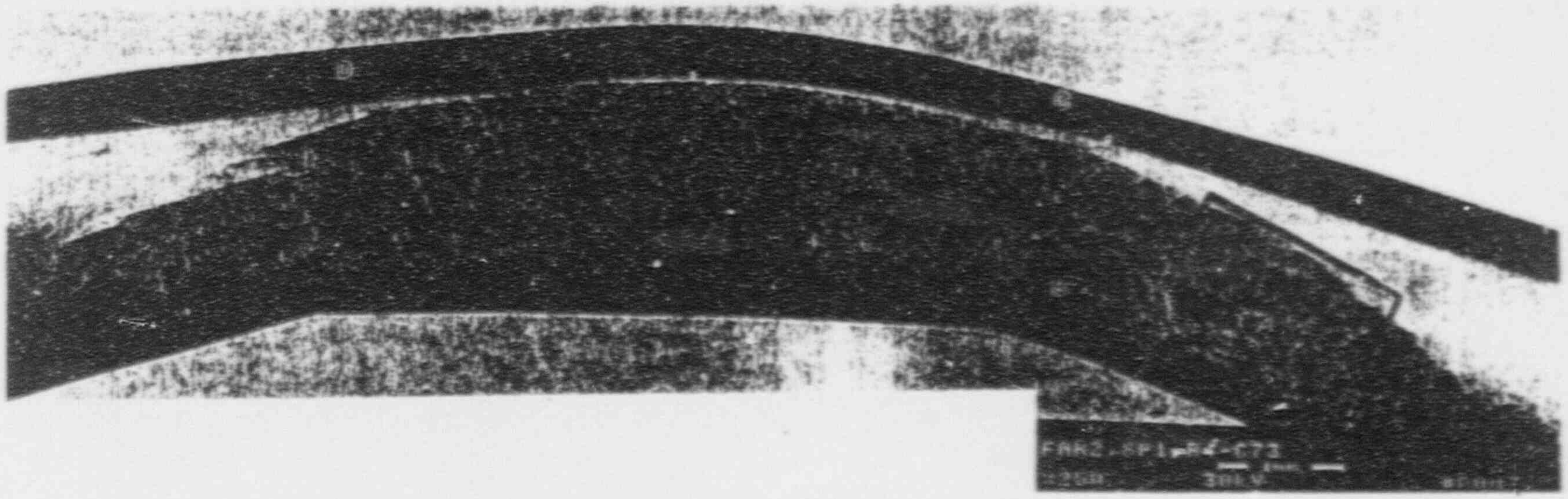
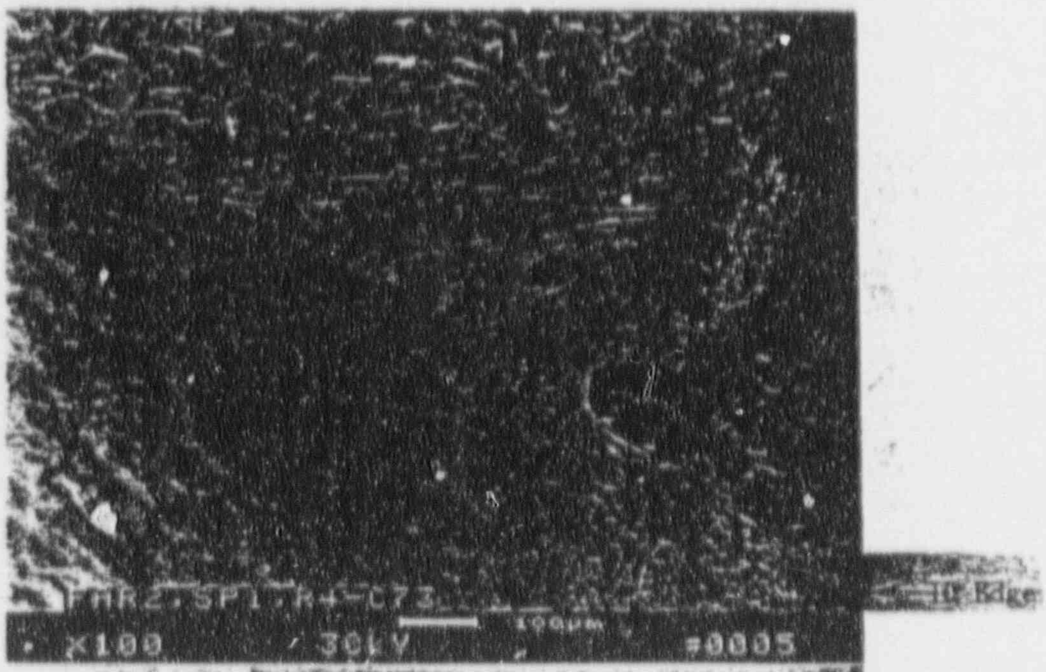


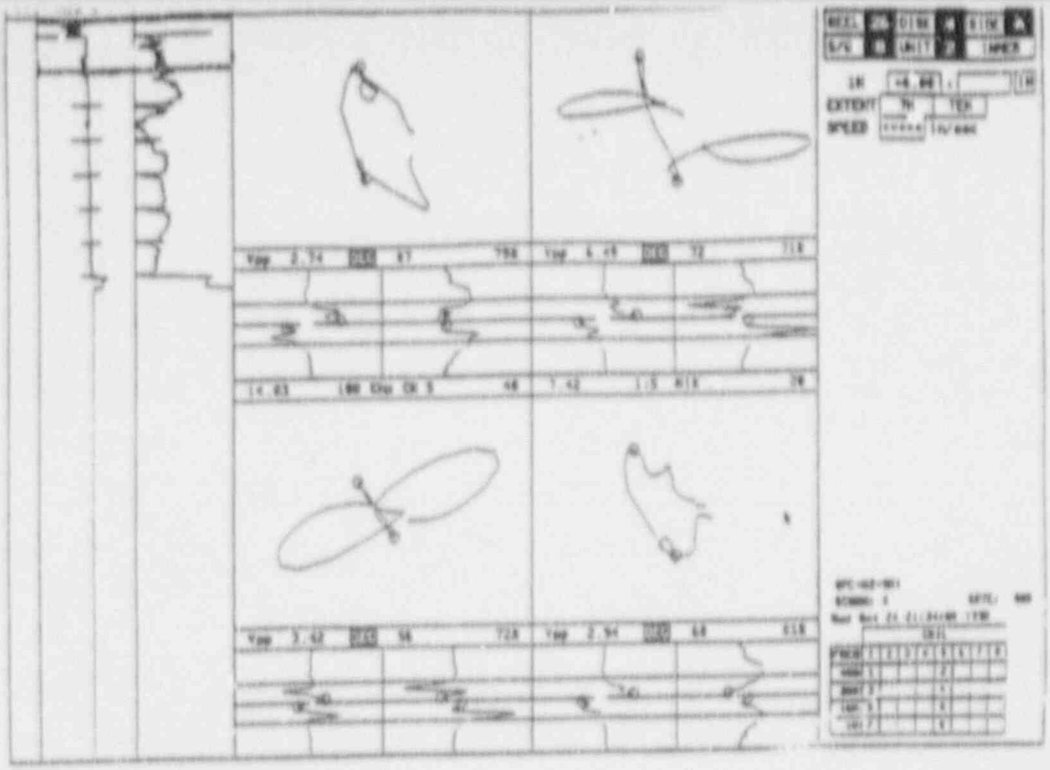
Figure 4-1. Fractographic features seen on the large crack near 20° after burst testing. Areas marked were examined in greater detail; Tube R4-C73, first support plate intersection.

Area A

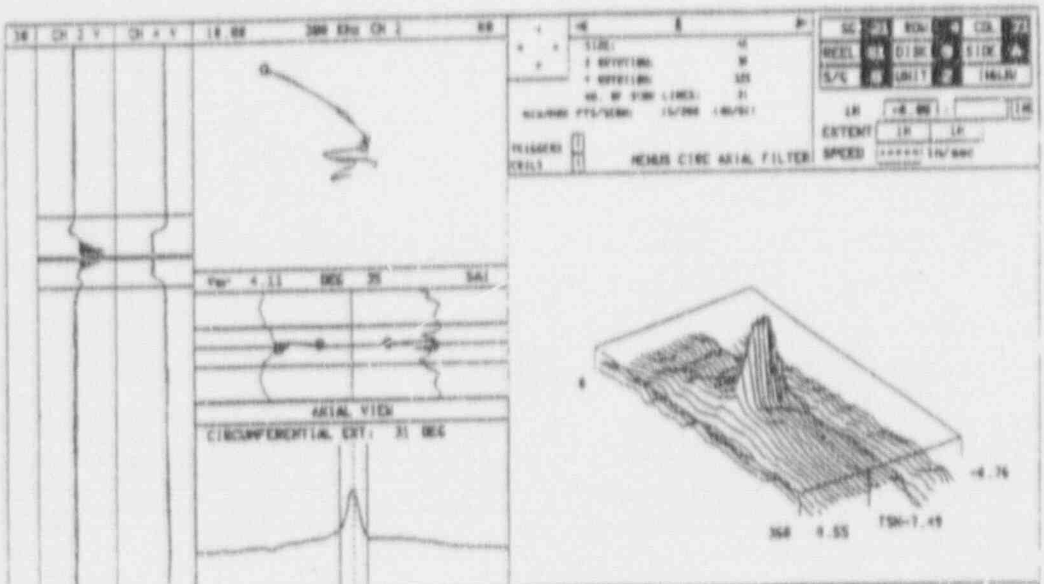


Area B

Figure 4-2. Fractographic details seen in Areas A and B. Areas are those marked in previous figure.

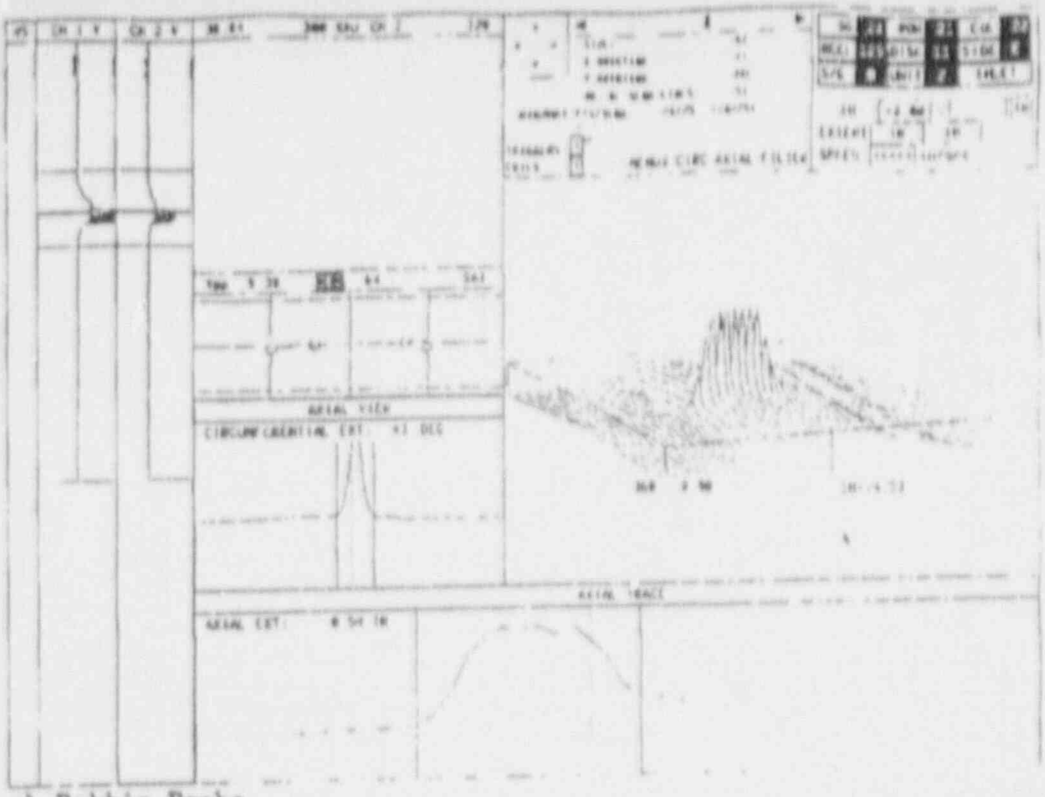


a) Bobbin Probe

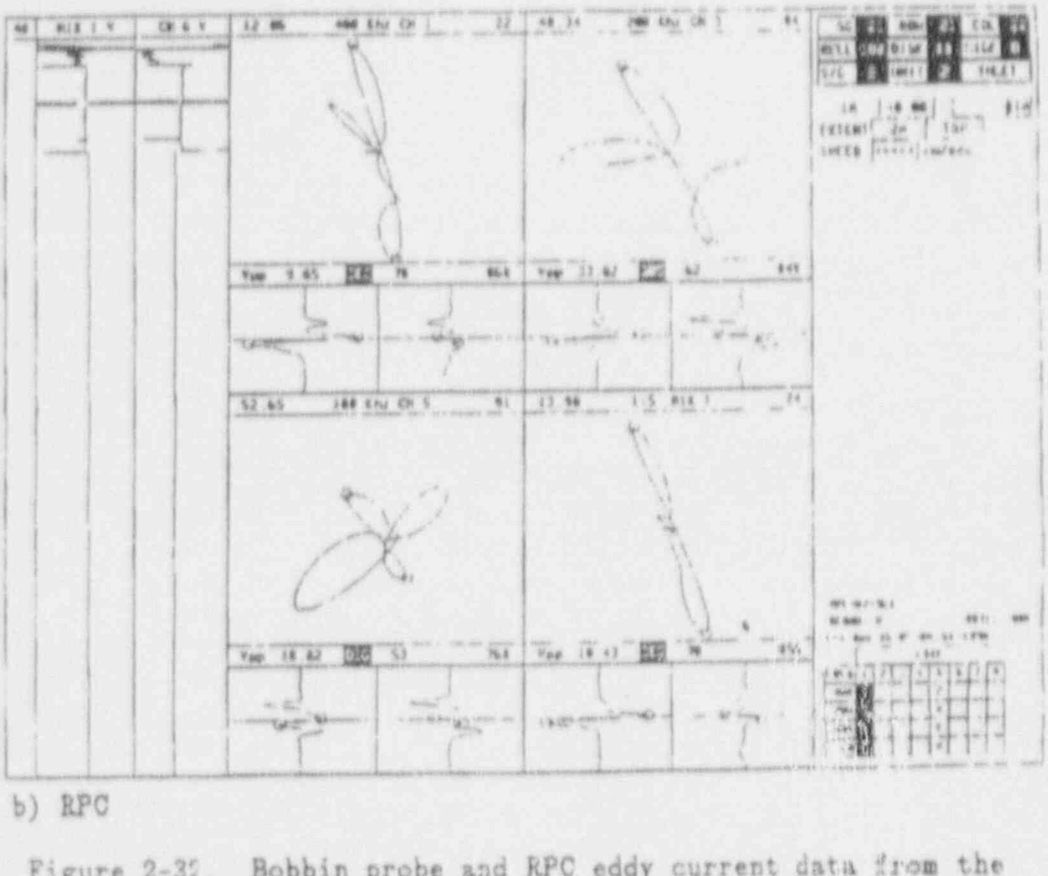


b) RPC

Figure 2-30. Bobbin probe and RPC eddy current data from the October-November 1990 field inspection of the first support plate intersection of Tube R4-C73. The bobbin probe data shows a 2.94 volts amplitude signal and an indicated crack depth of 81% throughwall. The RPC data shows one large axial indication (0.43 in).



a) Bobbin Probe



b) RPC

Figure 2-32. Bobbin probe and RPC eddy current data from the October-November 1990 field inspection of the first support plate intersection of Tube R21-C22. The bobbin probe data shows a 10.4 volts amplitude signal with an indicated crack depth of 85%. RPC data shows one axial crack indication whose length was estimated as 0.51 inches.

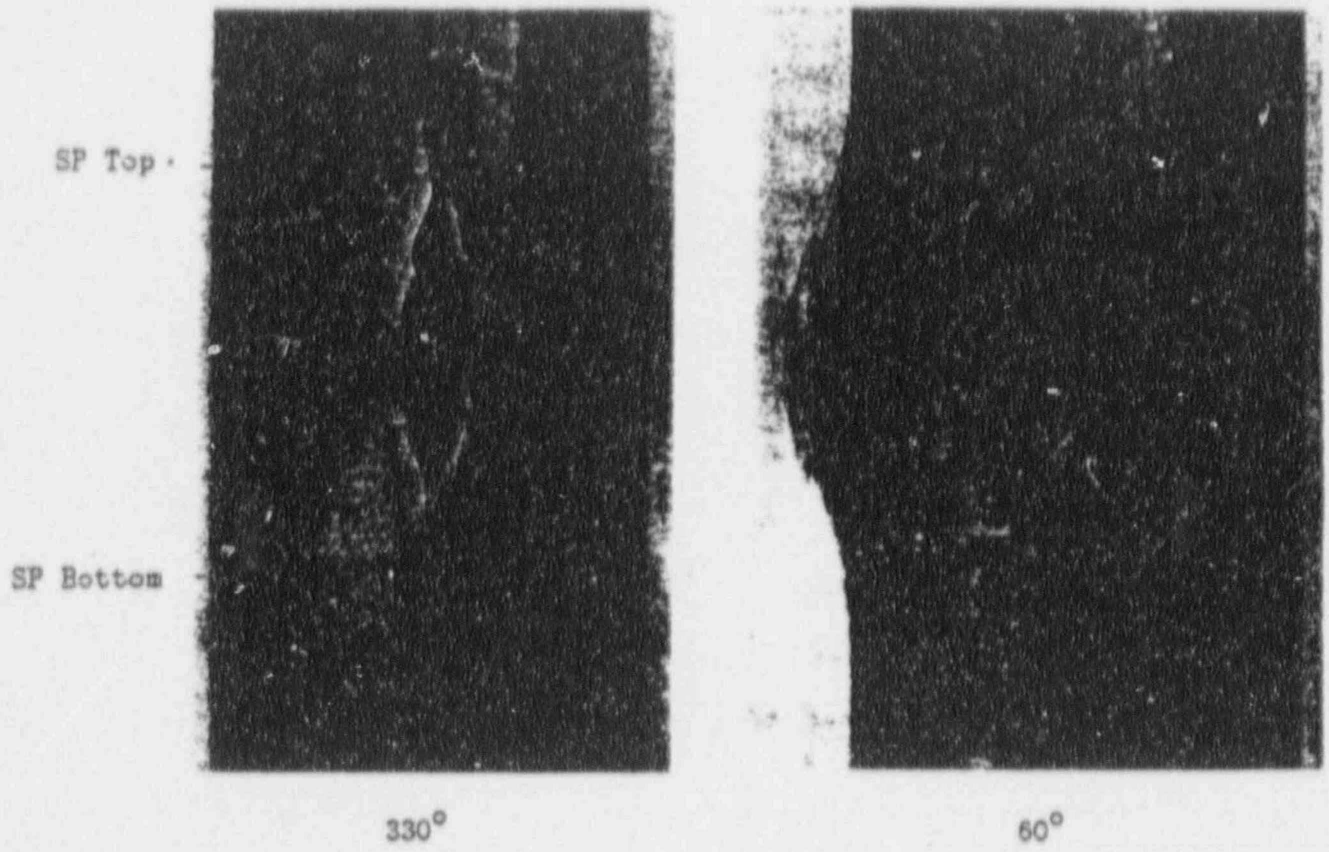
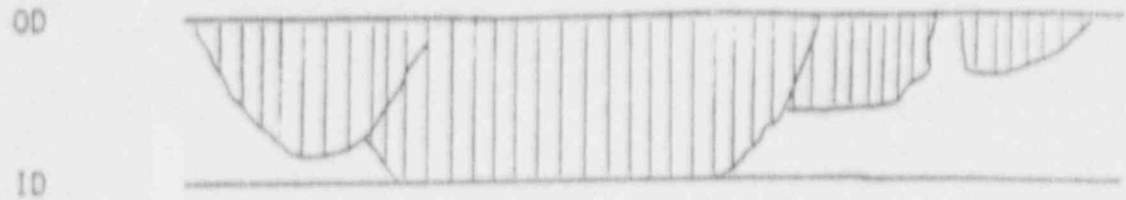


Figure 3-2. Appearance of the burst opening at the first support plate region in Tube R21-C22; mag. 3.25X

RM-26475



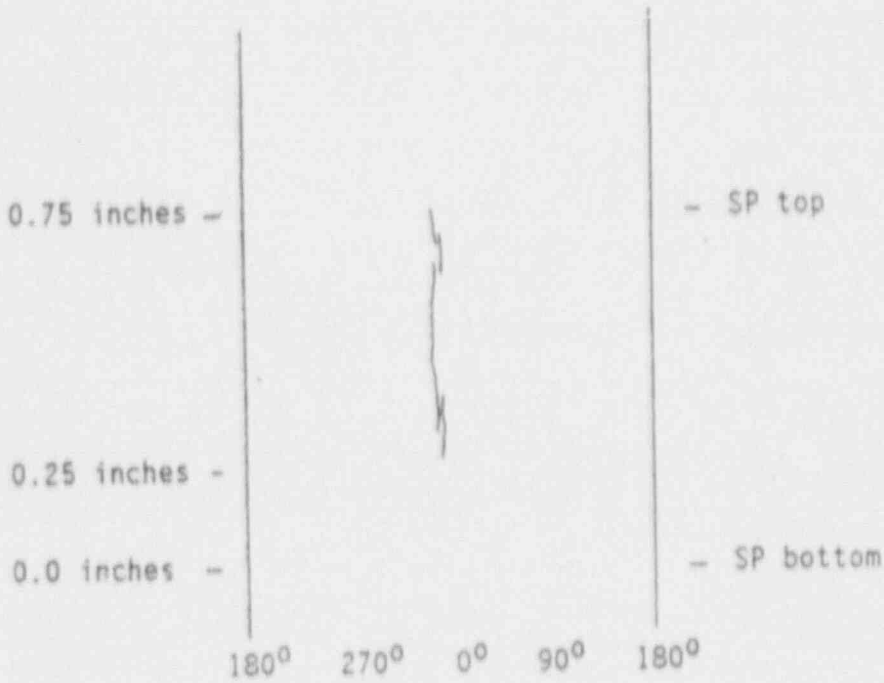
Sketch of Burst Crack

Macrocrack Length = 0.50 inches

Throughwall Length = 0.15 inches

Number of Microcracks = 4 (two ligaments with intergranular features, one with ductile overload features)

Morphology = Intergranular SCC with significant IGA characteristics (width of IGA 0.030 inches)



Sketch of Crack Distribution

Figure 4-21. Description of OD origin corrosion at the first support plate crevice region of Tube R21-C22.

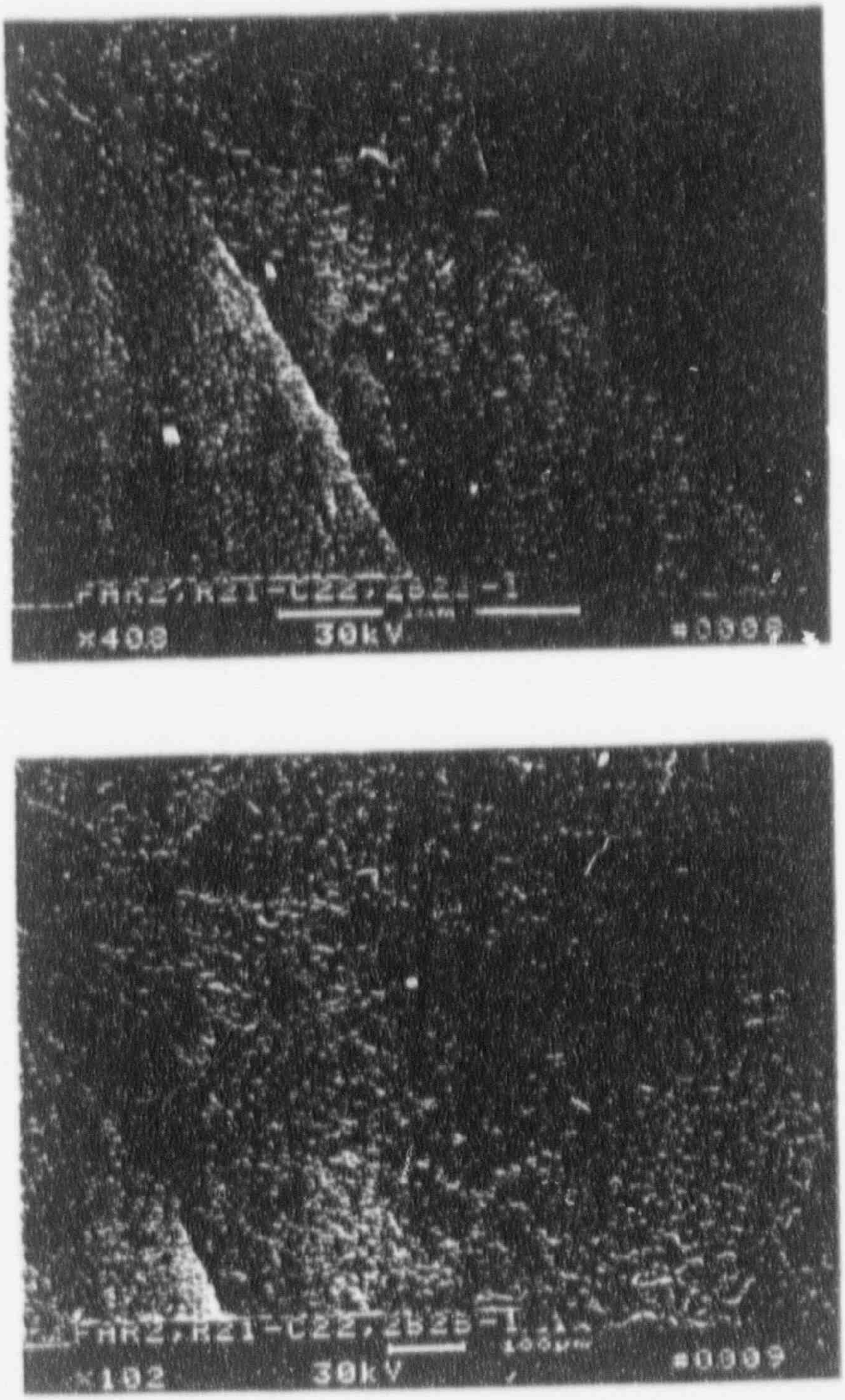
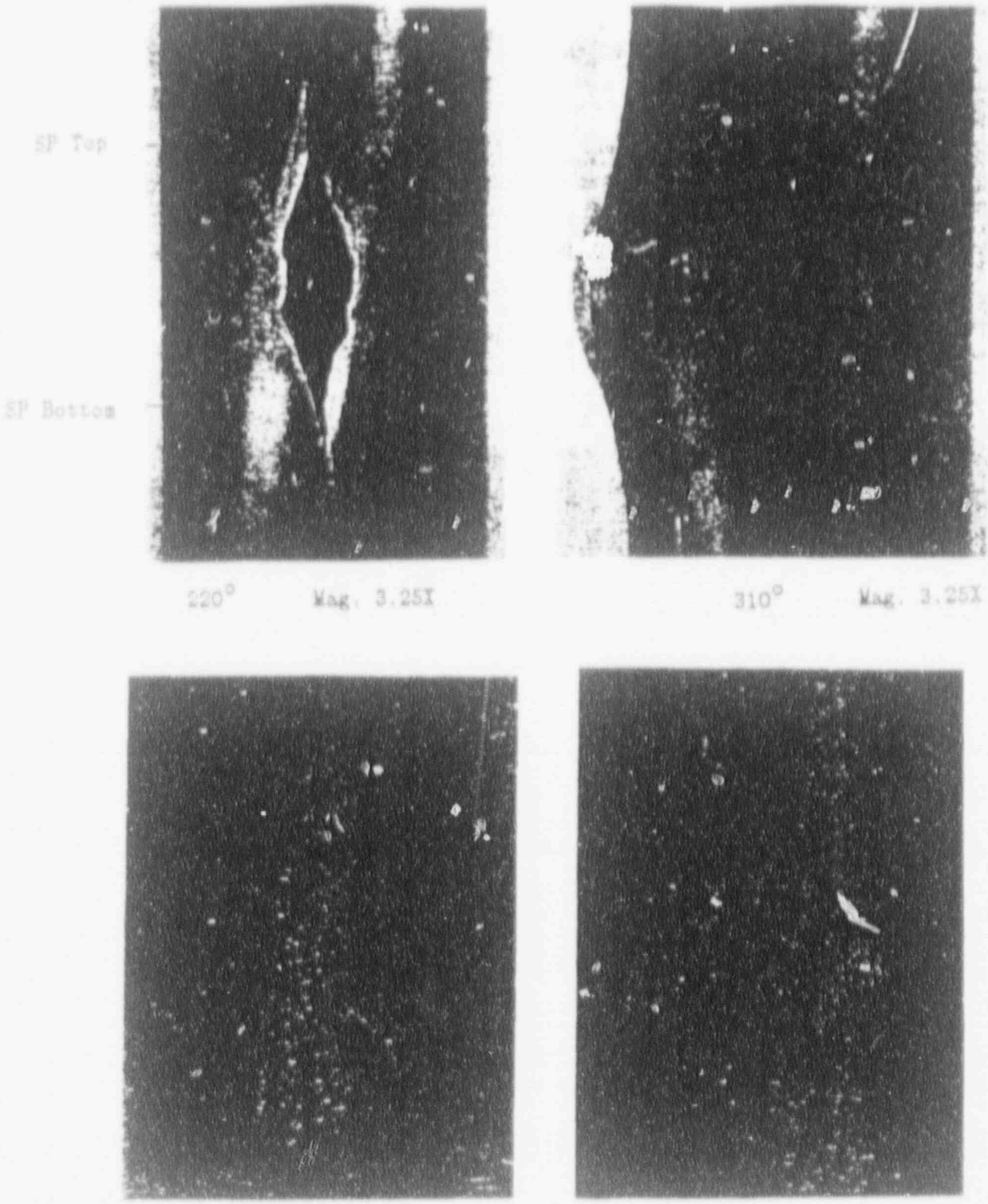


Figure 4-19. Fractographic details of Area C in Figure 4-17. Tube R21-C22.



220° Mag. 3.25X   310° Mag. 3.25X

320° Mag. 8.25X   10° Mag. 8.25X

Figure 3-3. Appearance of the burst opening and opened cracks around the circumference at the first support plate region in Tube R38-C46

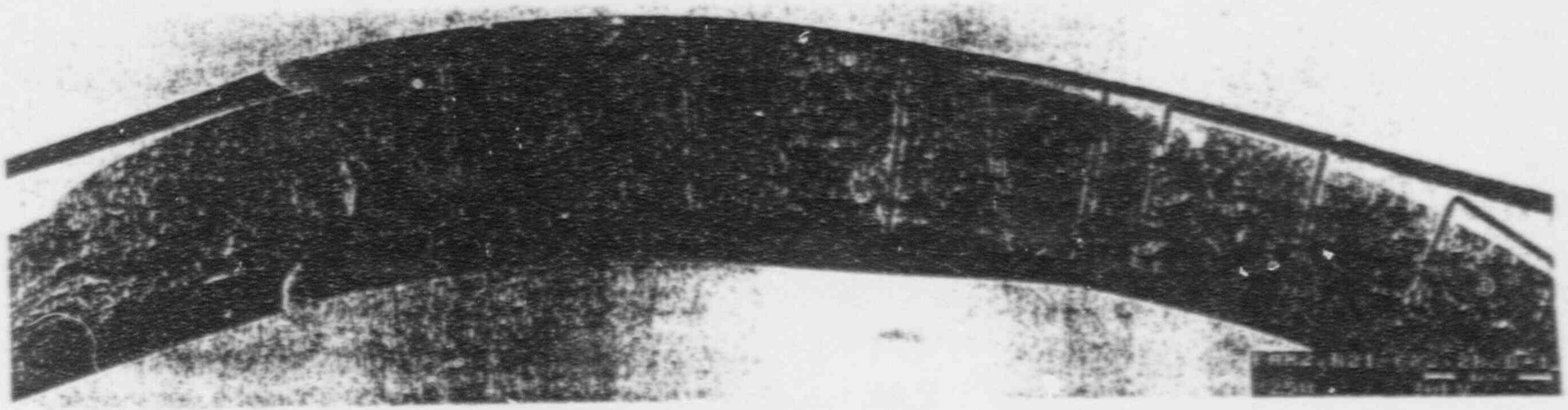
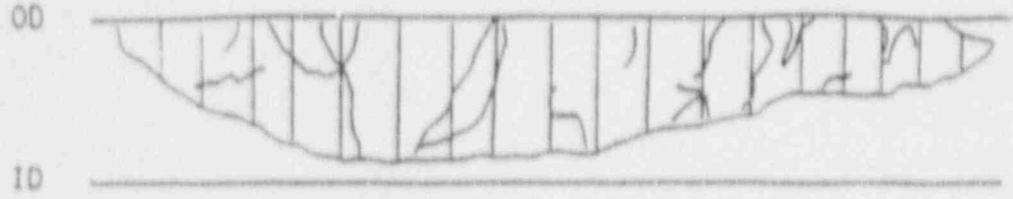


Figure 4-17. Fractographic features seen on the opened burst crack at 330°, at the first support plate intersection in Tube R21-C22. Areas marked were further examined in greater detail.

RM-2643



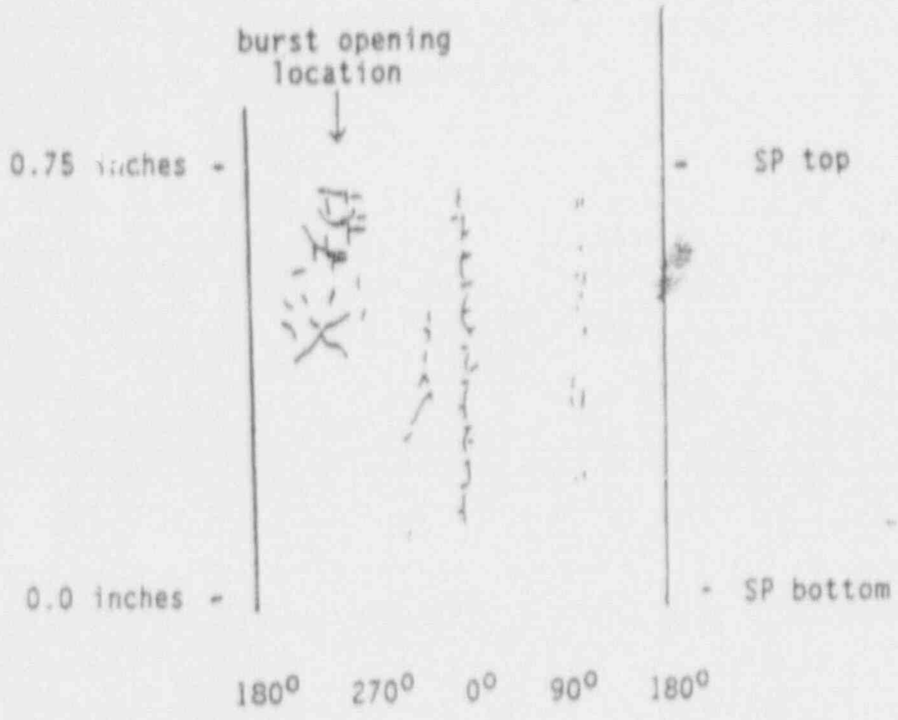
Sketch of Burst Crack

Macrocrack Length = 0.37 inches

Throughwall Length = 0 (78% throughwall)

Number of Microcracks = numerous (ligaments have intergranular features)

Morphology = Intergranular SCC with minor IGA features (Unusual spider-shaped crack distribution)



Sketch of Crack Distribution

Figure 4-28. Description of OD origin corrosion at the first support plate crevice region of Tube R38-C46.

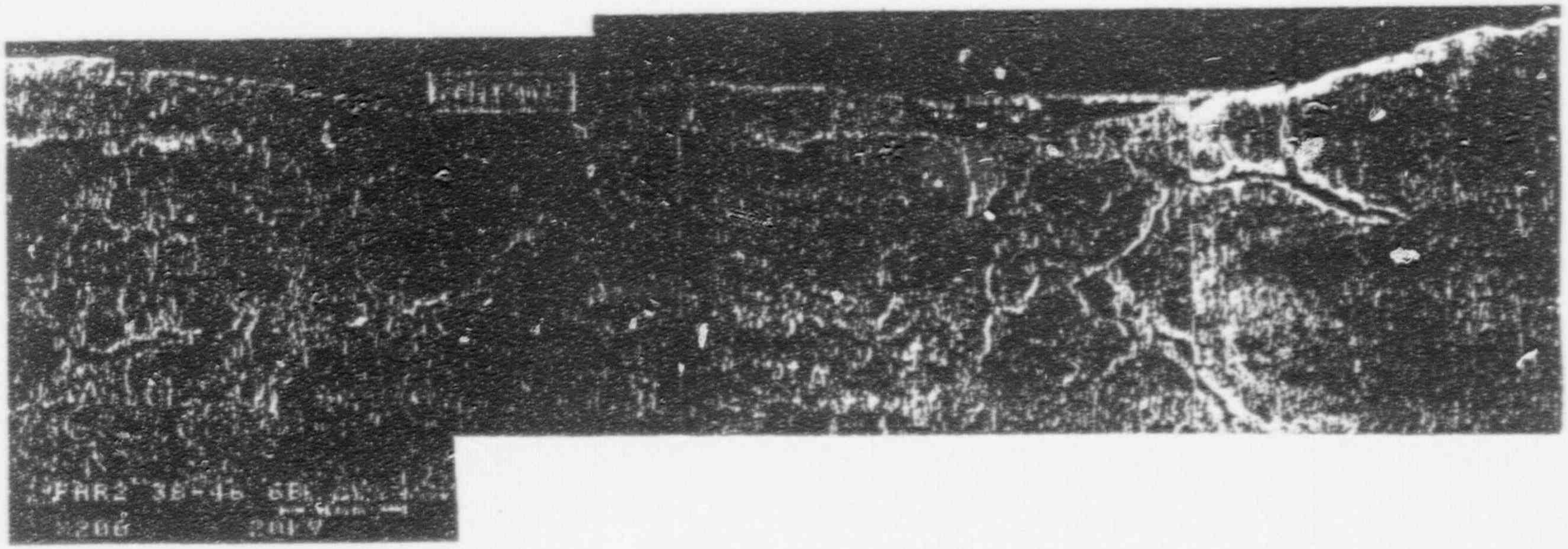


Figure 4-27. Appearance of the OD surface at burst opening in Tube R38-C46.

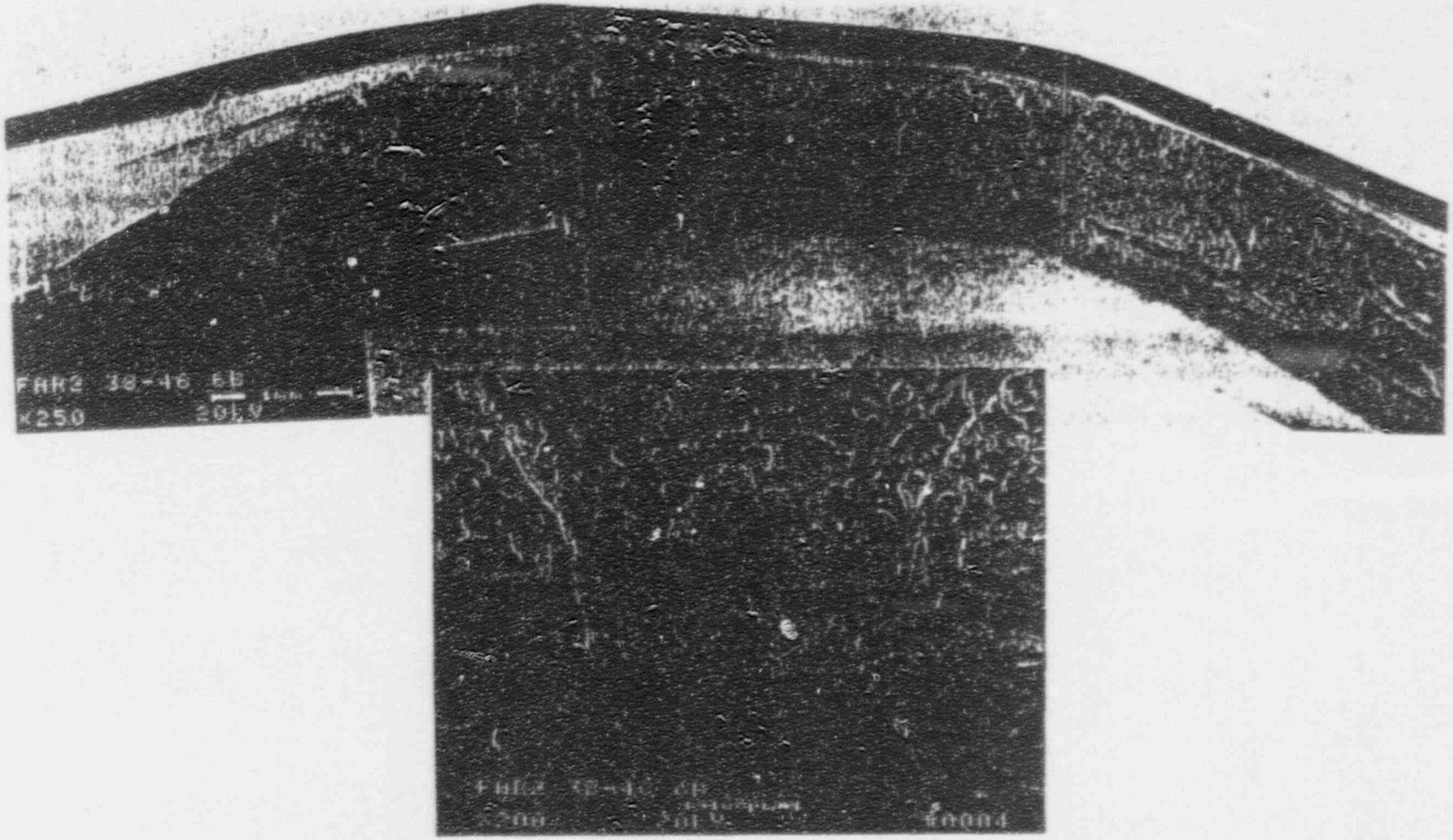


Figure 4-26. Fractographic features seen on the opened burst fracture in Tube R38-C46 at the first support plate.

RM-26501

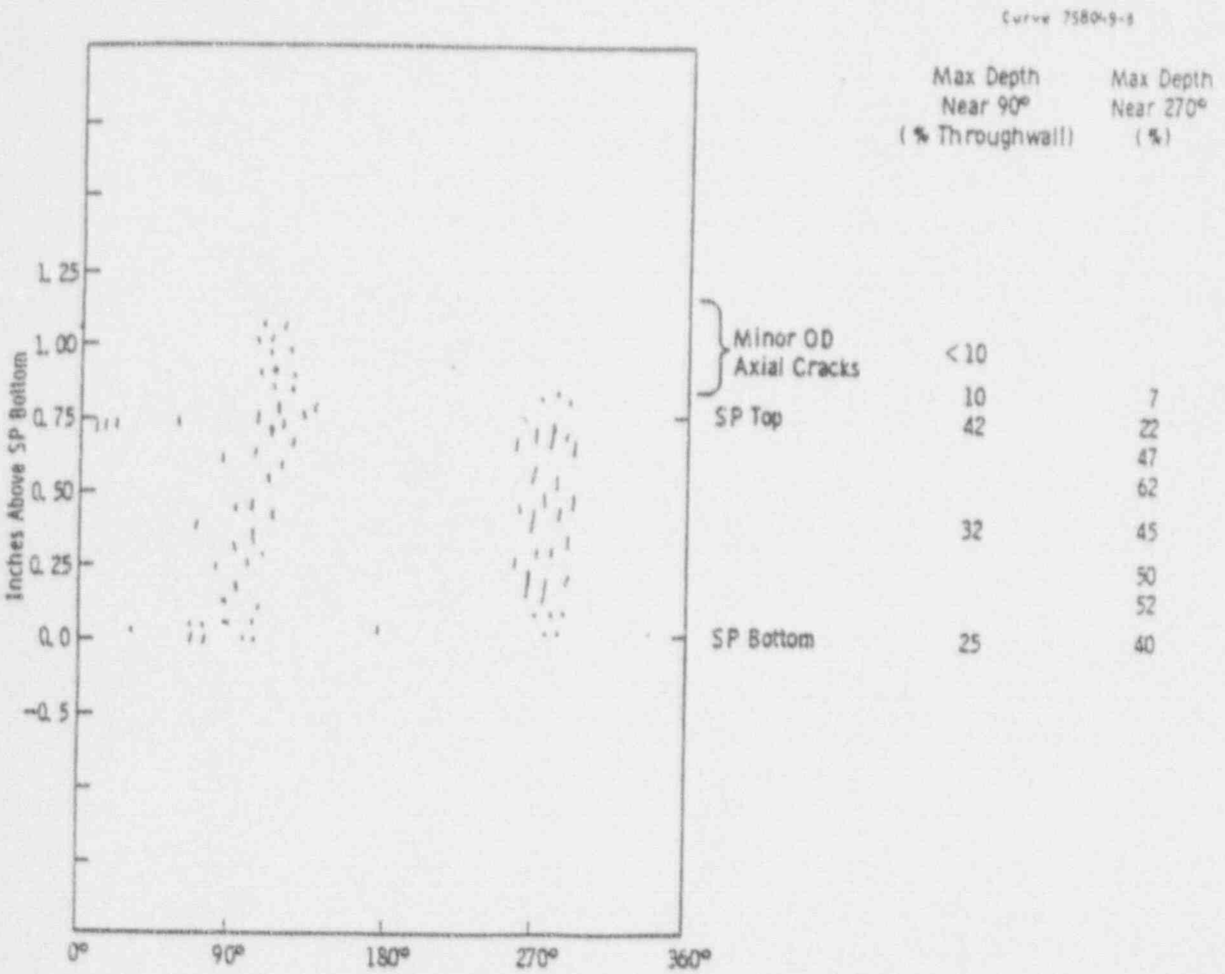


Figure 4-17. Crack network location at first support plate region on tube R20-C26 HL.

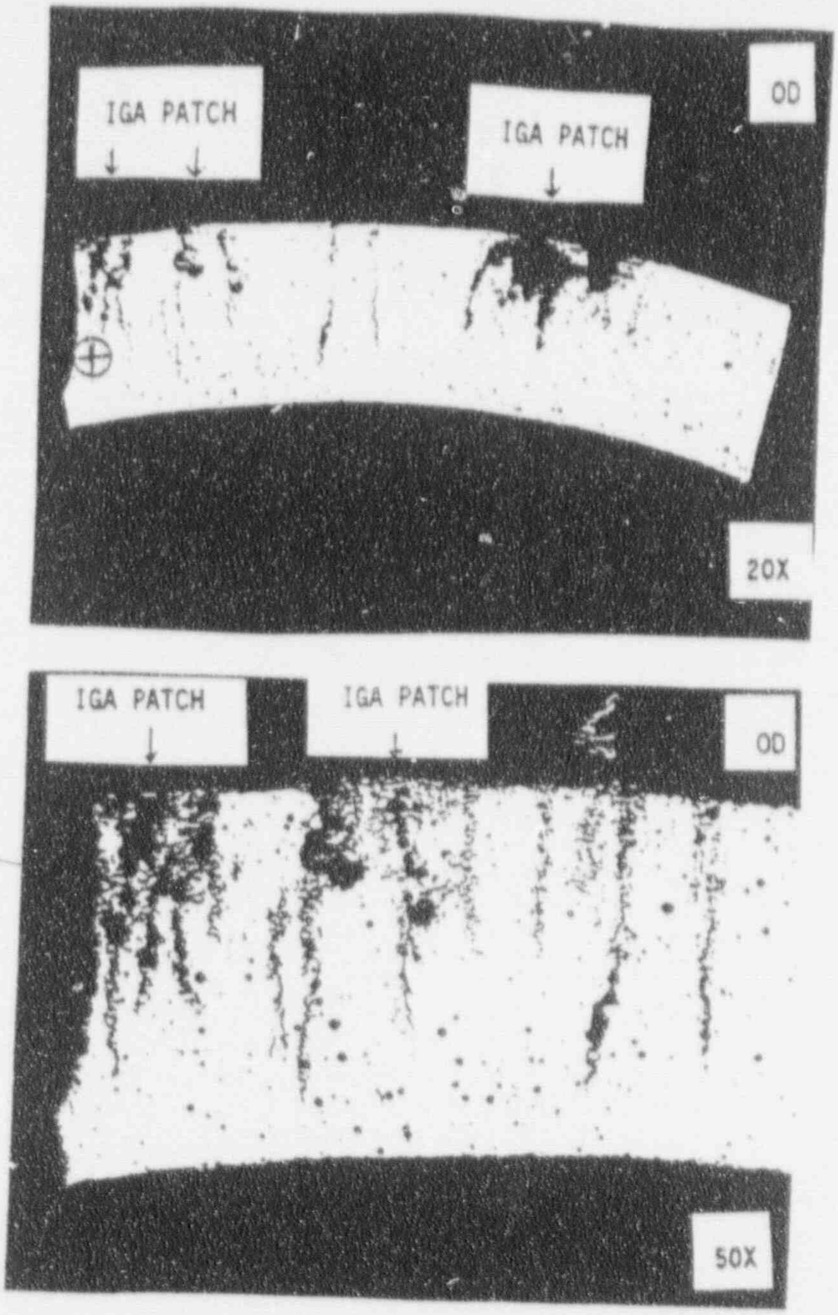
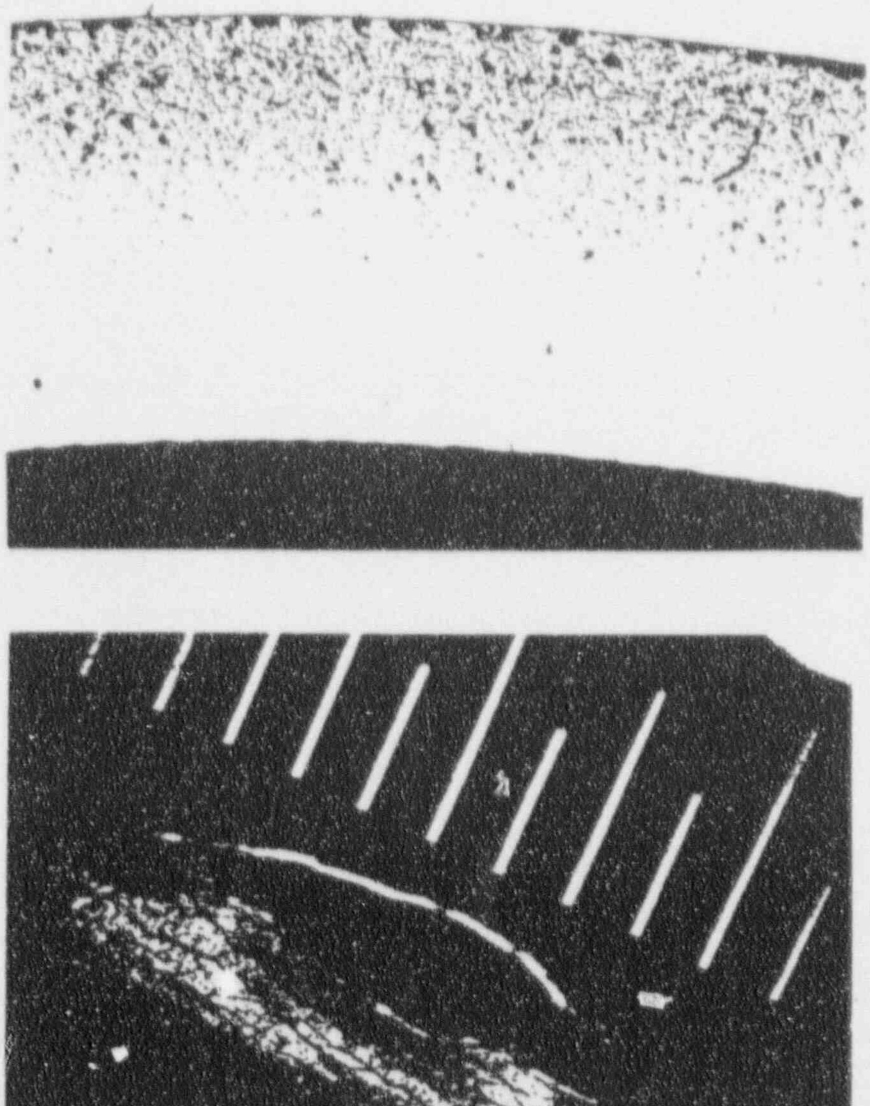


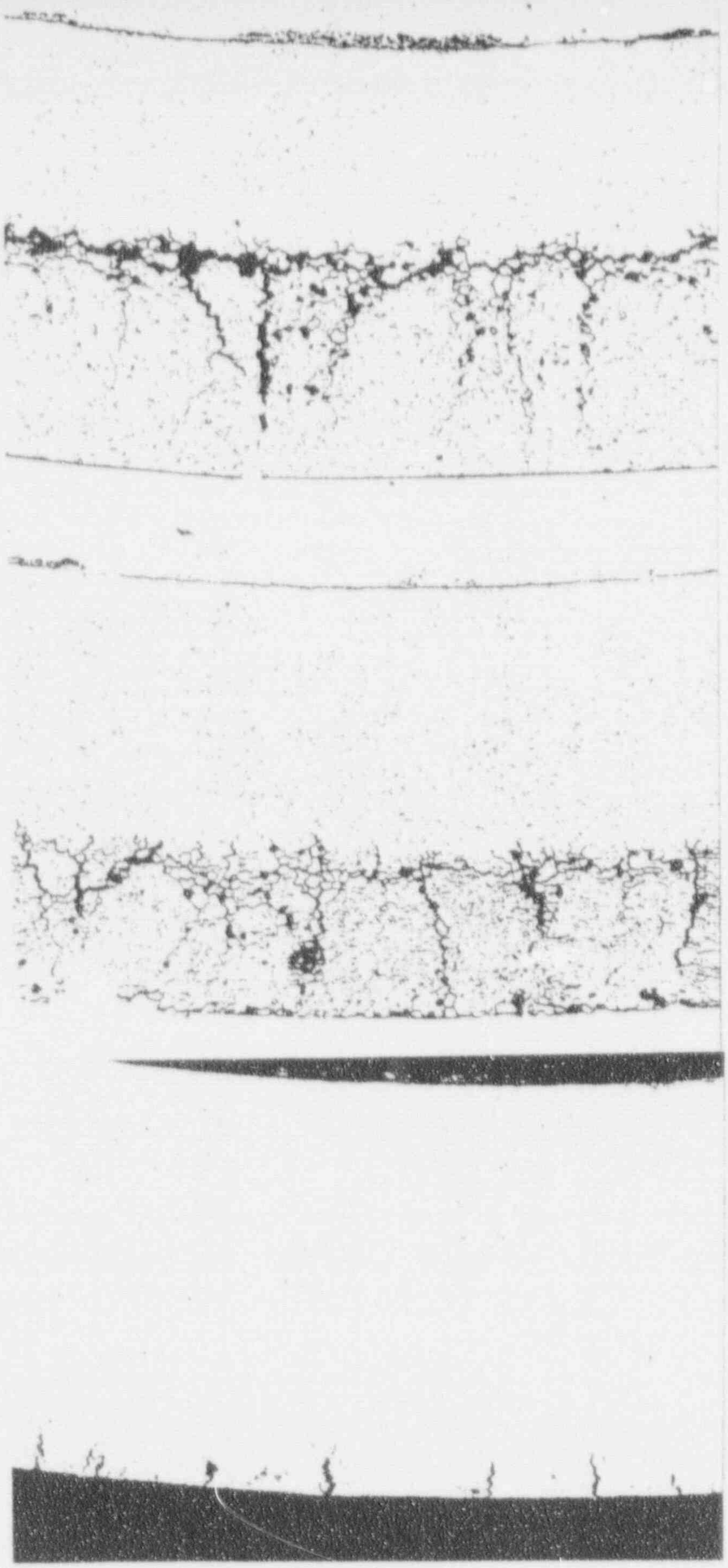
Figure 4-21. Transverse optical micrographs obtained just below the circumferential fracture at the center of the support plate. The circumferential location is that where the deepest corrosion was found. The deepest axial IGSCC is 85% through wall and three IGA patches are observed: one 43% through wall and 0.015 inch long, one 33% through wall and 0.05 inch long, and one 28% through wall and 0.015 inch long. The axial IGSCC had IGA aspects to individual cracks. These aspects can be characterized by ratios comparing the crack length (depth from OD surface) to IGA width at the mid-crack location. L/W ratios vary from 6 to 18. Plant L, R12C8



(a)

(b)

FIGURE 2 Metallograph of IGA in a Sensitized 0.75 inch Diameter Tube and Burst Test Fracture Appearance



52%

36%

9%

Figure 3 CRACKS IN IGA LAYERS CREATED DURING BURST TESTS.

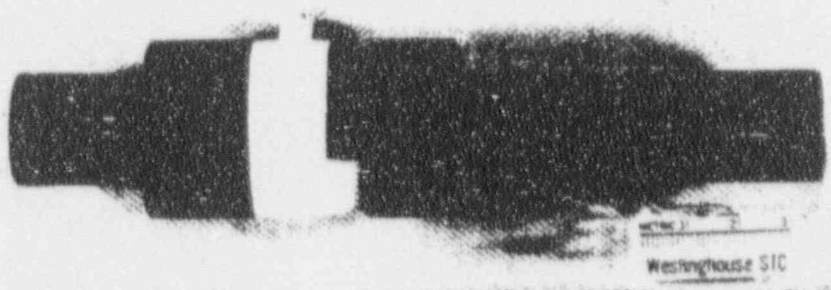


FIGURE Collars and a Teflon spacer ring on a portion of a model boiler specimen

a, c, e

Figure 7-1. Schematic of Model Boiler Facility

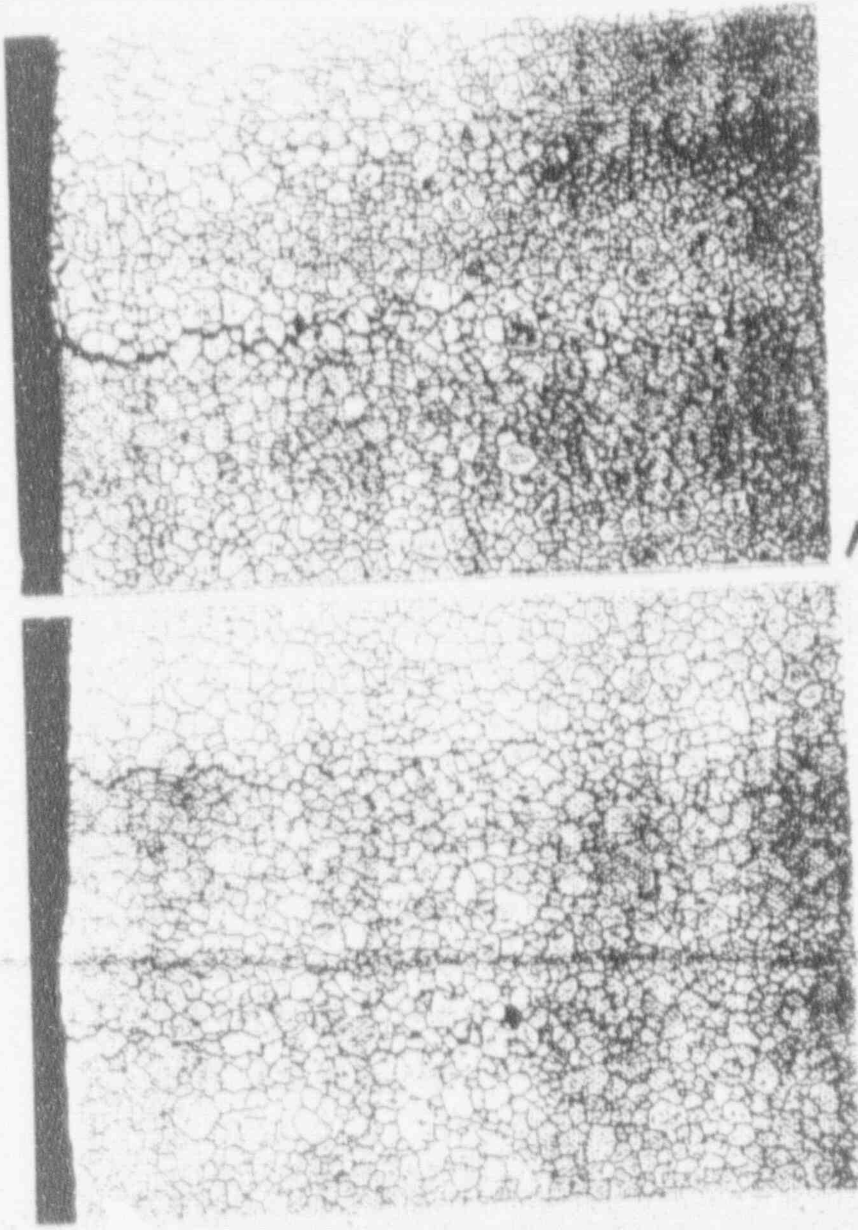
Table 6-1

THERMAL AND HYDRAULIC SPECIFICATIONS

a,c,e

Primary loop temperature	
Primary loop pressure	
Primary boiler inlet temperature	
Primary boiler outlet temperature	
Secondary T_{sat} at 5.5 MPa (800 psi)	
Steam bleed	
Blowdown	
Nominal heat flux	

DOPED STEAM SPECIMEN



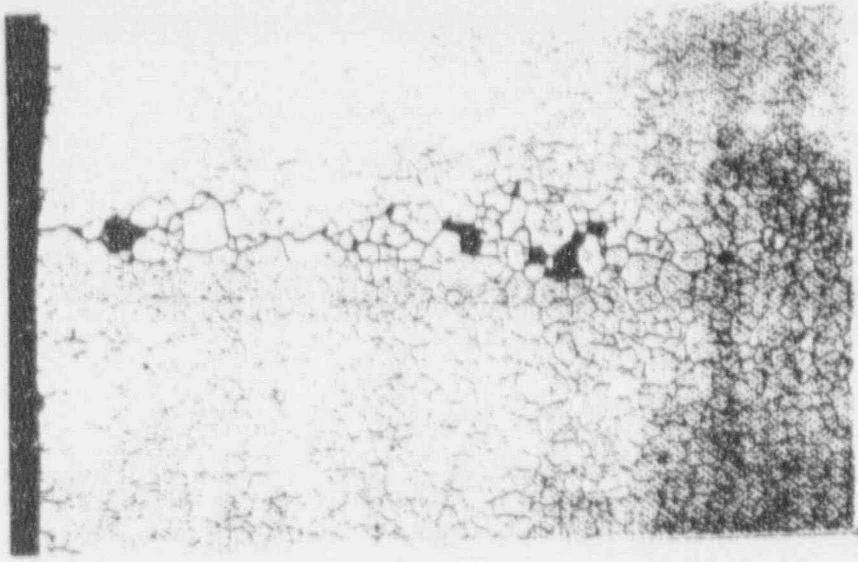
100X

MODEL BOILER SPECIMEN

100X

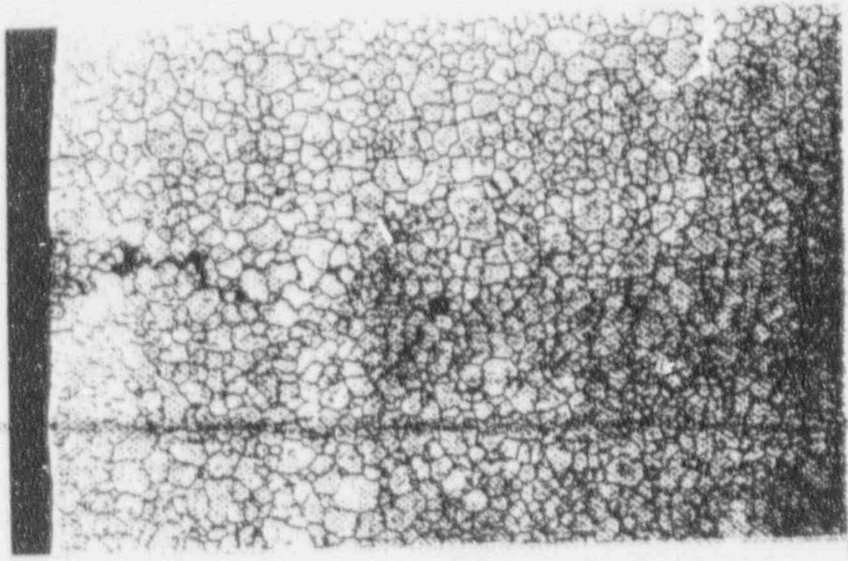
FIELD CRACK

FIGURE Metallography of Cracked Specimens



DOPED STEAM SPECIMEN

400X

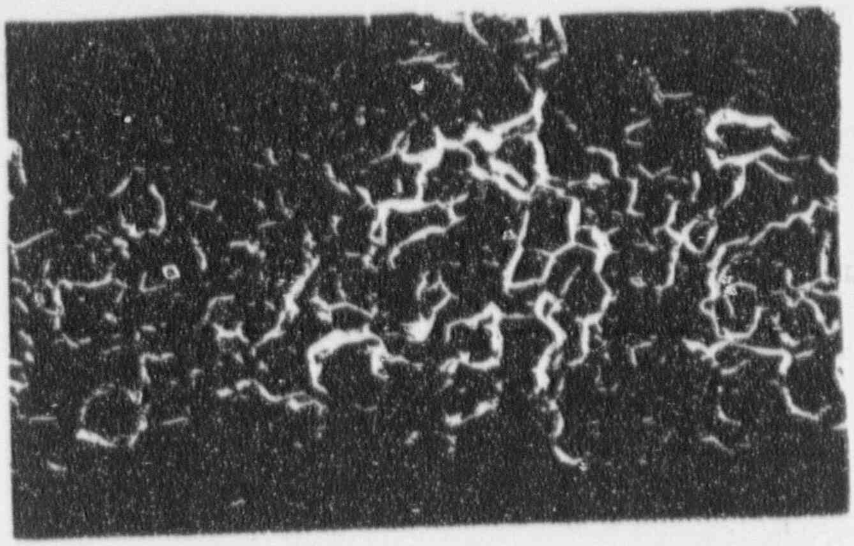


MODEL BOILER SPECIMEN

400X

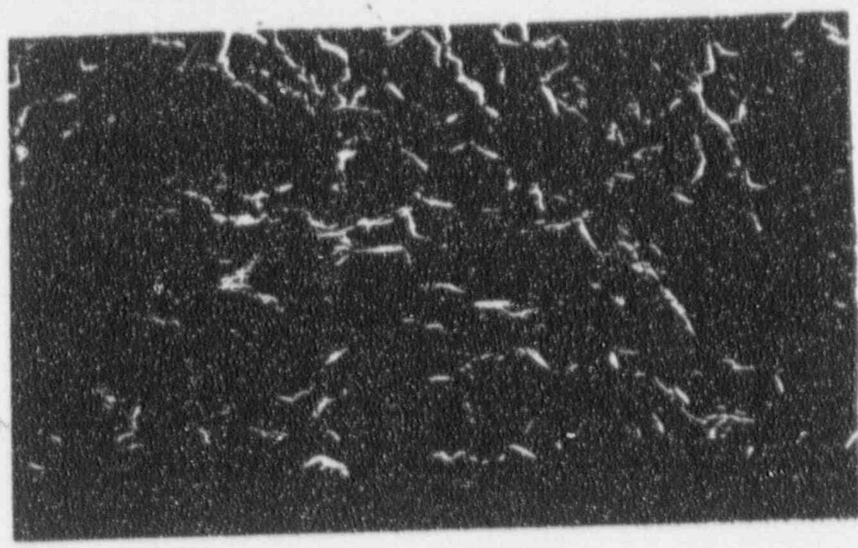
FIELD CRACK

FIGURE Metallography of Cracked Specimens



DOPED STEAM SPECIMEN

200X



MODEL BOILER SPECIMEN

200X

FIELD CRACK

Figure SEM FRACTOGRAPHS OF CRACKS IN DOPED STEAM SPECIMEN, MODEL BOILER SPECIMEN AND A SERVICE TUBE.

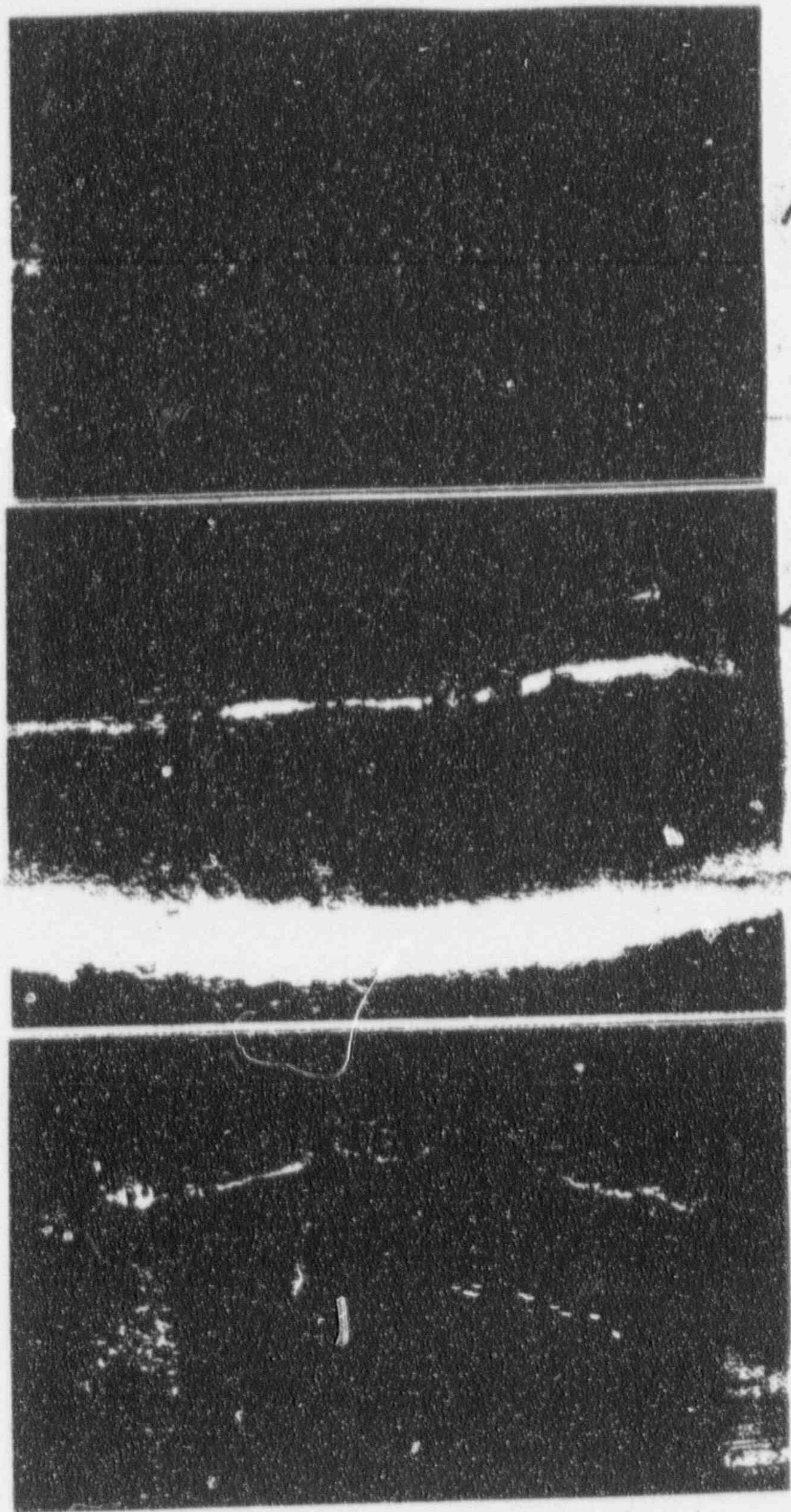


Figure Cracks in Model Boiler Specimens, (cracks opened by 4000 psi)

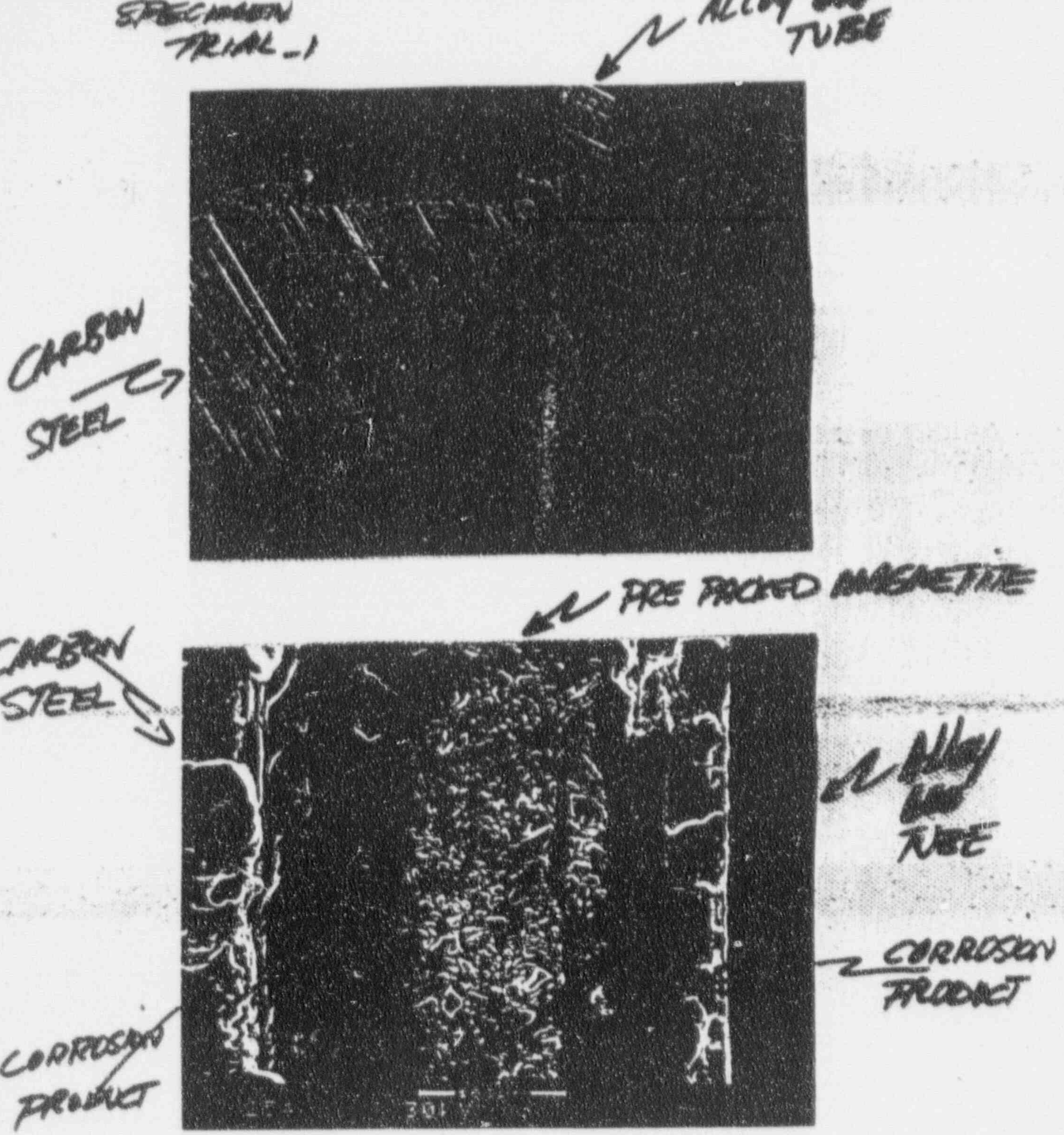


Figure Sections Through a Dented Tube Support Plate Intersection

Table 9.1

Summary of Leak and Burst Test Results

[ ] g

Figure 9-1

Burst Pressure Test Results versus Bobbin Voltage

g

Figure 9-3

SLB Leak Rate Correlation With Bobbin Voltage

Table 3

Summary of Dented Specimens

Specimen Identification	Dent Voltage	Average Radial Dent (inches)	Exposure Time (hours)	Friction Force (lbs.)	LEAK RATE
Trial_1	---	---	--		
FAT_1	7..3	0.00037	24		
FAT_2	6.09	0.00030	24		
FAT_3	12.11	0.00061	48		
FAT_4	12.0	0.00061	48		
FAT_5	4.55	0.00023	6		
FAT_6	0.00	0.0	6		
FAT_7	9.43	0.00047	24		
FAT_8	17.42	0.00087	48		
FAT_9	3.40	0.00017	6		
FAT_10	2.50	0.00012	6		
FAT_11	2.75	0.00014	6		
FAT_12	--	--	--		
BW_1	14.67	0.00073	24		
BW_3	6.27	0.00031	24		
BW_9	6.38	0.00032	48		
BW_14	7.03	0.00035	48		

Table 12.1

Model Boiler Specimens: Test Data Summary

	Model Boiler	Bobbin Coil		RPC		Leak Rate (l/hr)		Burst Press.	Destructive Exam. Length - inch*	
No.	Spec. #	Volts	% Depth	Volts	# Cracks	N. Op. ΔP	SLB ΔP	- psi	Max	Thruwall
1	500-1									
2	509-2									
3	509-3									
4	510-1									
5	525-1									
6	528-1									
7	528-2									
8	532-1									
9	532-2									
10	533-4									
11	535-1									
12	536-1									
13	542-4									
14	543-1									
15	543-2									
16	543-4									
17	555-3									
18	557-1									
19	557-2									
20	557-4									
21	558-1									
22	568-1									
23	568-2									
24	568-4									
25	568-6									
26	571-1									
27	574-4									
28	576-2									
29	576-4									

g

* For specimens without throughwall penetration, maximum depth of penetration is listed.

** Destructive examination and review of RPC data shows that only 1 crack has a significant response that contributes to the bobbin signal.

*** Tube not burst tested due to physical limitation of specimen.

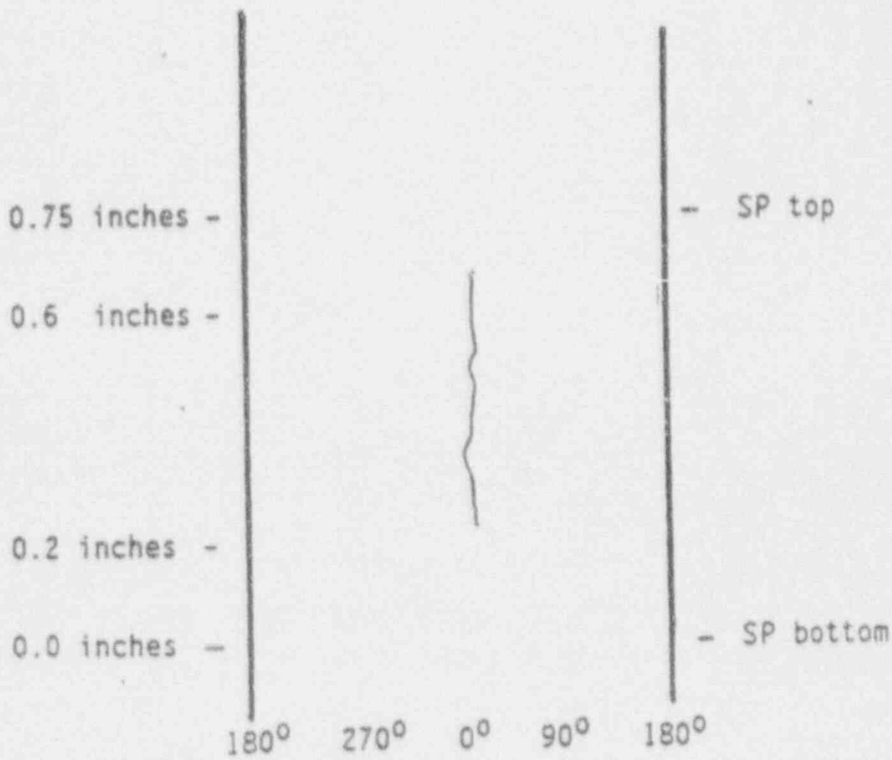
Sketch of Burst Crack

Macrocrack Length = 0.44 inches

Throughwall Length = 0.35 inches

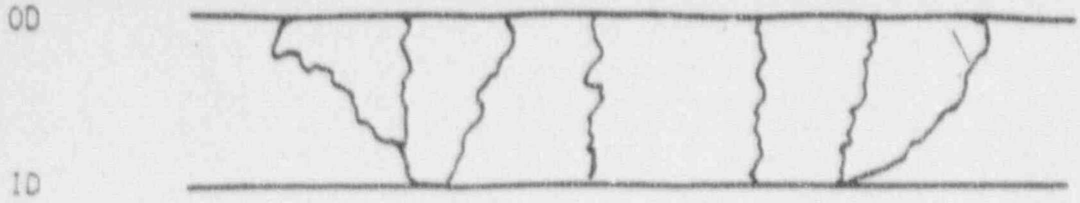
Number of Microcracks = 1 to 4

Morphology = IGSCC



Sketch of Crack Distribution

Figure 10-10 Summary of crack distribution and morphology observed on Tube 571-1.



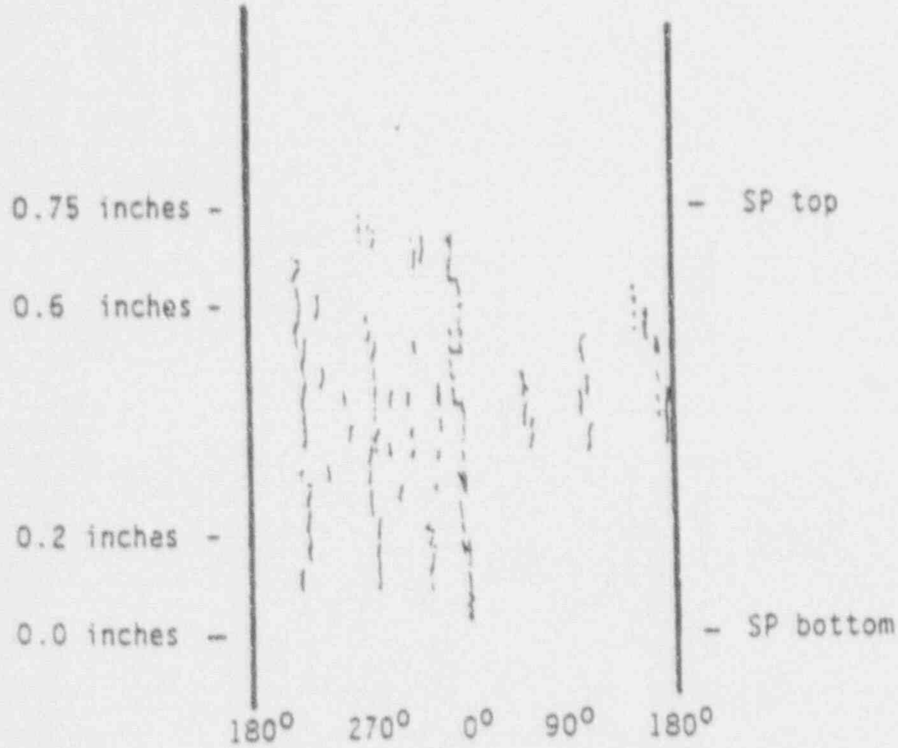
Sketch of Burst Crack

Macrocrack Length = 0.70 inch

Throughwall Length = 0.52 inch

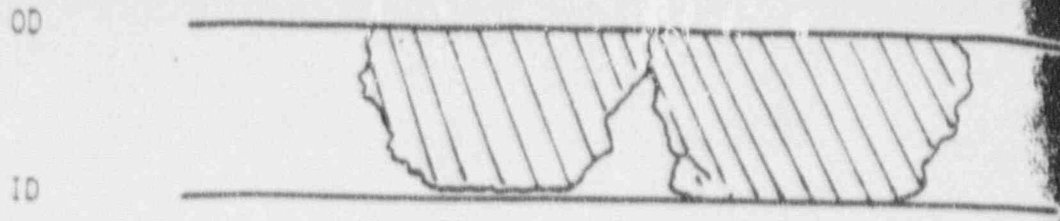
Number of Microcracks = 5 (ligaments have intergranular features)

Morphology = IGSCC



Sketch of Crack Distribution

Figure 10-25 Summary of overall crack distribution and morphology observed on tube 532-1.



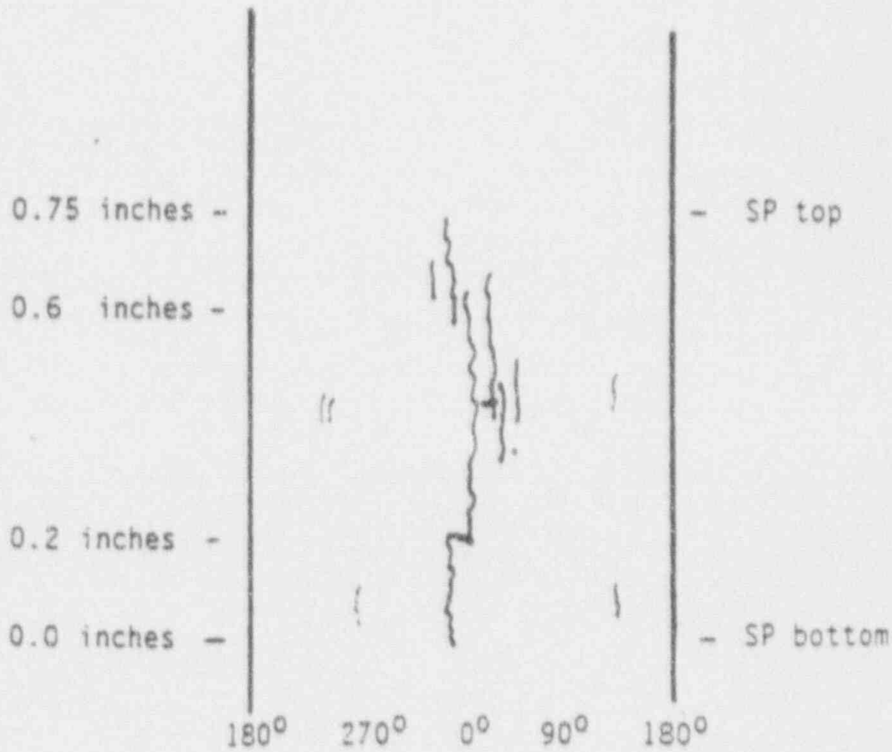
Sketch of Burst Crack

Macrocrack Length = 0.75 inch

Throughwall Length = 0.42 inch

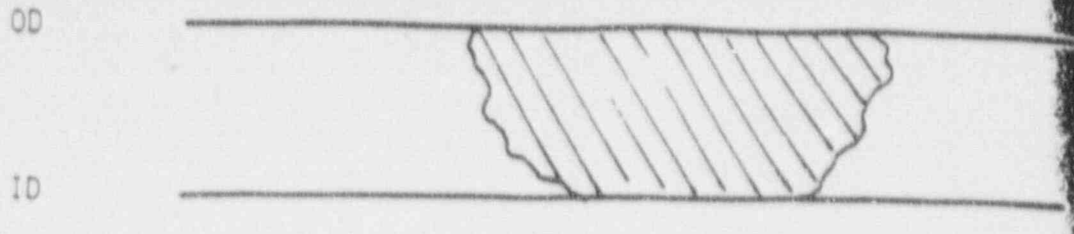
Number of Microcracks = 2 (separated by ductile ligaments)

Morphology = IGSCC



Sketch of Crack Distribution

Figure 10-34 Summary of burst crack observations and the overall cra distribution observed at the crevice region of tube 555



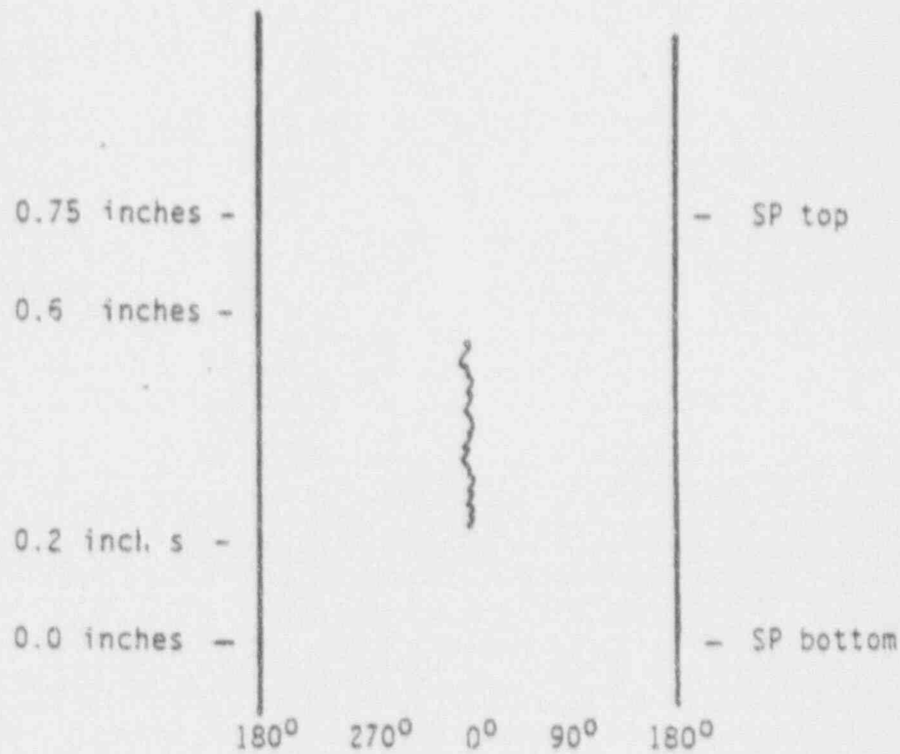
Sketch of Burst Crack

Macrocrack Length = 0.30 inch

Throughwall Length = 0.22 inch

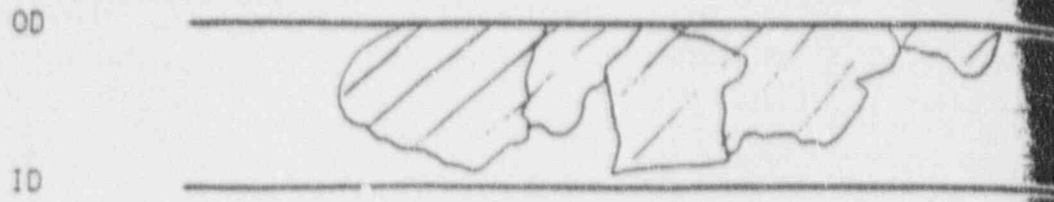
Number of Microcracks = 1 (no ligaments)

Morphology = IGSCC



Sketch of Crack Distribution

Figure 10-36 Summary of burst crack observations and the overall crack distribution observed within the crevice region of tube 576-2.



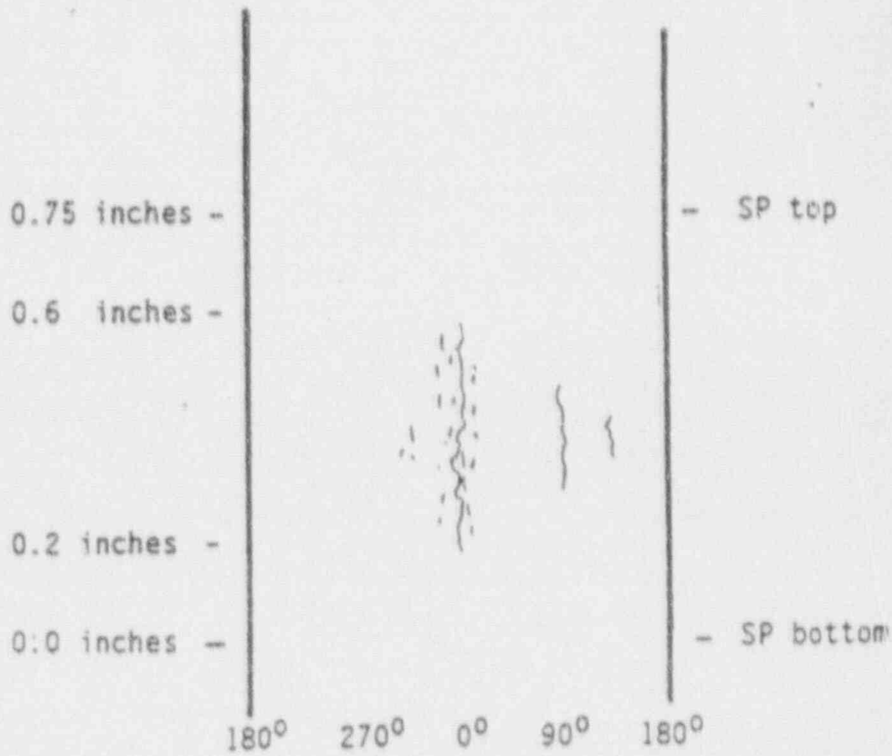
Sketch of Burst Crack

Macrocrack Length = 0.4 inches

Throughwall Length = 0 (90% throughwall)

Number of Microcracks = 5 (ligaments have mostly ductile features)

Morphology = IGSCC



Sketch of Crack Distribution

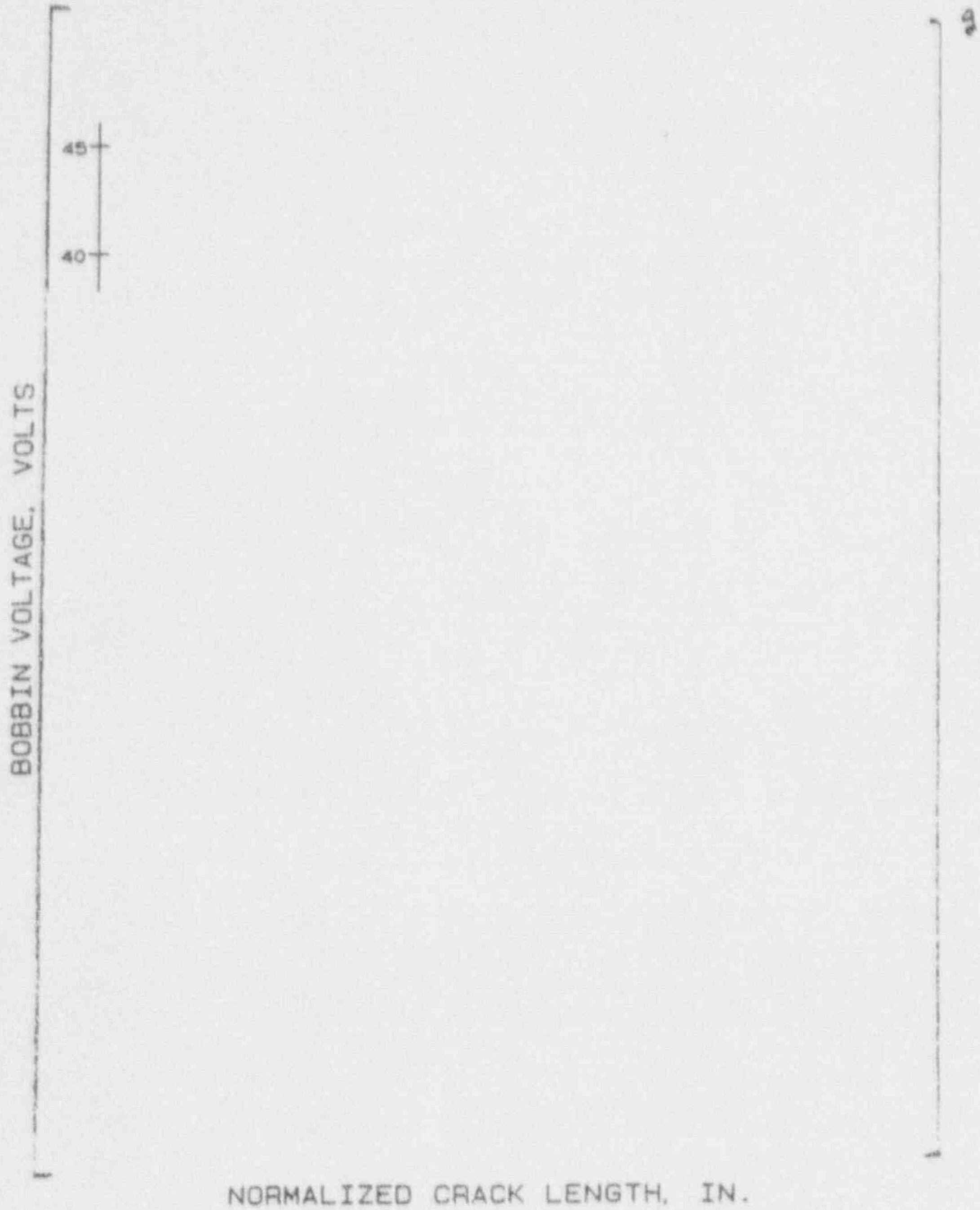
Figure 10-8 Summary of crack distribution and morphology observed on Tube 536-1.

NORMALIZED BURST PRESSURE
VERSUS NORMALIZED CRACK LENGTH

NORMALIZED BURST PRESSURE, PBAR

NORMALIZED CRACK LENGTH, LAMBDA

BOBBIN VOLTAGE VERSUS CRACK LENGTH



LATIVE BURST PRESSURE VERSUS RELATIVE DEGRADATION DEP

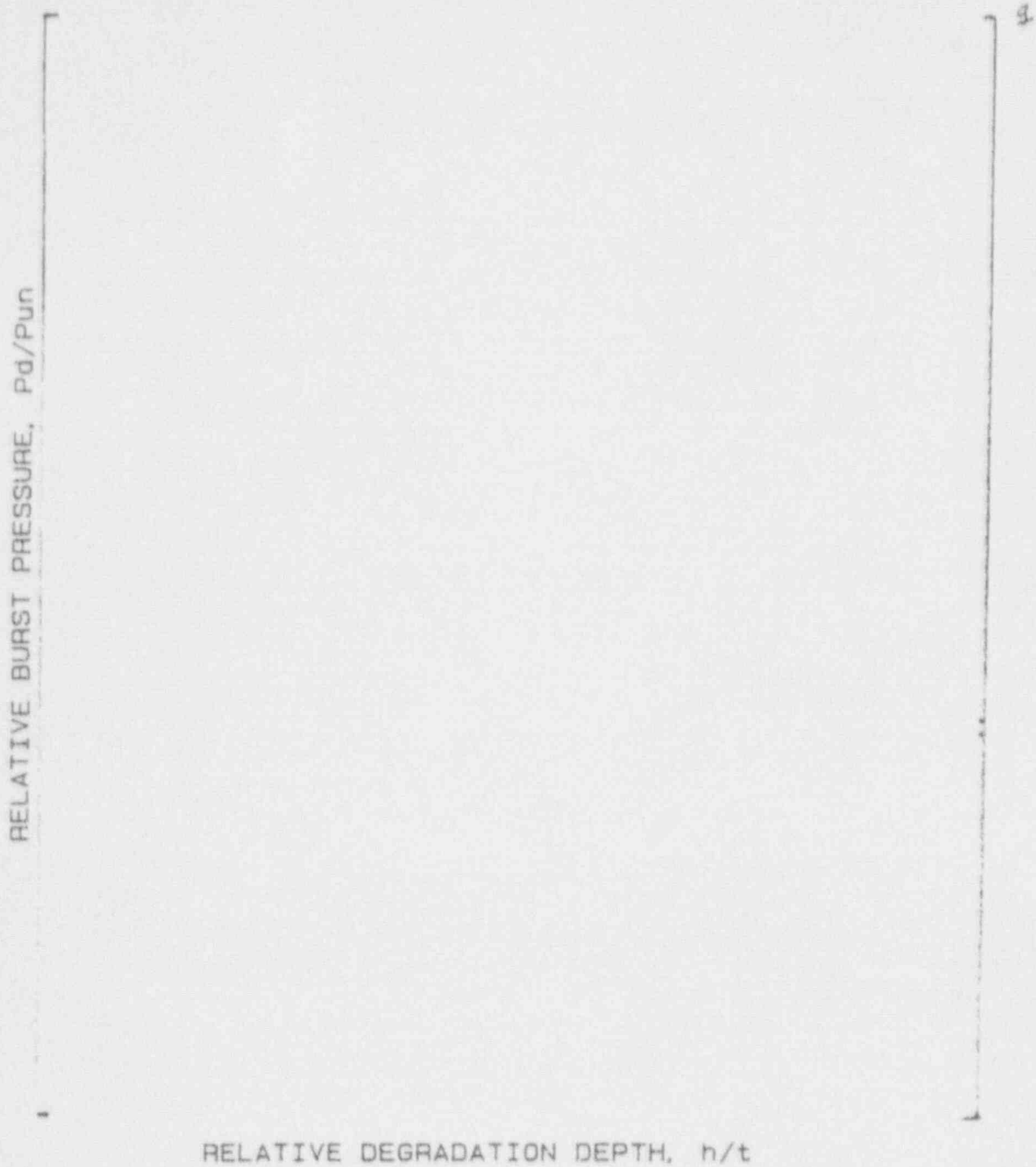


Figure 4 Relative Burst Pressure Versus Relative Degradation Depth

GIGA3 17-OCT-91 11:21 Page 1

BURST PRESSURE VERSUS UNIFORM IGA DEPTH

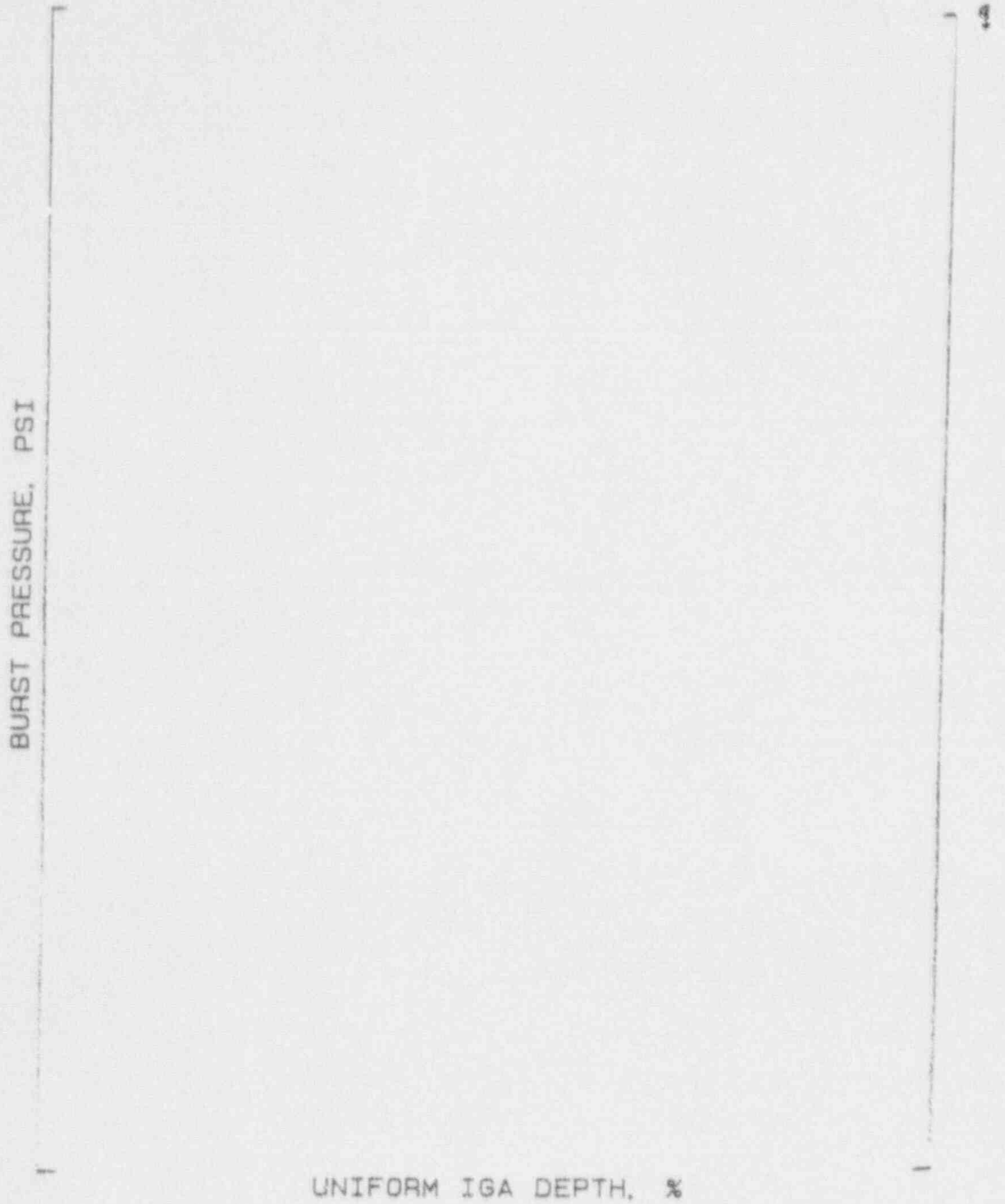


Figure 1 Burst Pressure Versus Uniform IGA Depth.

Figure 9-4

Burst Pressure Correlation With Bobbin Voltage -
IGA Specimen Burst Test Results Included

Figure 6-1

NORMALIZED BURST PRESSURE VS. CRACK LENGTH

1600 MA & TT TUBING

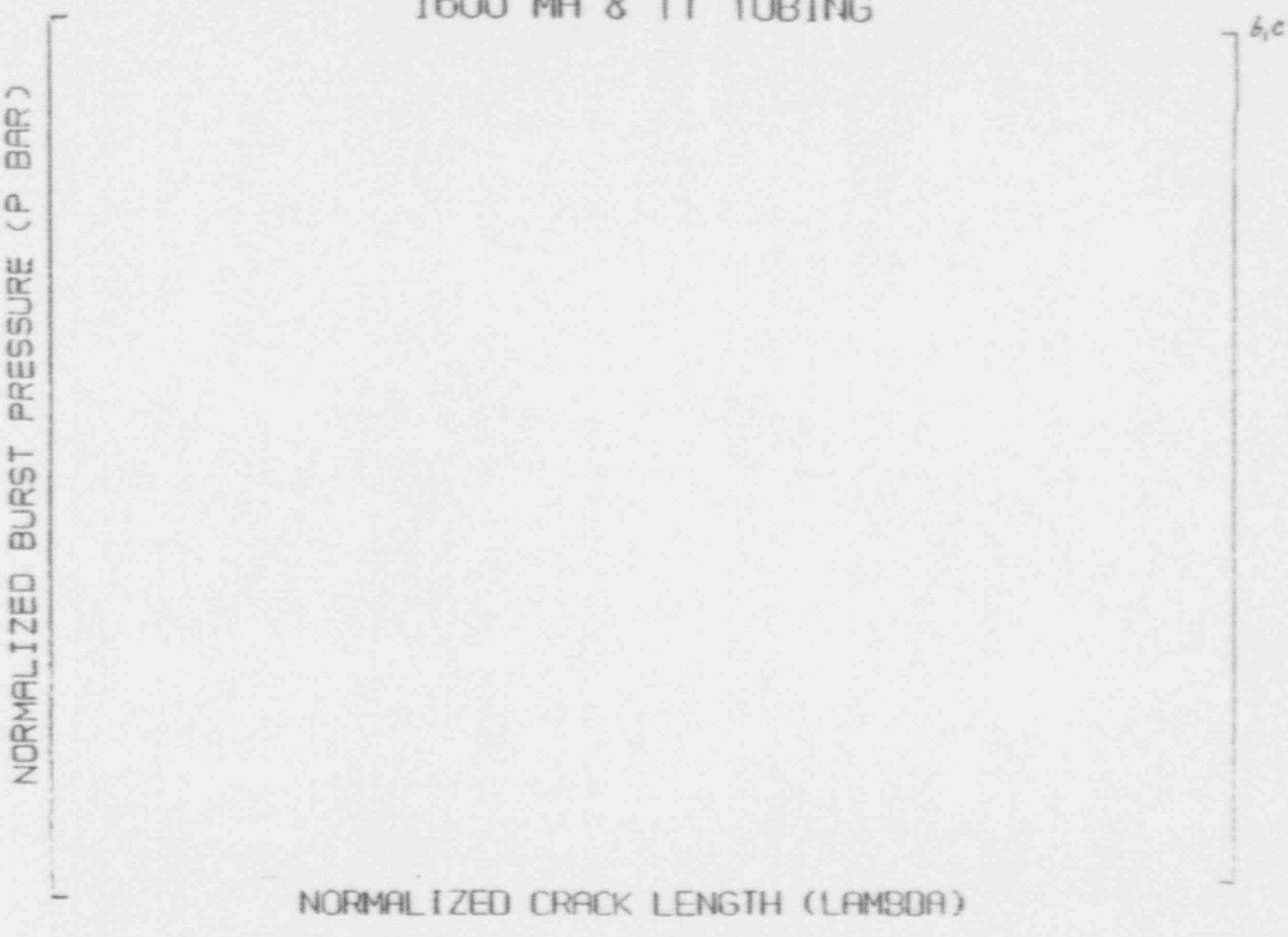


Figure 6-3

TEST VS CALCULATED BURST PRESSURE

I-600 WITH EDM PARTIAL DEPTH SLOTS

b,c

TEST BURST PRESSURE. KSI

CALCULATED BURST PRESSURE. KSI

Figure 6-2

TEST VS CALCULATED BURST PRESSURE

I-600 WITH EDM FULL DEPTH SLOTS

b,c

TEST BURST PRESSURE, KSI

CALCULATED BURST PRESSURE, KSI