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# Catawba Unit-1

# Technical Support for Steam Generator Interim Tube Plugging Criteria for Indications at Tube Support Plates

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Table of Contents

Table of Contents (Continued)

## Section 1

## INTRODUCTION

This report provides the technical basis for interim tube plugging criteria (IPC) for outside diameter stress corrosion cracking (ODSCC) at tube support plate (TSP) intersections in the Catawba Unit-1 steam generators (S/G). The recommended repair limits are based upon bobbin coil inspection voltage amplitude which is correlated with tube burst capability and leakage potential. The recommended criteria are demonstrated to provide conservative margins relative to the guidelines of Regulatory Guide (R.G.) 1.121.

The tube repair limits are based upon the conservative assumptions that the tube to TSP crevices are open (negligible crevice deposits or TSP corrosion) and that the TSPs are displaced under accident conditions. The ODSCC existing within the TSPs is thus assumed to be free span degradation under accident conditions and the principal requirement for tube plugging considerations is to provide margins against tube burst per R.G. 1.121. The open crevice assumption leads to maximum leak rates compared to packed crevices and also maximizes the potential for TSP displacements under accident conditions. However, a TSP displacement analysis has not been performed for Model D steam generators and hence the potential for TSP displacements under SLB conditions cannot be ruled out. Prevention of tube rupture by the reinforcement of the support cannot be assured without further analysis. Therefore the requirements for tube burst margins assuming free span degradation have been applied to develop the tube repair limits for Catawba-1 S/Gs.

The repair limits were developed from testing of laboratory induced ODSCC specimens, extensive examination of pulled tubes from operating S/Gs including Catawba-1 and field experience for leakage due to indications at TSPs. The recommended IPC represent very conservative limits based upon Electric Power Research Institute (EPRI) and industry supported development programs that are continuing toward further refinement of the repair limits. The currently available data base is used to define burst pressures at the lower 95% confidence bound. The IPC repair limits provide significant margins against the currently recommended correlations and satisfy R.G. 1.121 guidelines for alternate correlations reflecting current uncertainties in the burst pressure correlation.

Implementation of the tube repair limits is supplemented by 100% bobbin coil inspection at TSP elevations having ODSCC indications, reduced operating leakage requirements, inspection guidelines to provide consistency in the voltage normalization and rotating pancake coil (RPC) inspection requirements for the larger indications left in service to characterize the principal degradation mechanism as ODSCC. In addition, potential SLB leakage has been assessed by both Monte Carlo and deterministic analyses for tubes with TSP indications left in service to demonstrate that the cumulative leakage is less than allowable limits.

Nine tube to TSP intersections from five tubes pulled from Catawba Unit-1 in 1991 were burst tested and destructively examined to provide direct support for the IPC. Five of these burst tests were either incomplete bursts or burst at laboratory prepared grindmarks outside the TSP and hence could not be incorporated into the tube burst database. However, three intersections (one had no flaw indication from either NDE or destructive examination) could be combined with data from other plants and model boiler specimens. This results in a significant database supporting the IPC repair limits.

To provide the technical bases for tube plugging due to ODSCC at TSPs, the following activities have been performed as documented in this report:

- o Preparation of cracked test specimens, their non-destructive examination (NDE), leak rate testing, burst testing, and destructive examination - Section 4
- o NDE data analysis guidelines, NDE inspection results for the test specimens, voltage trends for EDM (electrodischarge machining) slots, voltage normalizations and overall NDE uncertainties - Section 5
- o Review of Catawba-1 and other plant pulled tube examinations - Section 6
- o Leak rate and burst correlations to relate the NDE parameters to burst strength and leak rate under SLB conditions - Section 7
- o Evaluations of combined accident conditions (LOCA + SSE) - Section 8
- o Review of Catawba-1 eddy current inspection results including historical growth rate data - Section 9
- o Integration of the inspection, leak rate and burst test results to develop the interim tube repair limits - Section 10.

The overall summary and conclusions for this report are described in Section 2.

## Section 2

## CONCLUSIONS

This report documents the technical support for a Catawba-1 interim plugging criteria (IPC) of 1.0 volt for ODSCC indications at TSPs. The database of pulled tube and model boiler specimens used in the evaluation of the IPC are described in this report. This database is used to develop correlations relating burst pressure to bobbin voltage and SLB leak rate to bobbin voltage. These correlations, including conservative variations allowing for data uncertainties at this time, are used in the tube integrity assessment to demonstrate Catawba-1 IPC margins against R.G. 1.121 criteria for tube plugging limits.

The overall conclusions of this report are:

- R.G. 1.121 criteria for tube integrity are conservatively satisfied at EOC 7 for an IPC repair limit of 1.0 bobbin volt.
- At EOC 7, burst pressure capability (expressed as margin ratios relative to $3\Delta P_{NO}$ and $\Delta P_{SLB}$) is expected to have ratios of about 1.25 relative to $3\Delta P_{NO}$ at 90% cumulative probability levels and about 1.35 relative to $\Delta P_{SLB}$ at 99% cumulative probability levels. A burst pressure margin ratio of 1.4 relative to $3\Delta P_{NO}$ for Catawba-1 at BOC conditions is comparable to typical values for plants with 7/8 inch diameter tubing with an IPC repair limit of 1.0 volt. Thus the two tubing sizes can be considered to have equivalent margins for IPC repair limit of 1.0 volt.
- Potential SLB leakage at EOC 7 is expected to be negligible (~0.01 gpm) as supported by both Monte Carlo and deterministic evaluations including sensitivity analyses.
- R.G. 1.121 criteria for tube burst are satisfied and negligible SLB leakage is expected even under conservative assumptions for the voltage/burst and voltage/leak rate correlations.
- The maximum EOC 7 bobbin voltage resulting from indications left in service below the repair limit is expected to be about 2.53 volts.
- The operating leak rate limit of 150 gpd implemented with the IPC satisfies R.G. 1.121 guidelines for leak before break. This limit provides for plant shutdown prior to reaching critical crack lengths for SLB conditions at a ~95% confidence level on leak rates and for $3\Delta P$ conditions at less than nominal leak rates.
- Inspection requirements for application of IPC repair limits were implemented in the 1992 inspection following Cycle 6 operation. The inspection included 100% bobbin coil inspection of TSP intersections, RPC inspection of all bobbin flaw indications >1.0 volt and an RPC sample inspection of dented TSP intersections. Tube repairs have been implemented at EOC 6 consistent with the IPC repair limit of 1.0 volt.
- The Catawba-1 pulled tubes (1991 outage) show that the crack morphology for indications at TSPs can be described as multiple ODSCC axial cracks within the TSP

length and with negligible volumetric IGA involvement. Burst data for 3 intersections from the Catawba-1 pulled tubes are included in the burst pressure vs bobbin voltage correlation.

- Recommended correlations of bobbin voltage to burst pressure and to SLB leakage, as well as alternate correlations for sensitivity analyses, are developed in this report. These correlations form the basis for determining margins for burst and leakage as summarized above.

- Pulled tube and model boiler data are used to define a 2.0 volt threshold for leakage at SLB conditions. Between 2.0 and 3.5 volts (3.5 volts exceeds maximum expected EOC indication of 2.53 volts, an SLB leak rate of 1.0 liter/hr can be conservatively applied for "deterministic" SLB leak rate analyses.

## Section 3

## SUPPORT PLATE REGION PULLED TUBE DATABASE (3/4 INCH TUBING)

### 3.1 Introduction & Definitions

The following provides summary information regarding OD originated corrosion at support plate crevice regions of Alloy 600 tubing pulled from steam generators at various plants including Catawba Units 1. The data is presented in support of the development of tube plugging criteria for Catawba-1. First, pulled tube data from the Catawba-1 are reviewed followed by data from other plants.

The type of intergranular corrosion with regard to crack morphology and density (number, length, depth) of cracks can influence the structural integrity of the tube and the eddy current response of the indications. To support the tube repair criteria, the emphasis for destructive examination is placed upon characterizing the morphology (SCC, IGA involvement), the number of cracks, and characterization of the largest crack networks with regard to length, depth and remaining ligaments between cracks. These crack details support interpretation of structural parameters such as leak rates and burst pressure, crack length and depth, and of eddy current parameters such as measured voltage with the goal of enhancing structural and eddy current evaluations of tube degradation. In selective cases, such as the 1990 Plant A-2 pulled tubes, the pulled tube evaluations included leak rate measurements, in addition to the more standard burst pressure measurements, for further support of the integrity and plugging limit evaluations.

Before the support plate region corrosion degradation can be adequately described, some key corrosion morphology terms need to be defined. Intergranular corrosion morphology can vary from IGA to SCC to combinations of the two. IGA (Intergranular Attack) is defined as a three dimensional corrosion degradation which occurs along grain boundaries. The radial dimension has a relatively constant value when viewed from different axial and circumferential coordinates. IGA can occur in isolated patches or as extensive networks which may encompass the entire circumferential dimension within the concentrating crevice. Figure 3-1 provides a sketch of these IGA morphologies. As defined by Westinghouse, the width of the corrosion should be equal to or greater than the depth of the corrosion for the degradation to be classified as IGA. The growth of IGA is relatively stress independent. IGSCC (Intergranular Stress Corrosion Cracking) is defined as a two-dimensional corrosion degradation of grain boundaries that is strongly stress dependent. IGSCC is typically observed in the axial-radial plane in steam generator tubing, but can occur in the circumferential-radial plane or in combinations of the two planes. The IGSCC can occur as a single two dimensional crack, or it can occur with branches coming off the main plane. Figure 3-2 provides a sketch of these IGSCC morphologies. Both of the IGSCC variations can occur with minor to major components of IGA. The IGA component can occur simply as an IGA base with SCC protruding through the IGA base or the SCC plane may have a semi-three dimensional characteristic. Figure 3-3 provides a sketch of some of the morphologies possible with combinations of IGSCC and IGA. Based on laboratory corrosion tests, it is believed that the latter, SCC protrusions with significant IGA aspects, grow at rates similar to that of SCC, as opposed to the slower rates usually associated with IGA. When IGSCC and IGA are both present, the IGSCC will penetrate throughwall first and provide the leak path.

To provide a semi-quantitative way of characterizing the amount of IGA associated with a given crack, the depth of the crack is divided by the width of the IGA as measured at the mid-depth of the crack, creating a ratio D/W. Three arbitrary D/W categories were created: minor (D/W

greater than 20) (all or most PWSCC would be included in this category if it were being considered in this analysis); moderate (D/W between 3 and 20); and significant (D/W less than 3) where for a given crack with a D/W of 1 or less, the morphology is that of patch IGA.

The density of cracking can vary from one single large crack (usually a macrocrack composed of many microcracks which nucleated along a line that has only a very small width and which then grew together by intergranular corrosion) to hundreds of very short microcracks that may have partially linked together to form dozens of larger macrocracks. Note that in cases where a very high density of cracks are present (usually axial cracks) and where these cracks also have significant IGA components, then the outer surface of the tube (crack origin surface) can form regions with effective three dimensional IGA. Axial deformations of the tube may then cause circumferential openings on the outer surface of the tube within the three dimensional network of IGA; these networks are sometimes mistakenly referred to as circumferential cracks. The axial cracks, however, will still be the deeper and the dominant degradation, as compared to IGA.

Recognizing all of the gradations between IGA and IGSCC can be difficult. In addition to observing patch IGA, cellular IGA/SCC has been recently recognized. In cellular IGA/SCC, the cell walls have IGSCC to IGA characteristics while the interiors of the cells have nondegraded metal. The cells are usually equiaxial and are typically 25 to 50 mils in diameter. The cell walls (with intergranular corrosion) are typically 3 to 10 grains (1 to 4 mils) thick. The thickness and shape of the cell walls do not change substantially with radial depth. Visual examinations or limited combinations of axial and transverse metallography will not readily distinguish cellular IGA/SCC from extensive and closely spaced axial IGSCC with circumferential ledges linking axial microcracks, especially if moderate to significant IGA components exist in association with the cracking. Radial metallography is required to definitely recognize cellular IGA/SCC. Cellular IGA/SCC can cover relatively large regions of a support plate crevice (a large fraction of a tube quadrant within the crevice region). Figure 3-4 shows an example of cellular IGA/SCC from Plant L.

A given support plate region can have intergranular corrosion that ranges from IGA through individual IGSCC without IGA components.

### 3.2 Catawba-1 Corrosion Degradation

Five tubes have been removed from Catawba-1 for which nine intersections have been destructively examined. Data collected in the post-pull laboratory examination that supports APC applications included NDE, burst tests, leak tests at room temperature (one at prototypic conditions) and metallography including sequential grinds to characterize crack patterns/depths and morphology. The NDE data for the Catawba-1 pulled tubes are discussed in Section 5 and the burst tests, leak tests and crack maps are presented in Section 6.6. This section focuses on the crack morphology for the Catawba-1 pulled tubes.

Degradation at the Catawba-1 TSP intersections has been found primarily in the form of axially oriented, intergranular stress corrosion cracks. Uniform IGA attack up to 5% throughwall was also found. In the tube examination results, isolated IGA patches are reported up to 50% throughwall. These regions called IGA patches would not be classified as significant IGA by the definitions given in Section 3.1 as the width of the IGA or volumetric involvement is small.

Four TSP intersections were incrementally ground and polished and metallography taken at each grind (maps given in Section 6.6). Examples of the metallography are shown in Figures 3-5 to

3-8. These Figures are typical of the variation from minimal degradation to the largest and most closely spaced cracks. Typical areas identified as IGA patches are shown in Figures 3-5 to 3-8. The volumetric involvement of IGA at these patches is too small to be significant for tube structural integrity considerations. Figures 3-7 and 3-8 show regions of closely spaced axial cracks. In some cases, the closely spaced cracks have similar wall penetration as seen in Figure 3-7.

Overall, the Catawba-1 tubes show multiple, axially oriented ODSCC cracks with minor volumetric IGA involvement. This morphology is very similar to other domestic pulled tubes with no or minimal cellular SCC.

### 3.3 Plant E-4 Corrosion Degradation

Steam generator tubes at support plate crevice regions in the European Plant E-4 have developed cellular IGA/SCC. The cellular IGA/SCC is localized in the crevice region such that most of the crevice region is free of corrosion. The crevice regions had moderate crack densities, moderate IGA components associated with individual major cracks, and no significant IGA independent cracking. Burst tests conducted produced the expected axial opening through complex mixtures of axial, circumferential and oblique cracks. For the more strongly affected areas, while the cracking remained multi-directional, there was a predominance of axial cracking. Figures 3-9 and 3-10 provide radial section photomicrographs through two of the more strongly affected areas showing cellular IGA/SCC at Plant E-4.

### 3.4 Plant B-1 Corrosion Degradation

A description of the corrosion found at TSP 5 of Plant B-1 is provided below. This region is singled-out for two reasons. First of all, it has through wall corrosion. Secondly, the tube had a small region believed to have cellular IGA/SCC.

OD origin, axially orientated, intergranular stress corrosion cracks were observed confined entirely within the fifth support plate crevice region on the hot leg side of tube R4-C61 from Steam Generator C of Plant B-1. Six axial macrocracks were observed around the circumference. The largest of these was examined by SEM fractography without any metallography. The macrocrack was 0.4 inch long and through wall for 0.01 inch. However, the crack was nearly (effectively) through wall for 0.1 inch. The macrocrack was composed of seven individual microcracks that had mostly grown together by intergranular corrosion (the separating ledges had intergranular features that ranged from 40 to 90% of the length of the ledges). Since no metallography was performed on the axial cracks, it is not possible to definitively describe the axial crack morphology at this location. At the eighth support plate region of the same tube, metallography showed that the morphology was that of SCC with a crack depth to IGA width ratio (D/W) of 15. Figure 3-11 summarizes the crack distribution and morphology data for the fifth support plate crevice region.

In addition to the OD origin axial macrocracks observed at the fifth support plate region, one location adjacent to the burst crack had five intergranular circumferential cracks. The maximum penetration observed for the circumferential cracking was 46% through wall. The morphology of the circumferential cracking was more that of IGA patches than of SCC. In addition to the 5 main circumferential cracks, the region had numerous smaller cracks aligned in both the axial and circumferential directions providing a crazed appearance. See Figure

3-12. This crazed degradation is now recognized as probably being cellular IGA/SCC. Previously the crazed pattern was thought to represent only shallow IGA type degradation that completely disappeared a short distance below the surface. Figure 3-13 provides micrographs of relevant cracks showing the morphology of axial and circumferential cracks. As stated above, the axial cracks had a morphology of IGSCC with a moderate D/W ratio of 15 while the circumferential cracking had a morphology more like that of IGA, with a D/W ratio of 1.

Field eddy current bobbin probe inspection (in June 1989, just prior to the tube pull) of the fifth support plate crevice region produced a 1.9 volt, 74% deep indication in the 550/100 kHz differential mix.

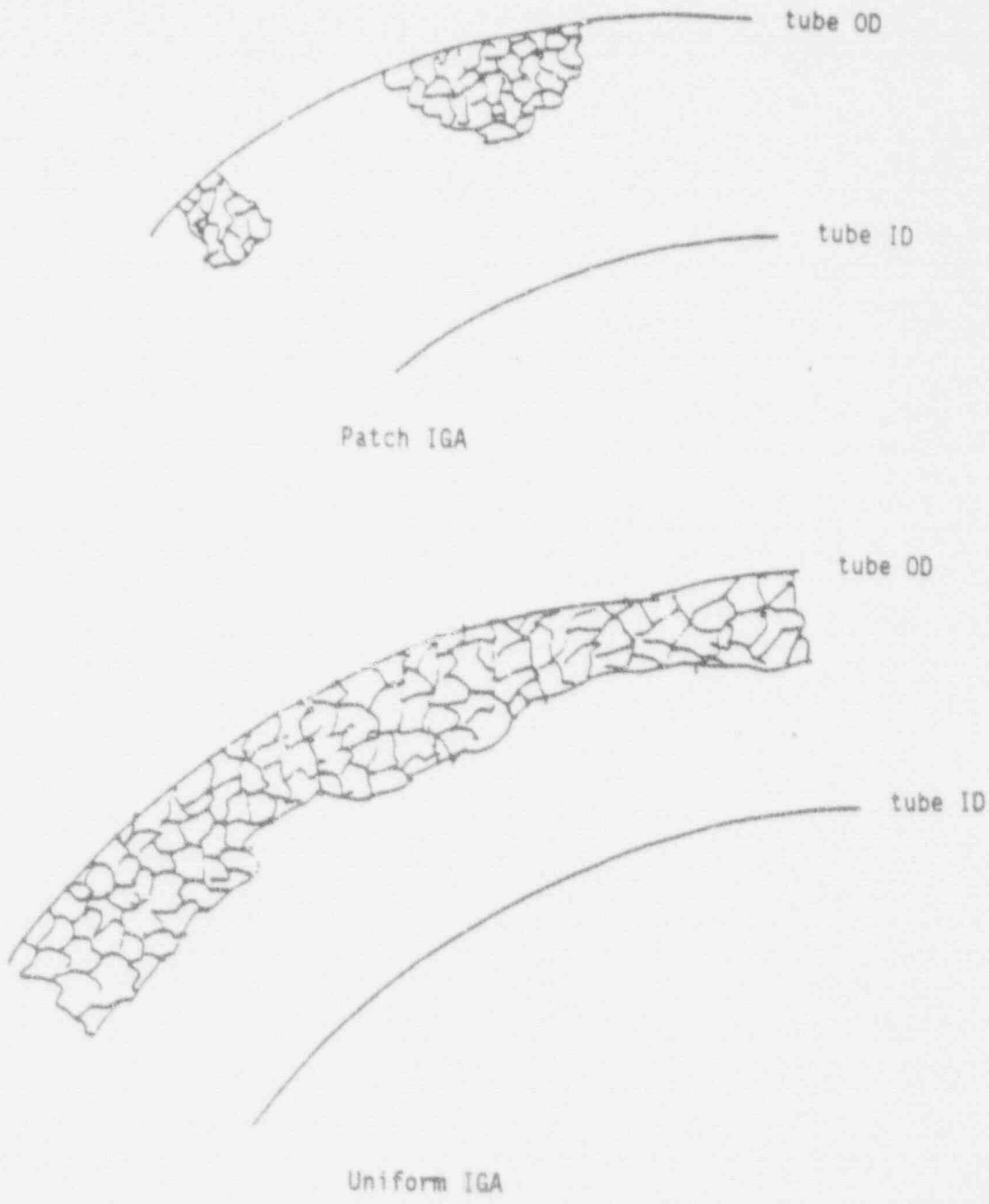



Figure 3-1 Patch and uniform IGA morphology as observed in a transverse tube section. (A similar observation would be made from a longitudinal section.)

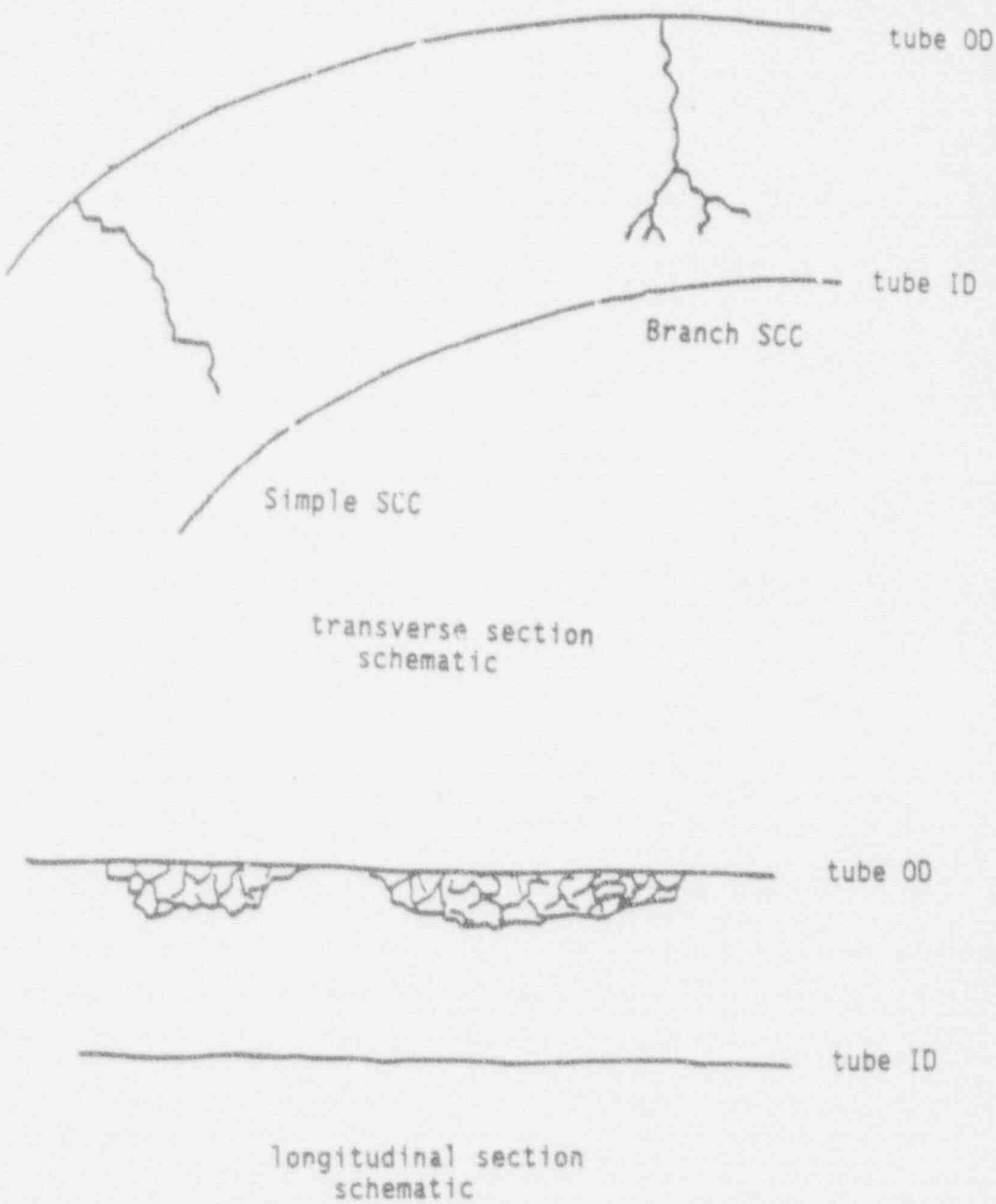
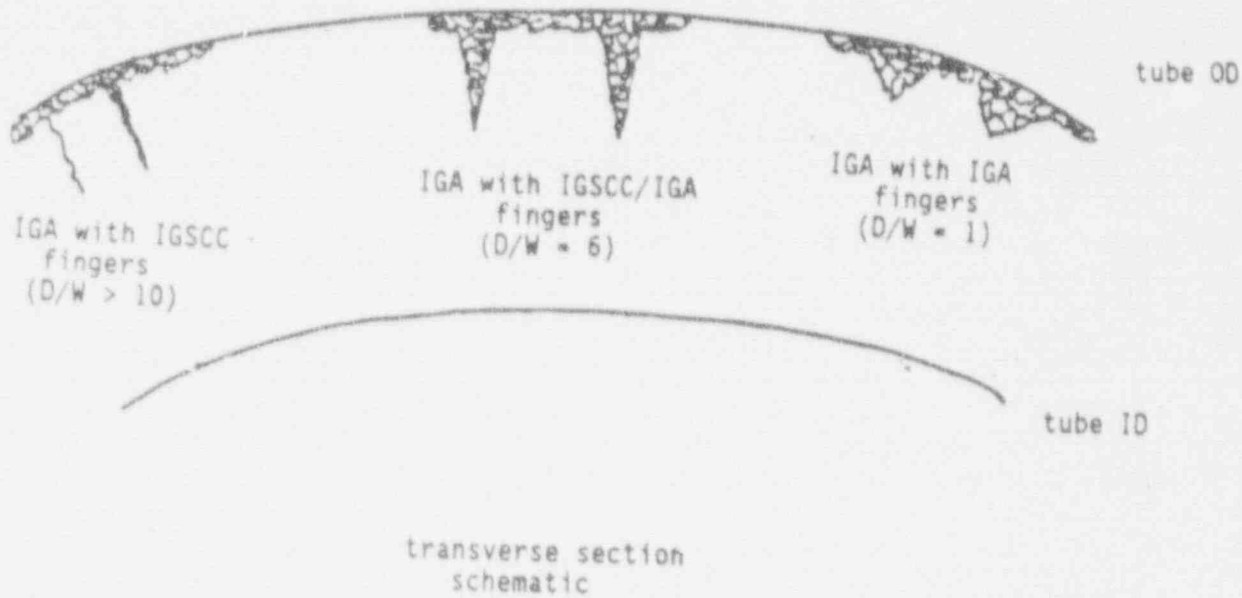



Figure 3-2 Schematic of simple IGSCC and branch IGSCC. Note that branch and simple IGSCC are not distinguishable from a longitudinal metallographic section. From a longitudinal section, they also look similar to IGA (See Figure 4.3).



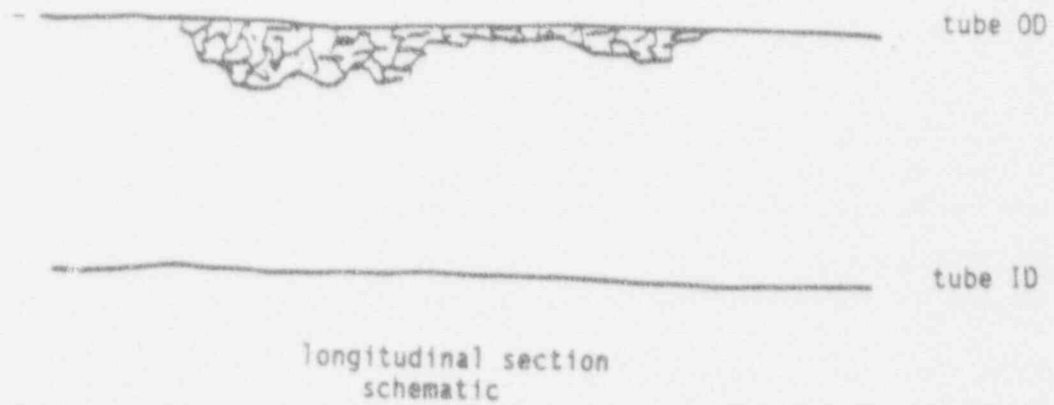




Figure 3-3 Schematic of IGA with IGSCC fingers and IGA with IGA fingers. Note that neither of the above variations can be distinguished from a longitudinal section.

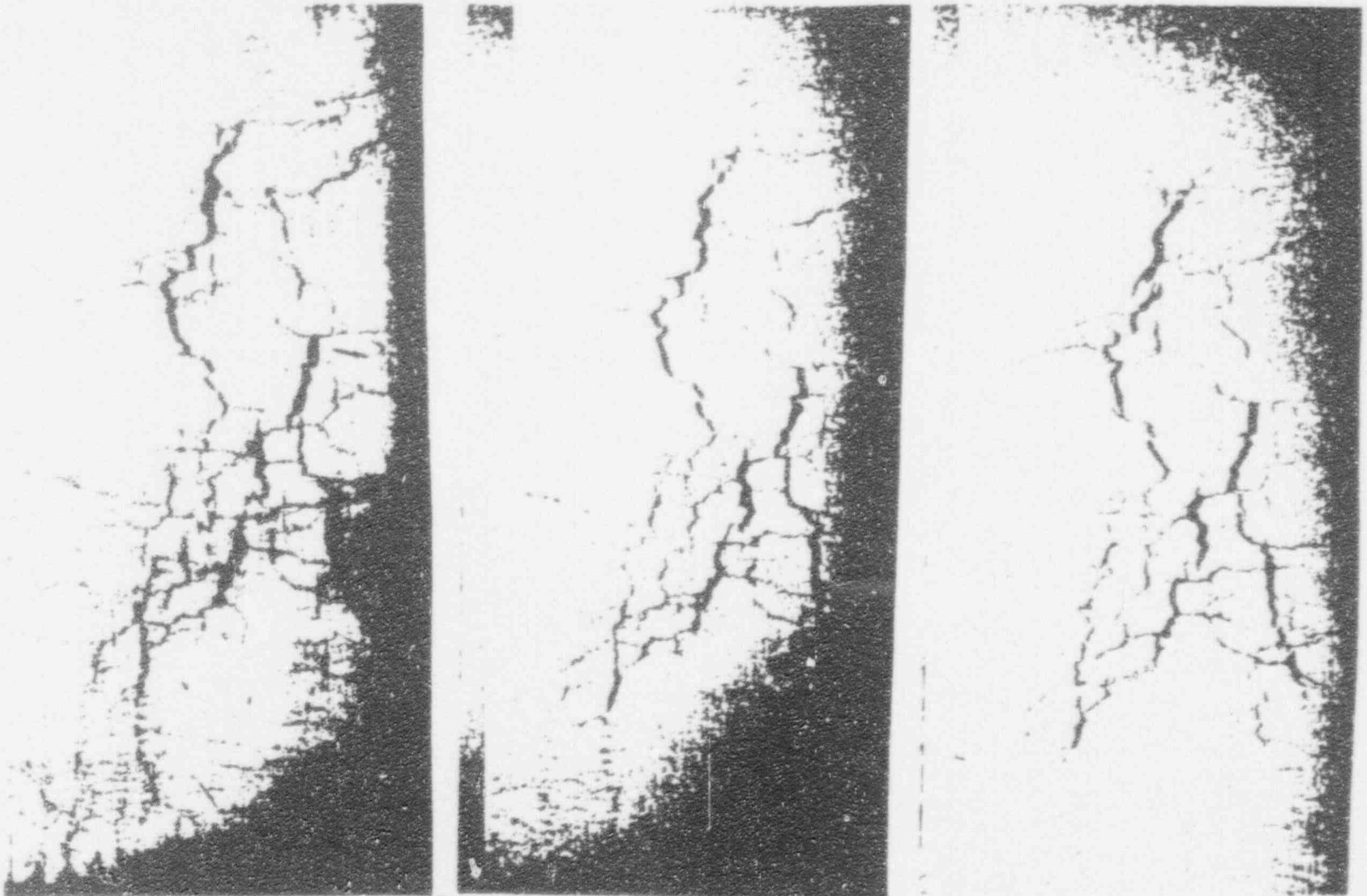
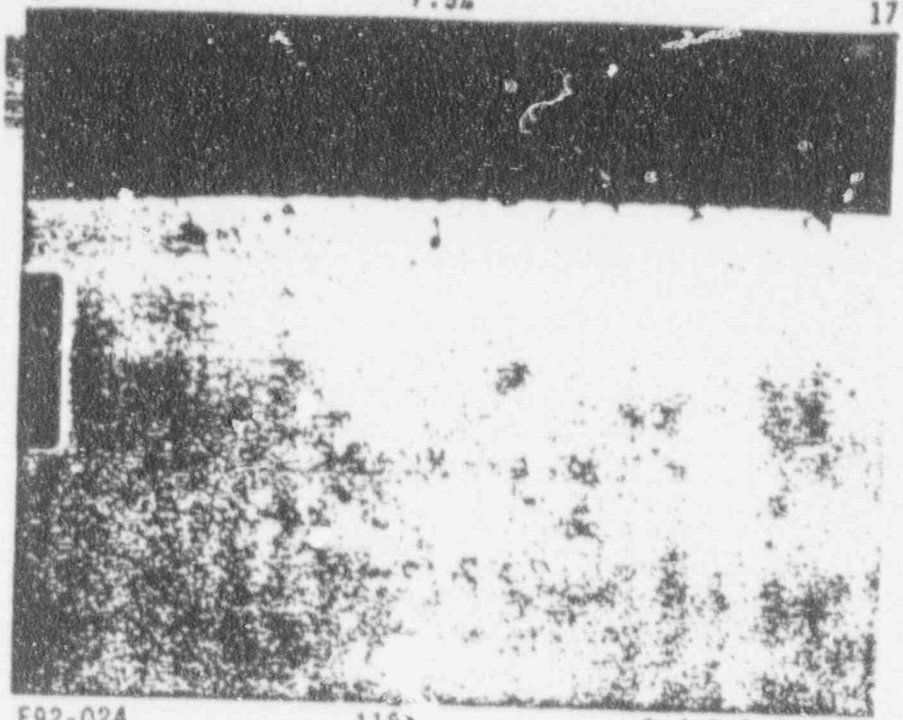
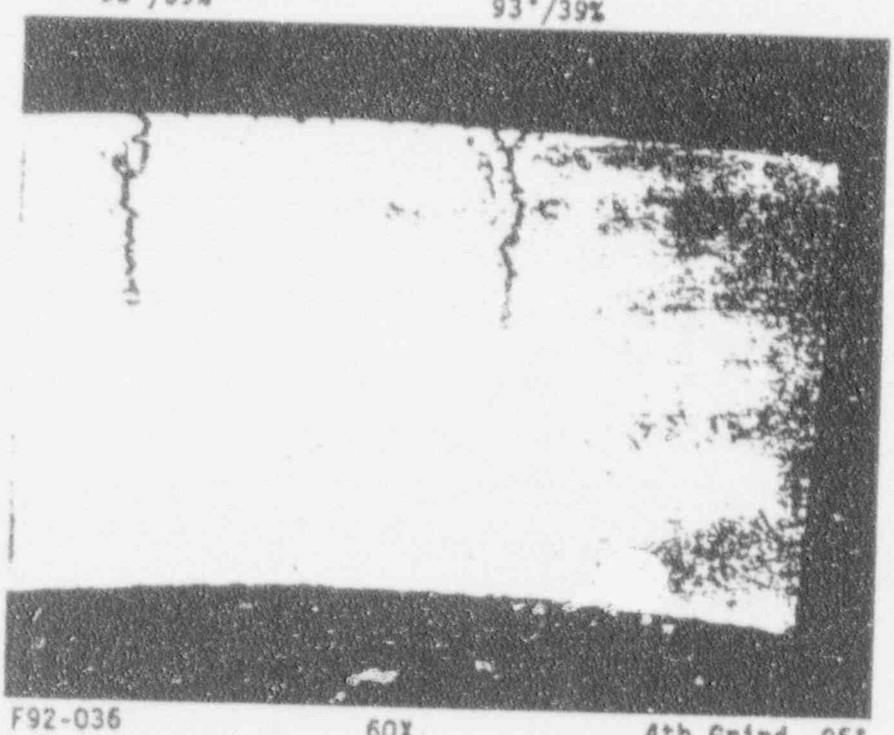



Figure 3-4 Photomicrographs of radial metallography performed on a region with axial and circumferential degradation on tube R16-C74, support plate 1. Cellular IGA was found with little change in the cell shape and cell wall thickness at depths of 4, 11 and 21 mils below the OD surface. Note that the cut section was flattened, preferentially opening the circumferential wall of the cells.

IGA Patch



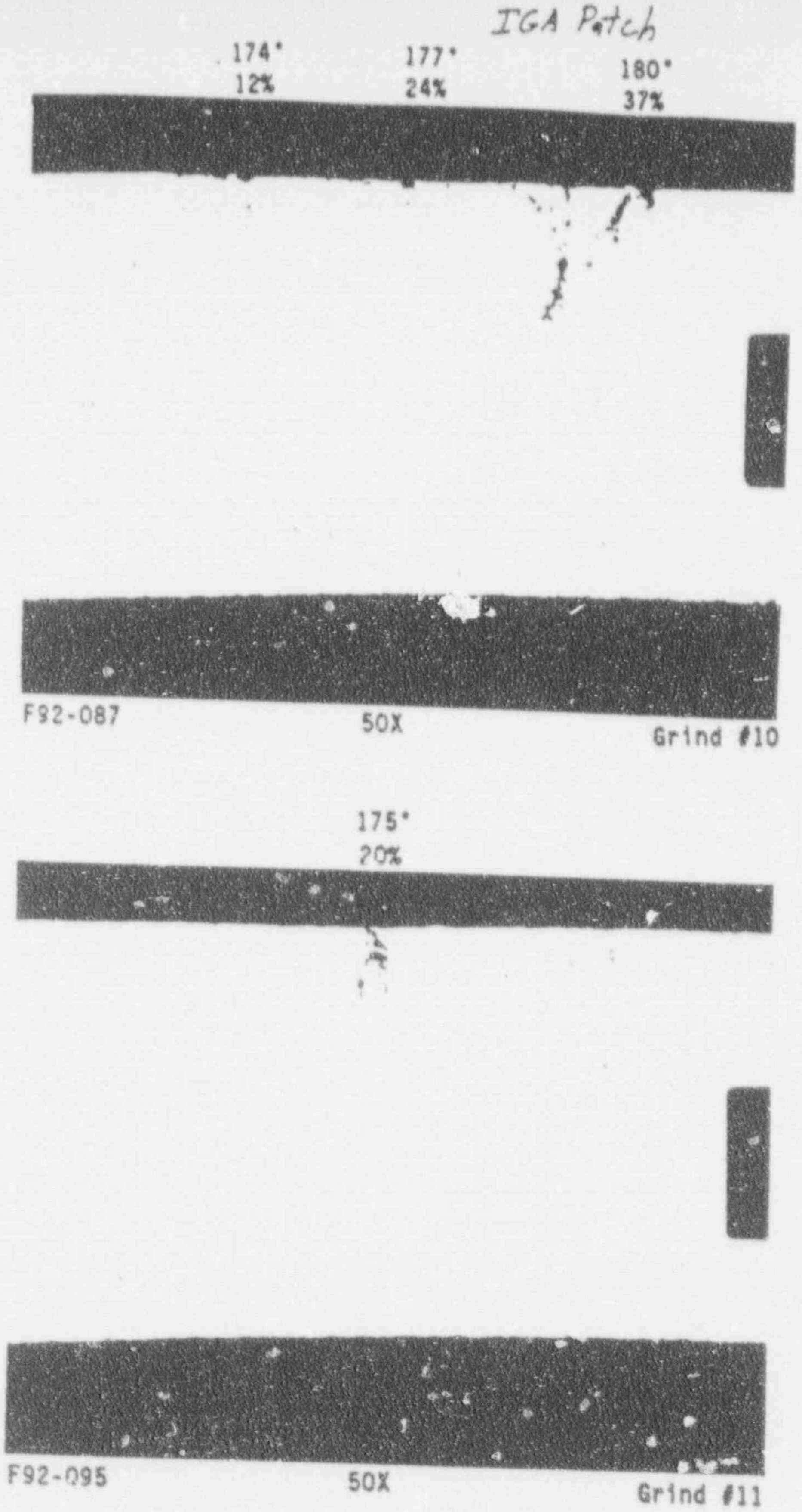

F92-024 118X 3rd Grind, 20°




F92-036 60X 4th Grind, 95°

Specimen 10-69-4B-2E

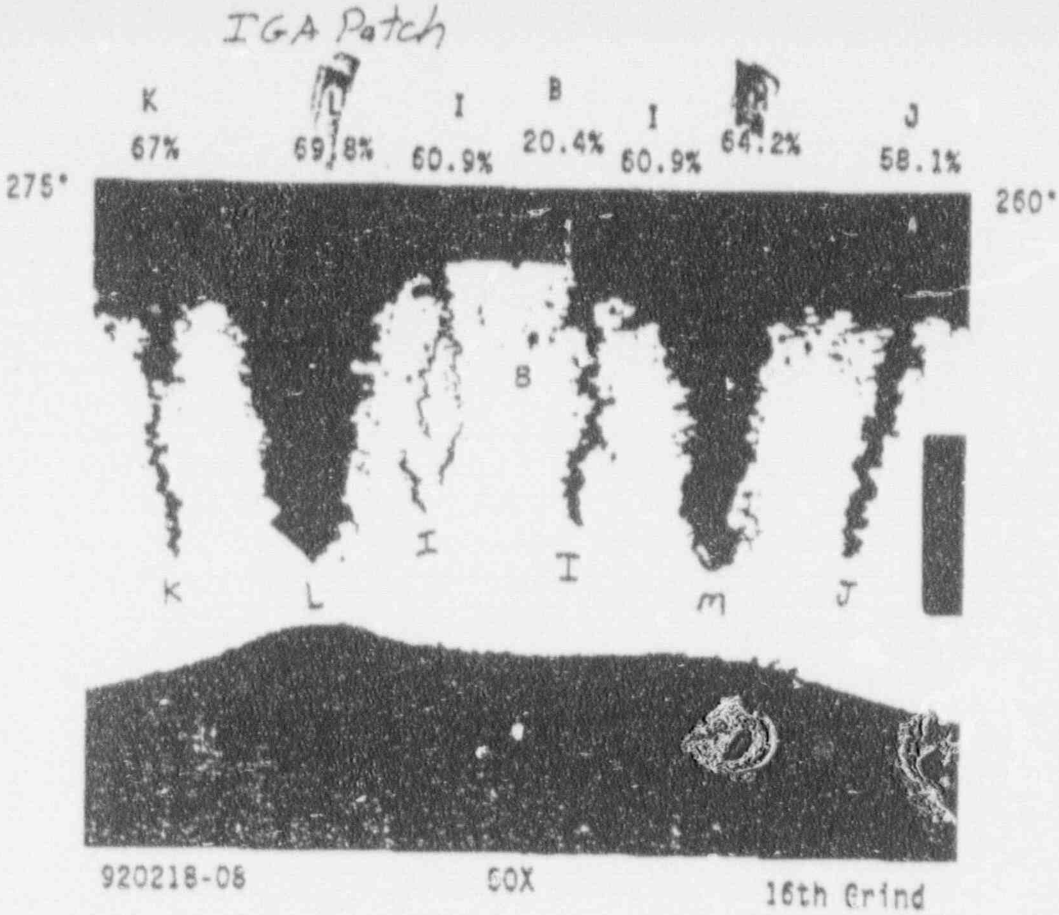
Figure 3-5 Metallography Results: R10C69, TSP 3

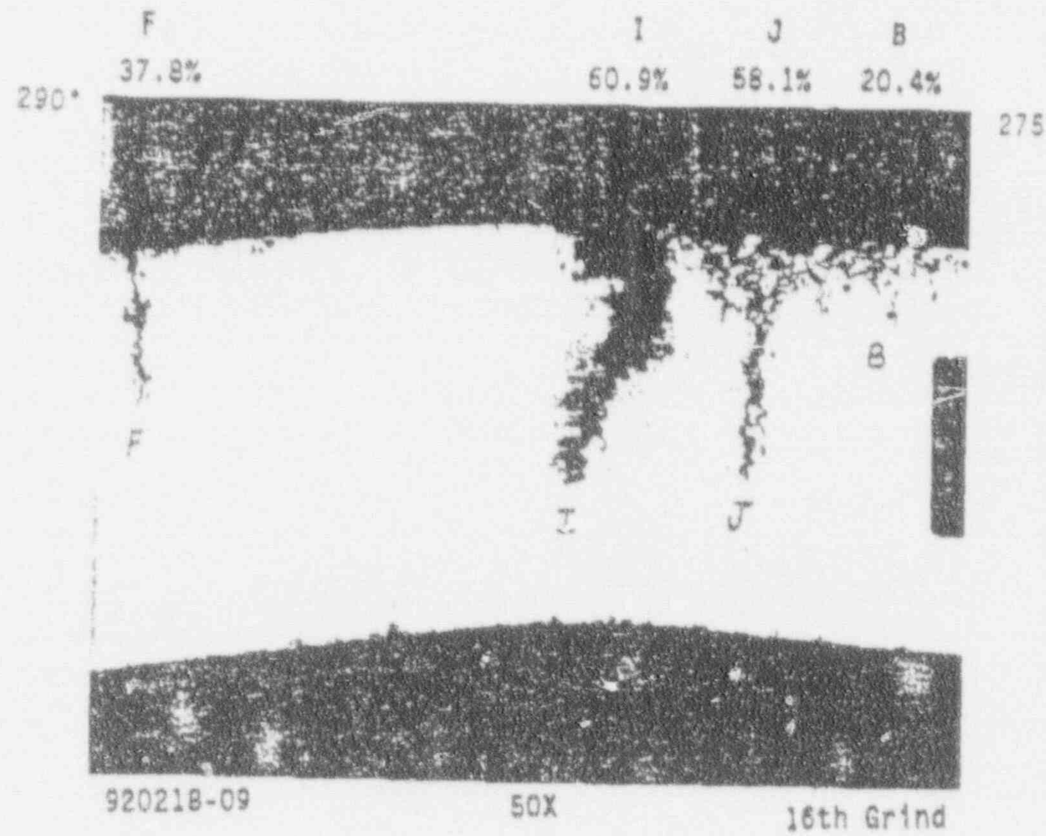



10-6-5B-2E, Mount #2

Figure 3-6 Metallography Results: R10C6, TSP 2

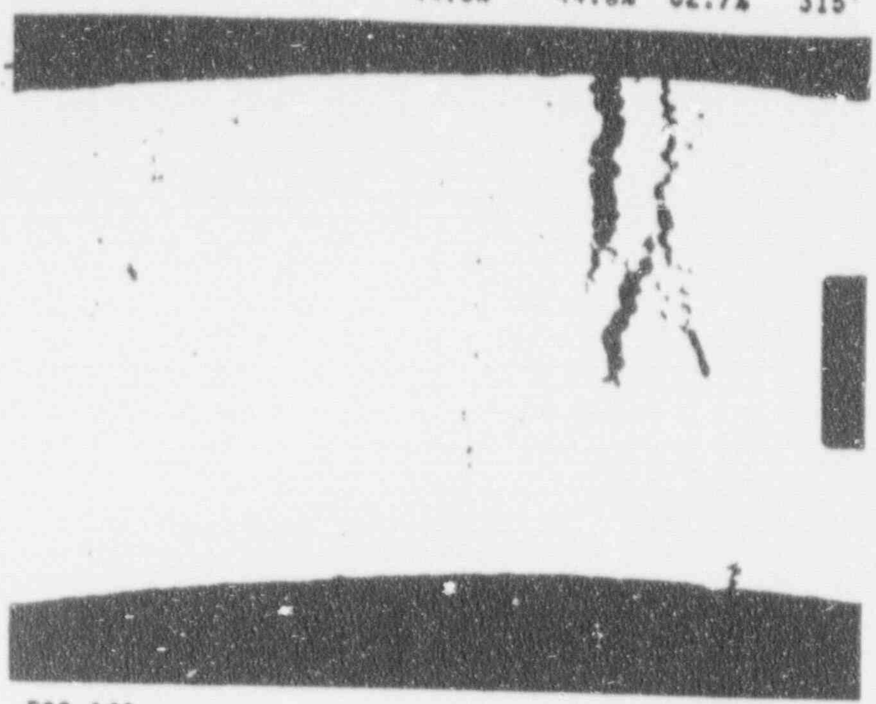
(14)

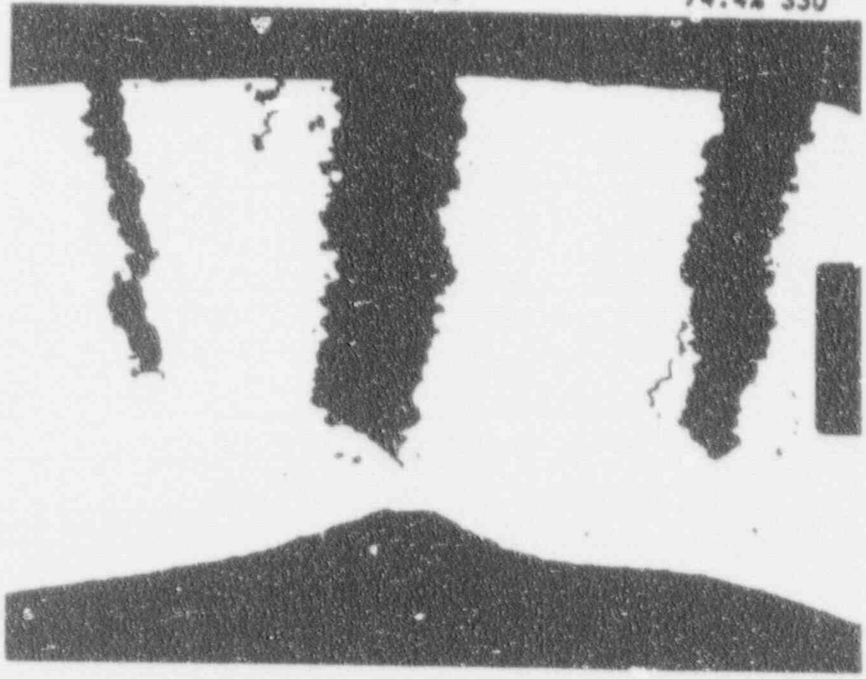



SPECIMEN 7-47-4B-2E

Figure 3-7 Metallography Results: R7C47, TSP 3




METALLOGRAPHY RESULTS ON 5-112-88-2B

Figure 3-8 Metallography Results: R5C112, TSP 3

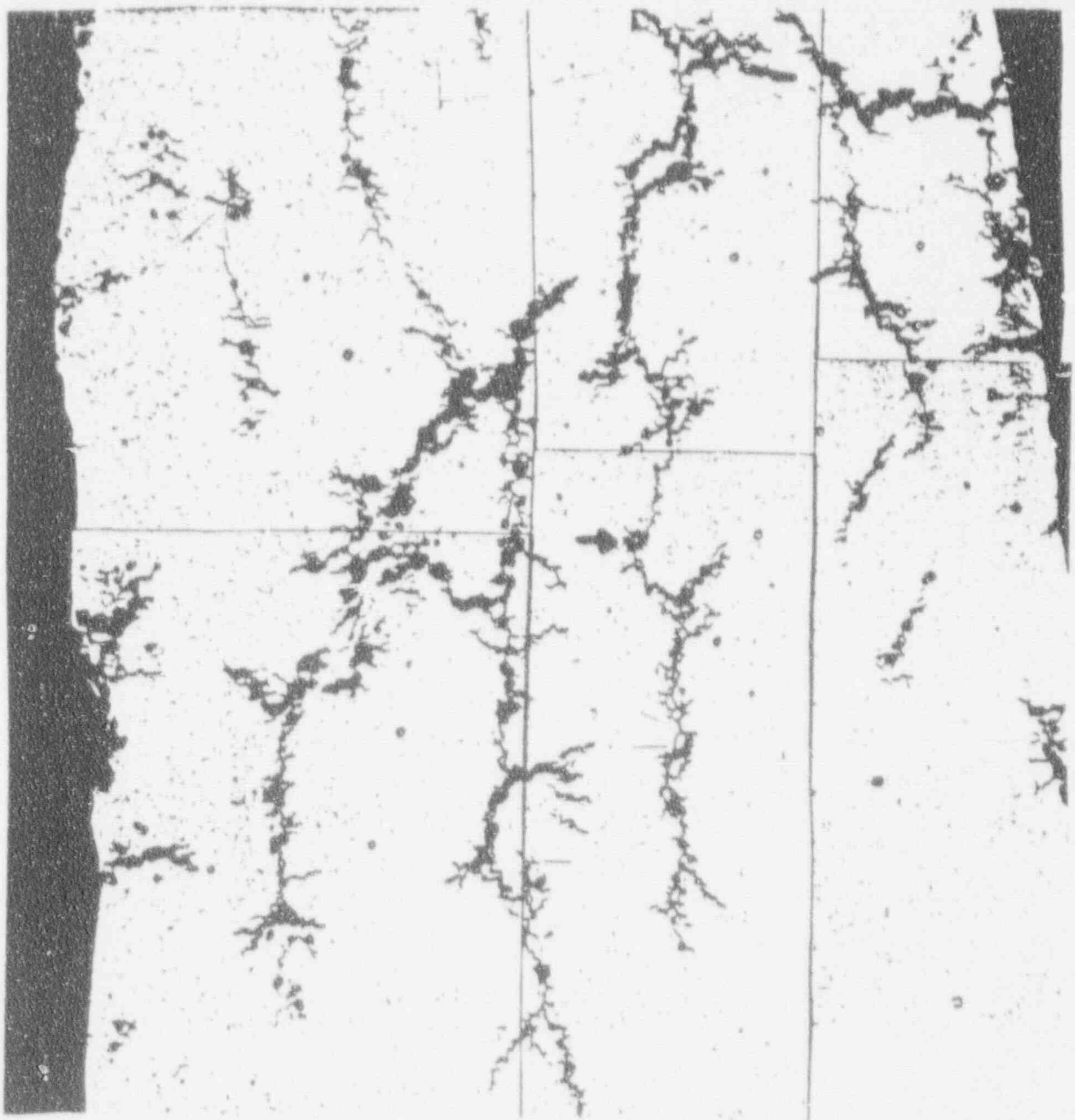
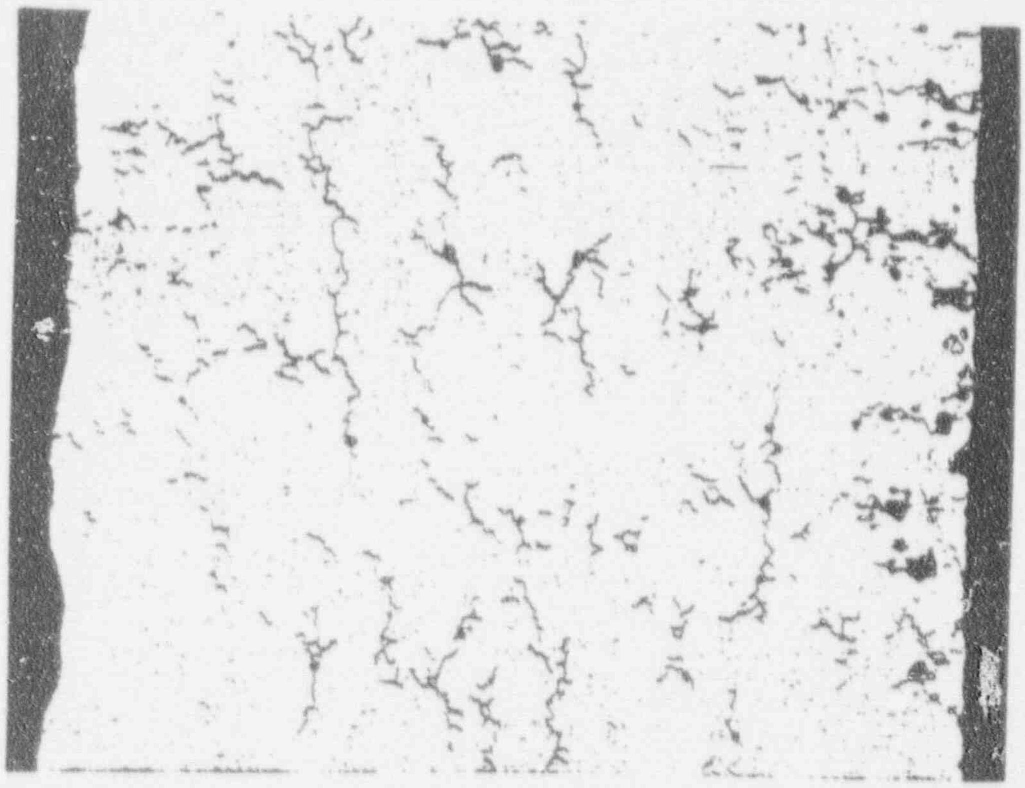
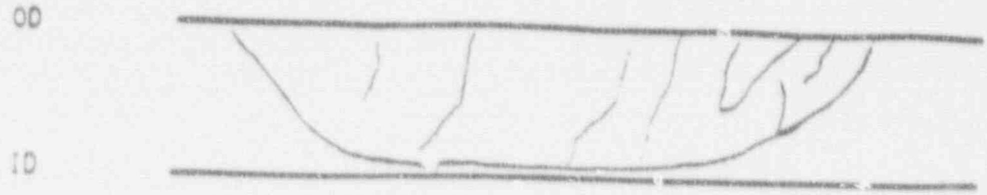



Figure 3-9 Radial metallographic section through a portion of the third support plate crevice region of tube R19-C35 from Plant E-4. A cellular IGA/SCC structure is observed. The depth of the section was not specified.




50X

Figure 3-10 Radial metallographic section through a portion of the fourth support plate crevice region of tube R19-C35 from Plant E-4. A cellular IGA/SCC structure is observed. The depth of the section was not specified.



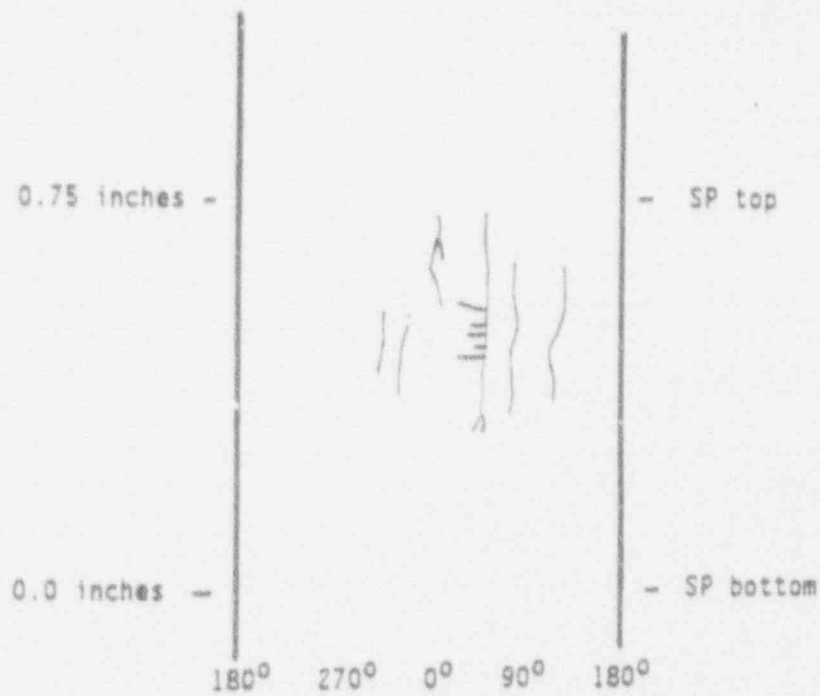

Sketch of Burst Crack

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 3-11 Description of OD origin corrosion at the fifth support plate crevice region of tube R4-C61, Plant B-1

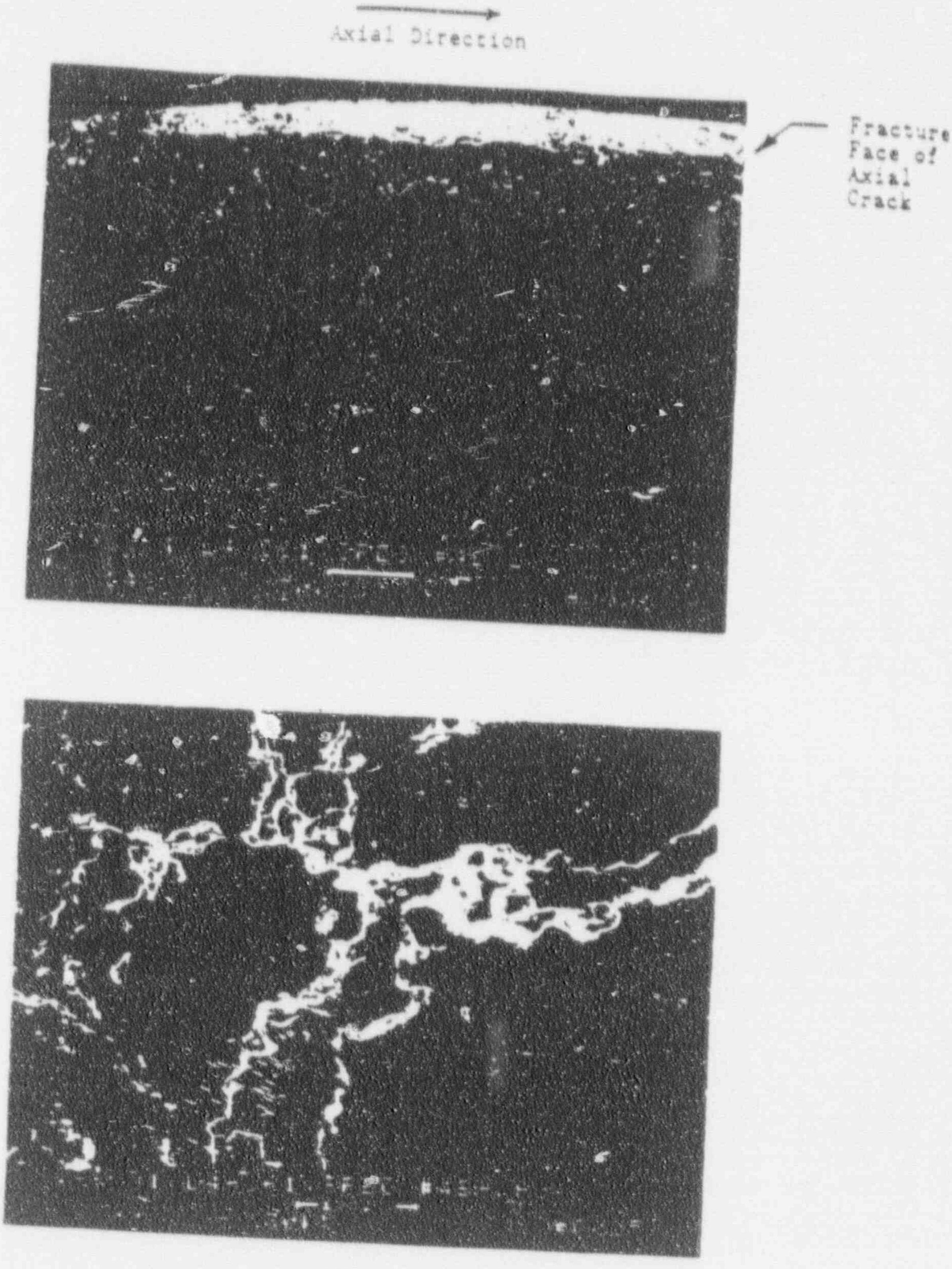
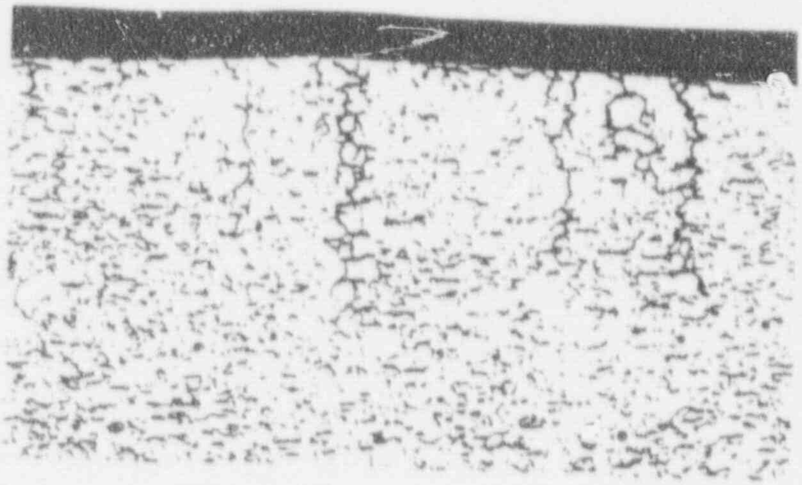
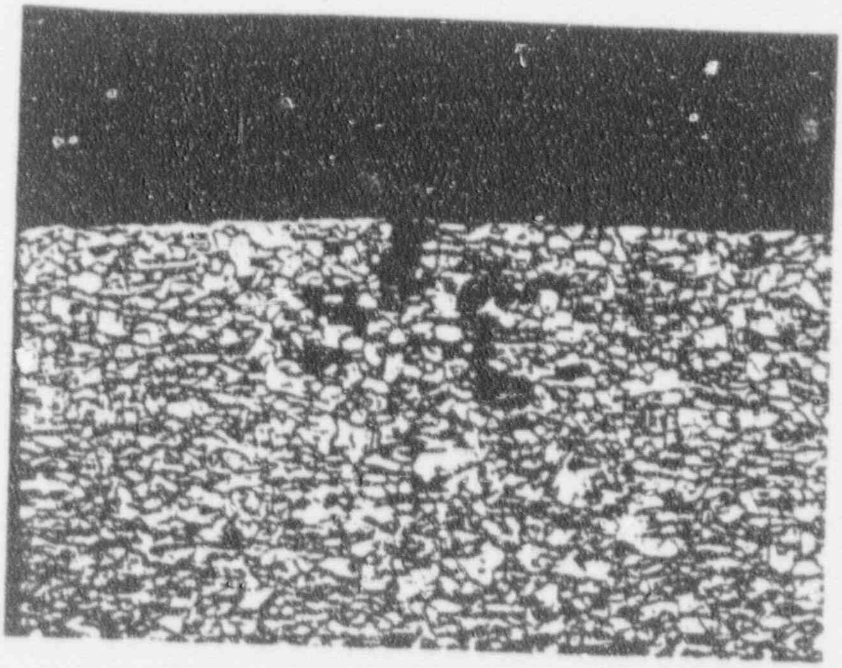



Figure 3-12 Network of small, mostly circumferentially oriented OD surface cracks observed in the 5th support plate region, Tube R4-C61.



Mag. 100X



Mag. 100X

Figure 3-13 Photomicrographs of tube R4-C61 corrosion degradation. Top photo shows axial crack morphology (transverse section) at the eighth support plate location (no transverse metallography was performed at the fifth support plate region). Bottom photo shows circumferential crack morphology (axial section) at fifth support plate region.

## Section 4

## LABORATORY SPECIMEN PREPARATION

### 4.1 Preparation of Specimens

Cracked tube specimens were produced in the Forest Hills Single Tube Model Boiler test facility. The facility consisted of thirteen pressure vessels in which a forced flow primary system transfered heat to a natural circulation secondary system. Appropriate test specimens were placed around a single heat transfer tube to simulate steam generator tube support plates. The tests were conducted in two boiler configurations, shown schematically in Figures 4-1 and 4-2. The majority of the tests were conducted in the vertically oriented boilers shown in Figure 4-1, in which four support plates were typically mounted on the tube. A few tests were conducted in horizontally mounted boilers, shown in Figure 4-2. Because there was no steam space in the horizontal boilers, seven support plates could be mounted on the heat transfer tube. Since capillary forces, rather than gravity forces, dictate the flow pattern in packed tube support plate crevices, the tube orientation should have little effect on the kinetics of the corrosion processes.

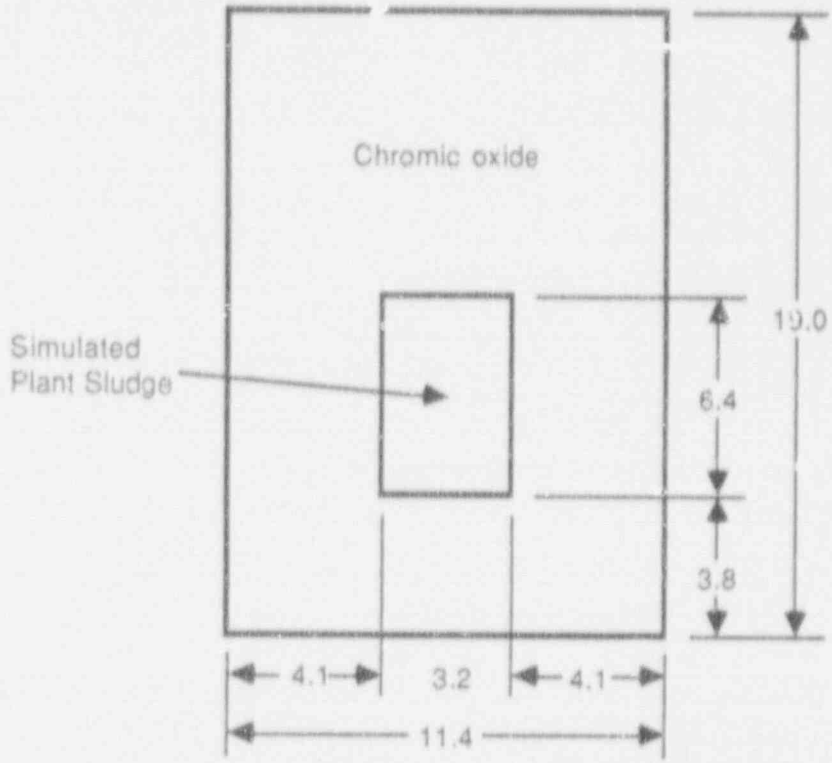
The thermal-hydraulic specifications utilized in the test are presented in Table 4-1. As indicated, the temperatures are representative of those found in PWR steam generators, and the heat flux is typical of that found on the hot leg side of the steam generator. The tests utilized 3/4 inch (1.9 cm) O.D. mill annealed alloy 600 tubing from heat NX7368. The tubing was manufactured by the Plymouth Tubing Co. to Westinghouse specifications. The chemical and physical properties of the tubing are presented in Table 4-2.

The cracks were produced in what is termed the reference cracking chemistry, consisting of either 600 ppb (1X) or 6 ppm (10X) sodium as sodium carbonate in the makeup tank. Typically a test was initiated with the 1X chemistry, and if a through wall leak was not identified after 30 days of operation, the 10X chemistry was applied. The occurrence of primary to secondary leakage was determined by monitoring the boilers for lithium, which would ordinarily only be present in the primary system. Because of hideout in the crevices, the boiler sodium concentration was typically between 50 and 75% of the makeup tank concentration. Hydrazine and ammonia were also added to the makeup tanks for oxygen and pH control, respectively.

A summary of the test pieces which were subsequently leak and burst tested is presented in Table 4-3. Two groups of tests are listed; the EPRI test pieces were prepared under (funded by) this program, while the Spanish test pieces were fabricated for a group of Spanish utilities. Permission from the utilities has been obtained to use the results of these tests in other applications. The only difference between the two groups of tests is that the crevices were packed with different sludge formulations. As in most previous model boiler test programs, the EPRI tests used what is termed simulated plant sludge while the Spanish tests used a formulation more representative of that typically found in steam generators in Spanish plants. As indicated in Table 4-4, the only difference between the two formulations is that magnetite has replaced the metallic copper content in the simulated plant sludge.

As outlined in Table 4-3, three means of packing the tube support plate crevices were utilized. In the fritted configuration, loose sludge was vibratorily packed into the crevice and then held in place with alloy 600 porous frits placed over both ends of the crevice. In this configuration, cracks were typically produced near the interface between the sludge and the frits. In some cases, multiple cracks were produced at both ends of the crevice.

The dual consolidated configuration consisted of two sludge regions, in which the outer region contained chromic oxide, while the inner region contained either simulated plant or Spanish sludge. The regions had the following dimensions, with the distances given in millimeters:




The two-region sludge configuration was specified in order to limit cracking to the small inner region, containing an oxidizing sludge. Chromic oxide is nonoxidizing, and previous testing had found that accelerated corrosion is less likely to occur in its presence. The outer region provided thermal insulation for the inner region, so that the temperature in the inner region was sufficiently high to produce accelerated corrosion. The two sludge regions were baked onto the tube using a mixture consisting of 5% sodium hydroxide, 2.5% sodium sulfate, and 0.8% sodium silicate. The support plates were then mounted on the tube over the sludge and held in place with externally mounted set screws. Since corrosion should be confined to the inner region, this configuration was intended to produce short, individual cracks.

The mechanically consolidated sludge configuration was fabricated by mechanically compacting sludge within a tube support plate simulant, drilling a hole in the sludge for the tube, and then sliding the tube through the hole until positioned properly. This configuration was used because relatively low voltage indications had been produced in previous tests using this configuration.

As indicated in Table 4-3, there was considerable variation in the time taken for a crack to be produced in a given test piece. In general, cracking was produced in shorter time spans with this heat of material (NX7368) than for the heats used in similar tests performed with 7/8 inch diameter tubes. Cracks were typically produced most rapidly with the fritted configuration and most slowly with the dual consolidated configuration although a few cracks were produced very quickly with the dual consolidated configuration. Details of crack networks produced in the model boiler specimens are presented in subsection 4.4.

### 4.2 Leak Rate Testing

The objective of the leak rate tests is to determine the relationship between eddy current characteristics and the leak rates of tubes with stress corrosion cracks. Leak rates at normal operating pressure differentials and under steam line break conditions are both of interest, since leakage limits are imposed under both circumstances. The SLB leak rate data are used to develop a formulation between leak rate and bobbin coil voltage.

Crevice condition is an important factor. Tightly packed or dented crevices are expected to significantly impede leakage through cracked tubes. Since denting is readily detectable by non destructive means while crevice gaps cannot be readily assessed, the emphasis is placed upon open crevices and dented crevices as the limiting cases.

Leak testing of cracked tubes is accomplished as follows. The ends of the tube are plug welded. One end has a fitting for a supply of lithiated (2 ppm Li), borated (1200 ppm B) and hydrogenated (1 psia) water to the tube inner diameter. The specimen is placed in an autoclave and brought to a temperature of 616°F and a pressure of 2250 psi. The pressure on the outer diameter is brought to 1000 psi. A back pressure regulator on the secondary side maintains the 1000 psi pressure. Any leakage from the primary side of the tube tends to increase the secondary pressure because of the superheated conditions. The back pressure regulator then opens, the fluid is released, condensed, collected and measured as a function of time. This provides the measured leak rate. The cooling coil is located prior to the back pressure regulator to prevent overheating and to provide good pressure control. Typical leakage duration is one hour unless leak rate is excessive and overheating of the back pressure regulator occurs. Pressure is controlled on the primary side of the tube by continuous pumping against another back pressure regulator set at 2250 psi. The bypass fluid from this regulator is returned to the makeup tank.

To simulate steam line break conditions the primary pressure is increased to 3000 psi by a simple adjustment of the back pressure regulator and secondary side is vented within one to three minutes to a pressure of 350 psi. The pressure differential across the tube is thus 2650 psi. Temperature fluctuations settle out in several minutes and the leakage test period lasts for approximately 30 minutes.

A summary of leak test results is provided in Table 4-5. Leak rates at normal operating pressure differential and at steam line break conditions were obtained for all specimens. The steam line break conditions increased the leak rates by about a factor of three compared to normal operating conditions. More variation in this factor can be expected. Prolonged leak rate testing under operating conditions is expected to lead to lower rates. The increase in the leak rate upon transition to accident conditions then becomes more variable.

### 4.3 Burst Testing

Given the assumption that significant support plate displacements cannot be excluded under accident conditions, burst tests of tubes with stress corrosion cracks are conducted in the free span condition and burst pressure is correlated with bobbin coil voltage. This burst pressure correlation is then applied to determine the voltage amplitude that satisfies the guidelines of Reg. Guide 1.121 for tube burst margins.

Burst tests were conducted using an air driven differential piston water pump at room

temperature. Pressure was recorded as a function of time on an X-Y plotter. Sealing was accomplished by use of a soft plastic bladder. Burst tests of tubes with stress corrosion cracks were done in the free span condition. No foil reenforcement of the sealing bladders was used since the crack location which was to dominate the burst behavior was not always readily apparent. Some of the maximum openings developed during burst testing were not sufficient to cause extensive crack tearing and thus represent lower bounds to the burst pressures. The openings were large enough in all cases to lead to large leakage. Burst test results are summarized in Table 4-5.

## 4.4 Destructive Examination

### 4.4.1 Objectives

The objective of this task is to characterize the size, shape, and morphology of the laboratory created corrosion in alloy 600 tube specimens which have been leak rate and burst tested. The crack morphology is also to be compared generally to the corrosion morphology observed in tubes pulled from operating power plant steam generators. A summary of the available results for 3/4 inch OD specimens is presented in this section.

### 4.4.2 Examination Methods

Examination methods include visual examinations, macrophotography, light microscopy and/or SEM (scanning electron microscopy) examinations, SEM fractography, and metallography. A number of model boiler test specimens were selected for destructive examinations. Most of these were leak and burst tested.

The specimens were initially examined visually and with a low power microscope. The burst opening and visible cracks around the circumference of the tube within the tube support plate intersection were visually examined and their location in relation to the burst crack noted. (When the crack networks were particularly complex, such as when circumferential components were strongly present, photographs of the crack networks were taken and included in this report for more complete documentation of the data.) The major burst crack was then opened for fractographic observations including crack surface morphology, crack length, and crack depth using SEM. One metallographic cross section of each tube specimen was selected containing the majority of secondary cracks within the tube support plate region. The location of the cracks within this metallographic cross section was noted, the cracks measured as to their depth and a crack was photographed to show the typical crack morphology. Note that the one metallographic section through each specimen will provide the secondary crack distribution at that location. Secondary cracks at other elevations would not be recorded unless the burst test happened to open the secondary cracks sufficiently for visual examination to record their location.

### 4.4.3 Destructive Examination Results

<u>Tube 590-1</u>

The crevice region of tube 590-1 showed only three axial cracks, two of which were through-wall. The longest of the two through-wall cracks caused the burst opening. At the tube burst opening, the macrocrack (composed of one microcrack) was 0.275 inch long at the OD and 0.21 inch long at the ID. The crack morphology was IGSCC. A metallographic cross section capturing the three axial cracks is shown by a sketch in Figure 4-3. The crack morphology is

shown in a photomicrograph in this figure. The shape of the burst crack and its morphology is described in Figure 4-4 together with the OD crack distribution found in this tube.

Tube 590-2

The crevice region of tube 590-2 had large numbers of axial and circumferential cracks. The cracking was concentrated on one quadrant of the tube's circumference. Photographs of the tube following burst testing are shown in Figures 4-5 and 4-6. The burst fracture occurred in a highly irregular fashion dictated by the axial and circumferential tube degradation. The burst opening was formed by at least five small cracks which joined partial circumferential cracks to form the irregular overall crack pattern. The macrocrack length due to corrosion measured 0.38 inch at the OD surface and it was through-wall for 0.30 inch. The microcracks and their ligaments had intergranular ligaments and the morphology of the burst crack was that of IGSCC (Figure 4-7). A metallographic cross section through the region with the highest crack density showed a crack distribution as sketched in Figure 4-8. A photomicrograph of two typical secondary cracks is also shown in this figure. They suggest that the cracking is primarily IGSCC with some IGA contributions. Figure 4-9 provides a summary of the overall crack distribution and summary information regarding the burst crack.

Tube 590-3

Rupture in tube 590-3 occurred from a single axial OD origin crack confined to the crevice region. The macrocrack was 0.31 inch long and was through-wall for a length of 0.27 inch. Only one microcrack could obviously be observed on the macrocrack. Its morphology was that of IGSCC. Figure 4-10 provides summary data regarding the corrosion observed on tube 590-3.

Tube 591-1

Burst in tube 591-1 occurred from a single, relatively small axial crack which was 0.24 inch long on the OD and 0.18 inch long on the ID. While two small axial secondary cracks were observed away from the burst near the bottom of the crevice region, no secondary cracks were observed near the burst opening. However, a metallographic cross section through the center of the burst opening revealed two additional axial secondary cracks which were located away from the burst. The location of these cracks in relationship to the burst opening is indicated by a sketch in Figure 4-11. A photomicrograph of one of the secondary cracks is also shown. All cracks had a morphology of IGSCC. The shape of the main crack and the distribution of cracks are depicted in Figure 4-12.

Tube 591-2

The burst fracture in tube 591-2 occurred in an area of the crevice region where many small but deep axial cracks were concentrated. The burst created a macrocrack which was 0.21 inch long on the OD and it was formed by four smaller microcracks. The crack was through-wall for a length of 0.03 inch. The ligaments forming the macrocrack all had ductile features and the morphology of the cracking was that of IGSCC. Figure 4-13 shows the crack distribution observed by metallography in a circumferential cut through the lower region of the crevice where the crack density was highest. A photomicrograph of one of the cracks is also shown. A sketch describing the shape of the burst macrocrack, as well as the overall distribution of secondary cracks within the crevice region as observed by visual examination, is shown in Figure 4-14.

Tube 591-4

A group of small, deep, OD origin, axial cracks, concentrated in one region of tube 591-4 within the crevice region, caused the burst fracture. The irregular shape of the burst opening (Figure 4-15) was formed by five small microcracks which grew together by intergranular corrosion to form the macrocrack. The morphology of the macrocrack was that of IGSCC. The macrocrack crack was 0.45 inch long and through-wall for 0.35 inch. A metallographic cross section through the center of the burst crack revealed many secondary cracks of considerable depth. The cracks are depicted by a sketch in Figure 4-16 together with a photomicrograph of the cracking. Summary data regarding the burst crack and the overall crack distribution are shown in Figure 4-17.

Tube 596-3

The burst fracture in tube 596-3 occurred from a group of small axial cracks of OD origin. Four of the deep microcracks joined together during the burst test to form the burst opening macrocrack. The ligaments between the microcracks had only intergranular features and the crack morphology was that of IGSCC. The macrocrack caused by IGSCC was 0.45 inch long on the OD and was through-wall for a length of 0.44 inch. A metallographic cross section through the region with the highest density of cracking revealed a crack distribution shown by a sketch in Figure 4-18. A photomicrograph in this figure shows the crack morphology of two of the secondary cracks. A summary of the burst crack data and of the overall crack distribution within the crevice region is shown in Figure 4-19.

4.4.4 Comparison with Pulled Tube Crack Morphology

Most of the support plate cracking on pulled steam generator tubes was OD origin, intergranular stress corrosion cracking that was axially orientated. Large macrocracks were frequently present and were composed of numerous short microcracks (typically < 0.1 inches long) separated by ledges or ligaments. The ledges could have either intergranular or dimple rupture features depending on whether or not the microcracks had grown together during plant operation. Most cracks had minimal to moderate IGA features (minor to moderate D/W ratios) in addition to the overall stress corrosion features. Even when the IGA was present in association with the cracks in significant amounts, it did not dominate over the overall SCC morphology. The numbers of cracks distributed around the circumference at a given elevation within the crevice region varied from a few cracks to typically less than 100. In a few cases, the number of cracks was significantly larger than this, in one case possibly approaching 500. For this situation, patches of IGA formed where the cracks were particularly close and the individual cracks had some IGA characteristics. Even for this situation, the axial SCC was still the dominant corrosion morphology as the IGA was typically one third to one half the depth of the IGSCC. In addition, cellular IGA/SCC was occasionslly observed confined to small areas within the crevice region. Finally, IGA, separate and independent of SCC, has been observed. It is usually present as small isolated patches of IGA. In the few cases where more uniform IGA has been observed, it is typically shallow and intermittently distributed within support plate crevice regions.

The model boiler corrosion observed in this investigation was similar to that observed within typical pulled tube support plate crevice locations. Most corrosion was axially orientated IGSCC with negligible to moderate IGA aspects (minor to moderate D/W ratios) in association with the cracking. Some of the model boiler specimens had cracking with almost pure IGSCC, i.e., with no obvious IGA aspects (D/W ratios of 50 or higher), more similar to PWSCC than to the typical OD IGSCC observed within support plate crevice corrosion on pulled tubes. IGA independent of the cracking was not observed in the model boiler specimens. The numbers of cracks at a given

elevation was typically less than 20, similar to that observed in many of the pulled tubes. However, only one model boiler specimen had a moderate crack density and none had high crack densities as have been occasionally observed in plants. A number of the model boiler specimens from the second set of tests conducted in 1991, however, did have very complex crack networks that frequently had circumferential cracking in association with the predominant axial cracking. Some of the complex crack networks may have had cellular IGA/SCC components similar to that occasionally observed in pulled tubes.

### 4.4.5 Conclusions from Specimen Destructive Examinations

It is concluded that the laboratory generated corrosion cracks have the same basic features as support plate crevice corrosion from pulled tubes. The laboratory created specimens frequently had somewhat lower crack densities, but individual cracks usually had similar IGA aspects (minor to moderate D/W ratios). IGA independent of IGSCC was not observed in the model boiler specimens as was sometimes observed in pulled tubes. The observed differences in corrosion morphology between the model boiler specimens and the pulled tubes is not believed to be significant.

## 4.5 Model Boiler Database Summary

As described in the above subsections, model boiler specimens have been fabricated and tested to augment the pulled tube database at support plate intersections. 53 laboratory specimens have been prepared using 3/4 inch OD tubing. The specimens were subjected to eddy current examination. Degradation at simulated tube support plate intersections have ranged from NDD to 65 volts in bobbin coil amplitude. All of these specimens have been burst tested, with the results displayed in Table 4-5. Specimens with significant degradation (41) have also been leak tested. Further, several of the samples were destructively examined to determine degradation characteristics and crack morphology. The currently available maximum and through wall crack length data obtained for many of these specimens from the destructive examinations are listed in Table 4-5. The model boiler database is combined with the pulled tube database and the total used for determining leak rate and burst correlations.

Table 4-1

**Model Boiler Thermal and Hydraulic Specifications**

| | |
|---|---|
| Primary loop temperature | 327°C (620°F) |
| Primary loop pressure | 13.8 MPa (2000 psi) |
| Primary boiler inlet temperature | 324°C ± 3°C (615°F ± 5°F) |
| Primary boiler outlet temperature | 313°C ± 3°C (595°F ± 5°F) |
| Secondary $T_{sat}$ at 6.1 MPa (900 psi) | 278°C ± 3°C (532°F ± 5°F) |
| Steam bleed | 0.1 - 0.2 l/day |
| Blowdown | 8 $cm^3$/min (continuous) |
| Nominal heat flux | 16.28 x $10^4$ kcal/$m^2$-hr (60,000 Btu/$ft^2$-hr) |

Table 4-2

Chemical and Physical Properties of Tubing Material (NX7368)

Chemical Composition (Weight %)

| | |
|---|---|
| Ni | 76.21 |
| Cr | 14.87 |
| Fe | 7.98 |
| C | 0.04 |
| Mn | 0.41 |
| Si | 0.30 |
| Cu | 0.15 |
| Cb | 0.04 |

Physical Properties

| | | |
|---|---|---|
| Ultimate Strength (KSI) | 109.4 | (744 mPa) |
| Yield Strength (KSI) | 54.2 | (368 mPa) |
| % Elongation | 37.0 | |
| Hardness | 83. | (Rockwell B) |

Table 4-3

**Test Specimen Summary**

| Specimen ID | Group | Crevice Configuration | Days in Test |
|---|---|---|---|
| 590-1 | EPRI | Frit | 8 |
| 590-2 | EPRI | Frit | 15 |
| 590-3 | EPRI | Frit | 15 |
| 590-4 | EPRI | Frit | 19 |
| 591-1 | EPRI | Frit | 8 |
| 591-2 | EPRI | Frit | 10 |
| 591-3 | EPRI | Frit | 21 |
| 591-4 | EPRI | Frit | 10 |
| 592-1 | EPRI | Mech. Cons. | 138 |
| 592-2 | EPRI | Mech. Cons. | 138 |
| 592-3 | EPRI | Mech. Cons. | 138 |
| 592-4 | EPRI | Mech. Cons. | 138 |
| 592-5 | EPRI | Mech. Cons. | 138 |
| 592-6 | EPRI | Mech. Cons. | 138 |
| 592-7 | EPRI | Mech. Cons. | 138 |
| 593-1 | EPRI | Dual Cons. | 133 |
| 593-2 | EPRI | Dual Cons. | 133 |
| 593-3 | EPRI | Dual Cons. | 133 |
| 593-4 | EPRI | Dual Cons. | 133 |
| 594-1 | EPRI | Dual Cons. | 85 |
| 595-1 | EPRI | Dual Cons. | 34 |
| 595-2 | EPRI | Dual Cons. | 84 |
| 595-3 | EPRI | Dual Cons. | 84 |
| 595-4 | EPRI | Dual Cons. | 113 |
| 596-1 | EPRI | Dual Cons. | 46 |
| 596-2 | EPRI | Dual Cons. | 10 |
| 596-3 | EPRI | Dual Cons. | 5 |
| 596-4 | EPRI | Dual Cons. | 48 |
| 597-1 | EPRI | Dual Cons. | 133 |
| 597-2 | EPRI | Dual Cons. | 133 |
| 597-3 | EPRI | Dual Cons. | 133 |
| 597-4 | EPRI | Dual Cons. | 133 |
| 598-1 | EPRI | Mech. Cons. | 27 |
| 598-2 | EPRI | Mech. Cons. | 27 |
| 598-3 | EPRI | Mech. Cons. | 27 |
| 598-4 | EPRI | Mech. Cons. | 46 |
| 603-1 | EPRI | Frit | 34 |
| 603-2 | EPRI | Frit | 34 |
| 603-3 | EPRI | Frit | 34 |
| 603-4 | EPRI | Frit | 34 |

(Continued on next page)

Table 4-3 (Continued)

**Test Specimen Summary**

| Specimen ID | Group | Crevice Configuration | Days in Test |
|---|---|---|---|
| 604-1 | EPRI | Frit | 14 |
| 604-2 | EPRI | Frit | 7 |
| 604-3 | EPRI | Frit | 22 |
| 604-4 | EPRI | Frit | 22 |
| 600-1 | Spanish | Dual Cons. | 10 |
| 600-2 | Spanish | Dual Cons. | 14 |
| 600-3 | Spanish | Dual Cons. | 38 |
| 601-1 | Spanish | Frit | 12 |
| 601-2 | Spanish | Frit | 12 |
| 601-3 | Spanish | Frit | 17 |
| 601-4 | Spanish | Frit | 17 |
| 601-5 | Spanish | Frit | 17 |
| 601-6 | Spanish | Frit | 17 |

Table 4-4

**Composition of Sludge Used for Crevice Packing**

| | Weight % | |
|---|---|---|
| Constituent | Simulated Plant Sludge | Spanish Sludge |
| Magnetite | 59.7 | 92.2 |
| Copper | 32.5 | |
| Cupric Oxide | 4.5 | 4.5 |
| Nickel Oxide | 2.1 | 2.1 |
| Chromic Oxide | 1.2 | 1.2 |

Table 4-5

**Leak Rate & Burst Test Results for 3/4 Inch OD Laboratory Specimens**

| No. | Specimen | Bobbin Amplitude (volts) | Leak Rate (l/hr) N. O. ΔP | Leak Rate (l/hr) SLB ΔP | Burst Pressure (psi) | Preliminary Destructive Exam. Length (inch) Maximum | Preliminary Destructive Exam. Length (inch) Thruw...ll* |
|---|---|---|---|---|---|---|---|

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(Continued on next page)

* When crack is not throughwall, maximum depth of penetration is shown.

Table 4-5 (Continued)

**Leak Rate & Burst Test Results for 3/4 Inch OD Laboratory Specimens**

| No. | Specimen | Bobbin Amplitude (volts) | Leak Rate (l/hr) |  | Burst Pressure (psi) | Preliminary Destructive Exam. Length (inch) |  |
|---|---|---|---|---|---|---|---|
|  |  |  | N.O. ΔP | SLB ΔP |  | Maximum | Thruwall* |

[ ] g

* When crack is not throughwall, maximum depth of penetration is shown.

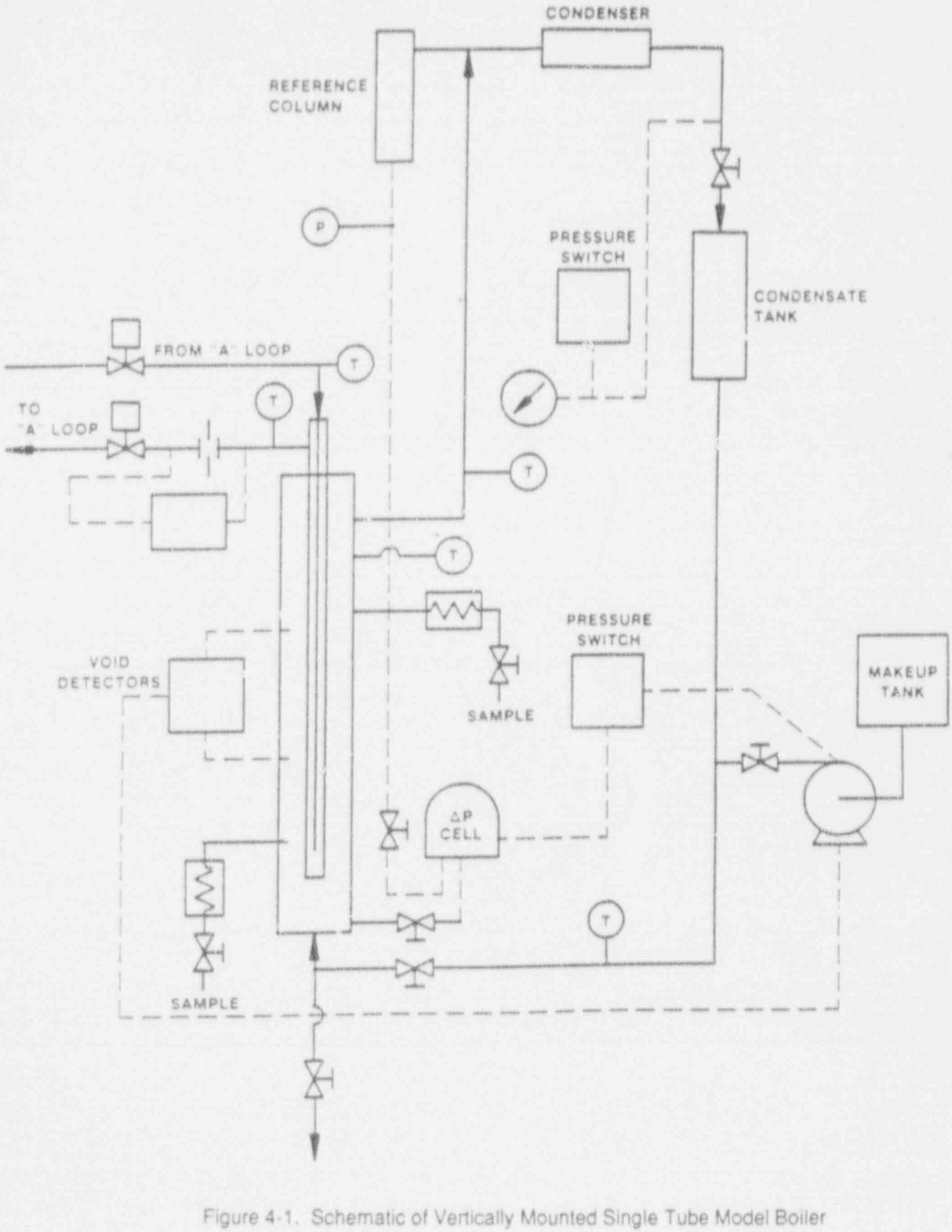



Figure 4-1. Schematic of Vertically Mounted Single Tube Model Boiler

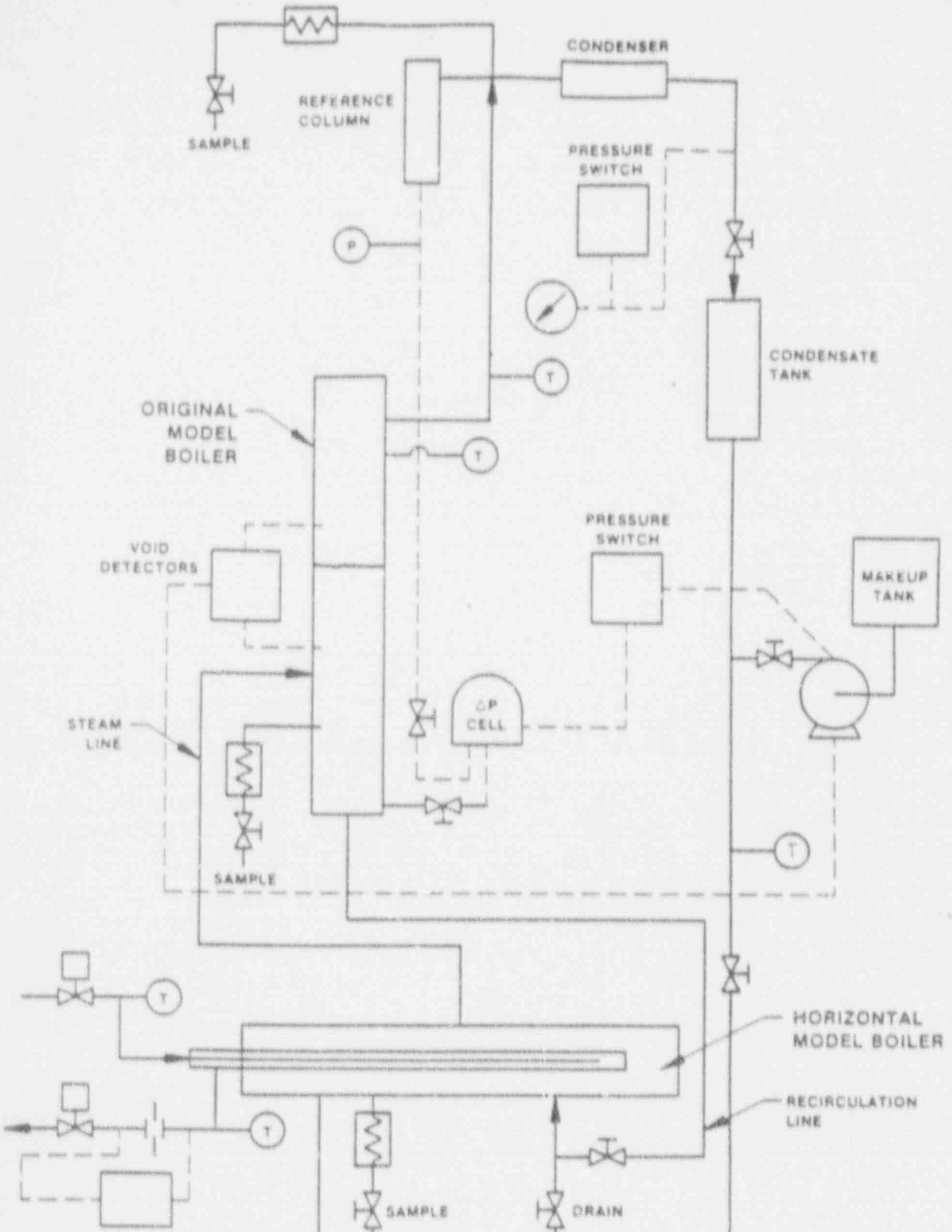
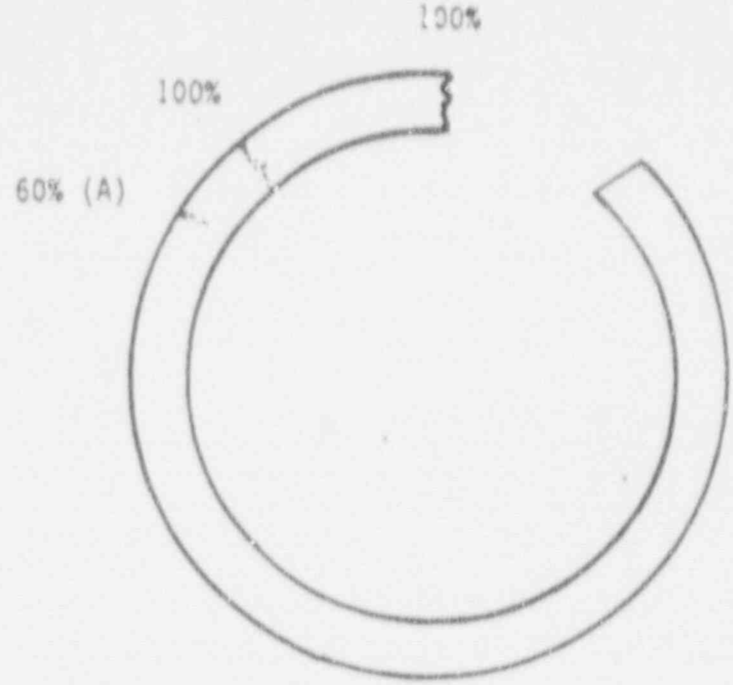



Figure 4-2. Schematic of Horizontally Mounted Single Tube Model Boiler



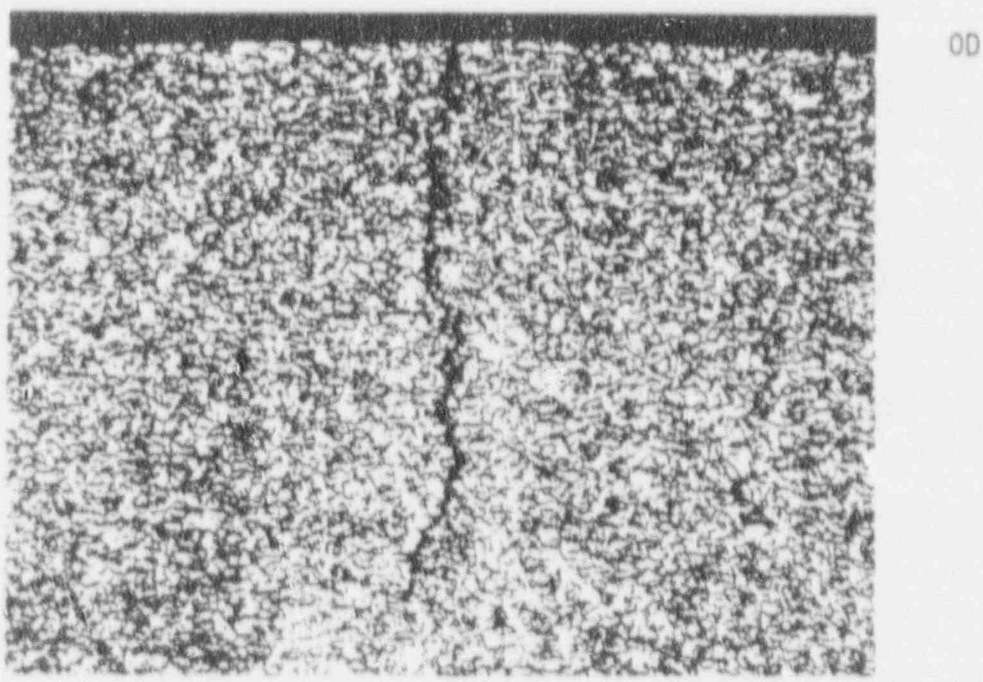
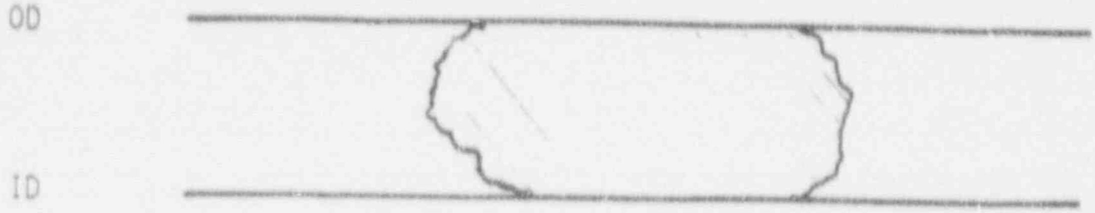




Figure 4-3. Sketch of a metallographic cross section through the crevice region of tube 590-1. The burst crack and two secondary cracks were observed. A photomicrograph of a secondary crack is also shown. The crack morphology is that of IGSCC. Mag. 100X



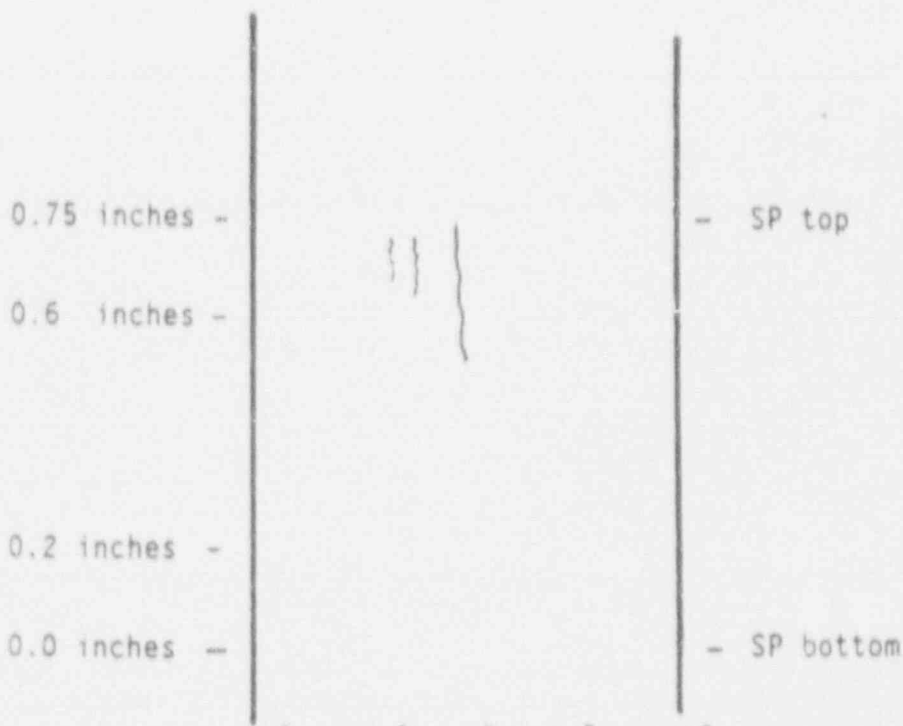

Sketch of Burst Crack

Macrocrack Length = 0.275 inch

Throughwall Length = 0.21 inch

Number of Microcracks = 3

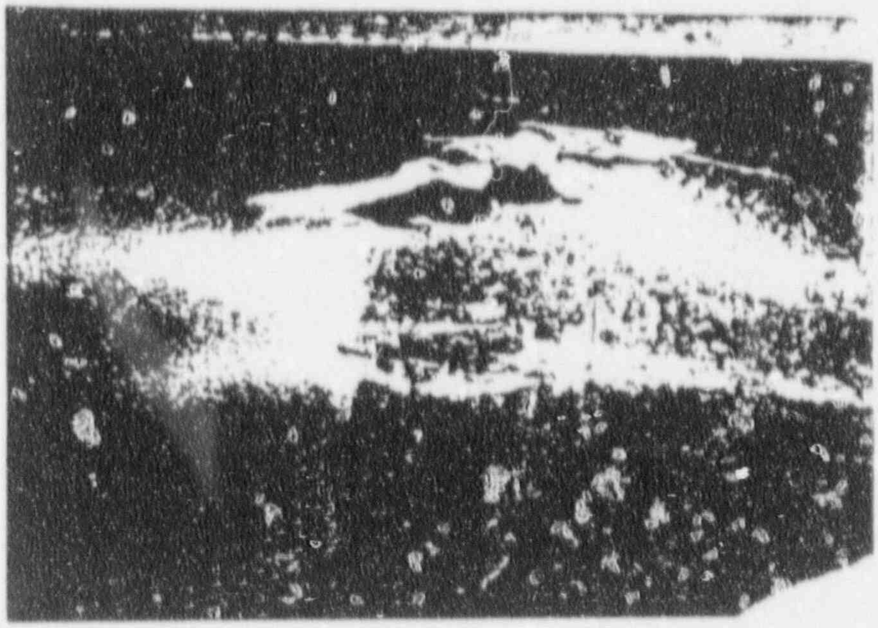
Morphology = IGSCC




Sketch of Crack Distribution

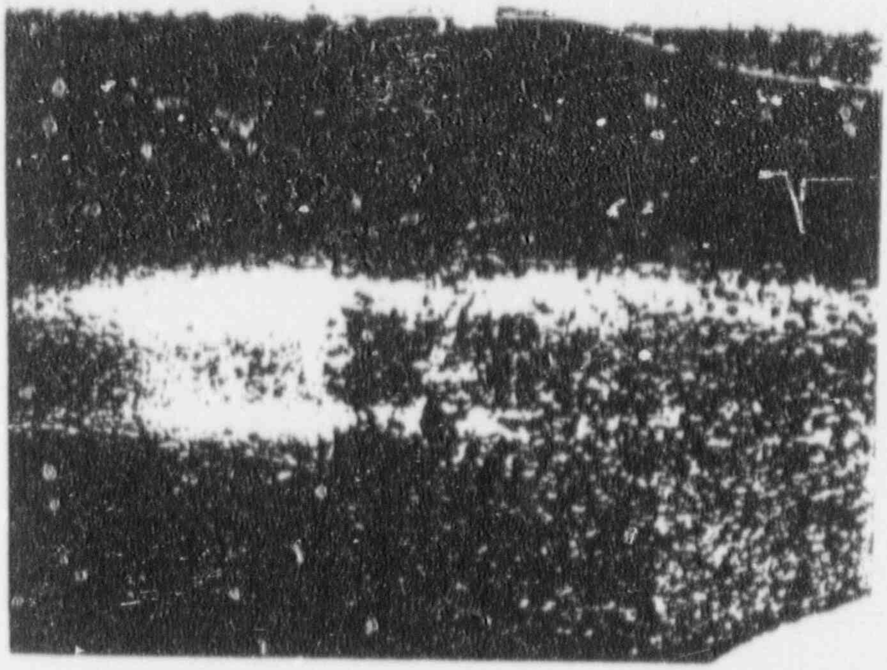
Figure 4-4. Summary of burst crack observation and the overall crack distribution at the crevice region of tube 590-1.

4 x

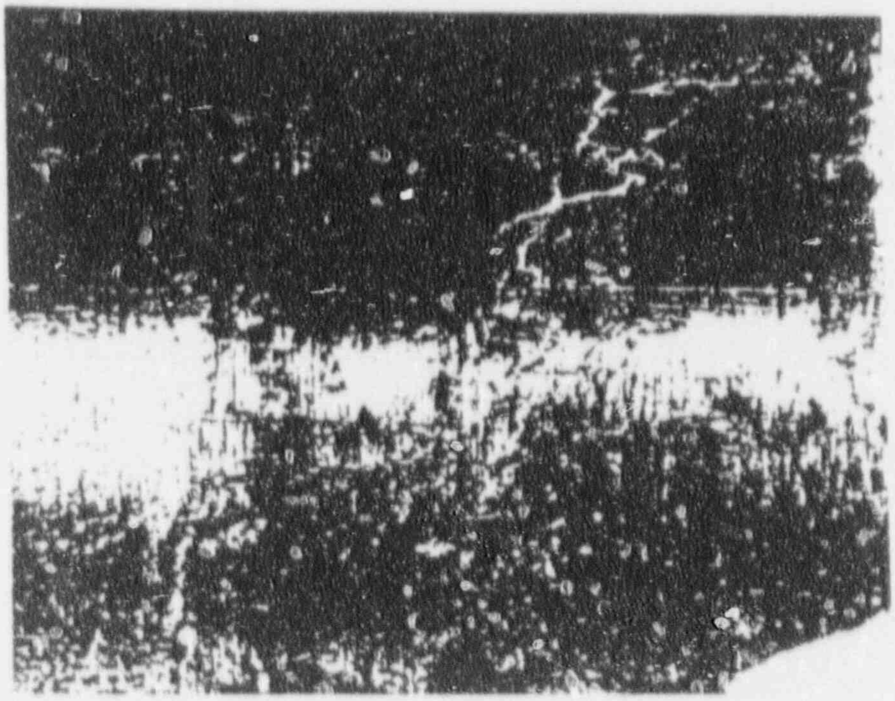


4 x

Figure 4-5. Photographs of the burst opening in tube 590-2 showing axial and circumferential cracking.



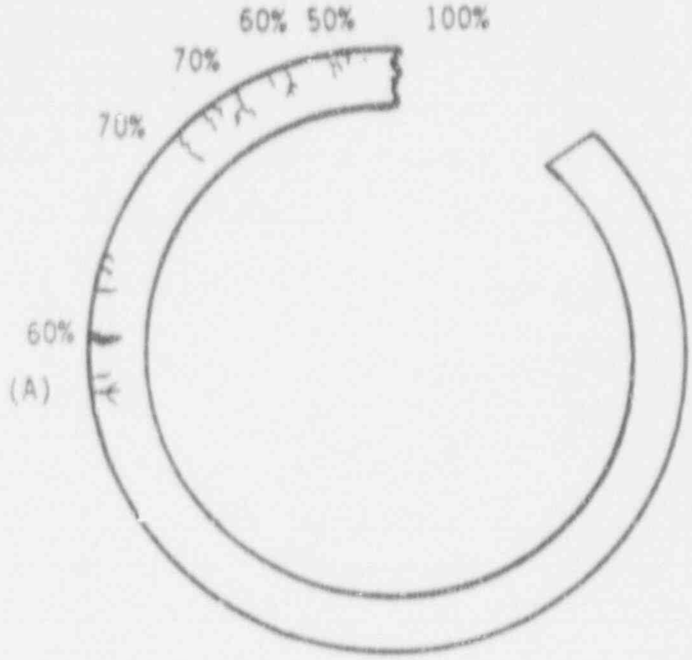
4X

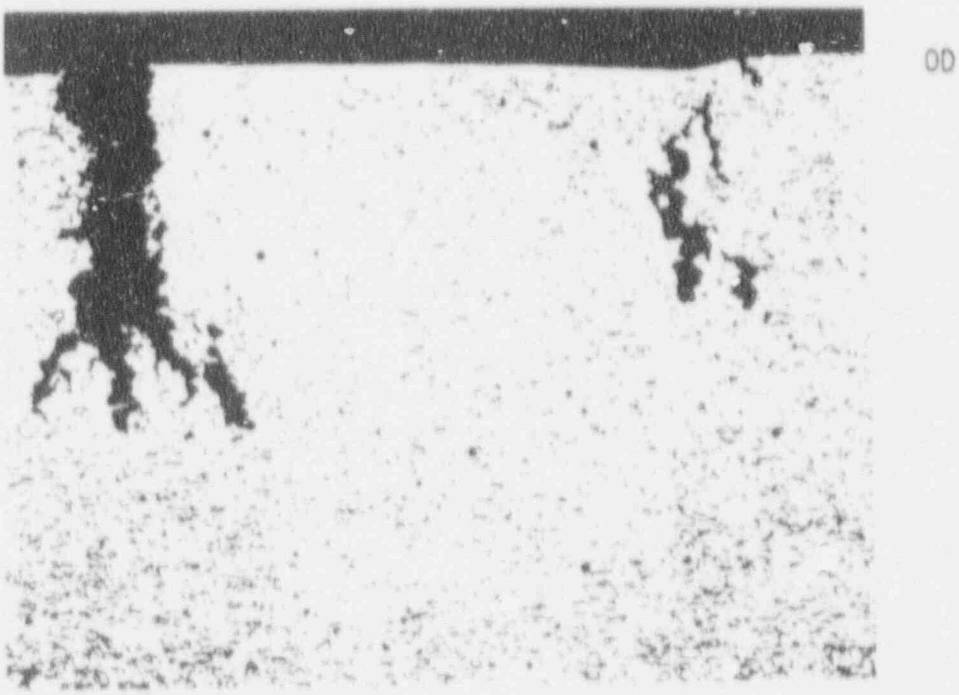


10X

Figure 4-6. Photographs away from the burst opening in tube 590-2 showing axial and circumferential cracking.

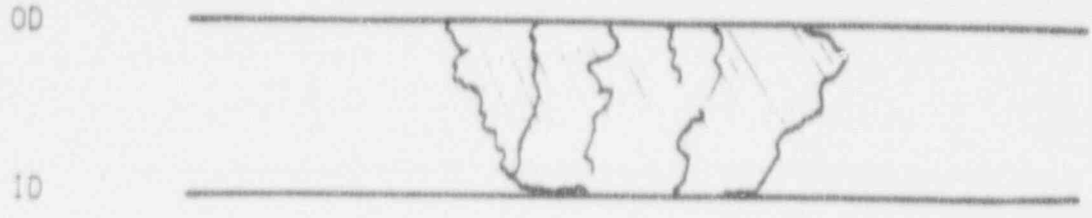

Figure 4-7. Photomicrograph of the burst crack in tube 590-2 showing IGSCC morphology.




Crack A

Figure 4-8. Sketch of a metallographic cross section through the crevice region of tube 590-2. The burst crack and a number of secondary cracks were observed. A photomicrograph of two secondary cracks is also shown. The crack morphology is that of IGSCC with some IGA contribution. Mag. 100X



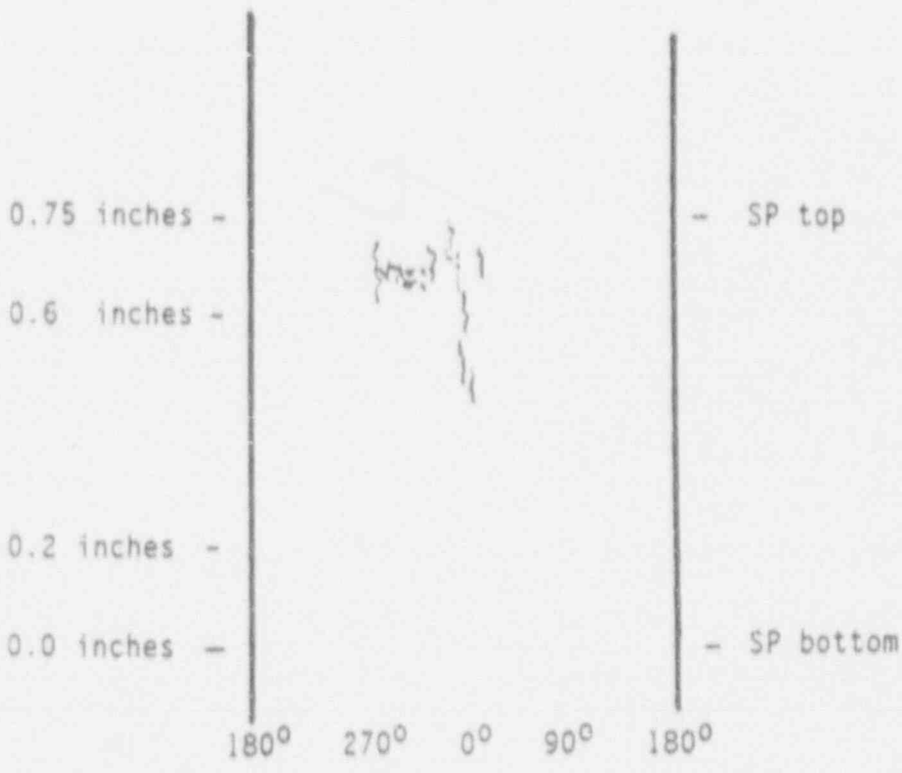

Sketch of Burst Crack

Macrocrack Length = 0.38 inch

Throughwall Length = 0.30 inch

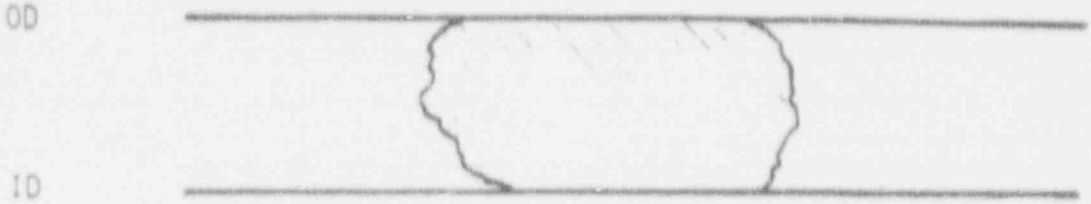
Number of Microcracks = 5 (ligaments have intergranular features)

Morphology = IGSCC




Sketch of Crack Distribution

Figure 4-9. Summary of burst crack observations and the overall crack distribution at the crevice region of tube 590-2.



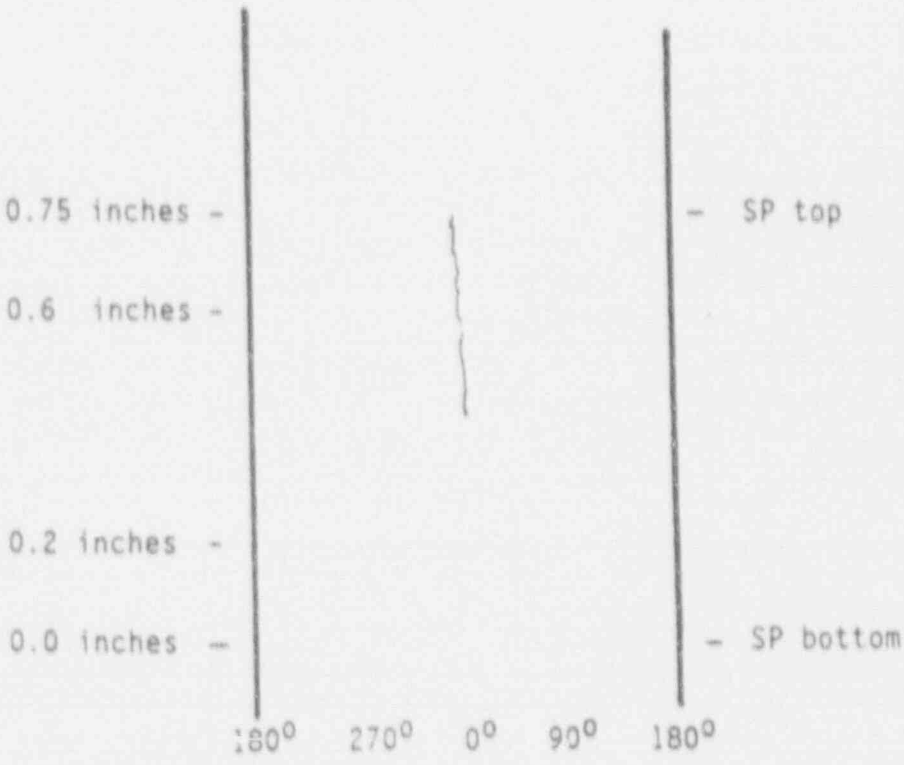

Sketch of Burst Crack

Macrocrack Length = 0.31 inch

Throughwall Length = 0.27 inch

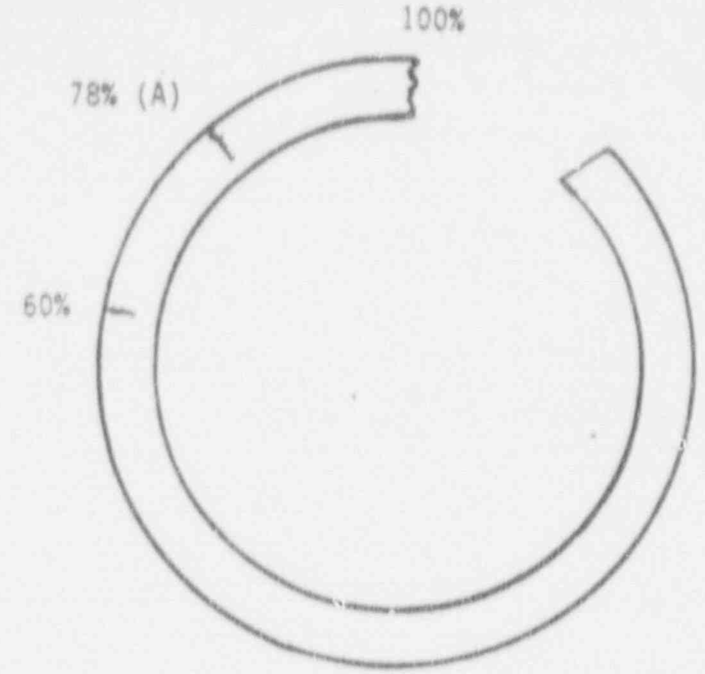
Number of Microcracks = 1

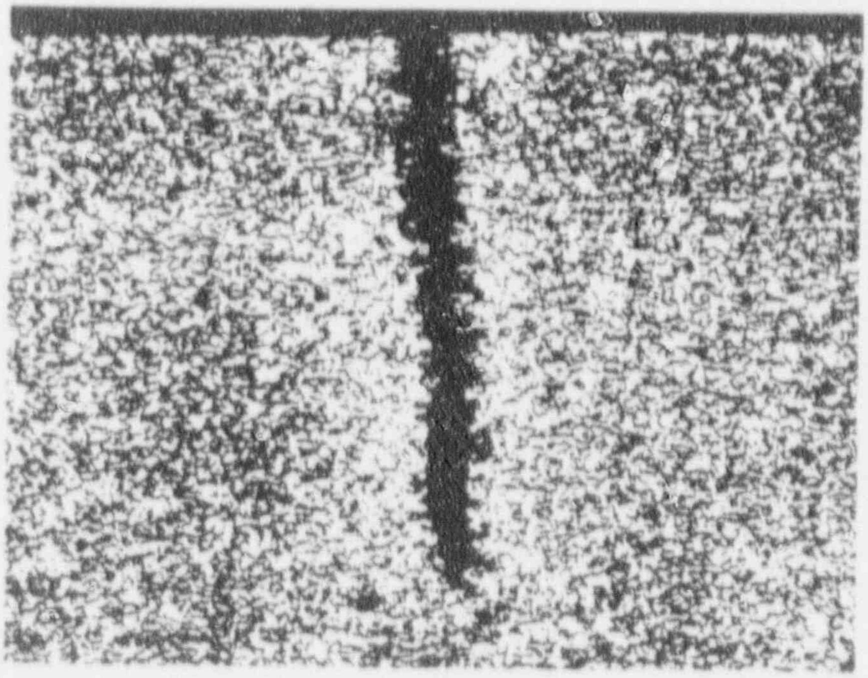
Morphology = IGSCC




Sketch of Crack Distribution

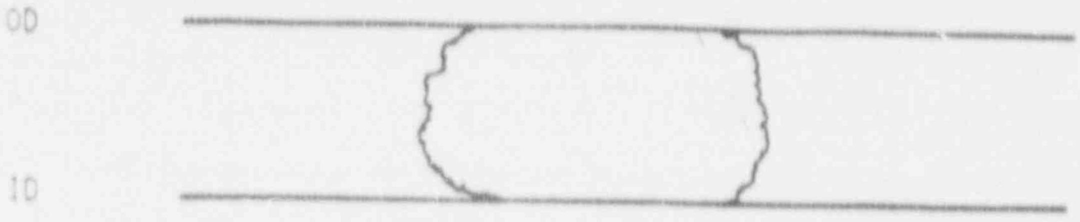
Figure 4-10. Summary of burst crack observations and the overall crack distribution at the crevice region of tube 590-3.




Crack A

Figure 4-11. Sketch of a metallographic cross section through the crevice region of tube 591-1. The burst crack and two secondary cracks on one quarter of the circumference were observed. A photomicrograph of a secondary crack is also shown. The crack morphology is that of IGSCC. Mag. 100X



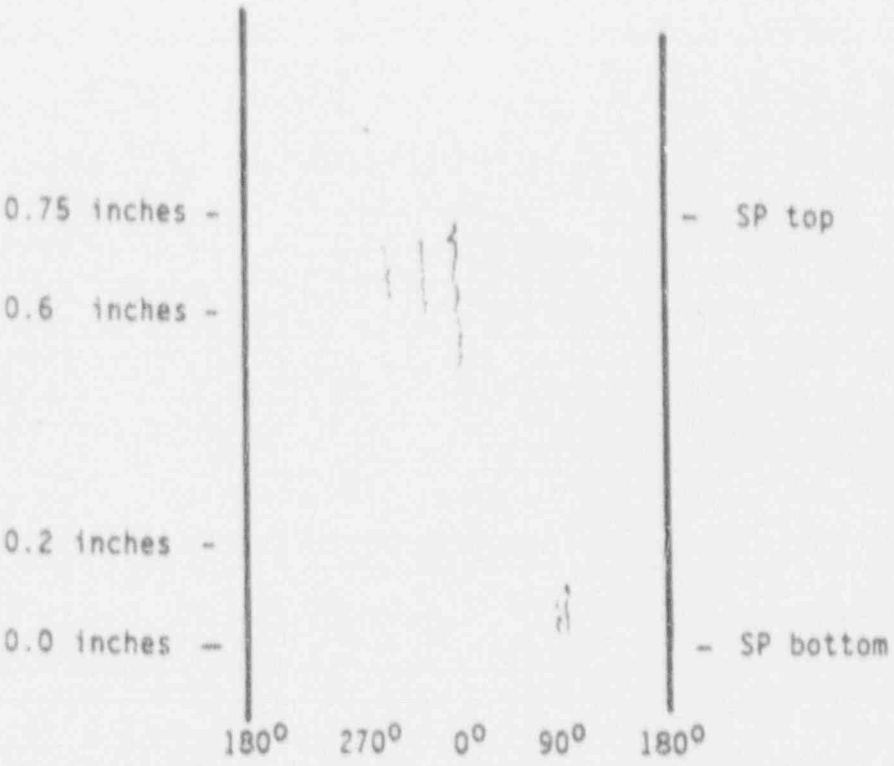

Sketch of Burst Crack

Macrocrack Length = 0.24 inch

Throughwall Length = 0.18 inch

Number of Microcracks = 1

Morphology = IGSCC




Sketch of Crack Distribution

Figure 4-12. Summary of burst crack observations and the overall crack distribution at the crevice region of tube 591-1.

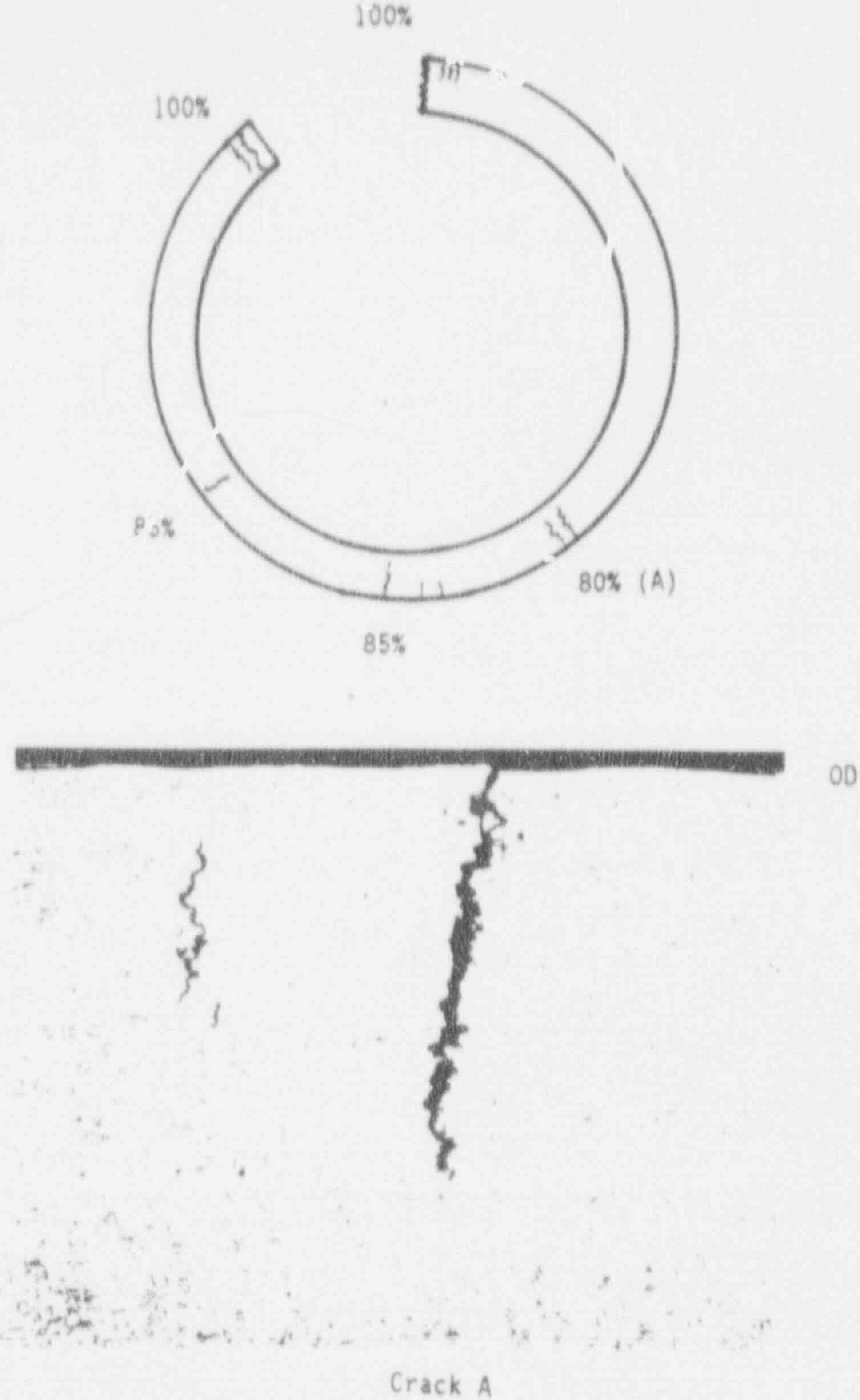
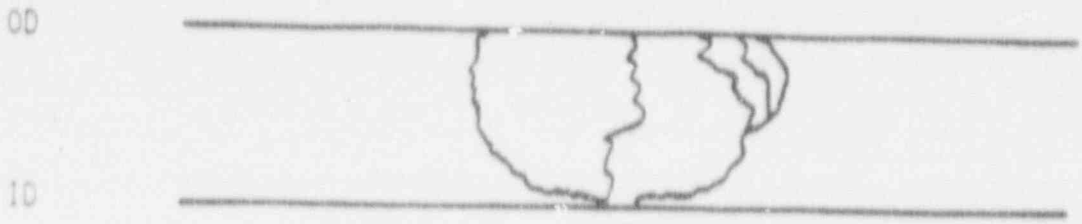



Figure 4-13. Sketch of a metallographic cross section through the crevice region of tube 591-2. The burst crack and a number of secondary cracks around the circumference were observed. A photomicrograph of two secondary cracks is also shown. The crack morphology is that of IGSCC. Mag. 100X



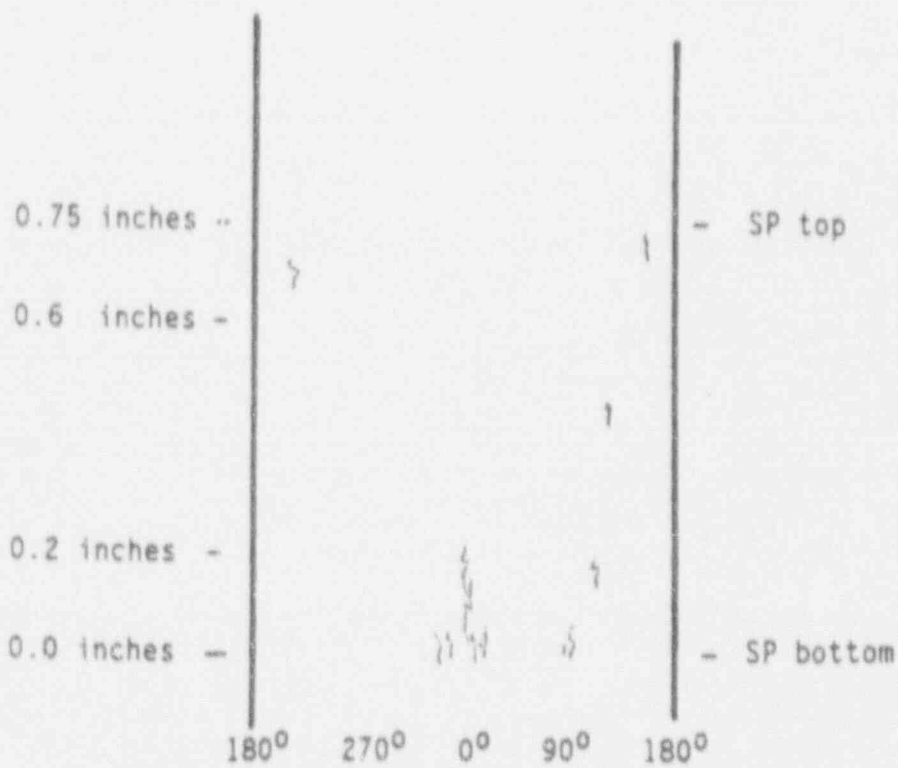

Sketch of Burst Crack

Macrocrack Length = 0.21 inch

Throughwall Length = 0.03 inch

Number of Microcracks = 4 (ligaments have ductile features)

Morphology = IGSCC




Sketch of Crack Distribution

Figure 4-14. Summary of burst crack observations and the overall crack distribution at the crevice region of tube 591-2.

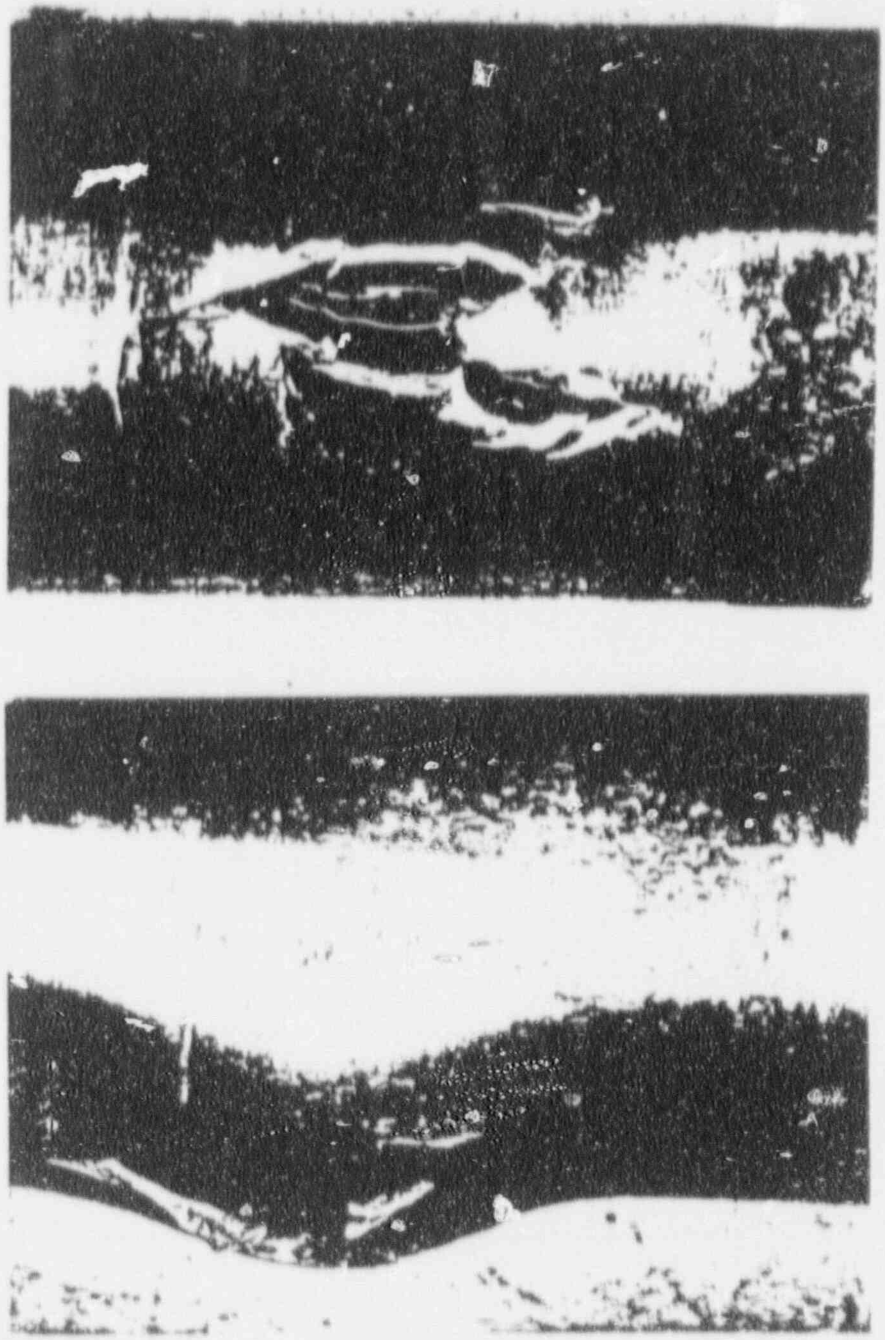
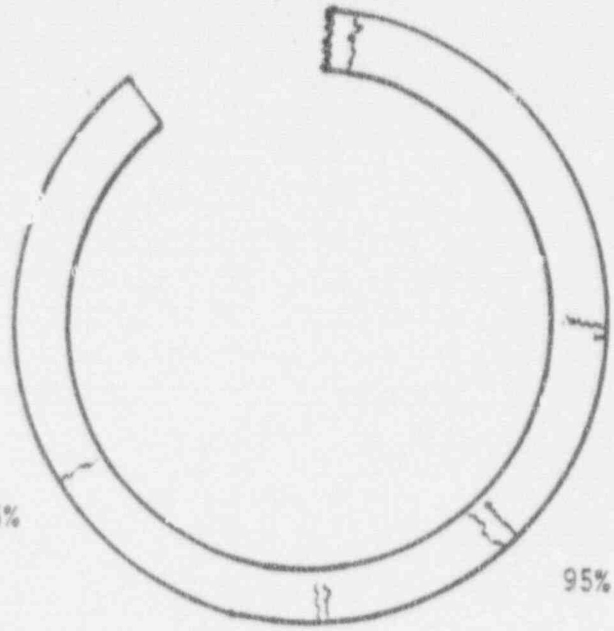


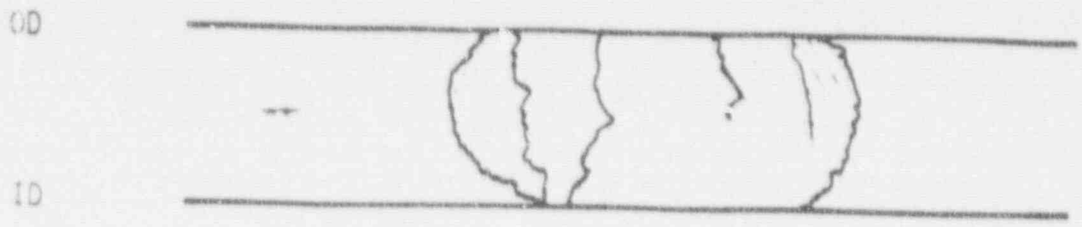
Figure 4-15. Photographs of the burst opening in tube 591-4.





Crack A

Figure 4-16. Sketch of a metallographic cross section through the crevice region of tube 591-4. The burst crack and a number of secondary cracks around the circumference were observed. A photomicrograph of the burst crack and a secondary crack is also shown. The crack morphology is that of IGSCC. Mag. 100X



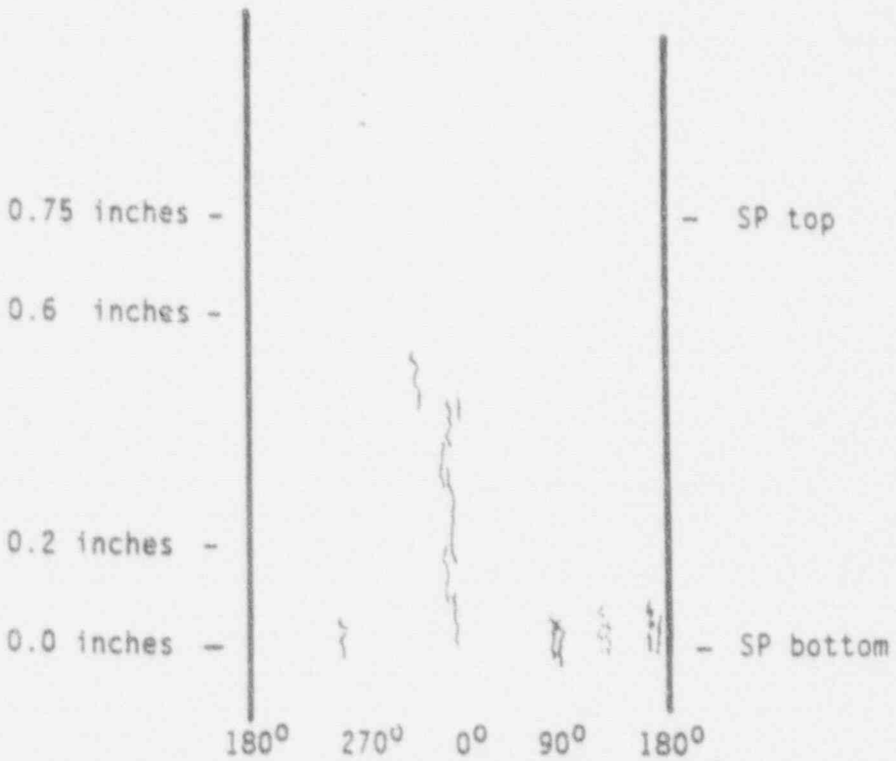

Sketch of Burst Crack

Macrocrack Length = 0.45 inch

Throughwall Length = 0.35 inch

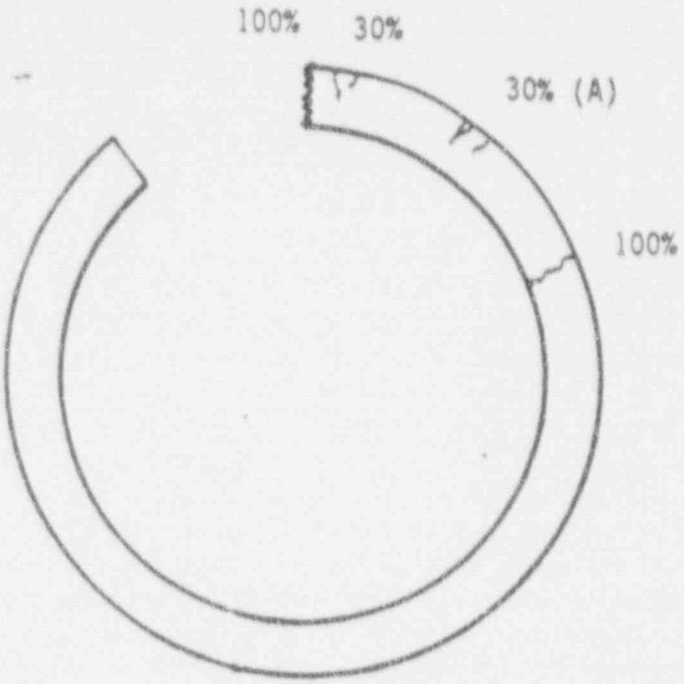
Number of Microcracks = 5 (ligaments have intergranular features)

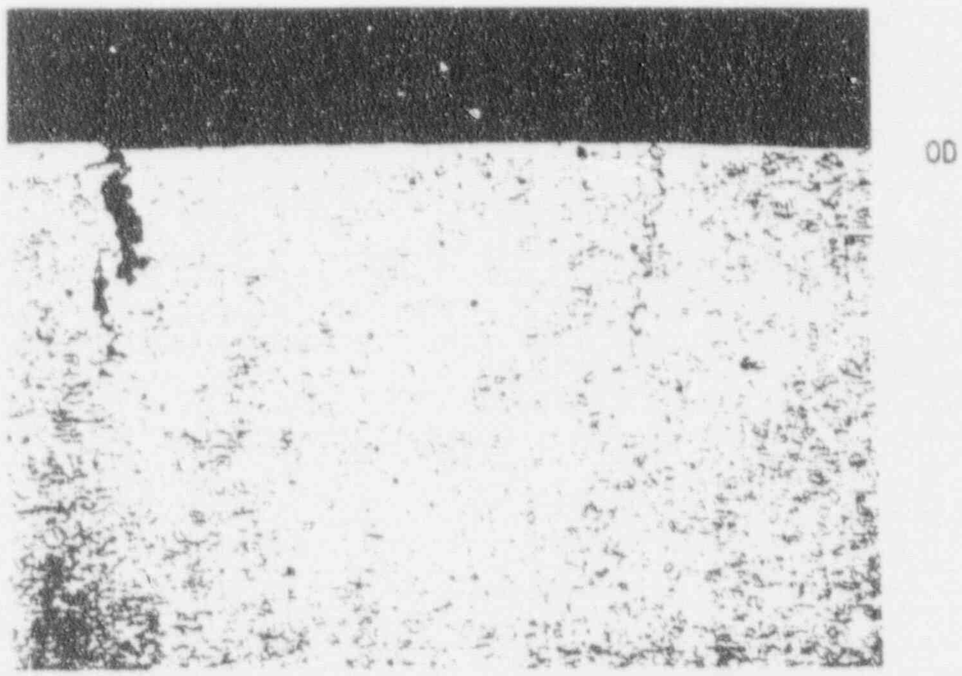
Morphology = IGSCC




Sketch of Crack Distribution

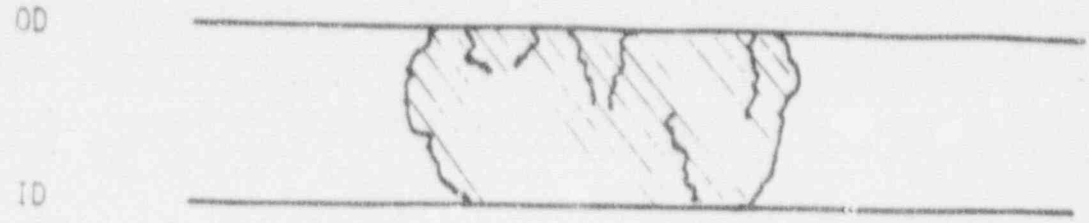
Figure 4-17. Summary of burst crack observations and the overall crack distribution at the crevice region of tube 591-4.




Crack A

Figure 4-18. Sketch of a metallographic cross section through the crevice region of tube 596-3. The burst crack and a number of secondary cracks in one quadrant of the circumference were observed. A photomicrograph of two secondary cracks is also shown. The crack morphology is that of IGSCC. Mag. 100X



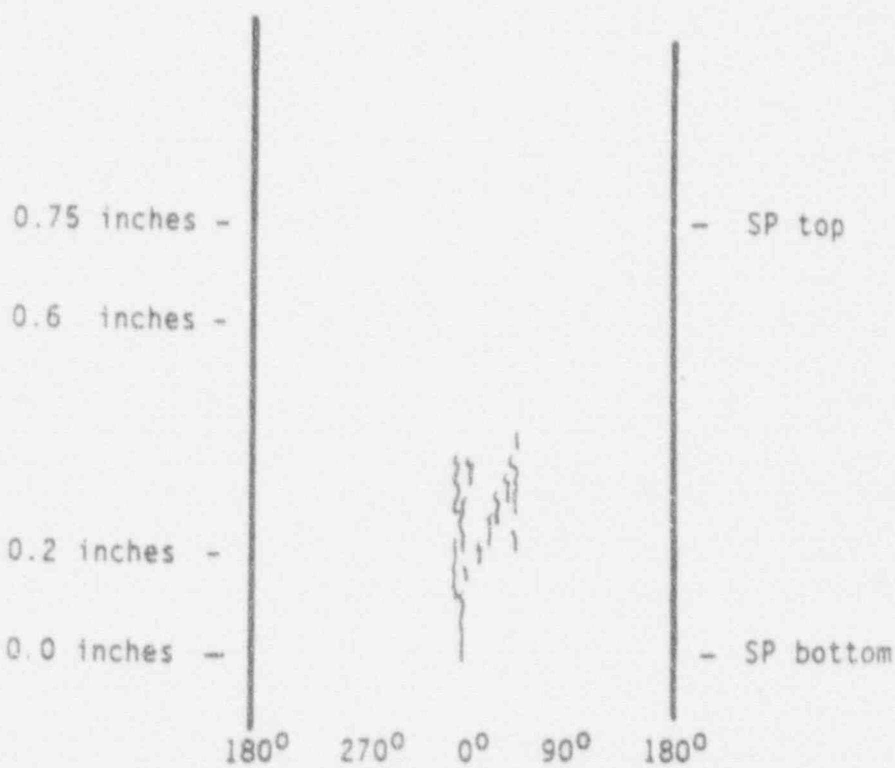

Sketch of Burst Crack

Macrocrack Length = 0.45 inch

Throughwall Length = 0.44 inch

Number of Microcracks = 4 (ligaments have intergranular features)

Morphology = IGSCC




Sketch of Crack Distribution

Figure 4-19. Summary of burst crack observations and the overall crack distribution at the crevice region of tube 596-3.

## Section 5

## NDE EXAMINATION

### 5.1 Eddy Current Voltage Normalization for APC

Normalization of observed support plate ODSCC signal amplitudes is performed to permit direct comparison of the voltage levels associated with field measurements with the laboratory calibration used to join pulled tube and model boiler signal amplitudes. In cases where field data is collected using different voltage calibrations or different frequencies, conversion factors are developed which permit the field data for tubes and ASME standards taken at different voltage normalizations to be integrated into the overall database for voltage, burst pressures and leakage correlations.

The existing data base for pulled tube and model boiler samples includes amplitude measurements which are referenced to a common voltage calibration for both 3/4 inch diameter 0.043 inch wall thickness and 7/8 inch diameter 0.050 inch wall thickness tubing. Specifically the bobbin EC coil reference calibrations for 3/4 inch x 0.043 inch tubing are:

> 4.00 volts at 550 kHz for 4 X 20% ASME holes, and
>
> 2.75 volts in the 550/130 kHz support plate suppression mix output, also for 4 x 20% ASME holes

The frequency and voltage normalizations applied for the 3/4 inch diameter APC data base, including all model boiler specimens, were developed based on scaling from the 7/8 inch diameter practices (400/100 kHz frequency mix). The 3/4 inch and 7/8 inch tube diameters are geometrically similar, that is, all linear dimensions are scaled by the same factor. Eddy current probe dimensions are scaled by the same factor applied to the 0.720 inch, 7/8 inch probe diameter to obtain a 0.620 inch, 3/4 inch probe diameter. The probe excitation frequency is inversely proportional to the square of the tubing thickness. This applies to the 550/130 kHz and 400/100 kHz frequencies used for 3/4 inch and 7/8 inch tubing, respectively. Thus the bobbin coil dimensions and test frequencies are intended to yield similar responses for the 3/4 inch and 7/8 inch tubing. However, the ASME calibration standard holes are not scaled and other probe characteristics such as coil size are not scaled so that the resulting 3/4 inch and 7/8 inch tubing eddy current measurements are not directly comparable.

For the above bobbin coil voltage normalization, the probes tested (Echoram, Zetec) in the laboratory yielded both 4.0 volts at 550 kHz and 2.75 volts at 550/130 kHz. However, testing of other probes with different frequency sensitivity can yield a different ratio between 550 and 550/130 kHz normalizations. For probes yielding the laboratory ratio between 550 and 550/130 kHz, the voltage normalization at 550 kHz to 4.0 volts is preferred as it is less sensitive to small analyst variations in setting up the mix. However, the voltage normalization to 2.75 volts is more generally applicable to different probes and should be used for probes differing from the laboratory ratio by more than about 5%. That is, if the voltage is normalizaed to 4.0 volts for the 20% ASME hole at 550 kHz and is outside the range (5%) of 2.6 to 2.9 volts when carried over to the 550/130 kHz mix, the bobbin voltage normalization to 2.75 volts for the mix should be used for the data evaluation. For Catawba-1 voltage measurements the 2.75v mix normalization was the basis employed for sizing the support plate indications.

Thus the 1992 Catawba-1 support plate amplitude measurements used for repair limits disposition were taken in a fashion consistent with "Appendix A" guidelines presented in the Farley and Cook APC submittals.

## 5.2 Eddy Current Data Analysis Guidelines

The general inspection protocol for bobbin probe EC testing specified that data be collected at 4 frequencies - 550 kHz, 400 kHz, 130 kHz and 35 kHz. For Catawba-1 this represented a change in that prior inspection data did not include 550 kHz and that 100 kHz was used as the quarter-frequency for support plate suppression. As explained in Section 5.5, renormalization factors were calculated to facilitate determination of cycle growth rates .

### 5.2.1 Duke Power Company Analysis Process for Support Plate ODSCC

The Catawba Unit 1 EOC 6 bobbin coil data was analyzed in accordance with the Eddy Current Analysis Guidelines, Catawba Nuclear Station Unit 1, Rev. 2, dated 7/9/92. All signals indicative of degradation were reported regardless of depth and with no minimum voltage threshold. All data were analyzed with 2 independent reviews (primary and secondary analysts). The results of the primary and secondary analysts were compared and resolved by a team of 2 resolution analysts.

Every HL (hot leg) TSP call was then remeasured to obtain a voltage value consistent with Westinghouse recommendation for measuring bobbin voltages for ODSCC degradation at HL TSP's. This process was simply a measurement exercise, to obtain a voltage value related to a specific normalization, channel (550/130 kHz MIX 5), and signal isolation. This was not a reanalysis as the presence of the degradation at each reported TSP had already been determined and was not changed. The remeasurement was performed in accordance with the Hotleg Tube Support Re-sizing Analysis Guidelines, Rev. 0, dated 8/12/92. An analyst remeasured each HL TSP call and generated bobbin coil graphics depicting the call. Each call was reviewed by a team of 2 resolution analysts who concurred with the accuracy of the measurement, and assured all HL TSP calls were resized.

Every HL TSP call was then remeasured two more times: Once again on the current EOC 6 bobbin data with a 400/130 kHz mix and also from the EOC 5 1991 data with a 400/100 kHz mix. These remeasurements were performed to obtain ODSCC growth trending information. The remeasurements were performed in accordance with the Hotleg Tube Support Re-sizing Analysis Guidelines for Growth Trending, Rev. 0, dated 8/12/92. These measurements were also performed by an analyst with two resolution analysts reviewing them for accuracy. The guidelines are attached as Appendix A.

To obtain growth trending information over 2 cycles, a set of HL TSP calls in tubes plugged after the EOC 5 analysis in 1991 were remeasured using the EOC 5 1991 data and the EOC 4 1990 data using a 400/100 kHz mix. Resizing and resolution were performed in identical fashion to the growth trending described in the paragraph above.

## 5.3 NDE Results for Model Boiler Specimens

The range of signal amplitude vs burst pressure data available from pulled tubes is supplemented by data produced from laboratory specimens prepared in model boilers. Table 4-5 presents a summary of NDE data (bobbin voltage) corresponding burst pressures and leak rates measured in the EPRI-sponsored laboratory study. The bobbin voltages were measured in accordance with the analysis guidelines used for the EPRI and consistent with the Appendix A guidelines provided for 7/8 inch tubing as typified by the Farley alternate plugging criteria (WCAP-12872, Rev. 2, February 1992). The 3/4 inch tubing analysis guidelines used in the laboratory as well as the Catawba 1 re-sizing analysis guidelines are consistent in the manner and techniques used for amplitude measurements with the Farley submittal guidelines. RPC testing and analysis done to assist in the characterization of the model boiler specimens was also performed in a fashion which assures consistency with the data obtained from 7/8 inch tubes.

## 5.4 Voltage Trends for EDM Slots

In order to anticipate the behavior (bobbin amplitude response) of cracks, EDM slots of varying depth and length were prepared for 3/4 inch tubing. As with the 7/8 inch data for EDM slots, the NDE measurements were made according to the EPRI study guidelines on which the Appendix A guidelines from the Farley submittal were based. For 3/4 inch tubing, the support plate mix (550 kHz/130 kHz) data obtained using a 610 mil bobbin probe were evaluated to determine the peak-to-peak voltage values for each notch. These data are displayed in Figure 5-1. The trends apparent in these data are virtually identical to those collected with a 720 mil probe from the 400 kHz/100 kHz mix channel for 7/8 inch tubing (Figure 5-2). A comparison of similar configurations for 3/4 inch and 7/8 inch tubing is given in Table 5-1 to illustrate the equivalence of the readings for the corresponding support plate mix measurements.

## 5.5 Frequency Renormalization Based on Calibration Standards

Past inspections at Catawba 1 did not employ the 550 kHz and 130 kHz channels for bobbin probe EC inspection. For 1992 the bobbin frequencies used included 550 kHz, 400 kHz and 130 kHz; the corresponding frequencies used in prior inspections were 300 kHz, 400 kHz and 100 kHz. To permit application of the Catawba-1 pulled tubes (400/100 kHz) and of growth estimates for prior cycles, it was necessary to develop conversion factors to translate 400/100 kHz and 400/130 kHz mix channel amplitudes for prior cycles into voltages comparable to the 550/130 kHz calibration basis for 1992.

For voltage differences between alternate normalizations and frequencies, bobbin voltage conversion factors can be obtained using machined calibration standards such as ASME Standards. Table 5-2 provides voltage values for the various frequency mixes based on an ASME standard, including the values for the APC voltage normalization at the 20% ASME hole for 550/130 kHz. Figure 5-3 demonstrates the excellent correlation obtained between the 550/130 kHz mix and the 400/100 kHz mix as obtained from the Catawba-1 pulled tube in the post-pull laboratory NDE.

Figure 5-4 presents a similar correlation as obtained from field measurements between 550/130 kHz and the 400/130 mix based on 1992 Catawba-1 inspection results. It is seen that 550/130 kHz mix correlations with both the 400/100 kHz mix used in prior inspections and the 400/130 kHz mix used in 1992 are very good. Therefore compensation for the

differences between 400/100 kHz and 400/130 kHz calibrations is obtained by multiplying the voltage value from the solution of the simultaneous equations relating each of them to the 550/130 kHz mix:

$$\text{Volts (400/100 kHz)} = 0.94 \times \text{Volts (400/130 kHz)} - 0.17 \quad (5\text{-}1)$$

The compensation developed in this fashion permits determination of per cycle growth estimates for the support plate ODSCC indications identified at the end of each cycle.

## 5.6 Renormalization of Catawba-1 Pulled Tube Data

Tubes which have been pulled from Catawba-1 steam generators in prior inspections were field examined using the 400/100 kHz mix, with the bobbin probe, as previously stated, calibrated on the basis of a carbon steel support simulator (ring) on an ASME standard tube yielding 5.0 volts at 400 kHz. To include this information in the 3/4 inch tubing database, the field EC data was recalibrated to the 2.75 volt APC normalization for the 4 X 20% hole on the ASME standard.

In addition, the post-pull data provided by B&W on Catawba-1 tubes was used to develop renormalization ratios from the field to the APC normalization. The field and post-pull laboratory data were taken on a 400/100 kHz mix calibrated to a support plate ring, as described above.

Post-pull laboratory data were also obtained for 550/130 kHz mix with the APC normalization at 2.75 volts. The post-pull voltages are much higher than pre-pull voltages and thus are not used to support the APC development. However, the post-pull data are used to develop the conversion factors for renormalizing the 400/100 kHz field data to the 550/130 kHz normalization. Using the correlation of the 550/130 kHz mix to the 400/100 kHz mix when both evaluations are independently normalized to 2.75 volts for the 20% ASME hole (Figure 5-3), one obtains:

$$\text{APC volts (550/130 kHz)} = 1.094^*(\text{400/100 kHz volts}) + 0.143 \quad (5\text{-}2)$$

The pre-pull Catawba-1 voltages were converted to the APC normalization using this equation.

For this voltage normalization, the standard TSP volts at 400 kHz were also obtained to permit adjustment of the field data to a normalization of 2.75 volts for the 400/100 kHz mix. The measured TSP volts for the 2.75 volt normalization are given in Table 5-3. Division of these TSP voltage measurements by the field normalization of 5.0 volts yields the voltage adjustment factor given in Table 5-3 for obtaining the 20% ASME hole normalization (2.75 volts for 400/100 kHz mix). This adjustment factor is applied to the field evaluation with TSP normalization as shown in the field evaluation columns of Table 5-4 to obtain the field voltages for the 400/100 kHz mix normalized to 2.75 volts for the 20% ASME hole. The Westinghouse evaluation for the 400/100 kHz mix is also shown in Table 5-4. The agreement is generally better than 15% between the field and Westinghouse evaluations.

Table 5-3 also shows B&W post-pull bobbin voltage evaluations for the 400/100 kHz and for the APC 550/130 kHz mix normalized to 2.75 volts for the 20% ASME hole. These voltages were used in Figure 5-3 to obtain voltage renormalization factors as given by the above equation. The voltage renormalization factors were then applied to the pre-pull 400/100 kHz voltages of Table 5-4 to obtain the APC normalization voltages also given in Table 5-4. The Westinghouse

evaluated voltages are used for the APC development although differences from the field evaluation are small. Also shown in Table 5-4 are the Westinghouse evaluated RPC voltages based on evaluation of the available field data at 300 kHz with normalization to 20 volts for a 0.5 inch long EDM notch. The field RPC voltages were normalized to 10 volts for the ASME holes and are not directly comparable to the APC voltage normalization.

Comparison of the pre-pull voltages of Table 5-4 with the post-pull voltages of Table 5-3 shows that the bobbin voltages for the larger voltage indications increased by factors of 1.5 to 4 as a result of the tube pull operations. The largest four voltage indications, which show increases of factors of ~ 2.4 to ~ 4.4, are associated with the lowest four burst pressures for the Catawba-1 pulled tubes.

## 5.7 Renormalization of Belgian Pulled Tube Data

The 3/4" tube database is significantly expanded by inclusion of tube pull and burst test data produced by Laborelec from Plant E in Belgium. In support of the industry effort to develop alternate plugging criteria for support plate ODSCC, Laborelec has collected field data using both Belgian and APC voltage calibrations on U.S. testing equipment (MIZ-18) as well as Belgian equipment; this data has included several pulled tubes among ~57 indications evaluated. The pulled tube data are summarized in Table 5-5; Figure 5-5 presents the relationship as reported by Laborelec between the 300 kHz calibration used in Belgium (4 x 100% - 49 mil holes = 2.00 volts) and the APC calibration for 3/4" tubing using Belgian test equipment for 300 kHz data and U.S. equipment for the 550/130 kHz (APC) data. The correlation between Westinghouse and Laborelec evaluations at the APC normalization is shown in Figure 5-6; excellent agreement is shown for the 550/130 kHz data evaluation with U.S. test equipment (MIZ-18). Similarly an excellent correlation is obtained (see Figure 5-7) for the Laborelec evaluation of data obtained at 300 kHz and 550/130 kHz using the MIZ-18 equipment. These data permitted development of the voltage renormalization factor (~4.93) based on Laborelec probes and calibration standards.

To merge the Belgian data into a consistent industry population for 3/4" tubing, a cross-calibration of the Belgian analyses with the U.S. laboratory ASME standard for 3/4" tubing (AS-009-91) was performed. The cross-calibration process began with the testing of an ASME transfer standard (ASR-002-92) together with the laboratory standard. For the four 20% holes used as the reference basis, the following results were obtained:

| Frequency | Lab. Std. AS-009-91 | Transfer Std. ASR-002-92 | U.S. Lab/Transfer |
|---|---|---|---|
| 550 kHz | 4.00 volts | 3.96 volts | 1.010 |
| 550/130 Mix | 2.85 volts | 2.78 volts | 1.026 |

The U.S. transfer standard was provided to Laborelec to obtain the cross-calibration ratio for the Belgian ASME standard (#62952). These two standards were tested with Belgian probes with a MIZ-18 (Zetec) EC tester to obtain 550 kHz and 130 kHz data; the following results were obtained for the four 20% holes:

| Frequency | U.S. Std. AS-002-92 | Belgian Std. #62952 | Belgian/U.S. Transfer |
|---|---|---|---|
| 550 kHz | 2.51 volts | 4.00 volts | 1.594 |
| 550/130 Mix | 1.56 volts | 2.75 volts | 1.763 |

Using this data, it is possible to complete the cross-calibration of the U.S. and Belgian data sets. Amplitudes measured from the 550 kHz/130 kHz mix channel in Belgium must be multiplied by 1.763 (Belgian/U.S. Transfer) x 1.026 (U.S. Lab/U.S. Transfer) to convert them to the amplitude scale of the U.S. data base:

Belgian Volts x 1.763 x 1.026 = U.S. Volts

U.S. Volts = Belgian Volts x 1.809

This cross-calibration, obtained using Belgian probes with a U.S. EC tester, yields a ratio quite consistent with the ratio predicted from the U.S. work, summarized in Table 5-6.

Laborelec is continuing a study of differences between U.S. and Belgian practices; preliminary results of their work is summarized in Table 5-7. These data suggest that part of the difference observed is found in the calibration bases; there appears to be little difference in responses between the U.S. and Belgian probes and test equipment. For conservatism in this report, the Belgian cross-calibration factor has been applied as 1.5 (rather than 1.809) pending completion of the Laborelec study.

## 5.8 NDE Uncertainties for Catawba Unit 1

### 5.8.1 General Approach for APC

The usual industry practice with respect to NDE uncertainty is based on the adequacy of a sizing model which relates the measured NDE parameter (e.g. depth from phase angle or amplitude for EC testing) to the true value as determined from metallographic examination of representative specimens, actual or simulated. It has been shown that unique interpretations of amplitude from bobbin signals are not to be expected and that depth as measured from phase angle is not an adequate predictor of the structural capability of a tube. The need to relate measured NDE parameters to structural adequacy has resulted in the subject amplitude (voltage)-based relationship with burst pressure as a predictor of structural adequacy. This approach is based on the relationship between amplitude and volume of tubing affected by degradation, a well-founded dependency which predicts that as the tube condition becomes more extensively degraded the EC signal response in volts becomes larger; concurrently the more extensively degraded the tube becomes the less capable is the tube with respect to the internal pressure it can withstand before burst.

Thus for NDE uncertainty the focus is placed on standards and measurement repeatability. Since all the measurements must be referenced to a known condition, the industry practice of using ASME standards is the cornerstone of the APC practice. To minimize effects of the variability of standards, each particular ASME tubing standard used to calibrate the field NDE responses is cross-calibrated to the ASME standard used in the EPRI laboratory study. Thus each standard is constrained to produce measurements which are directly comparable to those produced from each plant using the same size tubing. To assess the effects of probe construction differences on amplitude measurements, the EPRI study compared bobbin probes manufactured by Zetec and Echoram, finding them essentially equivalent for the purpose. Additionally Westinghouse has compared the responses of a number (12) of production probes built by Echoram on the same standard. It was found that the variability of the responses in the support plate mix channel was less than 5%. Eddy current system - cabling, instrumentation, etc. - variability arising from noise is of the order of 0.1 volt at the calibration used for field measurements; this is essentially

negligible compared to other sources of error for applications to plugging limits of the order of one or more volts.

Special concern attends measurement variability arising from wear of the probes' centering devices. Excessive play may result in off-center positioning of the probe relative to the flaws which affect the EC response. Thus a new probe with design centering produces the proper response, while the same probe with worn centering devices may lean away from the flaw or toward it producing smaller or larger amplitude responses. To reduce this variability, limits are placed on the usage of an otherwise electrically sound probe; each probe is required to give amplitudes no greater than ±15% different at any time from the responses when new to four identical, 100% deep holes staggered axially on a standard tube ("probe wear standard"). (This device was not available at Catawba-1; estimates or probe wear uncertainty are described in Section 5.8.2.) Periodic measurement of the probe wear standard identifies when the probe centering is inadequate and replacement is required. An allowance of 15% is provided in the plugging limit calculations, though somewhat lower variability is expected.

Data analysis guidelines for voltage measurements are provided in EC sizing guidelines, in Appendix A. It has been found through experience at Plants A, J and L that when given a common orientation to specific measurement guidelines that the variability arising from analysts' differences are reduced to less than ±10%. As expected, this uncertainty is larger at low voltages; this results from the lower signal to noise ratio. As the S/N value increases, measurement variability diminishes with the result that for plugging limit voltages the overall average is a conservative correction.

To reduce the spread of possible responses to a given morphological condition, the measurements used for the voltage/burst pressure correlation are taken from the field, pre-pull inspection data. It has been observed on many occasions that there are unpredictable differences in amplitudes of flaw signals between pre-pull and post-pull inspection data. This results from mechanical deformation of the tube, such as elongation, denting, scratching, etc. which occurs in the process of removal.

The contributions to the NDE uncertainty at the 90% cumulative probability are calculated for each of the error sources. These sources are treated as independent variables and combined as a root mean square (RMS) to obtain the net NDE uncertainty. This value is then applied in the calculation of the tube plugging voltage limit. For probabilistic SLB leak rate evaluation, the cumulative probability distribution or a normal distribution of NDE uncertainty is utilized.

### 5.8.2 Catawba-1 NDE Uncertainties

The EC uncertainty consists of the EC analyst variability and the probe wear contribution. For the 1992 Catawba-1 inspection, these are developed as described below:

<u>EC Analyst Variability</u>

The most extensive evaluation for the EC analyst uncertainty was performed at Plant L. Figures 5-8 and 5-9 show the indications and analyst uncertainty from the Plant L study. At 90% cumulative probability, the EC analyst uncertainty is 10%. The uncertainty in percent represents the voltage difference from Figure 5-9 divided by the mean voltage of 1.41 volts. An upper limit on the analyst variability uncertainty results from plant specific guidelines for resolving voltage differences between analysts as described below.

For Catawba-1, the 1992 indications and the associated 1991 indications for developing growth were reanalyzed by Duke Power using guidelines consistent with APC requirements as described in Section 5.2. A sample of 18 indications were independently reviewed by Westinghouse. This partial assessment for the largest indications in S/G C support consistency with the APC guidelines for the 1992 inspection evaluation. Thus it is reasonable to apply the Plant L EC analyst uncertainty for the 1992 Catawba-1 indications.

For the 1992 inspection, a resolution process was implemented to obtain the final voltage amplitudes for application of the IPC criteria. This resolution process required that each analyst call on resizing the indications to the APC guidelines was reviewed by a team of 2 resolution analysts who concurred with the accuracy of the measurement.

This resolution process can be expected to limit the EC variability described above for Plant L (based on differences between analysts with no resolution process) at upper/lower bound cutoff values. To estimate the cutoff or upper bound values for analyst variability, 123 indications were given a repeat analysis which can then be compared with the primary analysis (final outage voltages) for each indication. Emphasis on the primary voltage analysis was placed on conservative peak to peak voltages. The primary analysis was performed utilizing the voltage resolution process described above. The repeat analysis was a single analyst evaluation (no resolution process) of the voltages. Thus the voltage differences between the primary and repeat analyses can be expected to bound the voltage variability that would be expected with two independent analyses carried through the resolution process. The resulting voltage differences between the resolution process (resolved volts) and the single analyst are shown in Figure 5-10 as a function of the primary voltage call (resolved volts) for each indication. In most cases, the primary calls are higher amplitudes particularly above about 0.5 volt. At low (<0.5 volt) amplitudes, the voltage variability is higher with both plus and minus values. This result is generally expected for flaw signals of comparable magnitude to noise and residual signals. Above about 0.8 volts, the maximum voltage difference is <20% of the resolution process voltages. Since this range of voltages is of most significance for IPC applications, an EC analyst variability cutoff at 20% can be applied. Thus the EC analyst variability can be represented as the distribution of Figure 5-9 with a cutoff or maximum uncertainty at 20%. This uncertainty has been applied for final Catawba-1 analyses while preliminary analyses were performed with no cutoff on the distribution.

Probe Wear Uncertainty

Figures 5-11 and 5-12 show the database on voltage sensitivity to probe wear. For plants implementing the probe wear standard, the voltage variability of Figure 5-12 is obtained from the Figure 5-11 data by including all data to 20 mil radial wear for the Echoram probe and to 5 mils for the Zetec probe. The resulting probe wear uncertainty has a standard deviation of 7%.

The probe wear standard was not implemented in the 1992 Catawba-1 inspection. Zetec probes have been used for the 1992 Catawba-1 inspection. Thus the data for the Zetec probe (bottom figure) of Figure 5-12 are applicable to Catawba-1. Mockup tests with the probe wear standard have shown that at 0.0075 inch wear, the wear standard requires probe replacement for 90% of the tests and only the data up to 5 mils wear was used for the EC uncertainty of 7%. With the probe wear standard, the probe wear uncertainty is cut off at 15% by the probe wear replacement requirement. It is reasonable for estimating the Catawba-1 probe wear uncertainty to include the 7.5 mil data in determining the standard deviation and apply this uncertainty with no cut off.

Figure 5-13 shows the probe wear standard amplitudes and voltage differences from the mean for all Zetec probe measurements between no wear and 7.5 mils wear. This simulates measurements between a new and well-worn probe. The uncertainty of Figure 5-13 shows a standard deviation of 0.55 volts for an average of 6.05 volts or a standard deviation of 9%. For Catawba-1, the probe wear uncertainty can then be estimated by rounding to a standard deviation of 10% with no cut off at high confidence levels. It can be noted from Figure 5-11 that the average voltage, as well as the standard deviation, tends to increase (conservative for tube repair) at large probe wear (7.5 mils).

The probe wear uncertainty of 10% standard deviation was applied for preliminary Catawba-1 analyses. To further evaluate the probe wear uncertainty, data obtained during ASME standard calibration runs at the beginning and end of each data tape were collected for further evaluation. Table 5-8 shows an example of this data for one of the larger number of tubes inspected (1456 tubes) with a given probe. The single, 100% throughwall ASME hole data can be used to estimate the probe wear uncertainty by evaluating the variability in the 100% hole voltages. Data such as Table 5-8 were collected for 10 probes covering the inspection of 8947 tubes on 58 tapes for S/G's C and D. The 8947 tube inspection results spanned 95 tapes of which 100% hole voltages were collected at the beginning and end of 58 tapes. The number of tubes inspected per probe varied from 63 to 2391 for these data. To be representative of the IPC measurements made for each tape, the 100% hole measurements were adjusted to 2.75 volts for the corresponding 4 x 20% ASME holes used for data calibration of the field measurements.

The 100% hole data (116 calibration standard measurements) were then evaluated to determine the mean with the standard deviation about the mean (voltage differences) applied as a measure of the probe wear NDE uncertainty. Figure 5-14 shows the resulting distribution for the 100% hole measurements. The standard deviation is 16% of the average or mean voltage. This probe wear uncertainty of 16% is applied for the final Catawba-1 IPC analyses. It can be noted that the range of voltage differences from the mean is about -25% to +50%. The larger spread for overestimating voltages due to probe wear leads to conservatively large voltage measurements for the field applications. The negative voltage differences or underestimates of the voltage amplitude are bounded by less than two standard deviations.

Combined EC Uncertainty

The probe wear and EC analyst NDE uncertainties can be considered to be independent variables. For Monte Carlo analyses to obtain EOC voltages, separate distributions can be used and independently sampled for the two contributions to the NDE uncertainty. For deterministic analyses of tube integrity, the EC uncertainties at 90% and 99% cumulative probability are required. The independent uncertainties can be combined as root-mean-square (RMS) averages. The results of the preliminary and final analyses for the NDE uncertainties are summarized in Table 5-9. The preliminary values, as developed above, were a 10% standard deviation for probe wear and tube analyst variability of Figure 5-9 with no cutoff at the larger voltage differences. The final values are a 16% standard deviation for probe wear and the analyst variability of Figure 5-9 with a cutoff on the distribution at 20%.

Table 5-1

Comparison of Bobbin Signal Amplitudes
Between 3/4 Inch and 7/8 Inch Tubing for Different Flaws

| Flaw Type & Size | 3/4" - 43 Mil Tubing (550/130 kHz mix) | 7/8" - 50 Mil Tubing (400/100 kHz mix) |
|---|---|---|
| 20% ASME Holes | 2.78 volts | 2.75 volts |
| 100% ASME Hole | 6.4 volts | 8.2 volts |
| 1/4" Long, 100% Deep Axial Slot | 42 volts | 43.5 volts |
| 1/2" Long, 100% Deep Axial Slot | 77 volts | 75 volts |

Table 5-2

**Voltage Normalization Trends Between Frequency Mixes** (1)

| Frequency Mix | Signal Amplitudes for ASME Standard Hole Sizes 20 % | 40 % | 60 % | 80 % | 100 % |
|---|---|---|---|---|---|
| | **Voltages** | | | | |
| 550/130 kHz | 2.75 | 3.40 | 5.12 | 5.80 | 5.83 |
| 400/130 kHz | 2.75 | 3.30 | 4.80 | 5.26 | 5.15 |
| 400/100 kHz | 2.75 | 3.26 | 4.60 | 5.01 | 4.88 |
| | **Ratio of Voltages** | | | | |
| 550/130 / 400/130 | 1.00 | 1.03 | 1.07 | 1.10 | 1.13 |
| 550/130 / 400/100 | 1.00 | 1.04 | 1.11 | 1.16 | 1.19 |

1) Adjustments applied for Catawba-1 growth rates at 400/130 and 400/100 kHz to 550/130 kHz are based on voltage ratios for field indications. Evaluation of the ASME standard described in this table independently demonstrates larger renormalization factor for adjusting the 400/100 data of 1991 than for the 400/130 data of 1992.

Table 5-3

**Voltage Adjustment Factors to Obtain APC Normalization for 550/130 kHz Mix**

| Tube | TSP | Factor for Adjusting Field TSP Norm. to 20% ASME Norm. TSP Volts(1) | Adjustment Factor(2) | Post-Pull 550/130 kHz and 400/100 kHz Data(4) 400/100 kHz Volts | 550/130 kHz Volts |
|---|---|---|---|---|---|
| R5C112 | 2 | 6.92 | 1.38 | 0.25(5) | 0.37 |
| | 3 | | | 4.44 | 5.06 |
| R10C6 | 2 | 6.4 | 1.28 | 1.82 | 2.07 |
| | 3 | | | 4.77 | 5.34 |
| R10C69 | 2 | 6.4(3) | 1.28 | --- | NDD |
| | 3 | | | 2.92 | 3.31 |
| R20C46 | 2 | 6.04 | 1.21 | 0.59 | 0.82 |
| | 3 | | | 0.75 | 1.04 |
| R7C47 | 2 | 7.8 | 1.56 | --- | --- |
| | 3 | | | 3.65 | 4.13 |

Notes:

1. Westinghouse measure of standard TSP volts when 20% ASME volts set at 2.75 volts.
2. Voltage adjustment to convert voltages normalized to 5.0 volts at standard TSP to normalization of 2.75 volts for 20% ASME hole.
3. Adequate TSP not available on standard. Assumed same as tube R10C6.
4. B&W evaluations of post-pull data.
5. The 400/100 kHz data were renormalized to 2.75 volts for the 20% ASME hole.

Table 5-4

**Field and Westinghouse Evaluations of Catawba-1 Pre-pull Voltages**

| | | Field Evaluation | | | Westinghouse Evaluation | | |
|---|---|---|---|---|---|---|---|
| | | 400/100 kHz Mix | | 550/130 kHz | 400/100 kHz | 550/130 kHz | |
| | | | 20% Hole | 20% Hole | 20% Hole | 20% Hole | RPC |
| Tube | TSP | TSP Norm. | ASME Norm. | ASME Norm. | ASME Norm. | ASME Norm. | Volts (1) |
| R5C112 | 2 | NDD | --- | | 0.31 | 0.48 (2) | |
| | 3 | 1.15 | 1.59 | 1.88 (2) | 1.53 | 1.82 | 1.30 |
| R10C6 | 2 | 0.82 | 1.05 | 1.29 | 1.20 | 1.46 | 0.98 |
| | 3 | 0.77 | 0.99 | 1.23 | 1.07 | 1.31 | 1.20 |
| R10C69 | 2 | NDD | --- | --- | NDD | --- | |
| | 3 | 0.93 | 1.19 | 1.45 | 1.22 | 1.48 | 0.97 |
| R20C46 | 2 | 0.31 | 0.38 | 0.56 | 0.25 | 0.42 | |
| | 3 | 0.40 | 0.48 | 0.67 | 0.59 | 0.79 | |
| R7C47 | 2 | 0.33 | 0.40 | 0.58 | 0.34 | 0.51 | |
| | 3 | 0.80 | 1.25 | 1.51 | 1.30 | 1.57 | 1.40 |

Notes:

1. RPC volts at 300 kHz normalized to 20 volts for 0.5" EDM notch.
2. Obtained from 400/100 kHz evaluation using Equation 5-2.

Table 5-5

**Belgian and Westinghouse Evaluations of Plant E-4 Eddy Current Data[1,2]**

| | | Belgian Field Evaluation | | | | Westinghouse Evaluation | | |
|---|---|---|---|---|---|---|---|---|
| | | Zetec Equip. | | Belgian Equip.[3] | | | | |
| Tube | TSP | 550/130 kHz | 300 kHz | 300 kHz | | 550/130 kHz | | 300 kHz |
| | | Volts | Volts | Volts | Depth | Volts | Depth | Volts |
| R26C34 | 2H | 4.95 | 1.17 | 1.33 | 71% | 5.03 (9.10)[7] | 70% | 1.11 |
| R16C31 | 1H | 5.75 | 1.43 | 1.27 | 65% | 5.85 (10.58)[7] | 69% | 1.32 |
| | 2H | 9.30 | 2.02 | 2.25 | 70% | 9.25 (16.73)[7] | 72% | 1.95 |
| R40C47 | 1H | 0.17 | 0.09 | NDD[5] | -- | 0.17 (0.31)[7] | 41% | 0.09 |
| R45C54 | 1H | 9.57 | 2.29 | 2.25 | 65% | 9.53 (17.24)[7] | 69% | 2.21 |
| | 2H | 0.45 | 0.22 | 0.20[4] | -- [6] | 0.83 (1.50)[7] | 53% | 0.16 |
| R47C66 | 1H | 9.28 | 2.26 | 2.12 | 72% | 9.39 (16.99)[7] | 69% | 2.13 |
| | 2H | 1.39 | 0.53 | 0.52 | 40%[4] | 1.37 (2.48)[7] | 38% | 0.51 |
| R33C96 | 1H | 3.57 | 0.96 | 1.07 | 68% | 3.54 (6.40)[7] | 67% | 0.88 |

Notes:

1. Voltages at 550/130 kHz mix normalized to 2.75 volts on 20% ASME hole
2) Voltages at 300 kHz normalized to 2.0 volts on 4 throughwall, 1.25 mm (0.049") holes
3) Amplitudes and depth measured by automated signal analysis
4) Manual correction for small signal to noise ratio
5) Signal below automated detection threshold
6) No depth measurement for insufficient signal to noise ratio
7) Voltages in parentheses corrected for cross calibration factor of 1.809 between Belgian made ASME standard and the reference laboratory standard. Laborelec is conducting additional studies to determine if other adjustments are appropriate.

## Table 5-6

## Ratio of U.S. 550/130 kHz to Belgian 300 kHz

| Frequency KHz | Probe | Probe Type | 100' Ext. | Standard | APC 20% | 40% | 60% | 80% | 100% | ASME 4 TW 0.025 | 0.027 | Belgian 4 TW 1.25mm 0.048 | 0.049 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 550/130 | Zetec | Non-mag. | No | Lab | 2.75 | 2.62 | 4.13 | 4.54 | | 4.17 | | | 18.1 |
| 550 | | | | | 3.93 | 3.14 | 4.17 | 4.17 | | 3.50 | | | 15.7 |
| 300 | | | | | 0.89 | 0.65 | 0.69 | 0.66 | | 0.52 | | | 2.0 |
| 550/130 | Echo. | Mag-bias | Yes | Lab | 2.75 | 2.51 | 4.15 | 4.81 | | 4.44 | | | |
| 550 | | | | | 3.86 | 3.01 | 4.18 | 4.43 | | 3.72 | | | |
| 300 | | | | | 0.68 | 0.51 | 0.62 | 0.62 | | 0.5[illegible] | | 2.0 | |
| 550/130 | Echo. | Mag-bias | Yes | Transfer | 2.68 | 3.18 | 4.23 | 5.63 | | | 5.51 | 18.6 | |
| 550 | | | | | 3.82 | 3.82 | 4.31 | 5.22 | | | 4.69 | 16.1 | |
| 300 | | | | | 0.62 | 0.60 | 0.65 | 0.72 | | | 0.63 | 2.0 | |
| 550/130 | Belgian | | Yes | Belgian | 2.75 | 2.56 | 3.17 | 3.63 | 3.09 | | | 16.32 | |
| 550 | | | | | 3.57 | 2.91 | 3.31 | 3.49 | 2.90 | | | 9.58 | |
| 300 | | | | | 0.94 | 0.72 | 0.79 | 0.77 | 0.59 | | | 2.0 | |

Ratio 550/130 (APC) to 300 (Belgian)

| Probe | Probe Type | 100' Ext. | Standard | 20% | 40% | 60% | 80% | 100% | 0.025 | 0.027 | 0.048 | 0.049 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zetec | Non-mag | No | Lab | 3.09 | 4.03 | 5.99 | 6.88 | | 8.02 | | | 9.05 |
| Echo. | Mag-bias | Yes | Lab | 4.04 | 4.92 | 6.69 | 7.76 | | 8.71 | | | |
| Echo. | Mag-bias | Yes | Transfer | 4.32 | 5.30 | 6.50 | 7.82 | | | 8.75 | 9.30 | |
| Belgian | | Yes | Belgian | 2.93 | 3.47 | 4.01 | 4.71 | 5.24 | | | | 5.16 |

TAP2081:072192

Table 5-7

**Preliminary Laborelec Results for Renormalization of Belgian to U.S. Volts**

| Item | 3/4" Tubing-Volts 300 KHz | 3/4" Tubing-Volts 550/130 KH | 7/8" Tubing-Volts 240 KHz | 7/8" Tubing-Volts 400/100 KHz |
|---|---|---|---|---|
| A. Manufacturing Process: 4-TW 1.25 mm Holes | | | | |
| U. S. Drilled | 1.99 | 10.58 | 1.88 | 9.26 |
| Belgian EDM | 2.00 | 10.56 | 2.00 | 10.17 |
| Ratio EDM/Drilled | 1.005 | 0.998 | 1.064 | 1.098 |
| Manufacturing Process: 4-20% ASME Holes | | | | |
| U. S. Drilled | 0.63 | 1.56 | 0.71 | 1.90 |
| Belgian EDM | 0.94 | 2.75 | 0.94 | 2.75 |
| Ratio EDM/Drilled | 1.492 | 1.763 | 1.324 | 1.447 |
| B. Influence of Probe Design: U. S. ASME Std. | | | | |
| 20% Holes (U.S. Standard) | | | | |
| Echoram | 0.61 (1) | 2.76 (2) | 0.94 (1) | 2.77 (2) |
| Laborelec | 0.64 | 2.74 | 0.76 | 2.74 |
| Ratio APC to Belgian Normalization at 20% Depth | | | | |
| o Echoram | 4.52 | | 2.95 | |
| o Laborelec | 4.28 | | 3.61 | |
| 4 TW 1.25 mm Holes (U.S. Standard) | | | | |
| Echoram | 2.00 | 18.52 | 2.00 | 11.10 |
| Laborelec | 2.01 | 18.77 | 2.00 | 13.11 |
| Ratio APC to Belgian Normalization at 100% Depth | | | | |
| o Echoram | 9.26 | | 5.55 | |
| o Laborelec | 9.34 | | 6.56 | |
| o Ratio applied in Catawba-1 Evaluation | -4.93*1.5=7.4 | | | |

Notes: 1) Normalized to 2.0 volts for 4-TW 1.25 mm holes.
2) Normalized to 2.75 volts for 4-20% ASME drilled holes (APC Calibration).

Table 5-8

## VOLTAGE COMPARISON FOR THE LIFE OF A PROBE

S/G C-INLET

Probe S/N 0144619, same probe from tape001 to 014.
Probe type .610 M/ULC
ASME Std. S/N 050415

Calibration setup IAW RESIZE guidelines. Voltage normalized at 2.75 P/P on 20% FBH's on 550/130 mix at tape001.cal01 and not changed for measurements taken for the life of the probe.

Approximate number of tubes examined with this probe: 1456

Voltage measurements taken peak-to-peak on 550/130 mix.

| TAPE | CAL#<br>INITIAL-01<br>FINAL-02 | ASME FLAT BOTTOM HOLES | | | | | | ASME 10% OD GROOVE | ASME 20% ID GROOVE |
|---|---|---|---|---|---|---|---|---|---|
| | | 100% | 80% | 60% | 40% | 4 X 20% | 4 X 100% | | |
| 001 | 01-1st pull<br>01-2nd pull<br>01-3rd pull | 4.68<br>4.60<br>4.57 | 5.13 | 4.29 | 3.02 | 2.74<br>2.75<br>2.75 | 4.66<br>4.69<br>4.61 | 4.52 | 86.02 |
| 001 | 02 | 4.59 | 5.04 | 4.33 | 3.06 | 2.79 | 4.47 | | |
| 005 | 01<br>02 | 4.36<br>4.32 | 4.95<br>4.84 | 4.04<br>4.12 | 3.01<br>2.90 | 2.90<br>2.87 | 4.77<br>4.61 | | |
| 009 | 01<br>02 | 4.36<br>4.56 | 4.85<br>5.14 | 4.23<br>4.36 | 2.98<br>3.10 | 2.86<br>2.87 | 4.72<br>4.81 | | |
| 014 | 01 | 4.09 | 4.52 | 3.83 | 2.80 | 2.95 | 4.90 | | |
| 014 | 02-1st pull<br>02-2nd pull<br>02-3rd pull | 3.92<br>3.90<br>3.88 | 4.50 | 3.80 | 2.77 | 3.05<br>3.00<br>2.90 | 4.82<br>4.86<br>4.87 | 4.52 | 84.07 |
| | | Circumferentially Assymetrical | | | | Circumferentially Symetrical | | | |

Table 5-9

Summary of Catawba-1 EC Uncertainty

| | Analyst Variability | Probe Wear | RMS Average |
|---|---|---|---|
| **Preliminary Estimate** | | | |
| Distribution for Monte Carlo | Cum. Prob. in % Columns 2 and 3 of Table 5-10 | Normal Distr. mean=0,r=10% | Apply separate distributions |
| Value at 90% Cum.Prob. | 10% | 13% (1.28r) | 16% |
| Value at 99% Cum.Prob. | 34% | 23% (2.33r) | 41% |
| **Final Estimate** | | | |
| Distribution for Monte Carlo | Cum. Prob. in % Columns 2 and 4 of Table 5-10 | Normal Distr. mean=0,r=16% | Apply separate distributions |
| Value at 90% Cum.Prob. | 10% | 20% (1.28r) | 22% |
| Value at 99% Cum.Prob. | 20% | 37% (2.33r) | 42% |

Table 5-10

**Cumulative Probability for EC Analyst Variability**

| Voltage Bin | % Uncertainty for Voltage Bin[1] | Percent Cumulative Probability Preliminary | Final |
|---|---|---|---|
| -1.0 | -71 | 0.11 | |
| -1.00 to -.75 | -53 | 0.39 | |
| -0.75 to -0.50 | -35 | 0.93 | |
| | -20 | | 0.00 |
| -0.50 to -0.25 | -18 | 3.94 | 3.94 |
| -0.25 to -0.20 | -14 | 5.49 | 5.49 |
| -0.20 to -0.15 | -11 | 8.56 | 8.56 |
| -0.15 to -0.10 | -7.1 | 12.6 | 12.6 |
| -0.10 to -0.05 | -3.5 | 21.6 | 21.6 |
| -0.05 to 0.00 | 0.0 | 48.3 | 48.3 |
| 0.00 to 0.05 | 3.5 | 75.3 | 75.3 |
| 0.05 to 0.10 | 7.1 | 86.9 | 86.9 |
| 0.10 to 0.15 | 11 | 91.8 | 91.8 |
| 0.15 to 0.20 | 14 | 95.1 | 95.1 |
| 0.20 to 0.25 | 18 | 97.2 | 97.2 |
| | 20 | | 100.0 |
| .25 to 0.50 | 35 | 99.2 | |
| 0.50 to 0.75 | 53 | 99.8 | |
| 0.75 to 1.00 | 71 | 99.97 | |
| 1.00 to 1.30 | 92 | 100.0 | |

Note 1: % Uncertainty obtained as mid-voltage value for each bin divided by mean voltage of 1.41 volts from Figure 5-2.

Figure 5-1

Bobbin Coil Voltage Dependence on Slot Length and Depth - 0.75" Tubing

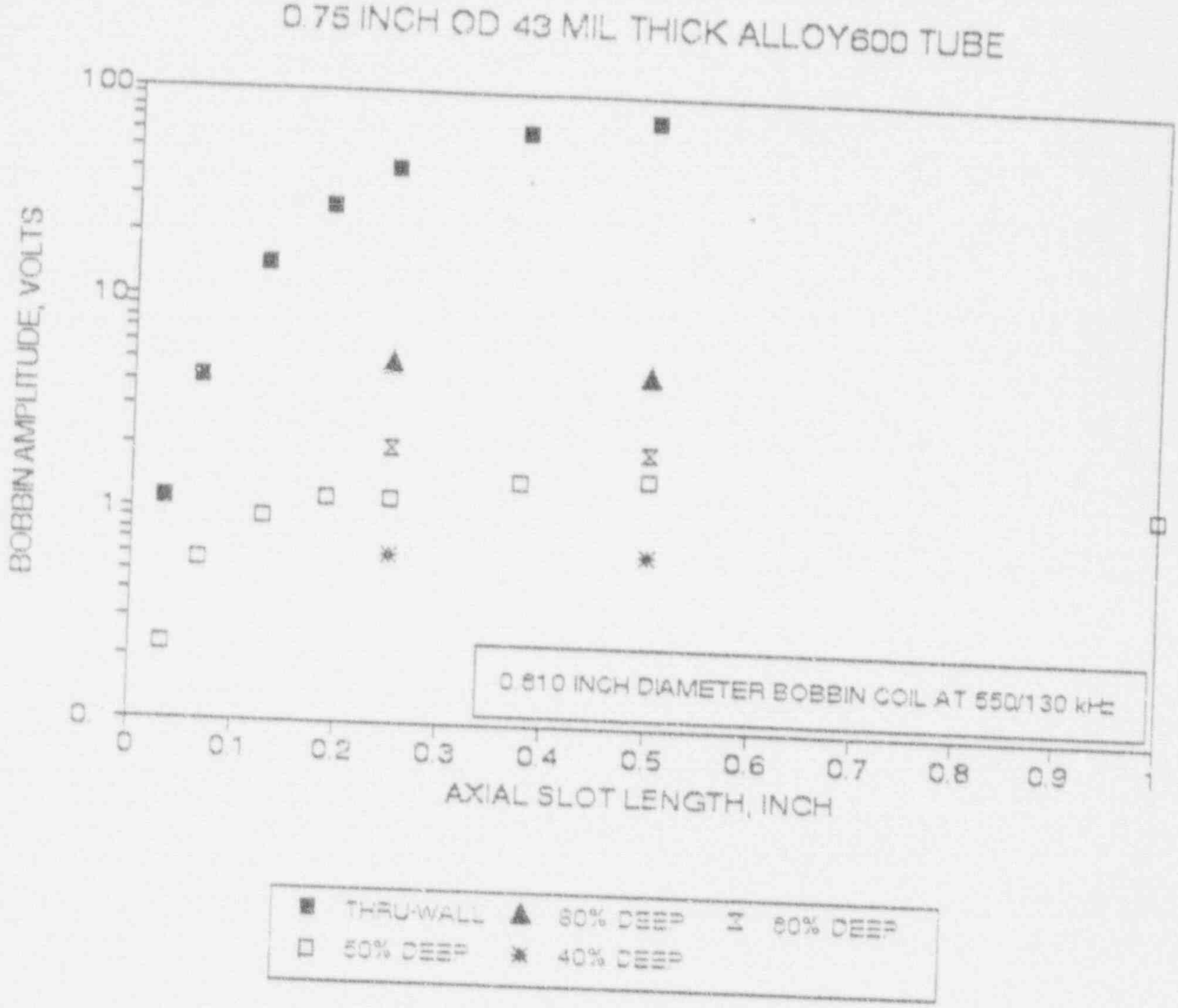


Figure 5-2

Bobbin Coil Voltage Dependence on Slot Length and Depth - 0.875" Tubing

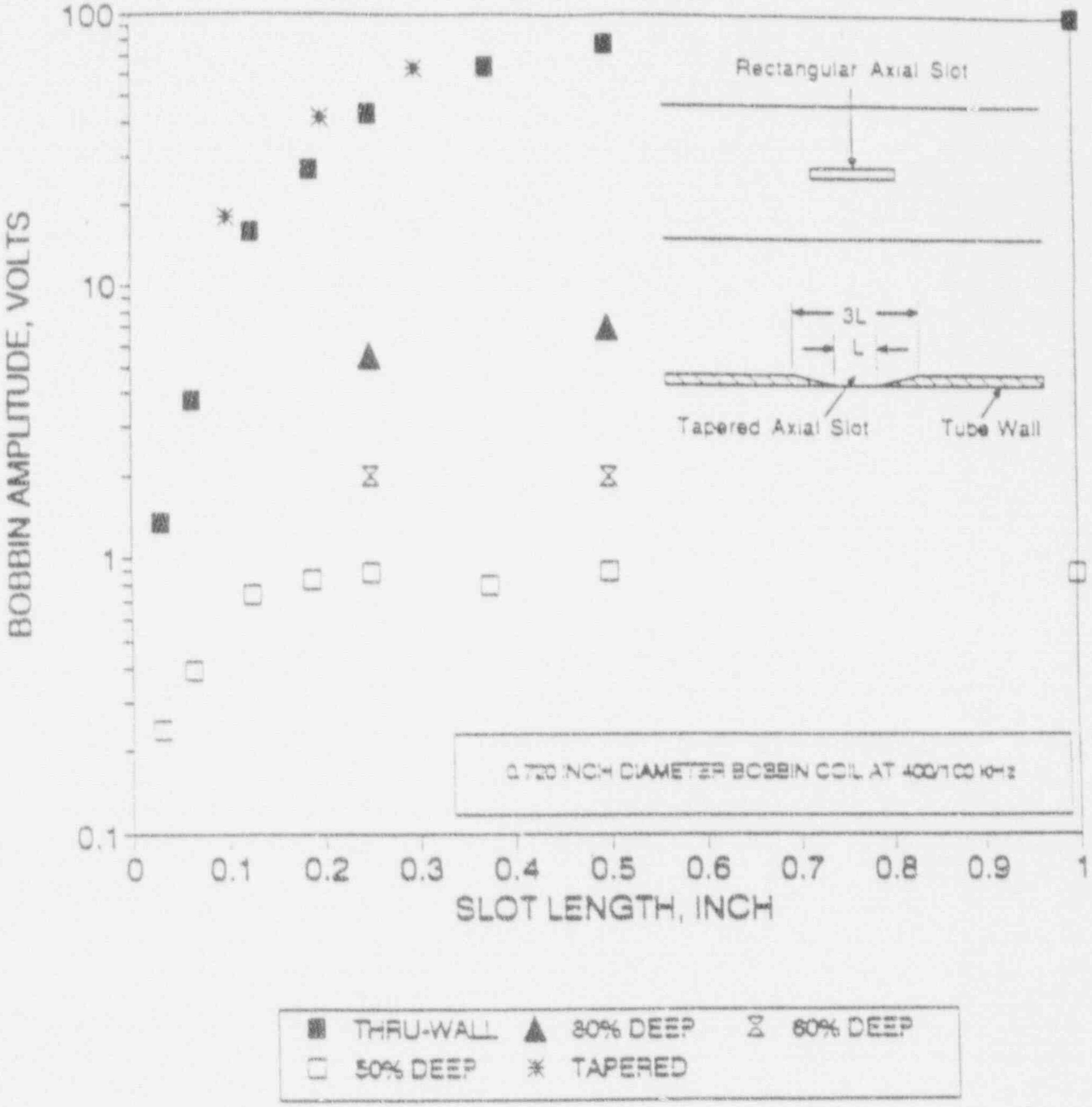


Figure 5-3

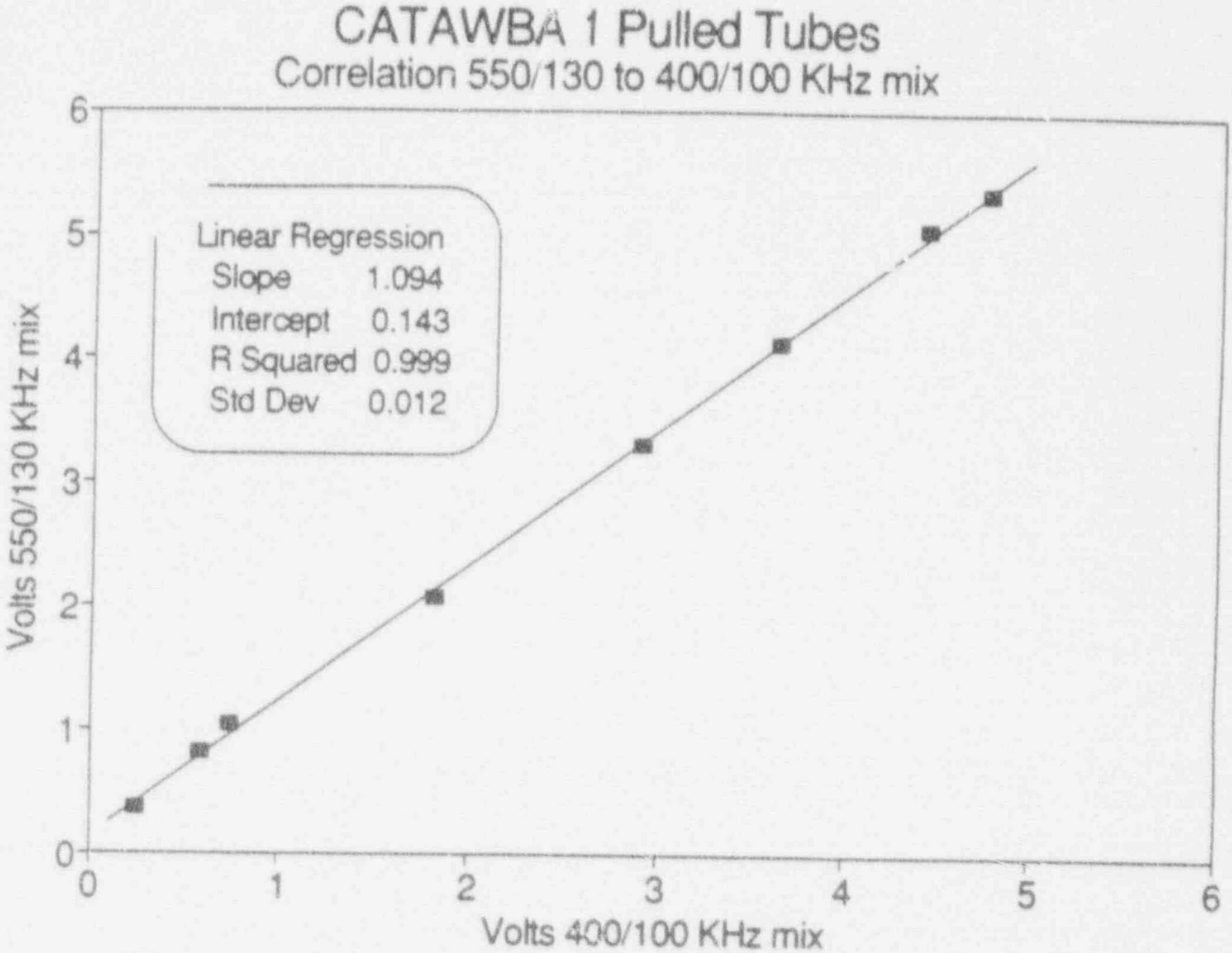

CATAWBA 1 Pulled Tubes
Correlation 550/130 to 400/100 KHz mix
Linear Regression
Slope 1.094
Intercept 0.143
R Squared 0.999
Std Dev 0.012
Volts 550/130 KHz mix
Volts 400/100 KHz mix
0
1
2
3
4
5
6

Figure 5-4

Signal Amplitudes at 550/130 and 400/130 kHz for Catawba-1 TSP Indications (1992)

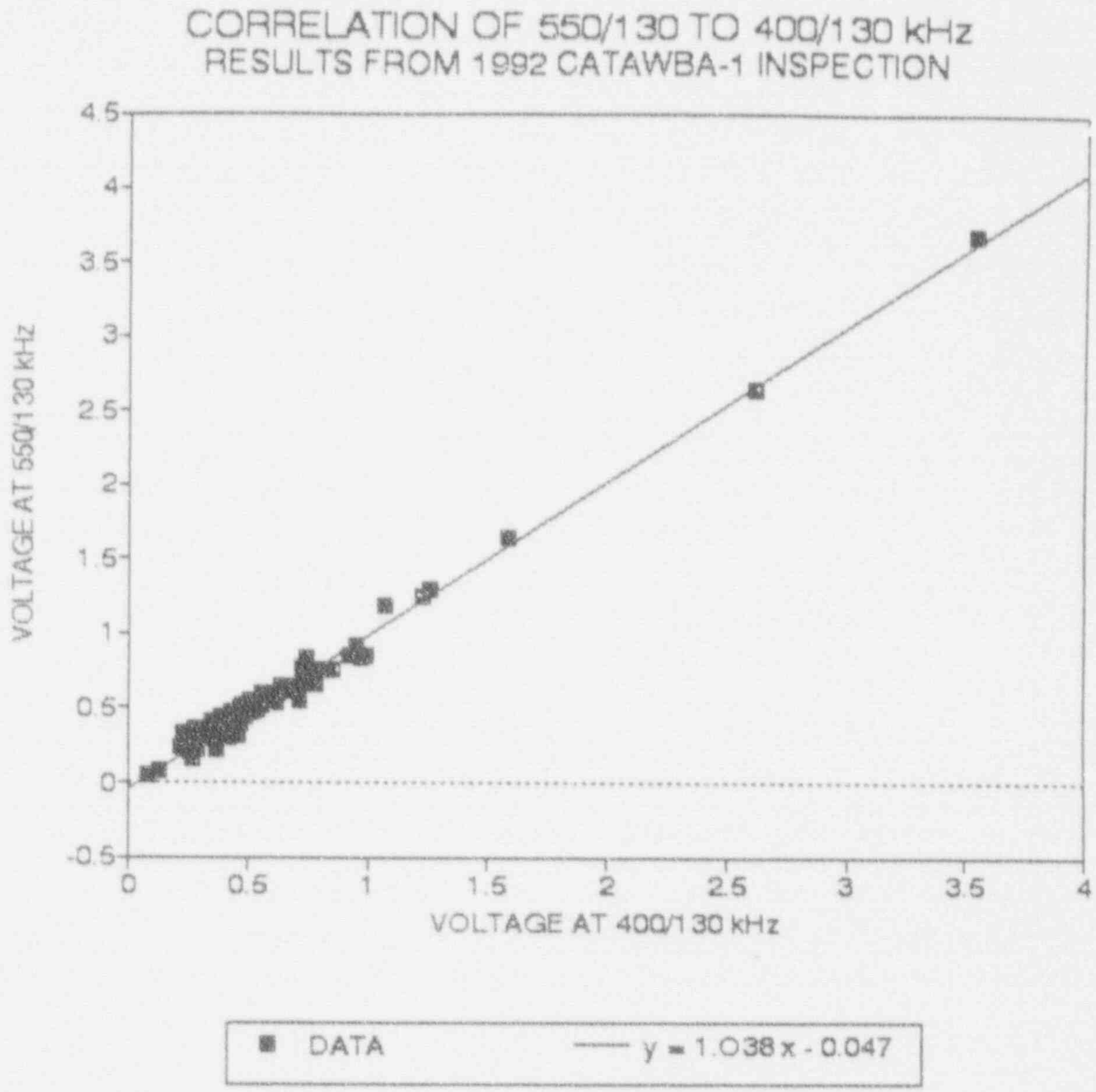
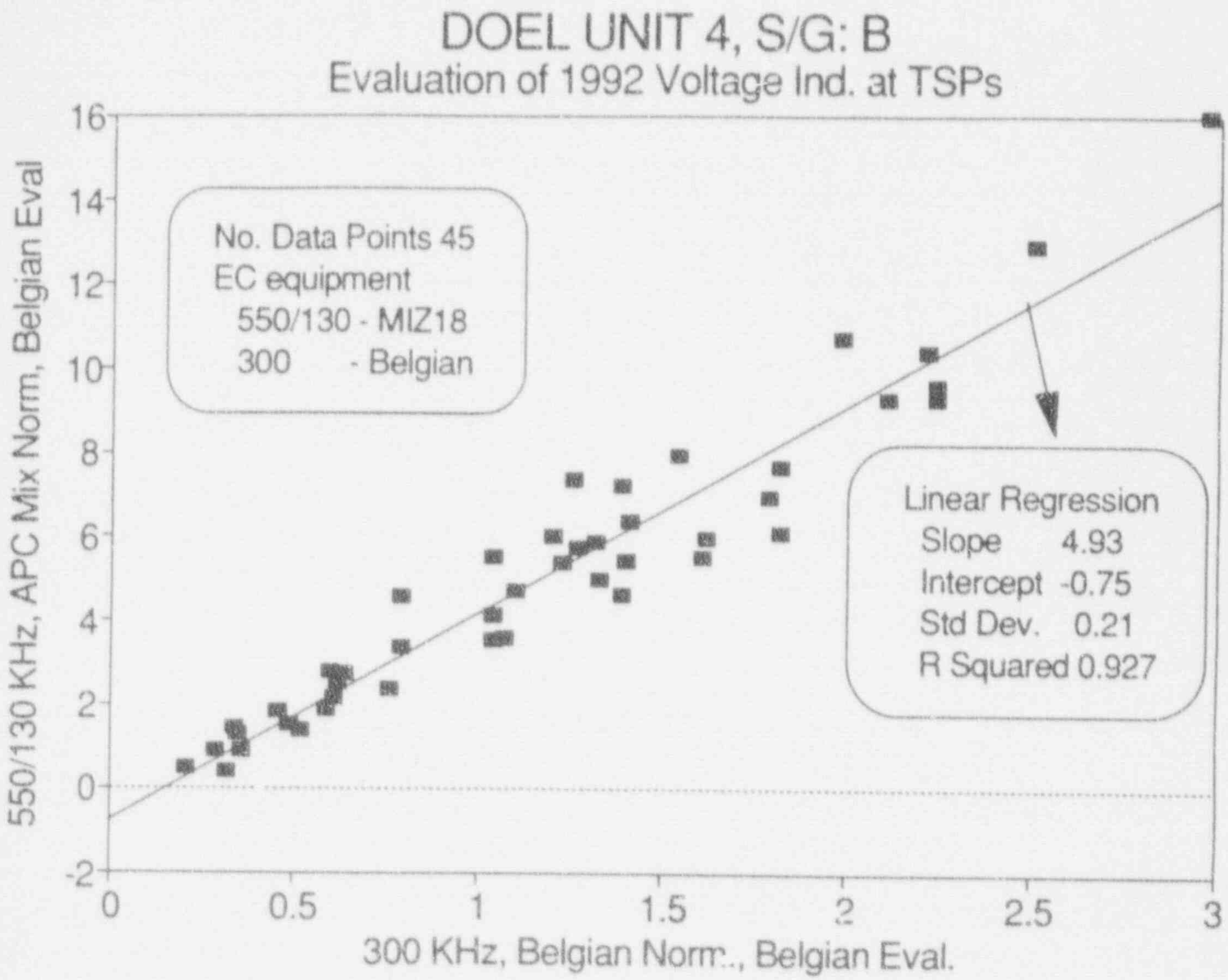


Figure 5-5



DOEL UNIT 4, S/G: B
Evaluation of 1992 Voltage Ind. at TSPs
No. Data Points 45
EC equipment
550/130 - MIZ18
300 - Belgian
Linear Regression
Slope 4.93
Intercept -0.75
Std Dev. 0.21
R Squared 0.927
550/130 KHz, APC Mix Norm, Belgian Eval
300 KHz, Belgian Norm., Belgian Eval.
16
14
12
10
8
6
4
2
0
-2
0
0.5
1
1.5
2
2.5
3

Figure 5-6

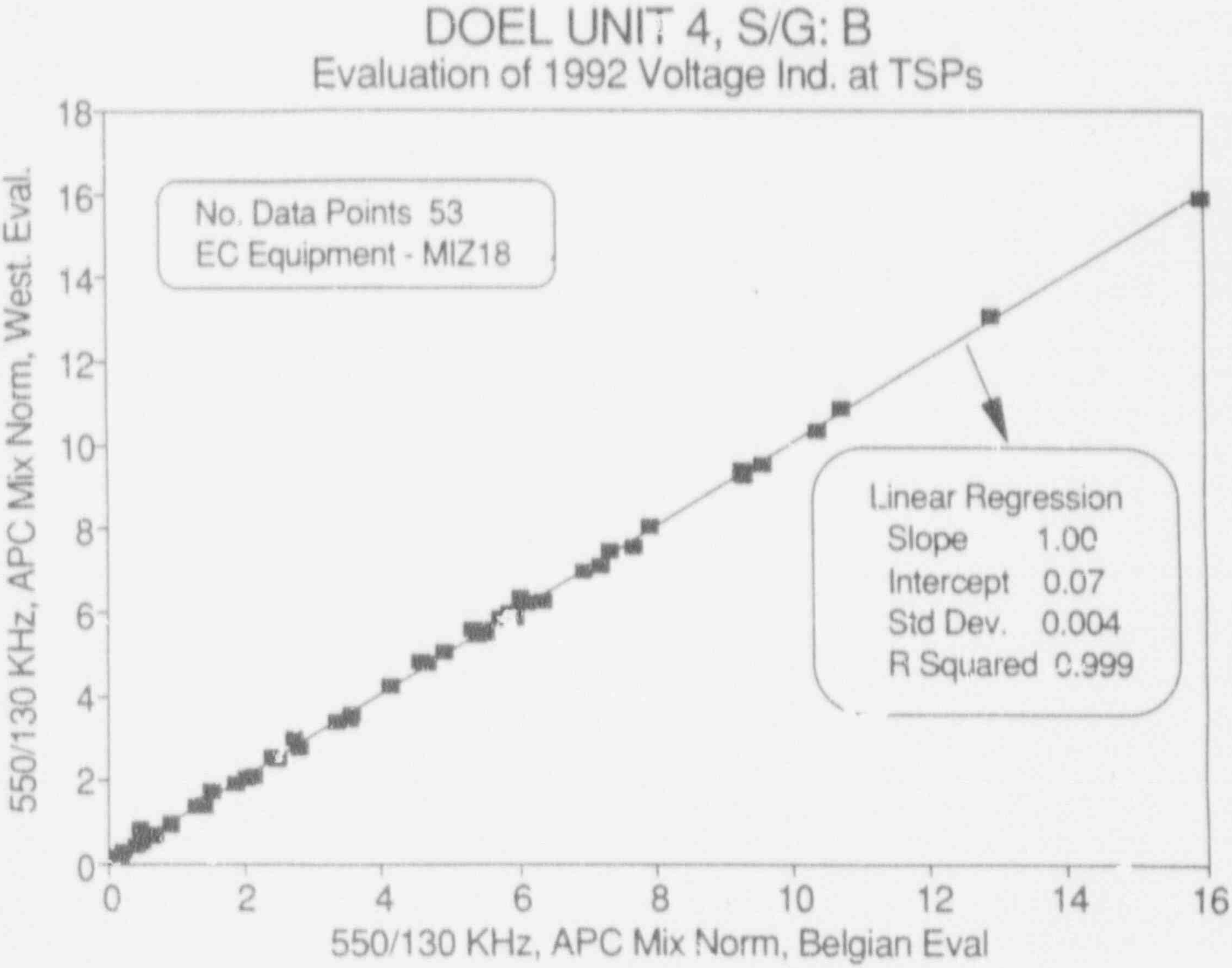

DOEL UNIT 4, S/G: B
Evaluation of 1992 Voltage Ind. at TSPs
No. Data Points 53
EC Equipment - MIZ18
Linear Regression
Slope 1.00
Intercept 0.07
Std Dev. 0.004
R Squared 0.999
550/130 KHz, APC Mix Norm, West. Eval.
550/130 KHz, APC Mix Norm, Belgian Eval
0
2
4
6
8
10
12
14
16
18

Figure 5-7

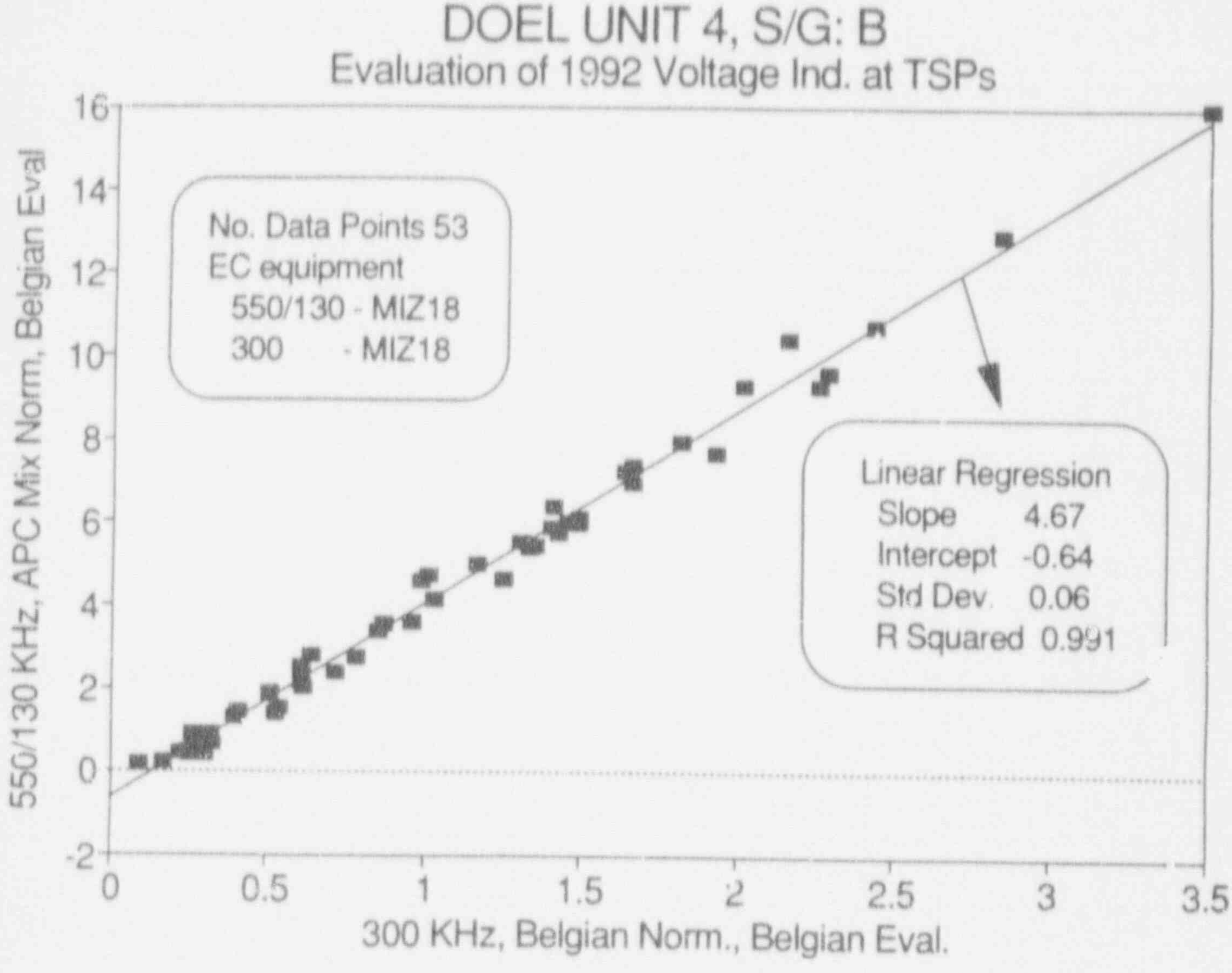

DOEL UNIT 4, S/G: B
Evaluation of 1992 Voltage Ind. at TSPs
No. Data Points 53
EC equipment
550/130 - MIZ18
300 - MIZ18
Linear Regression
Slope 4.67
Intercept -0.64
Std Dev. 0.06
R Squared 0.991
550/130 KHz, APC Mix Norm, Belgian Eval
300 KHz, Belgian Norm., Belgian Eval.
16
14
12
10
8
6
4
2
0
-2
0
0.5
1
1.5
2
2.5
3
3.5

Figure 5-8

Distribution of Voltage Indications Used for EC Analyst Variability Evaluation

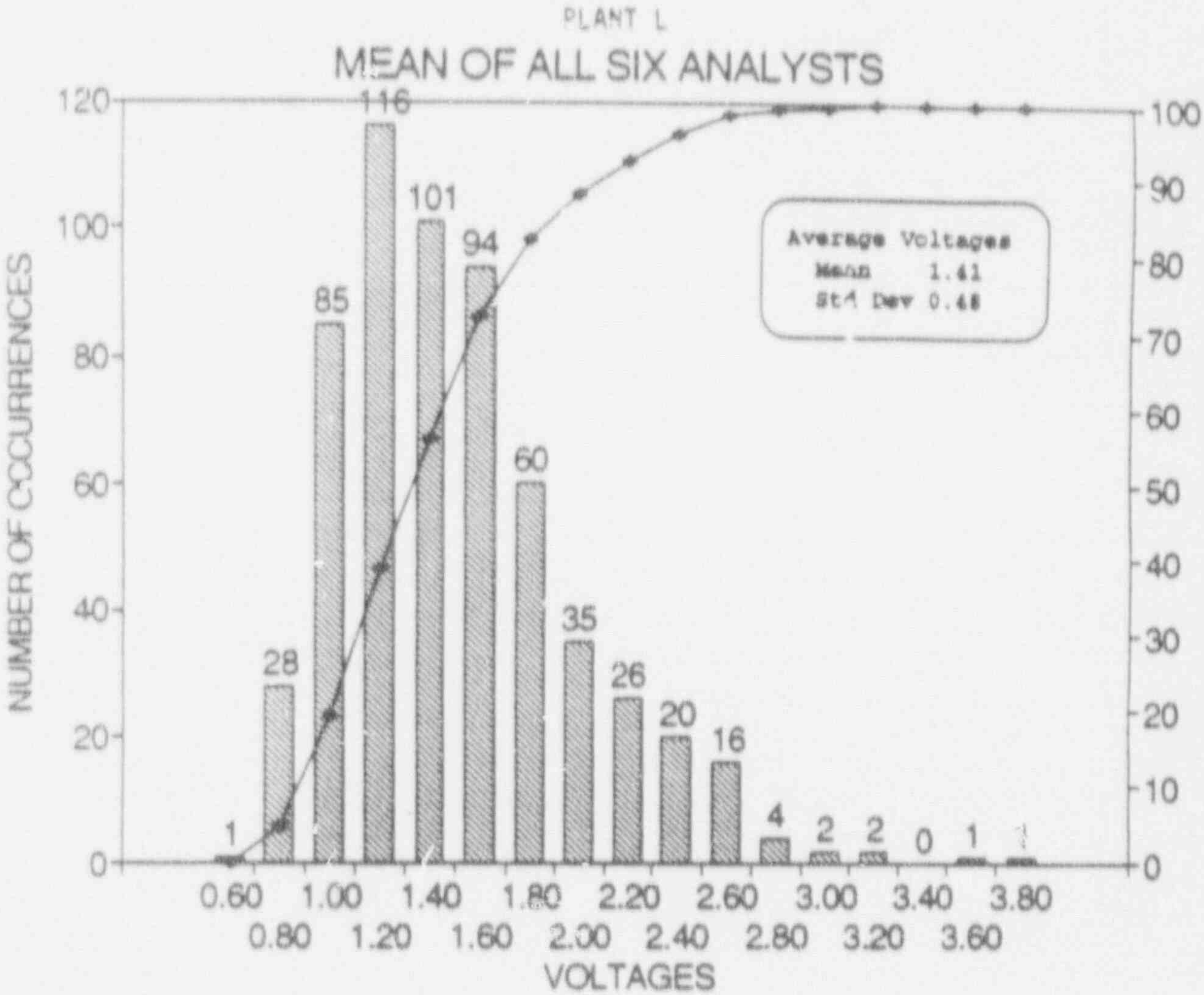


Figure 5-9

Distribution of Voltage Differences Between Individual Analysts and Mean Values

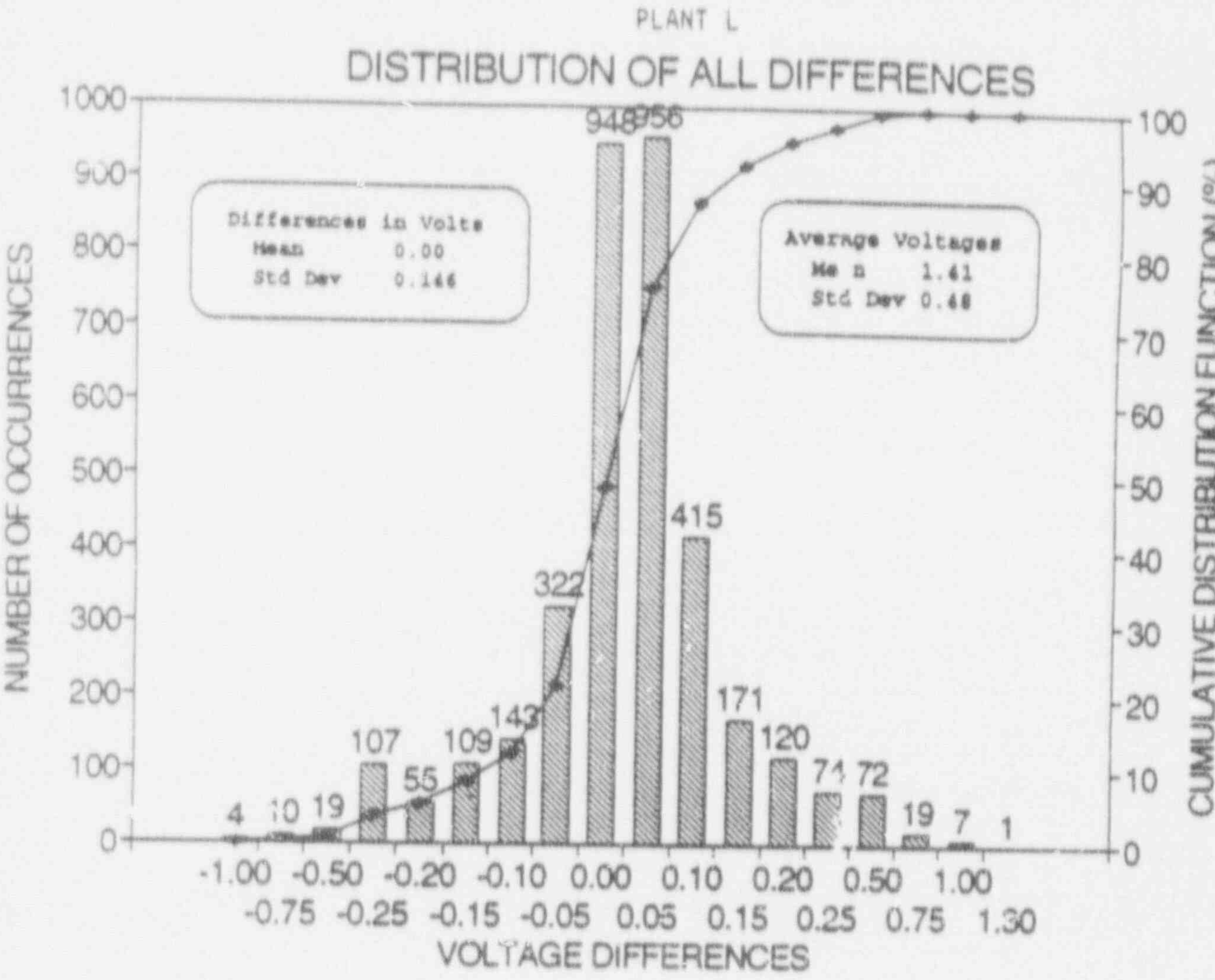


Figure 5-10

Catawba-1 EC Analyst Variability: Comparison of Voltage Differences Between Resolution Process and Single Analyst

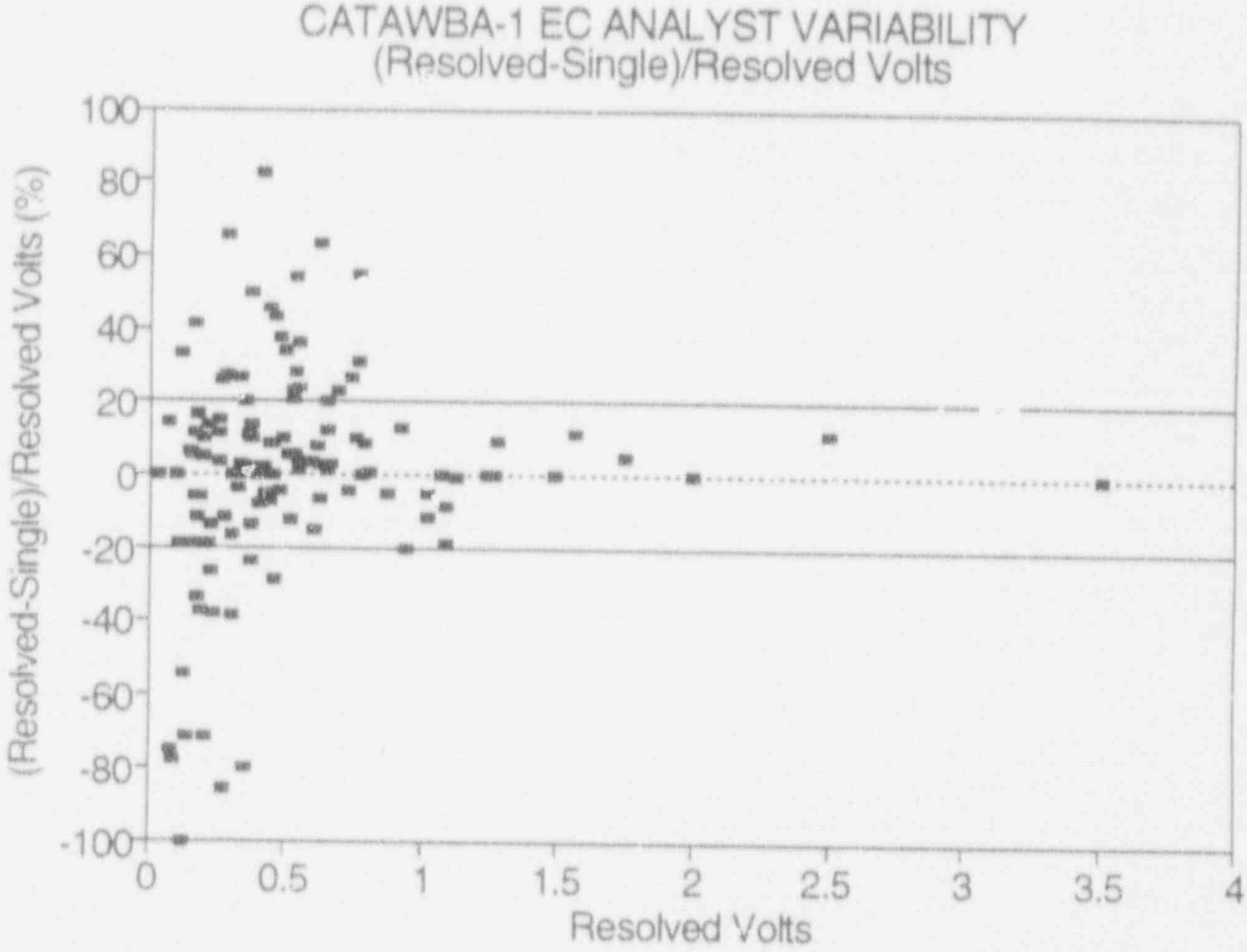
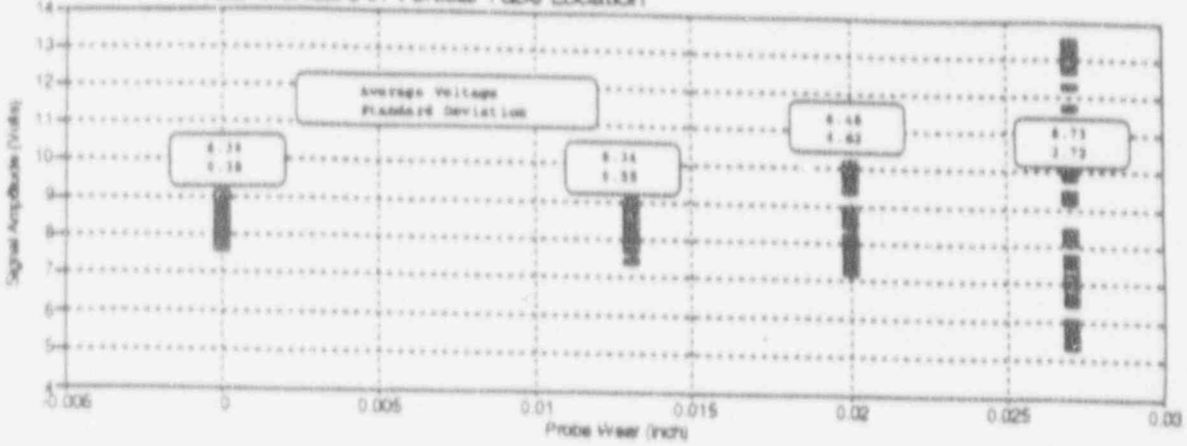


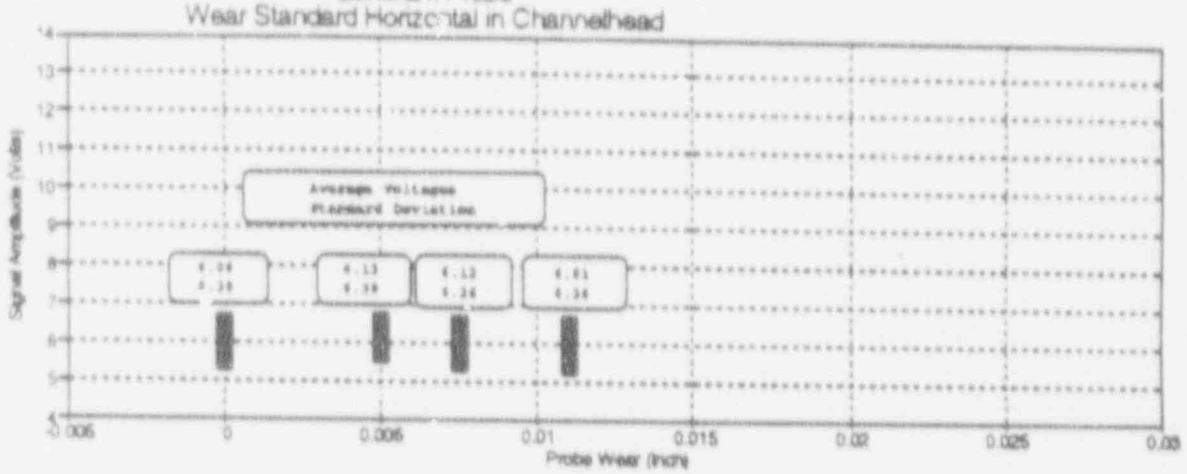
Figure 5-11

Bobbin Coil Amplitude Dependence on Probe Wear

Echoram Probe
Wear Standard in Vertical Tube Location




Echoram Probe
Wear Standard Horizontal in Channelhead




Zetec Probe
Wear Standard Horizontal in Channelhead

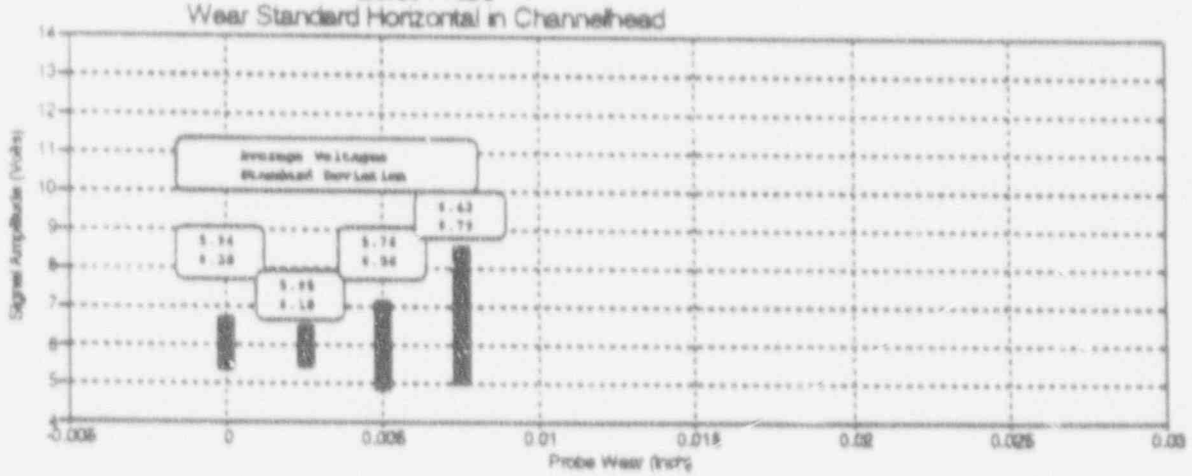


Figure 5-12

Voltage Variability Due to Bobbin Probe Wear

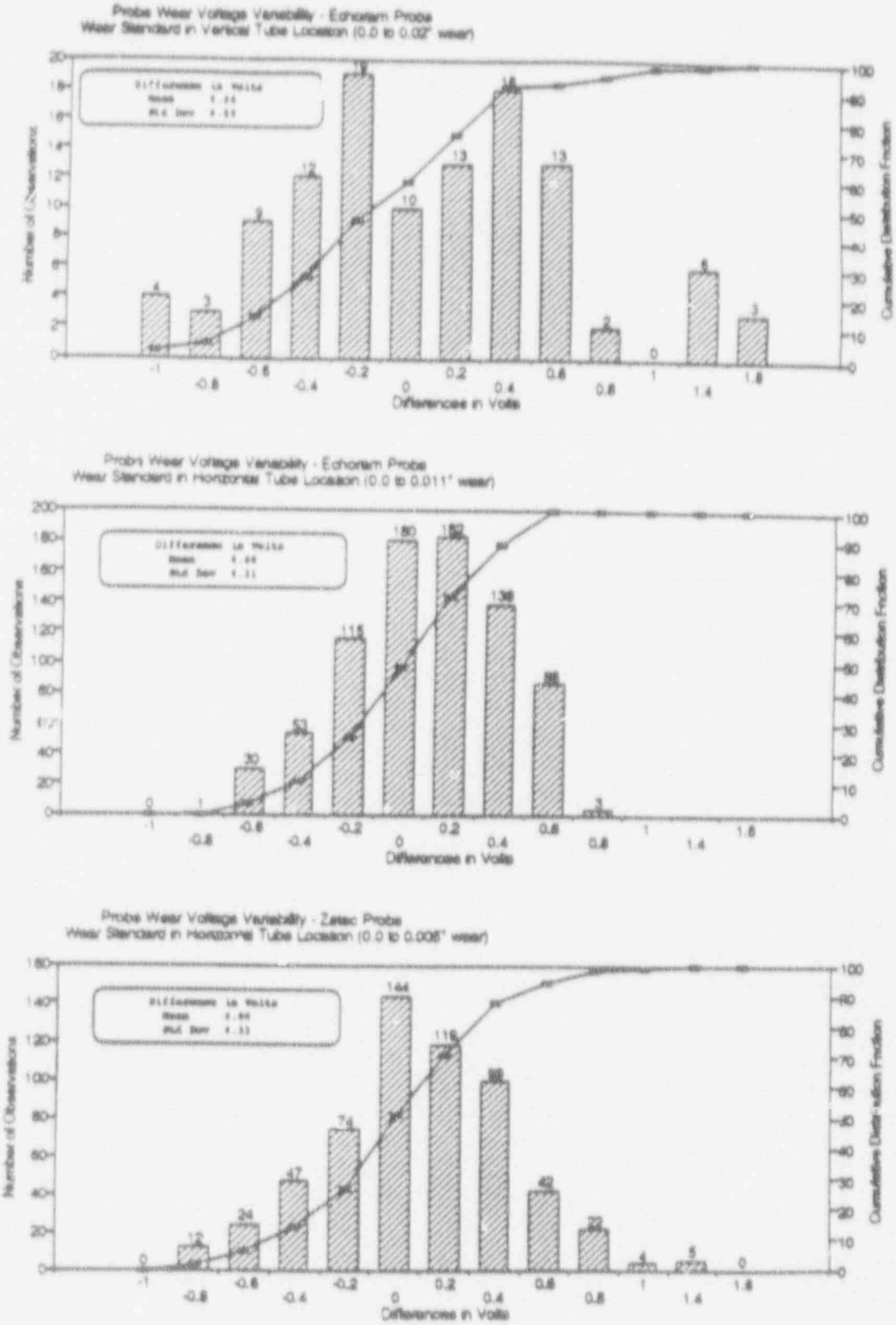
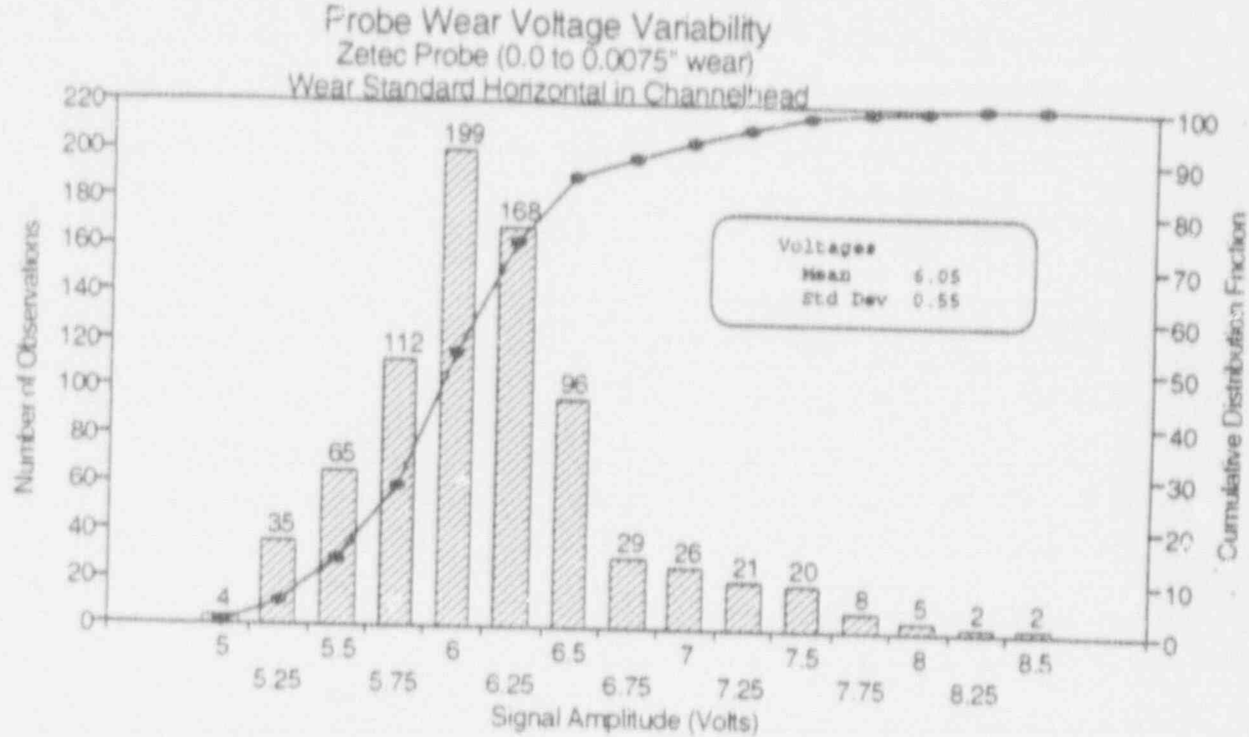


Figure 5-13


Probe Wear Voltage Variability
Zetec Probe (0.0 to 0.0075" wear)
Wear Standard Horizontal in Channelhead
Voltages
Mean 6.05
Std Dev 0.55
Number of Observations
Cumulative Distribution Fraction
Signal Amplitude (Volts)

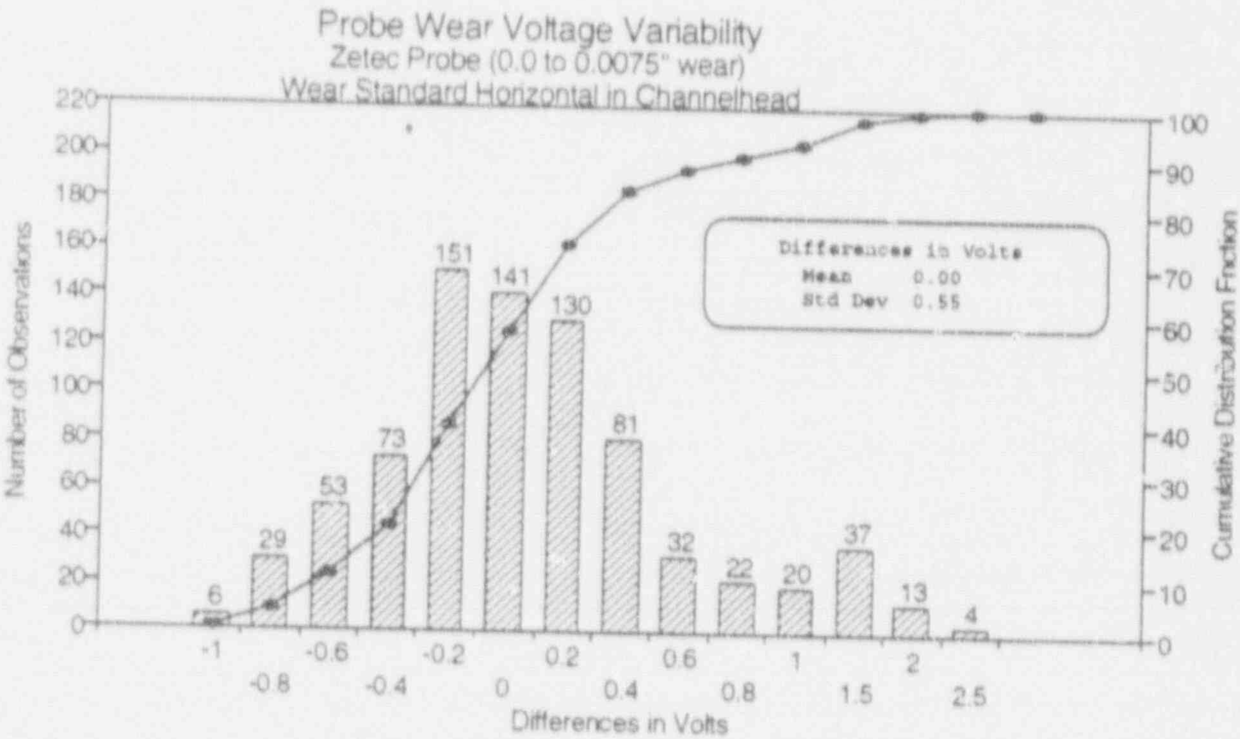
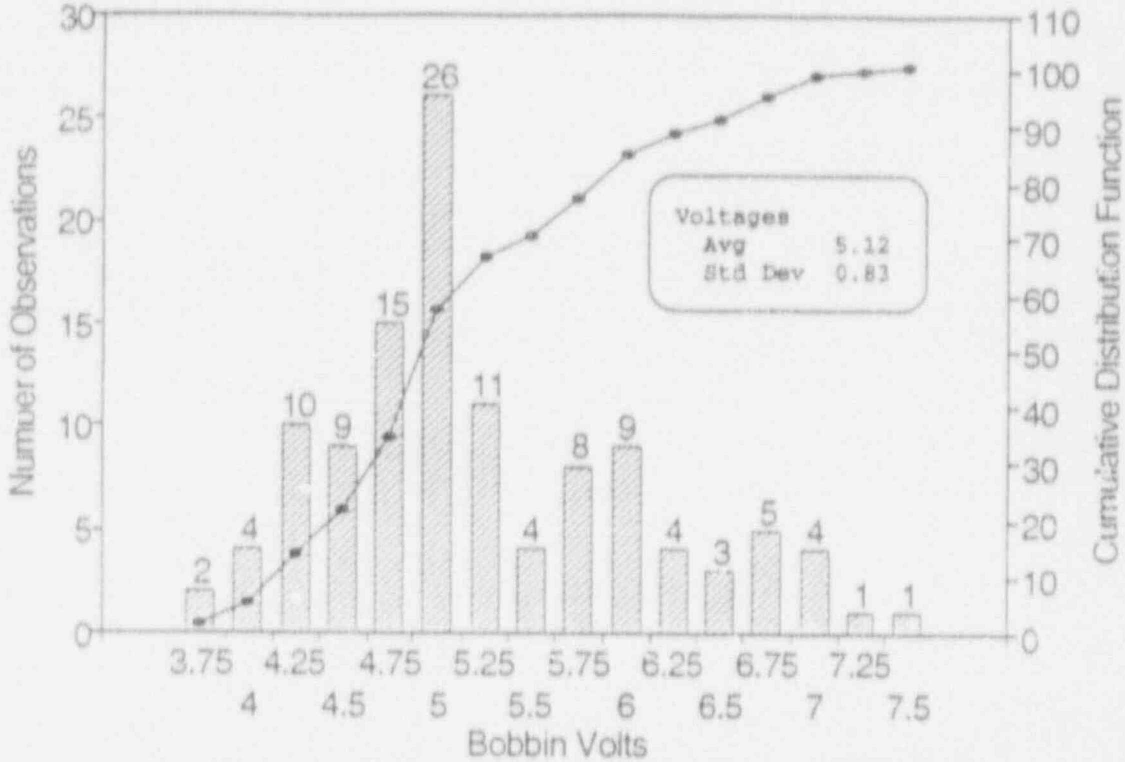

Probe Wear Voltage Variability
Zetec Probe (0.0 to 0.0075" wear)
Wear Standard Horizontal in Channelhead
Differences in Volts
Mean 0.00
Std Dev 0.55
Number of Observations
Cumulative Distribution Fraction
Differences in Volts

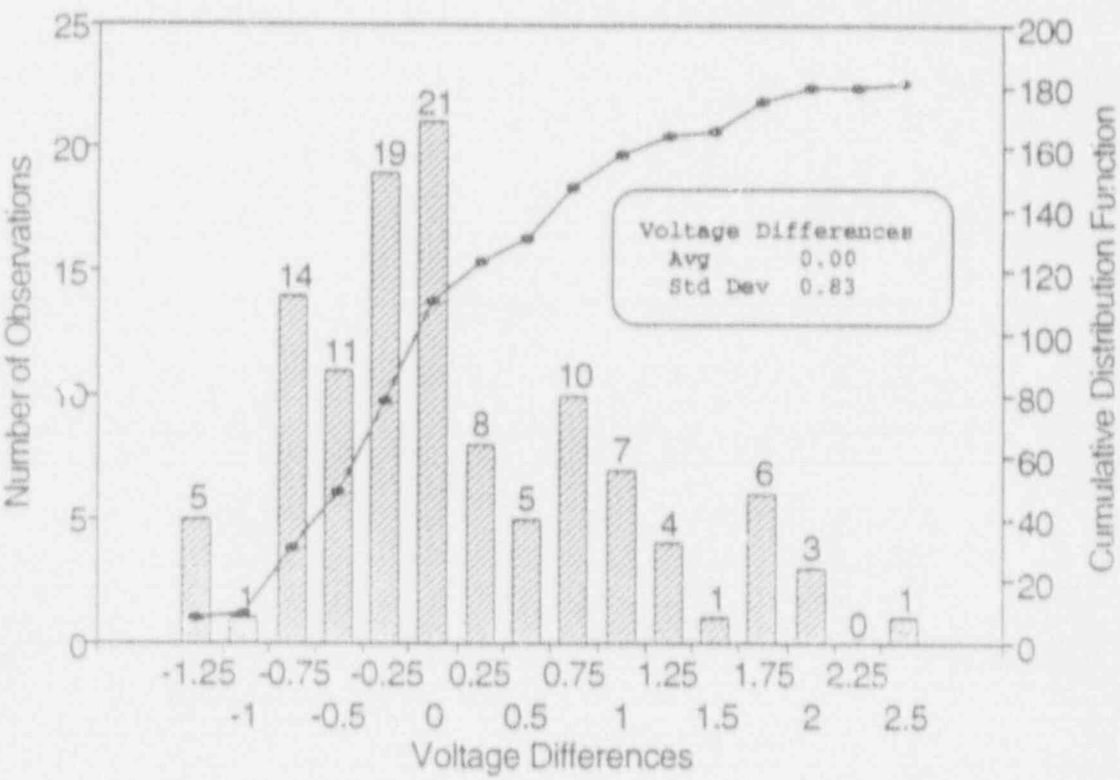
Figure 5-14

CATAWBA-1 PROBE WEAR DATA

Volts for ASME Hole over Probe Life




Voltage Differences from Mean for 100% ASME Hole



Section 6

# PULLED TUBE AND FIELD DATA EVALUATION

This section identifies the field experience data from operating steam generators that are utilized in the development of tube plugging criteria for ODSCC at TSPs. The field data utilized include pulled tube examination results including tubes pulled from Catawba Unit 1 during 1991 and occurrences of tube leakage for ODSCC indications at support plates. Emphasis for the pulled tube data are placed on bobbin coil voltages, burst pressures and leak rate measurements.

## 6.1 Utilization of Field Data in Tube Repair Limits

Operating steam generator experience represents the preferred source of data for the plugging criteria. Since the available operating data are insufficient to fully define plugging criteria, data developed from laboratory induced ODSCC specimens are used to supplement the field data base. The field data utilized for the plugging criteria are identified in this section.

The overall approach to the tube plugging criteria is based upon establishing that R.G. 1.121 guidelines are satisfied. It is conservatively assumed that the tube to TSP crevices are open and that the TSPs are displaced under accident conditions such that the ODSCC generated within the TSPs becomes free span degradation under accident conditions. Under these assumptions, preventing excessive leakage and tube burst under SLB conditions is required for plant operability. Tube rupture under normal operating conditions is prevented by the constraint provided by the drilled hole TSPs with small tube to TSP clearances (typically ~16 mil diametral clearance for open crevices). For the plugging criteria, however, the R.G. 1.121 guidelines for burst margins of 3 times normal operating pressure differentials are applied to define the structural requirements against tube rupture.

In addition to providing margins against tube burst, it is necessary to limit SLB leakage to acceptable levels based on FSAR evaluations for radiological consequences under accident conditions. Thus SLB leakage models are required for the plugging criteria in addition to tube burst data.

Based on the above considerations and the plugging criteria objective of relating tube integrity to NDE measurements, the primary data requirements for the plugging criteria are the correlation of burst pressure capability and SLB leak rates with bobbin coil voltage. For plant operational considerations, it is desirable to minimize the potential for operating leakage to avoid forced outages. The field data of this section indicate very low leakage potential for ODSCC at TSPs even at voltage amplitudes much higher than the plugging limits.

## 6.2 Summary of Pulled Tube Data Base

The available pulled tube data base for ODSCC at TSPs in Westinghouse steam generators is summarized in Table 6-1 for both 3/4 and 7/8 inch diameter tubing. The number of 7/8 inch pulled tubes is provided as a general comparison with the 3/4 inch data and is not utilized in the 3/4 inch evaluation of this report. Both tubing sizes have a comparable number of pulled tube intersections although the 7/8 inch tubing has more tube burst data. This group includes five tubes from Catawba-1 with nine intersections destructively examined. None of the pulled tubes

have been reported as leakers during plant operation. The field eddy current data for all pulled tubes were reviewed for voltage normalization consistent with the standard adopted (see Section 5.1) for the plugging criteria development.

Operating plant leakage experience for ODSCC at TSPs is summarized in Section 6.3. Evaluations of the 3/4 inch diameter, pulled tube burst and leak rate data are given in Sections 6.6 to 6.8. The Catawba-1 burst and leak rate data are evaluated in Section 6.6. It is shown that three of the nine Catawba-1 burst tests did not result in sufficient opening of the cracks and the burst pressures are not considered reliable. In addition, two intersections burst outside the TSP at hand ground location marks and thus also are not reliable data. The remaining four Catawba-1 burst tests are found to require some adjustments to the measured burst pressures as described in Section 6.6. It is also found that the one Catawba-1 intersection found to leak at normal operating and SLB conditions in the laboratory most likely resulted in throughwall penetration of the 97% deep corrosion crack during the tube pulling operation and thus does not provide a representative leak rate for including in the data base.

## 6.3 Operating Plant Leakage Data for ODSCC at TSPs

Table 6-2 summarizes the available information on three suspected tube leaks (3/4 inch tubing) attributable to ODSCC at TSPs in operating steam generators. These leakers occurred in European plants with two of the suspected leakers occurring at one plant in the same operating cycle. In the latter case, five tubes including the two with indications at TSPs were suspected of contributing to the operating leakage. Leakage for the two indications at TSPs was obtained by a fluorescein leak test as no dripping was detected at 500 psi secondary side pressure.

For the Plant B-1 leakage indication, other tubes also contributed to the approximately 63 gpd total leak rate. Helium leak tests identified other tubes leaking due to PWSCC indications. Using relative helium leak rates as a guide, it was judged that the leak rate for the ODSCC indication was less than 10 gpd. These leakage events indicate that limited leakage can occur for indications above about 6.2 volts. No leakage at Catawba-1 has been found that could be attributable to ODSCC at TSPs.

## 6.4 Voltage Renormalization for Alternate Calibrations

To increase the supporting data base, it is necessary to renormalize available data to the calibration values used in this report. For data on 3/4 inch diameter tubing, voltage renormalization has been obtained by applying a normalization for the ASME 20% holes of 4.0 volts in the 550 kHz channel and 2.75 volts in the 550/100 kHz mix. The APC voltage normalization and data analysis guidelines have been discussed in Sections 5.1 and 5.2. The voltage renormalization for the Catawba-1 and Belgian pulled tubes are described in Sections 5.6 and 5.7. The Catawba-1 renormalization from 400/100 kHz mix to the 550/130 kHz mix was obtained from post-pull laboratory measurements and is shown in Figure 5-3. The Belgian renormalization was obtained by direct measurements of field indications as shown in Figure 5-4. As discussed in Section 5.7, the Belgian voltages have been increased by a 1.5 factor pending completion of further Laborelec studies of the voltage renormalization to the APC guidelines.

## 6.5 Tensile Property Considerations

The 3/4 inch diameter model boiler specimens have above average tensile properties while the pulled tube data have both higher and lower tensile properties than average values. The tensile property differences between model boiler and pulled tube data are greater for 3/4 inch tubing than found for 7/8 inch tubing. The 3/4 inch model boiler tubing had above average (6%) material properties while the 7/8 inch model boiler tubing had properties slightly below average. For the 3/4 inch tubing APC development, all model boiler and pulled tube burst pressure data are renormalized to average tensile properties for 3/4 inch tubing as described in this section.

Tubing manufacturing data have been utilized to develop mean tensile properties together with the standard deviation and lower 95% tolerance limit at room temperature and 650 °F. These data are given in Table 6-3. Also given in the table are the values for (Sy + Su). The mean (Sy + Su) value of 154 ksi (twice the flow stress) at room temperature (WCAP-12522) is used to normalize the measured burst pressures for the model boiler and pulled tube data. The ratio of the 95/95 Lower Tolerance Limit (LTL) flow stress at 650 °F to the mean flow stress at room temperature is utilized to adjust the voltage/burst correlation obtained at room temperature to obtain the operating temperature LTL correlation. This ratio is 0.848.

Table 6-3 also includes the tensile properties for the 3/4 inch model boiler specimens and for each of the available pulled tubes. Since burst pressures are proportional to the flow stress, the measured burst pressures are normalized to mean properties by the ratio of the tubing mean (Sy + Su) of 154 ksi (flow stress of 77 ksi) at room temperature to the tube specific (Sy + Su) given in Table 6-3.

## 6.6 Evaluation of Catawba-1 Pulled Tubes

This section describes an evaluation of the Catawba-1 pulled tube burst test and leak rate measurements. The burst test data are evaluated to assess whether the measured pressures are representative of a burst or a more limited crack opening causing leakage. A completed burst test is characterized by fishmouth opening of the crack, bulging of the tube and/or tearing at the edges of the corrosion crack. In general, the burst test opens up the entire macrocrack length or a very large fraction of the crack length. It is shown below that three of the Catawba-1 burst tests resulted in minor crack opening such that the resulting pressures do not represent a burst test. The bobbin voltages for the Catawba-1 tubes are discussed in Section 5.6. The first four columns of Table 6-4 provide the tube locations, bobbin volts and measured burst pressures. Column five provides the flow stress adjustment factor for adjusting the burst pressures to average material properties as developed in Table 6-3. The following evaluations form the basis for the adjusted burst pressure column of Table 6-4.

<u>Tube R5C112, TSP3</u>

Catawba-1 pulled tube R5C112, TSP-3 had a field bobbin voltage indication of 1.82 volts and a post-pull bobbin voltage of 5.06 volts. By destructive exam, the maximum corrosion depth (at 1 of 23 axial grinds) was 97%. In the laboratory, the indication was found to leak at about 500 psi while pressurizing for a burst test. The tube section was then leak tested at prototypic conditions before further burst testing and found to have leak rates of 0.078 and 0.56 l/hr. at normal operating and SLB pressure differential, respectively. A bladder was then inserted to

continue burst testing. The "burst" pressure measured was 4,150 psi. A burst pressure of this magnitude would be associated with a uniformly throughwall crack size of about 0.45 inch length. This section evaluates the destructive examination data to assess the likelihood of the low burst pressure and whether the leakage was due to tearing of the crack to throughwall during tube removal operations or during leak testing.

Figures 6-1, 6-2 and 6-3 show, respectively, the post-burst test crack, a map of OD crack indications and the crack depth vs length of the macrocracks that opened during leak and burst testing. Figure 6-3 also shows the location and length (~0.19 inch) of throughwall crack opening following the burst test. From Figure 6-1, it is seen that two post-burst crack openings are separated by a ligament. The lengths of the two throughwall penetrations are about 0.11 inch and 0.08 inch. These lengths are typical of individual crack initiation sites (sometimes called microcracks). From observations of the metallography obtained at the various grind depths of Figure 6-2, the two opened cracks are parts of separate macrocracks with an untorn ligament seen between the opened cracks. Even the end to end opened crack length of about 0.19 inch is much less than the 0.45 inch throughwall crack expected for a burst pressure of 4,150 psi. A completed burst test is characterized by fishmouth opening of the crack and/or tearing at the edges of the corrosion crack. This burst test shows neither of these burst features and did not open up either of the macrocracks. The overall macrocrack length from Figure 6-2 is about 0.43 inch which is less than the 0.45 inch throughwall crack length expected for a 4,150 psi burst pressure. It is concluded that the "burst" test is an incomplete test. It is postulated that a slow pressurization rate permitted the bladder to enter the microcracks as they opened and caused the bladder to tear which terminated the test. The burst test was not repeated at a higher pressurization rate. As a consequence, the "burst" test is not considered reliable and is not included in the voltage/burst correlation data base.

A threefold increase in eddy current bobbin voltage and the appearance of leakage at a pressure of 500 psi in a post-pull test raises questions of damage to tube R5C112 prior to leak rate testing and the suitability of including this leakage data in leak rate - bobbin voltage correlations. The measured crack depth of Figure 6-3, as obtained from the metallography of the successive axial grinds of Figure 6-2, was used to estimate the pressure at which fracture of the remaining crack depth ligaments would be expected. As discussed below, the estimated pressure at which ligament fracture and thus leakage would be expected is many times higher than the observed pressure of 500 psi. This indicates the tube was damaged prior to leak rate testing and should not be included in the general leak rate database. The measured SLB leak rate for this indication of 0.56 liter/hr would be expected to have a throughwall crack length of about 0.1 inch or larger.

Typically, the burst pressure of a cracked steam generator tube is expected to reach the full plastic collapse value. However, very deep cracks with consequently very small remaining ligaments in the depth direction can exhibit ductile tearing prior to reaching the full plastic collapse pressure. For full plastic collapse or burst, the remaining wall thickness ligament spanning the crack faces must be able to stretch without tearing until full plastic collapse of the tube occurs. A ligament which is only a few mils in depth cannot stretch more than a few mils in height. Obviously this situation is exacerbated by long cracks which, if they were throughwall, would open much more than shorter cracks. Thus a small wall thickness ligament may open to leakage prior to bursting of the tube.

A partial throughwall crack can be viewed as a throughwall crack whose opening is opposed by springs, that is, ligaments. For a ligament to survive until full plastic collapse of the tube, the ligament must be large and strong enough to limit the crack opening to some acceptable value. To

a first approximation, the maximum amount a ligament can be expected to stretch is about equal to its width. Hence, the critical value of the crack tip opening displacement, $CTOD_{critical}$ is equal to the size of the remaining ligament. As one limiting case, $CTOD_{critical}$ for a throughwall crack is then expected to be equal to the tube wall thickness. This agrees with the fracture appearance of past test specimens and a private communication from Belgatom. As a general criterion for the fracture of the remaining ligament of a partial throughwall crack, $CTOD_{critical}$ is taken equal to the remaining ligament depth.

Elastic plastic calculations of CTOD for partial throughwall cracks in cylinders are available in the literature. However, the crack depth is assumed to be uniform as opposed to the trapezoidal shape of the crack in R5C112. An equivalent uniform shape was therefore assumed but $CTOD_{critical}$ was based on the deepest part of the crack. On an area basis the equivalent crack depth in tube R5C112 is 60%. With a maximum crack depth of 97% and a remaining ligament of 3%, the $CTOD_{critical}$ value is 0.0013 inch. From the calculations of Erdogan, Irwin and Ratwani[1], tube R5C112 is expected to tear throughwall at a pressure of about 3300 psi. A modified Dugdale approach to the same problem led to a calculated pressure of about 3700 psi for throughwall tearing. This pressure would be associated with leakage and would be expected to be below the burst pressure for plastic collapse of the resulting throughwall crack. Even for deeper equivalent crack depths, for example 80%, the computed pressures for crack tearing are many times greater than the first leakage pressure of 500 psi. Hence, it is concluded that damage to tube R5C112 occurred prior to leak rate testing and the leak rate measurement should not be included in the database.

R10C69, TSP 3

This indication had a bobbin voltage of 1.48 volts which increased to 3.31 volts in the post-pull inspection. Figure 6-4 shows the burst crack opening after the burst test and after cutting and bending of the tube to open the macrocrack. It is seen that only minor crack opening has occurred and the opened length is very short (0.1 inch). After bending to open the macrocrack, a large part of the macrocrack is not throughwall. Figure 6-5 shows that the burst opening represents only part of the approximately 0.37 inch macrocrack length which had a maximum depth of 75%. The measured burst pressure of 5000 psi is approximately the expected burst pressure for a 0.37 inch throughwall crack (see Figure 7-12) and much less than expected for an average depth equal to the maximum 75% depth. It is concluded that the burst test did not result in a complete burst. Therefore, this indication is not included in the burst pressure data base.

R7C47, TSP 3

The 3rd TSP intersection of R7C47 had a 1.57 volt indication that increased to 4.13 volts in the post-pull inspection. Figure 6-6 shows the burst crack opening for this indication and Figure 6-7 shows the crack map. The macrocrack associated with the burst opening is about 0.43 inch long with a maximum depth of about 87%. Figure 6-8 shows the crack depth vs length which indicates an average depth of about 60 to 65%. The crack length having depths greater than

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1) Erdogan, F., Irwin, G. R., and Ratwani, M., "Ductile Fracture of Cylindrical Vessels Containing a Large Flaw," Cracks and Fracture, ASTM STP 601, American Society for Testing and Materials, 1976.

70% is <0.1 inch. The burst pressure for a 0.43 inch long crack with an average depth of 65% would be expected to be at least 6900 psi compared to the measured 5800 psi. From Figure 6-6, it is seen that the burst test resulted in only a minor crack opening of about 0.05 inch which again indicates an incomplete burst test. The burst pressure for this indication would be expected to be more than 15% higher than the measured value. Thus the burst pressure should be increased by at least 15% or the data point excluded from the database. The latter option was selected for this report.

R20C46, TSPs 2 and 3

Both intersections of tube R20C46 burst just above the TSP elevation at hand held grinding tool marks. These marks were applied in the laboratory for location purposes. Since the burst pressures are associated with the grinding marks outside the TSP rather than the degradation within the TSP, these indications are not included in the database.

R10C69, TSP 2

No detectable bobbin indication was found in either the field or post-pull inspection for the 2nd TSP intersection of R10C69. The destructive exam also shows no measurable degradation at this TSP intersection. Figure 6-9 shows the burst opening which is centered at the TSP indication. The burst shows a ductile, fishmouth rupture typical of bursts for indications with modest degradation. The measured burst pressure was 9,400 psi.

To evaluate the potential need to adjust the measured burst pressure for this type of indication, an undegraded freespan piece of tube R7C47 was burst by Westinghouse for comparison with burst of the Catawba-1 freespan tubing as part of the destructive examination program. The Westinghouse test yielded a burst pressure of 11,100 psi which is similar to that found for undegraded model boiler tubing. The freespan burst pressures during the destructive exam program were in the range of 9,400 to 9,900 psi or about 12% lower than the Westinghouse tests. Historically, burst pressures for undegraded 3/4 inch tubing have been in the range of 10,600 to 12,000 psi. The low burst pressures obtained during the destructive exam tests tend to indicate a potential systematic problem in the time frame of these tests. Based on the comparisons of the Westinghouse and destructive exam burst test results, a minimum increase of 10% to the destructive exam results should be applied. Applying the 10% increase to R10C69, TSP 2 yields an adjusted burst pressure of 10,340 psi for this intersection as shown in Table 6-4.

R5C112, TSP 2

The 2nd TSP of R5C112 was called NDD in the field evaluation, 0.48 volts by reevaluation of the field data and 0.25 volt for the post-pull evaluation. The burst opening is shown in Figure 6-9 for a burst pressure of 9,700 psi. It is seen in the figure that the tube burst above the TSP location and thus should correspond to an undegraded tube burst pressure. The expected range of burst pressures for undegraded tubing is 10,600-12,000 psi. For the near mean material properties for this tube (See Table 6-3), the undegraded burst pressure would be expected to be about 11,000 psi. As described above, an adjustment factor of 1.12 was found between the Westinghouse and destructive exam burst test on an undegraded tube section. Thus the burst pressure for the 2nd TSP of R5C112 should be increased by at least 10%. The flow stress and burst pressure adjustments lead to a burst pressure of 10,880 psi as shown in Table 6-4.

R10C6, TSP 2

The 2nd TSP of R10C6 had a 1.46 volt bobbin indication which increased to 2.07 volts in the post-pull inspection. The burst crack opening is shown in the upper part of Figure 6-[illegible] at two magnifications. The crack opening is about 0.33 inch long with minor bulging or tearing. Figure 6-11 shows the OD crack map and associated depths. The macrocrack that opened in the burst test is about 0.33 inch long with a maximum depth of 72%. The expected burst pressure for a 0.33 inch long crack conservatively assuming an average depth of 72% would be about 7260 psi or significantly in excess of the measured 6,000 psi. It is concluded that the reported burst pressure underestimates a complete burst by at least 15%. The 15% adjustment factor is typical of that found upon repeat burst tests following crack opening with no significant crack tearing and envelopes the above discussion for a 10% factor. As shown in Table 6-4, the adjusted burst pressure for the 2nd TSP of R10C6 is 7,100 psi for use in the voltage/burst correlation.

R10C6, TSP 3

The 3rd TSP of R10C6 had a 1.31 volt bobbin indication which increased to 5.34 volts in the post-pull examination. Figure 6-10 shows the burst crack opening for this indication. The burst opening length is about 0.38 inch with a maximum depth of 85%. Similar to the 2nd TSP for this tube, a minimum increase of 15% in the measured burst pressure of 4,850 psi is appropriate for this indication. The adjusted burst pressure for the burst data base is then 5,740 psi as shown in Table 6-4.

Crack Morphology

Figures 6-2, 6-5, 6-7 and 6-11 show available OD crack maps and associated maximum depths found in the tube examination. These figures also show regions on the tube which were characterized in the destructive examination as IGA. The IGA depth was generally negligible (<5%). However, the 3rd TSP of R7C47 was identified as having very local IGA depths up to the 51-75% range as shown in Figure 6-7. The IGA characterization used to define the OD crack maps is not known. A review of the metallography data indicates negligible volumetric IGA involvement. As described in Section 3.2, the Catawba-1 pulled tube crack morphology can be classified as multiple ODSCC with minor IGA.

Summary of Catawba-1 Pulled Tube Results

Based on the above assessment of the Catawba-1 pulled tube data, the evaluated results are given in Table 6-5. The NDE data evaluation supporting Table 6-5 is given in Section 5.6.

## 6.7 Evaluation of Plant E-4 Data

Recent (1992) tube pulls from Plant E-4 provide a major contribution to the 3/4 inch tubing burst pressure and leak rate data base. In addition, the eddy current data were obtained to the Belgian and APC voltage normalizations to provide the basis, as described in Section 5.7, to convert prior and future Belgian data to the APC data base. In Section 5.7, the results of cross calibration of Belgian (EDM holes) and domestic (drilled holes) ASME calibration standards are discussed. The cross calibration factor of 1.8 can be applied to the Belgian data for APC applications. However, Laborelec is continuing further studies on voltage normalization to APC guidelines. Pending finalization of the Laborelec study, a factor of 1.5 increase is conservatively applied to the Plant E-4 voltages. The Plant E-4 data are described in this

section.

Leak rate and burst test measurements were performed on the Plant E-4 pulled tubes as summarized in Table 6-6. These data include bobbin voltages up to ~ 10 volts which are higher than obtained for other 3/4 inch pulled tubes.

The Plant E-4 burst tests were performed with a plastic bladder and no foil reinforcement. The burst test results showed tearing and are considered to require no adjustments to burst pressures other than the adjustment for material properties. Free span burst pressures were obtained for six intersections with bobbin indications and one NDD intersection.

The leak rate measurements are also given in Table 6-6. This table includes tube R19C35 which had been previously (1991) pulled and examined. Leak rates were measured in free span at room temperature. The Plant E-4 leak rate measurements were made at room temperature at 1450 to 1525 psig and 2400 to 2750 psig for normal operating and SLB differential pressures, respectively. Laborelec has applied an analytical procedure using measured leak rate dependence on pressure differentials to adjust the room temperature test results to prototypic temperatures and pressure differentials. Only the leak rate data are used for R19C35 and R45C54 TSP 2 in the APC data base. Pending review of the analytical procedure for the leak rate adjustment, the leak rate data are not used in the reference correlation of this report.

## 6.8 Evaluation of Plant B-1 Pulled Tubes

Bobbin and destructive examination data are available for 16 intersections from Plant B Units 1 and 2 pulled tubes. However, only the 5th TSP intersection of R4 C61, Unit 1 was burst tested and this data point is described in this section. The bobbin data was obtained at a 550/100 kHz mix normalized to 2.75 volts for the mix at the 20% ASME hole. The 550/100 kHz mix is sufficiently close to the 550/130 kHz mix of the APC normalization such that no voltage adjustment is necessary. The pre-pull field bobbin voltage for this indication was 1.91 volts and the depth was 74%. The post-pull bobbin data was 2.33 volts and 80% depth.

Tube R4C61 at the 5th TSP was burst tested with no bladder and inside a TSP simulant (0.75 inch long, 0.016 inch diametral gap). No leakage was detected (by loss at pressure) until the crack opened to a large leak rate and loss of pressure at 6750 psi. The initial crack was found by destructive exam to be 0.40 inch long with a 0.01 inch long throughwall penetration. Given the throughwall penetration and that leak rates were not measured with significant accuracy, this indication is not used in the APC leak rate database. The post-burst crack had minor opening of the crack faces with negligible tearing at the edges of the crack. The maximum change in tube diameter as a result of the burst test was 1.3% OD or about 0.010 inch which is less than the 0.016 inch diametral clearance in the simulated TSP. Thus there is no apparent influence of the TSP on the leak/burst test such that the data point can be used as a lower bound to the burst pressure.

No metallography was performed on the axial indications at the 5th TSP. A mapping of the OD indications was obtained visually following the burst test. The axial indications are typical ODSCC with negligible IGA involvement. Short circumferential branch indications show more IGA involvement at the faces of the cracks. The largest axial macrocrack was examined by SEM fractography and found to be 0.4 inch long with 0.01 inch throughwall penetration. The crack was nearly throughwall for a 0.1 inch length. Seven individual microcracks comprising the

macrocrack had mostly grown together by corrosion with only partially uncorroded ligaments remaining. The maximum depth found in the circumferenticl branching cracks was 46% throughwall.

## 6.9 Growth Rate Trends

For implementation of alternate plugging criteria (APC) in the range of 2.5-4.0 volt repair limits, growth rate dependence on BOC voltage amplitude becomes important to establish the repair limits. This results as current domestic plugging limits result in little data in the higher range of voltage amplitudes near the APC repair limits. For the Catawba-1 interim plugging criteria (IPC) limit of 1.0 volt, the growth rate data developed in Section 9.5 do not require any extrapolation to higher BOC voltages. It may be noted that the BOC voltages for Catawba-1 over the last two cycles exceeded the 0.0 to 1.0 volt range, in several cases. It is desirable to compare the Catawba-1 average growth rate trends with other domestic plants and with European plants. This comparison is provided to show that the Catawba-1 growth data are comparable to other domestic plants for percentage growth with a trend for percentage growth to decrease with increasing BOC voltages. French and Belgian plants, which operate with higher voltage indications in service due to differences in plugging criteria, tend to show less dependence of percentage growth on BOC amplitudes.

Available French data (Plant H-1) indicate percent growth rates nearly independent of initial amplitude (WCAP-12871). Belgian growth data from Plant E-4 have not been evaluated for percentage growth although the trends appear similar to the French units. For Plant E-4 BOC amplitudes in the range of about 0.5 (0.1 volt Belgian) to about 3 volts (0.6 volt Belgian), the average growth increase in amplitude was about 2.8 volts (0.57 volt Belgian). No strong trend of growth dependence on initial amplitude was found although a linear fit to the broad scatter of growth data indicate a trend for the change in voltage to increase with amplitude. Overall, the European plants operate with higher voltage amplitudes in service and with trends toward higher growth rates than domestic plants.

The Catawba-1 percentage growth trends (developed in Section 9.5) are compared with other domestic plants and French Plant H-1 in Figure 6-12. This figure shows that the Catawba-1 growth rates are comparable in magnitude and dependence on BOC amplitude with other domestic plants. The other domestic plants shown in Figure 6-12 have 7/8 inch diameter tubing.

## 6.10 Summary of Pulled Tube Test Results

Based on the above evaluations, the 3/4 inch tube diameter, pulled tube data for application in tube burst and leak rate correlations is summarized in Table 6-7. Catawba-1 tube R5C112, TSP 3 is not included as both the burst and leak rate measurements are not considered reliable as noted previously in Section 6.6. Three Catawba-1 voltage and burst points are applicable to the voltage/burst correlation. The Belgian Plant E-4 data provides 7 burst data points and 9 SLB leak rate data points (8 points with >0 leakage). The bobbin coil voltages are shown without and with the 1.5 factor on voltages (Section 5.7) applied as a preliminary adjustment in this report. As noted in Section 6.7, the Belgian leak rate data have not been included in the reference leak rate correlation of this report. It is shown in Section 7.4 that the Belgian data with the adjusted voltages and leak rates are in generally good agreement with the model boiler data.

The overall pulled tube database having bobbin voltages and destructive examination depths for 3/4 inch tubing is shown in Figure 6-13. For comparisons, the equivalent 7/8 inch data is shown in Figure 6-14 and the 3/4 inch and 7/8 inch data are combined in Figure 6-15. A voltage reduction factor of 1.36 (Section 5.5) was applied to the 7/8 inch data for comparison with the 3/4 inch data. Overall, the data sets are comparable in size and general trend toward higher voltages at increasing depth. The European pulled tube data show a number of pulled tubes in the 10 to 30 volt range.

Table 6-1

Number of Pulled Tubes with NDE and Destructive Exam Data

| Plant | Number of Tubes | Number of Intersections: Burst Tested | Leak Tested | Destructive Exam |
|---|---|---|---|---|
| **3/4 Inch Pulled Tube Data Base Summary** | | | | |
| Catawba-1 | 5 | 4 (5)[1] | 0(8)[2] | 9 |
| E-4 | 9 | 7 | 9 | 13 |
| B-1 | 1 | 1 | 0(1)[2] | 5 |
| B-2 | 3 | 0 | 0 | 11 |
| C-2 | 2 | 0 | 0 | 4 |
| Totals | 20 | 12 | 9 | 42 |
| **7/8 Inch Pulled Tube Data Base Summary** | | | | |
| A-1 | 1 | 0 | 0 | 1 |
| A-2 | 4 | 3 | 3 | 4 |
| D-2 | 5 | 3 | 0(3)[2] | 11 |
| L | 8 | 21 | 0(22)[2] | 23 |
| P-1 | 2 | 2 | 0(3)[2] | 3 |
| J-1 | 9 | 1 | 5 | 13 |
| Totals | 29 | 30 | 8 | 55 |

Notes:

1) Number in parentheses represents number of additional pressurization tests performed without complete burst. Data not included in data base.

2) Number in parentheses represents room temperature pressure tests performed with no identified leakage at pressure differentials exceeding SLB conditions. One additional Catawba-1 tube was leak tested but throughwall penetration is likely the result of tube pulling and results are not included in data base.

Table 6-2

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

| Plant | Inspection | Bobbin Coil Volts (3/4" Tubing) | Bobbin Coil Depth | Comments |
|---|---|---|---|---|
| B-1: R22C58 | Outage following suspected leak | 7.7 | 92% | Total plant leak rate varied from ~19 near beginning of cycle to ~63 gpd at end of cycle prior to inspection. Other tubes with PWSCC contributed to the total leakage. Based on helium leak test results, it was estimated that the ODSCC leak rate was <10 gpd. |
| E-4: R11C87 | Outage following suspected leak | 6.2(1.4)(2) | 75% | Total leak rate from SG was ~149 gpd. Five leaking tubes were detected by fluoresceine leak test at ~500 psi. EC data obtained after leak test indicated that 3 leakers were affected by roll transition PWSCC and 2 by TSP ODSCC. From visual observation, the largest leaker showed slight dripping and was associated with PWSCC. UT inspection indicated one axial crack in each tube of length 12 and 11 mm (0.47 and 0.43 inch), respectively. |
| R17C58 | Outage following suspected leak | 20.0(4.2)(2) | 80% | |

Notes:

1) Field experience noted is for nominal 0.75 inch OD tubing with 0.043 inch wall thickness. No data are known to be available for tubes with 0.875 inch OD.

2) Field voltages of 1.4 and 4.2 volts, as given in parentheses, were obtained at 300 kHz with Belgian normalization. Voltages converted to 3/4 inch tubing normalization of this report utilizing Figure 5-4.

Table 6-3

**Tensile Strength Properties for 3/4 Inch Diameter Tubing**

| Source of Tubing | Sy=Yield Strength-Ksi | | Su=Ultim. Strength-Ksi | | Sy+Su,Ksi | |
|---|---|---|---|---|---|---|
| | Room Temp. | 650°F | Room Temp. | 650°F | Room Temp. | 650°F |
| Tubing Manufacturing Data: | | | | | | |
| Mean | 53.05 | 45.78 | 101.29 | 97.35 | 154.34 | 143.13 |
| Standard Deviation | 4.86 | 3.91 | 4.22 | 3.97 | 8.28 | 7.13 |
| Lower 95% Tolerance | 44.55 | 38.95 | 93.92 | 90.40 | 139.85 | 130.65 |
| Model Boiler Samples | 54.2 | -- | 109.4 | -- | 163.6 | -- |
| Catawba-1 Pulled Tubes | | | | | | |
| R5C112 | 52.3 | -- | 98.9 | -- | 151.2 | -- |
| R10C6 | 49.7 | -- | 99.5 | -- | 149.2 | -- |
| R10C69 | 53.7 | -- | 101.5 | -- | 154.2 | -- |
| R20C46 | 54.2 | -- | 103.4 | -- | 157.6 | -- |
| R7C47 | 52.4 | -- | 103.4 | -- | 155.8 | -- |
| Plant E-4 Pulled Tubes | | | | | | |
| R26C34 | 53 | 49 | 100 | 93 | 153 | 142 |
| R16C31 | 60 | 59 | 112 | 108 | 172 | 167 |
| R40C47 | 46 | 46 | 101 | 101 | 147 | 147 |
| R45C54* | 54 | 44 | 97 | 22 | 151 | 136 |
| R47C66 | 51 | 40 | 97 | 91 | 148 | 131 |
| R33C96* | 54 | 44 | 97 | 92 | 151 | 136 |
| Plant B-1 Pulled Tubes | | | | | | |
| R4C61 | 52.0 | -- | 101.0 | -- | 153.0 | -- |

* Same Heat

Table 6.4

**Burst Pressures for Catawba-1 Pulled Tubes**

| Tube | TSP | Bobbin Volts | Measured Burst-psi | Flow Stress Adjust. Factor | Crack Opening Adjust. Factor | Adjusted Burst-psi | Comments |
|---|---|---|---|---|---|---|---|
| R5C112 | 2 | 0.48 | 9,700 | 1.02 | 1.10 | 10,880 | Ductile, fishmouth rupture just outside TSP. |
| | 3 | 1.82 | 4,150 | 1.02 | >1.25 | Unreliable | Crack opened (largest ~0.1", others <0.05"), no apparent bulging or tearing. Max. corrosion depth 97%. Max. single macrocrack length ~0.43 (<0.2" TW by burst). |
| R10C6 | 2 | 1.46 | 6,000 | 1.03 | 1.15 | 7,100 | Crack opened, minor bulging or tearing. Maximum corrosion depth ~72%. Burst crack ≃ macrocrack length ~0.33". |
| | 3 | 1.31 | 4,850 | 1.03 | 1.15 | 5,740 | Crack opened, minor bulging or tearing. Maximum corrosion depth ~85%. Burst crack length ~0.43". |
| R10C69 | 2 | NDD | 9,400 | 1.0 | 1.10 | 10,340 | Ductile, fishmouth rupture TSP region. |
| | 3 | 1.48 | 5,000 | 1.0 | >1.25 | Unreliable | Minor crack opening, no bulging or tearing. Maximum corrosion depth ~75%. Maximum single macrocrack length ~0.37" (not completely or <.2" opened by burst). |
| R20C46 | 2 | 0.42 | 8,600 | 0.98 | -- | Unreliable | Both R20C46 intersections burst just above TSP at a hand held grinding tool mark applied for location purposes. |
| | 3 | 0.79 | 7,200 | 0.98 | -- | Unreliable | |
| R7C47 | 3 | 1.57 | 5,800 | 0.99 | >1.25 | Unreliable | Minor crack opening, no apparent bulging or tearing. Maximum corrosion depth ~87%. Maximum single microcrack length (~0.05" opened by burst) ~0.44". |

## Table 6-5

### Summary of Catawba-1 Pulled Tube Results

| | Westinghouse Field Data Eval. | | | | Lab | Destructive Exam | | | Leak Rate (l/hr) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Bobbin | | RPC | Post-Pull | Max. | | Burst | | |
| Tube | TSP | Volts | Depth | Volts | B.C. Volts | Depth | Length | psi | Norm.Op. | SLB |
| R5C112 | 2 | 0.48 | ~0% | | 0.37 | Superficial | | 10,880 | 0.0(3) | 0.0(3) |
| | 3 | 1.82 | 86% | 1.30 | 5.06 | 97%(2) | 0.50" | N.R.(1) | N.R.(1) | N.R.(1) |
| R10C6 | 2 | 1.46 | 83% | 0.98 | 2.07 | 72% | 0.40" | 7,100 | 0.0(3) | 0.0(3) |
| | 3 | 1.31 | 76% | 1.20 | 5.34 | 85% | 0.43" | 5,740 | 0.0(3) | 0.0(3) |
| R10C69 | 2 | NDD | | | NDD | None | | 10,340 | 0.0(3) | 0.0(3) |
| | 3 | 1.48 | 72% | 0.97 | 3.31 | 75% | 0.45" | N.R.(1) | 0.0(3) | 0.0(3) |
| R20C46 | 2 | 0.42 | 30% | | 0.82 | 12% | 0.05" | N.R.(1) | 0.0(3) | 0.0(3) |
| | 3 | 0.79 | 28% | | 1.04 | ~0% | | N.R.(1) | 0.0(3) | 0.0(3) |
| R7C47 | 3 | 1.57 | 78% | 1.40 | 4.13 | 85% | 0.42" | N.R.(1) | 0.0(3) | 0.0(3) |

Notes:
1. N.R. = Not Reliable.
2. Evaluation indications crack opening for leakage may have resulted during tube pull.
3. No leak identified during room temperature pressurization tests.

## Table 6-6

### Plant E-4 Pulled Tube Burst Pressures and Leak Rates

| Tube | TSP | Bobbin Volts | Actual Max.Depth | Leak Rates (l/hr) Norm.Op.(1305 psi) | Leak Rates (l/hr) SLB (2610 psi) | Burst Pressures Measured | Burst Pressures Adj.for Mat.Prop. |
|---|---|---|---|---|---|---|---|
| R26C34 | 3 | | | | | | |
| R16C31 | 2 | | | | | | |
| | 3 | | | | | | |
| R40C47 | 2 | | | | | | |
| R45C54 | 2 | | | | | | |
| | 3 | | | | | | |
| R47C66 | 2 | | | | | | |
| | 3 | | | | | | |
| | 4 | | | | | | |
| R33C96 | 2 | | | | | | |
| R19C35 | 2 | | | | | | |
| R26C47 | 2 | | | | | | |

Notes:
1. Belgian voltage converted to APC volts using Figure 5-4.
2. Burst test conducted inside TSP. TSP constraint judged to have influenced the burst pressure and thus the burst value is not included in APC data base.
3. Room temperature test results given in parentheses were adjusted to operating temperatures (without parentheses) by Laborelec.
4. Bobbin voltages do not include any adjustments to Belgian voltages.

Table 6-7

**Pulled Tube Leak Rate and Burst Test Measurements**
**for 3/4 Inch Diameter Tubing**

| Plant / Row/Col | TSP | Bobbin Coil Volts[1] | Bobbin Coil Depth | RPC Volts | Destructive Exam Max.Depth | Destructive Exam Length[2] | Leak Rate l/hr N.Oper. | Leak Rate l/hr SLB | Burst[7] Pressure |
|---|---|---|---|---|---|---|---|---|---|
| Catawba-1: | | | | | | | | | |
| R5C112 | 2 | 0.48 | ~0% | | Superficial | -- | -- | | 10,880 |
| R10C6 | 2 | 1.46 | 83% | 0.98 | 72% | 0.40 | 0.0[3] | 0.0[3] | 7,100 |
| | 3 | 1.31 | 76% | 1.20 | 85% | 0.43 | 0.0 | 0.0 | 5,740 |
| Plant E-4: | | | | | | | | | |
| R26C34 | 3 | | | | | | | | |
| R16C31 | 2 | | | | | | | | |
| | 3 | | | | | | | | |
| R45C54 | 2 | | | | | | | | |
| | 3 | | | | | | | | |
| R47C66 | 2 | | | | | | | | |
| R33C96 | 2 | | | | | | | | |
| R19C35 | 2 | | | | | | | | |
| R26C47 | 2 | | | | | | | | |
| Plant B-1: | | | | | | | | | |
| R4C61 | 5 | | | | | | | | |

Notes:

1. Voltage normalization for 550/130KHz to 2.75 volts on 20% ASME holes. For the Belgian data, voltages include 1.809 factor for cross calibration of Belgian made ASME standard (EDM 20% holes) to the reference laboratory standard (drilled 20% holes). Voltages with cross calibration factor reduced to 1.5, as used in this report, pending completion of Laborelec study are shown in parenthesis.
2. Maximum burst crack corrosion length in inches with throughwall length in parentheses.
3. Tested at room temperature.
4. Not measured at 550/130 KHz. Voltage renormalized from 300 KHz data.
5. Leak rates measured at room temperature conditions and analytically adjusted to operating conditions.
6. Observed during burst test at room temperature.
7. Burst pressures adjusted to mean flow stress of 77 ksi.

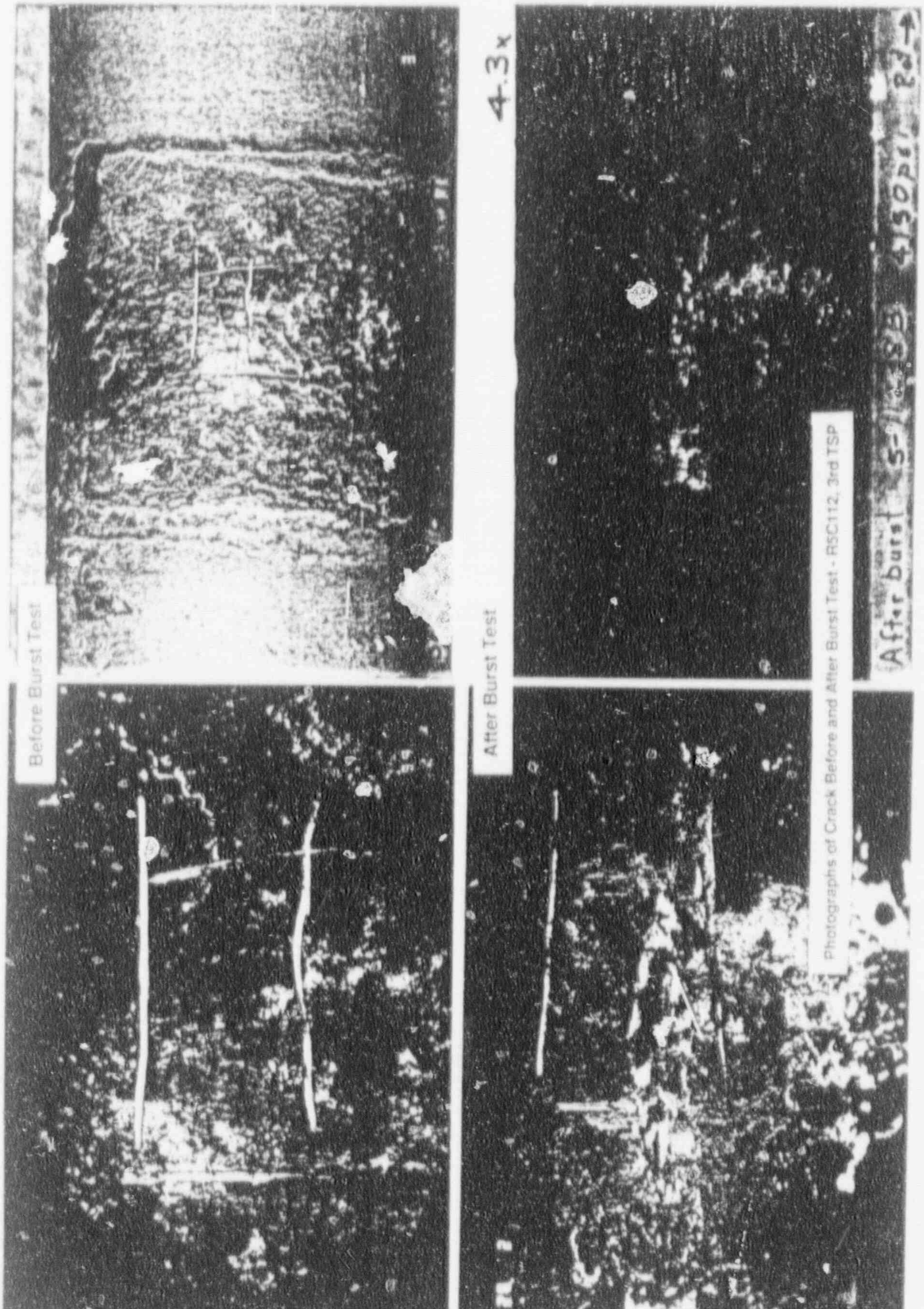



Figure 6-1. Catawba-1 Pulled Tube R5C112, TSP-3: Crack Before and After Burst Test

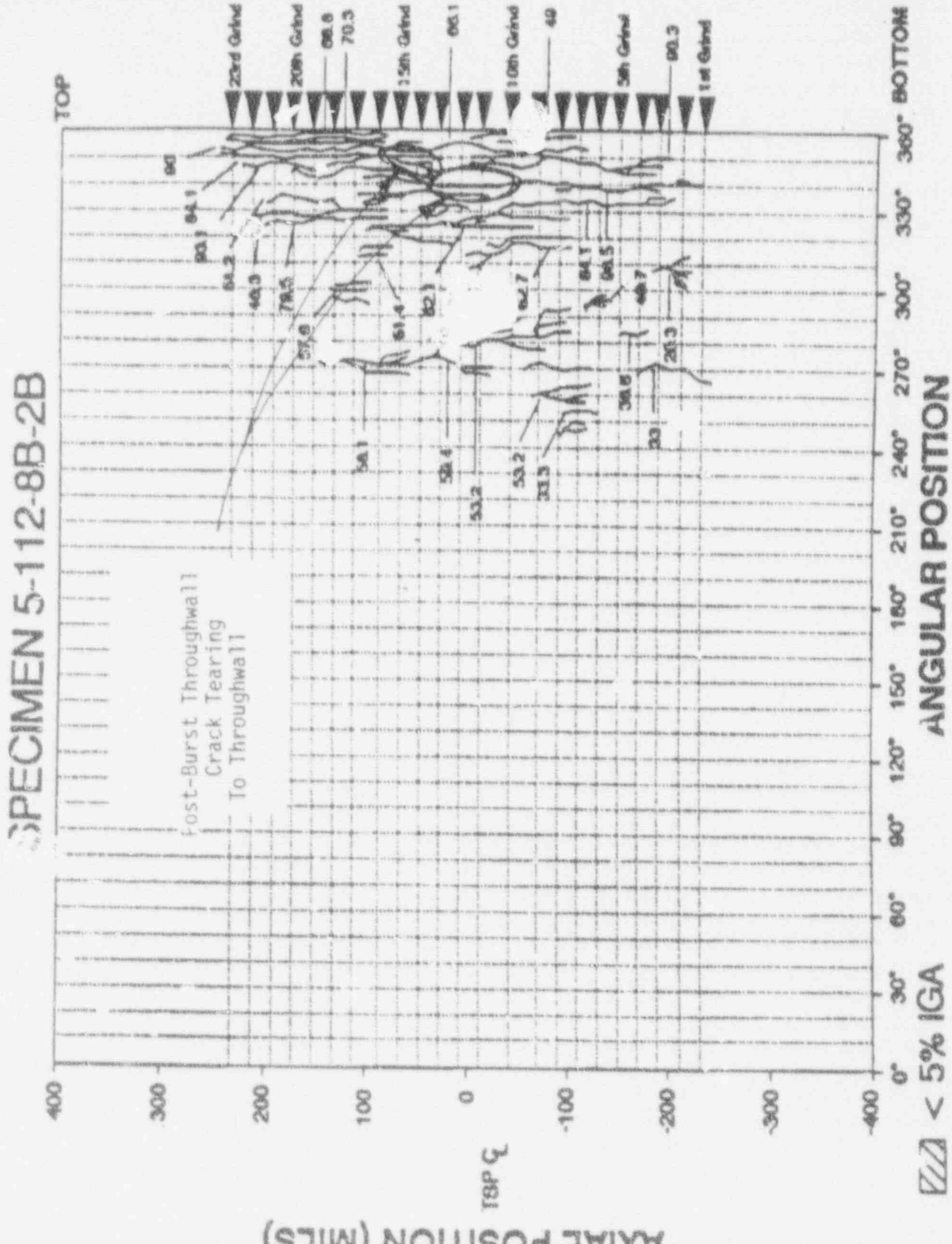



Figure 6-2. Catawba-1 Pulled Tube R5C112, TSP-3: Incremental Grind and Polish Results

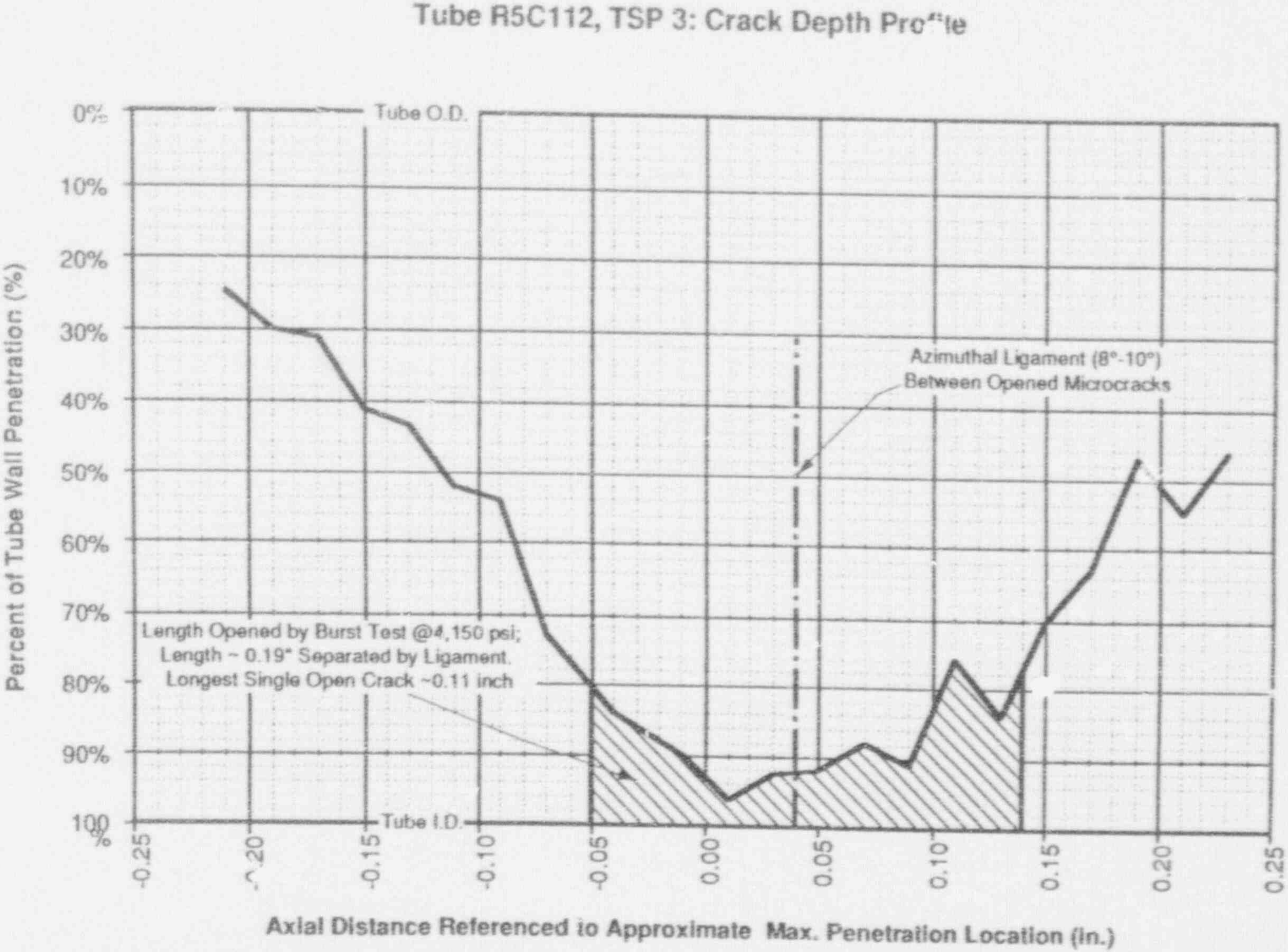



Figure 6-3. Catawba-1 Pulled Tube R5C112, TSP-3: Crack Depth Profile

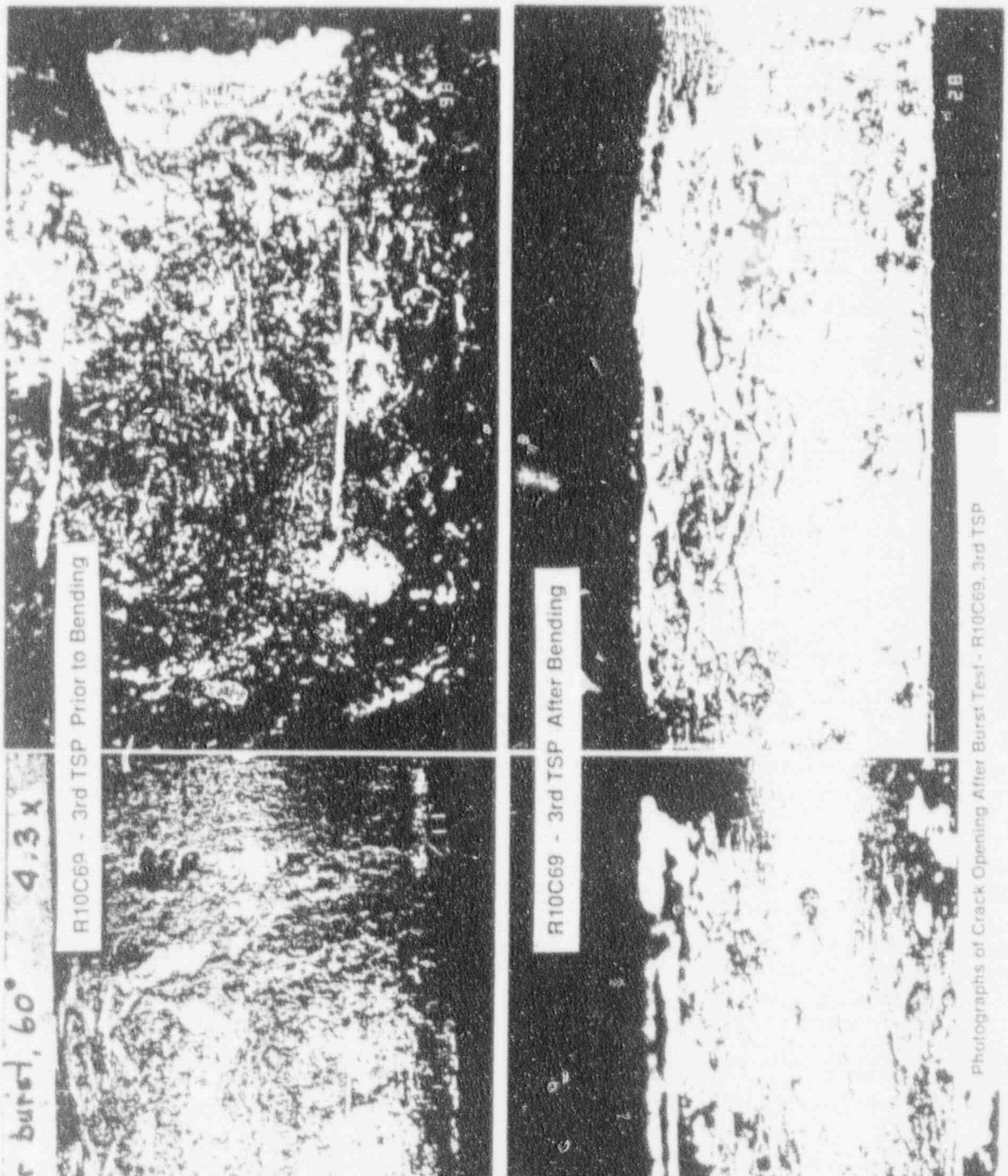



Figure 6-4. Catawba-1 Pulled Tube R10C69, TSP-3: Crack Opening After Burst Test

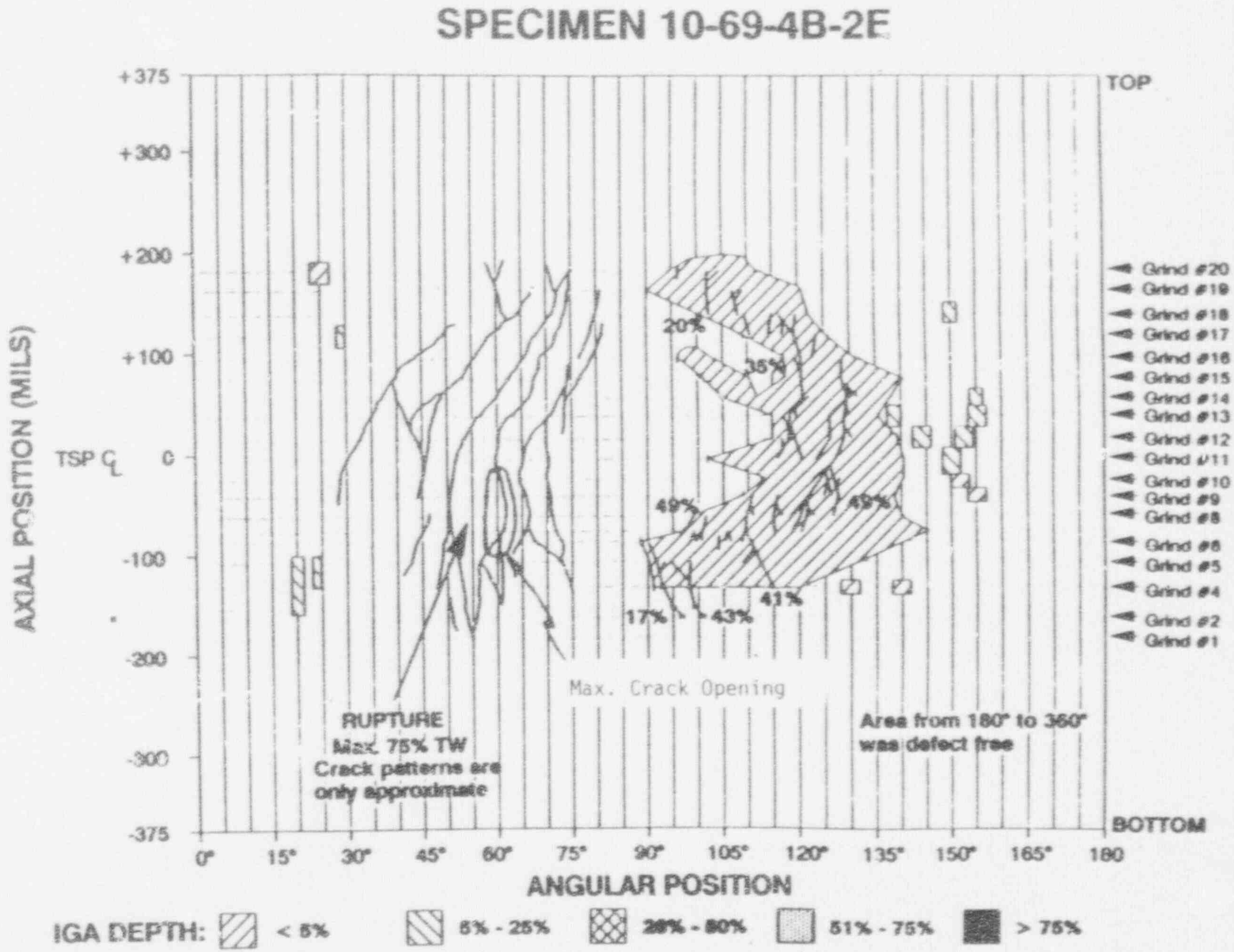
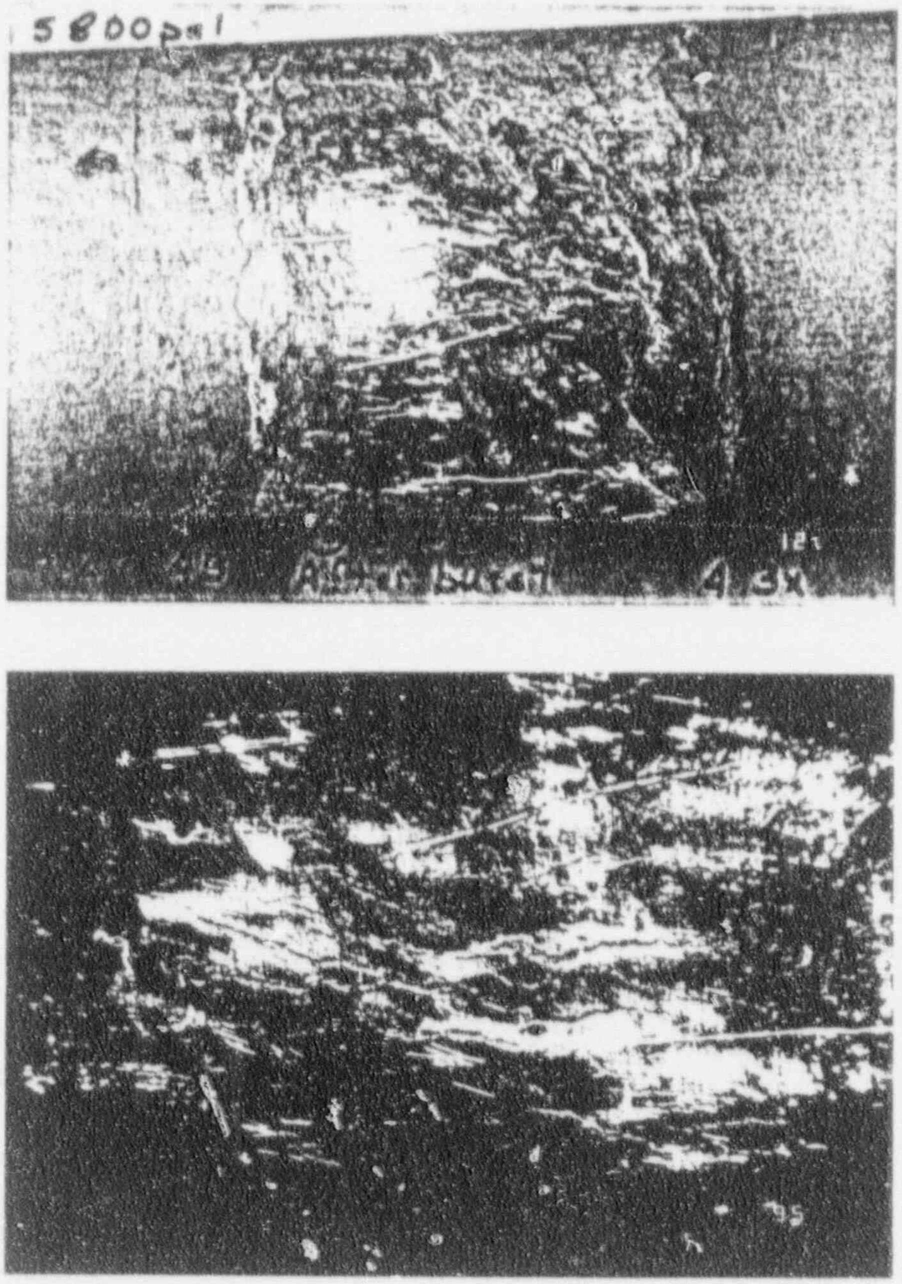



Figure 6-5. Catawba-1 Pulled Tube R10C69, TSP-3: Incremental Grind and Polish Results




Photographs of Crack Opening After Burst Test - R7C47, 3rd TSP

Figure 6-6. Catawba-1 Pulled Tube R7C47, TSP-3: Crack Opening After Burst Test

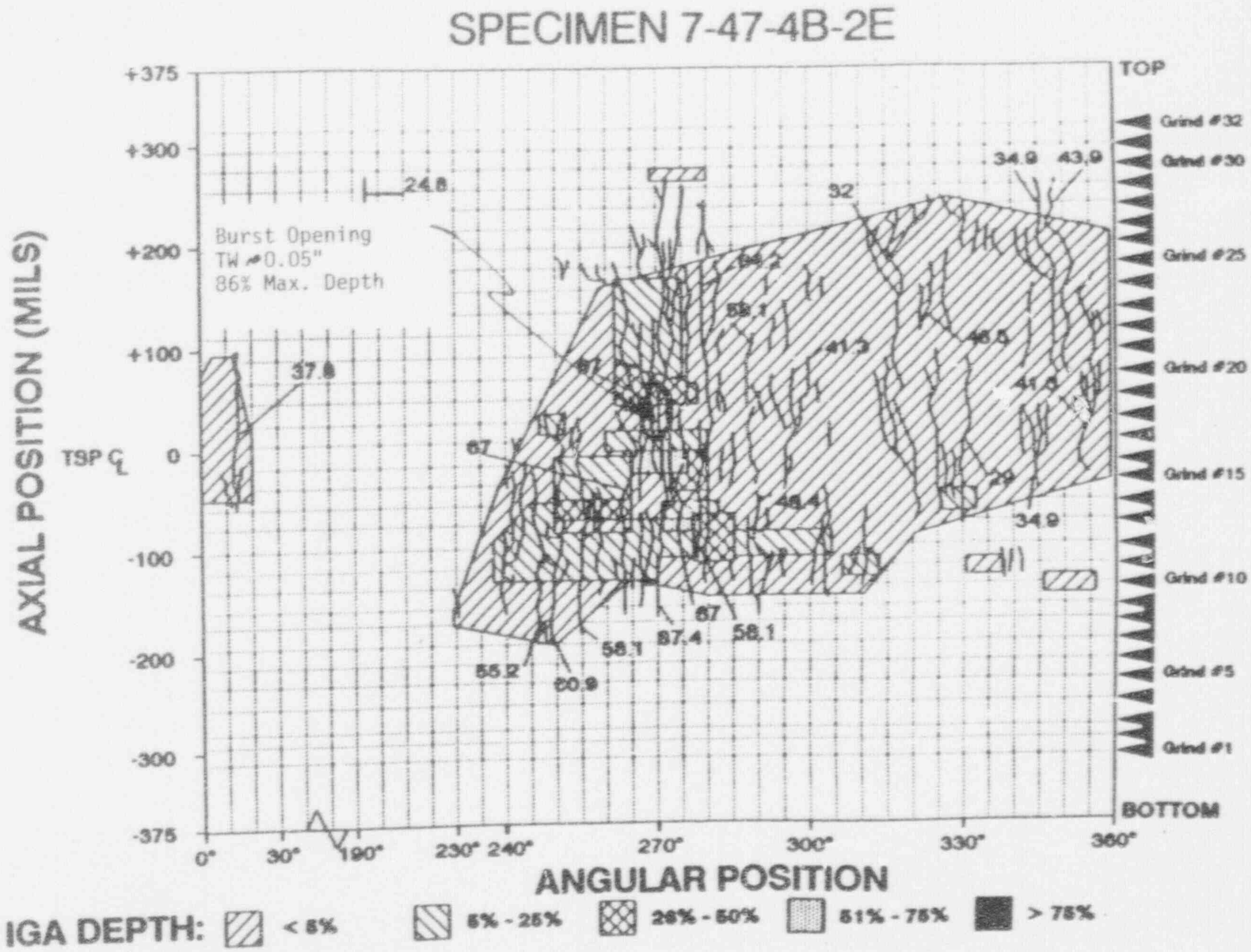



Figure 6-7. Catawba-1 Pulled Tube R7C47, TSP-3: Incremental Grind and Polish Results

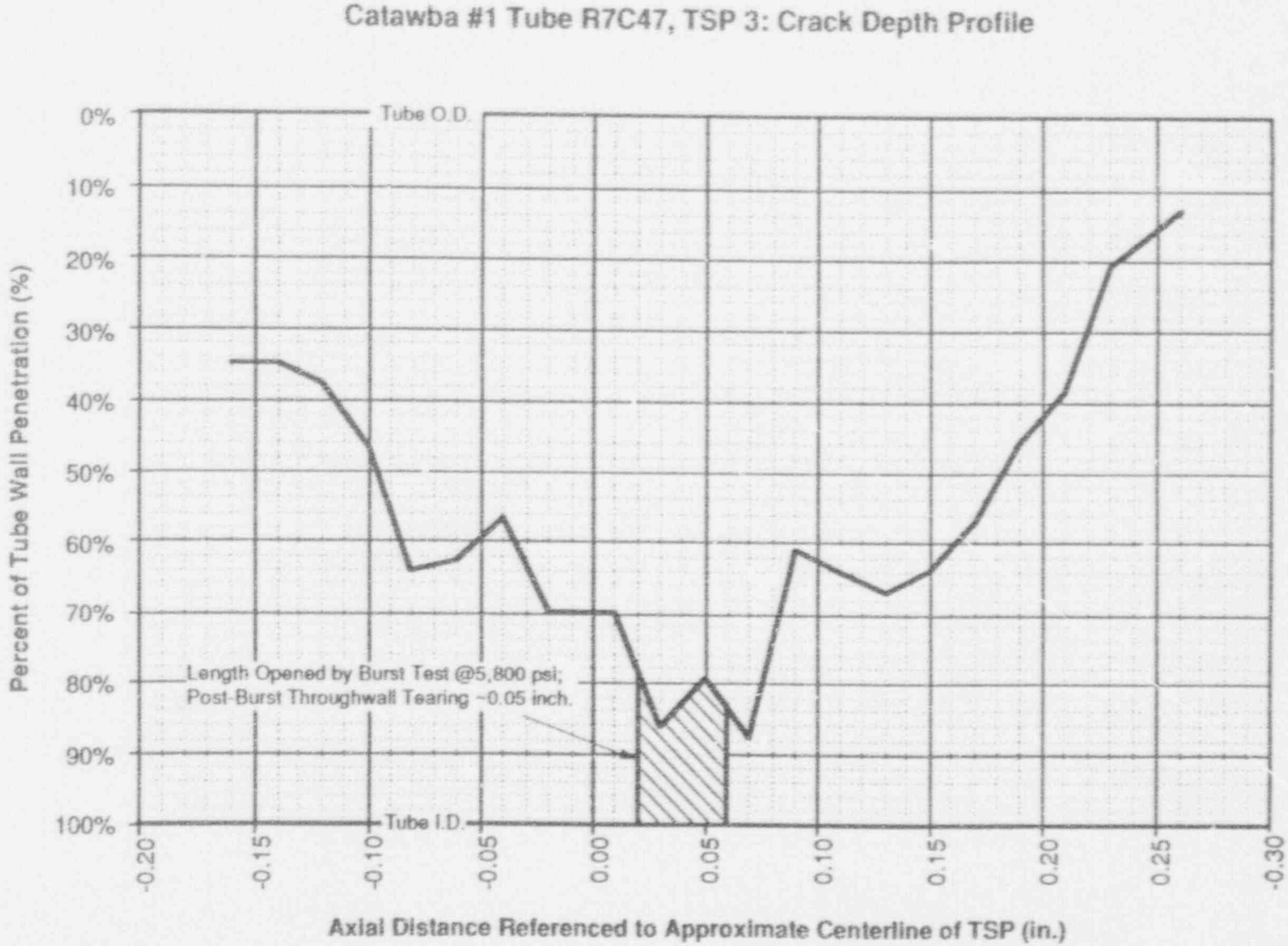
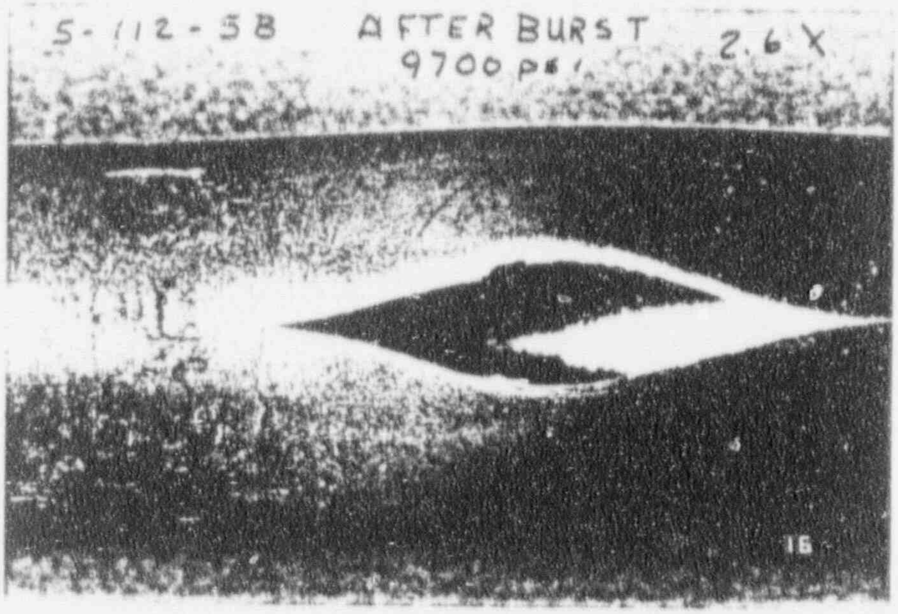
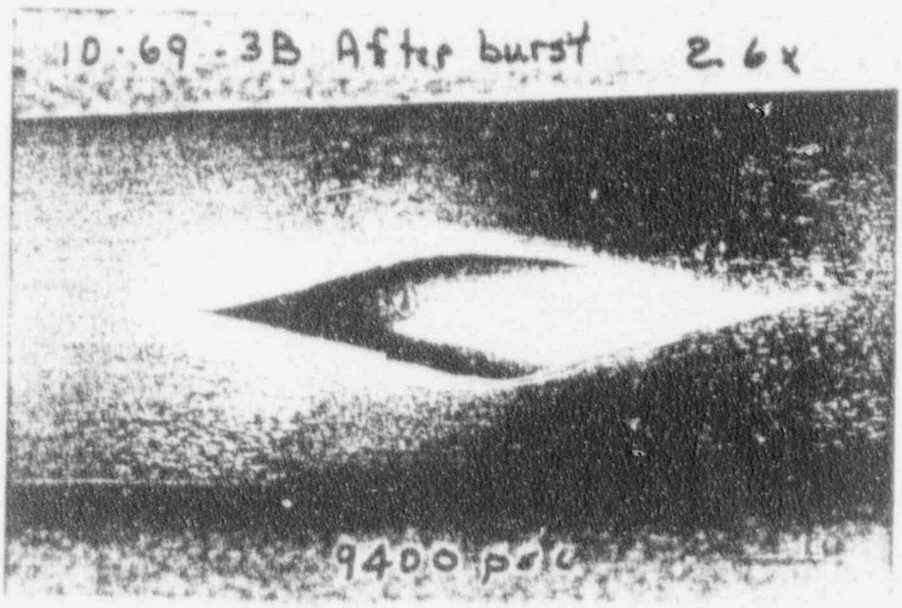



Figure 6-8. Catawba-1 Pulled Tube R7C47, TSP-3: Crack Depth Profile

R5C112 - 2nd TSP




R10C69 - 2nd TSP




Photographs of Burst Openings for 2nd TSP - R5C112 and R10C69

Figure 6-9. Catawba-1 Pulled Tube R5C112, TSP-2 and R10C69, TSP-2: Crack Opening After Burst Test

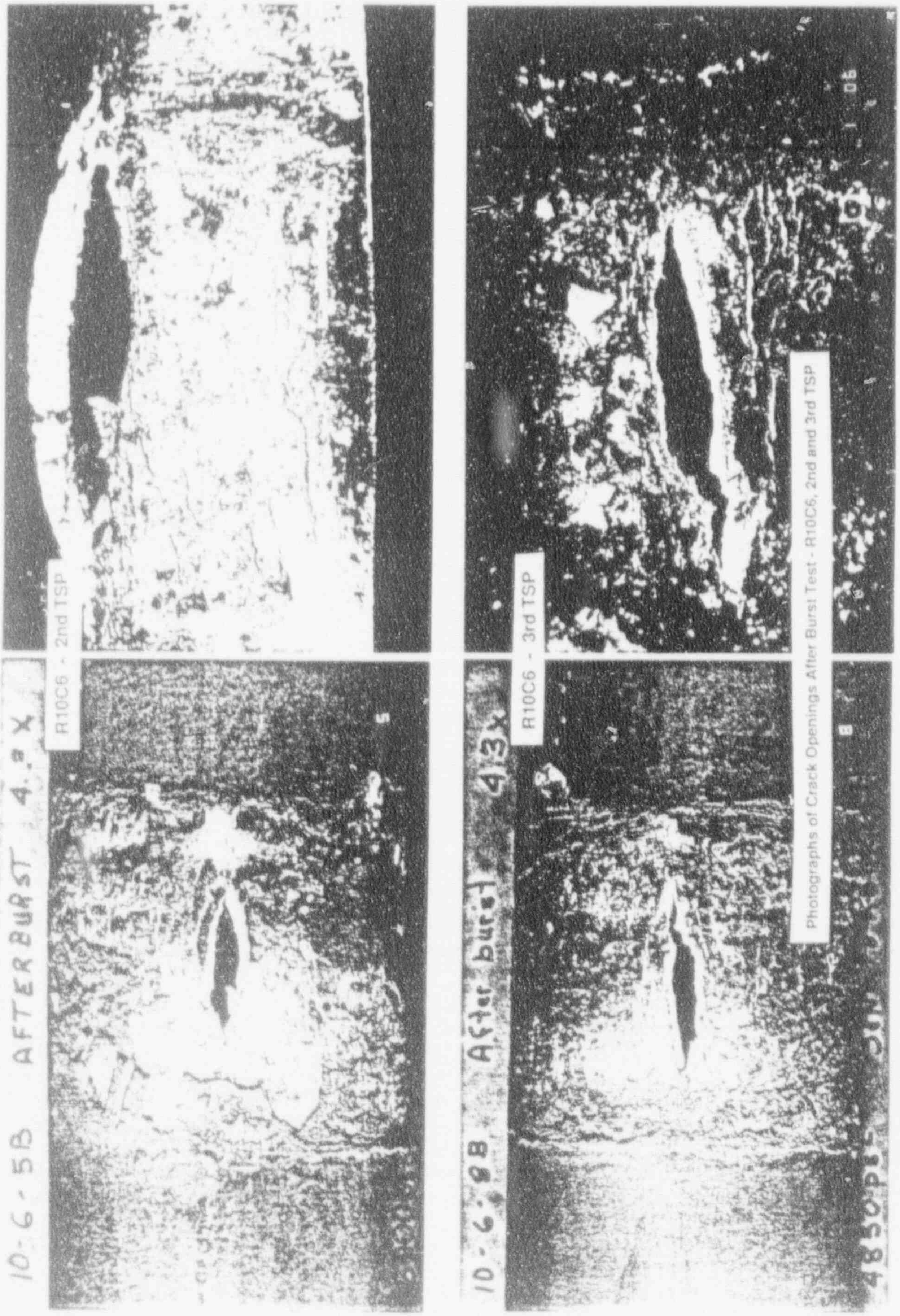



Figure 6-10. Catawba-1 Pulled Tube R10C6, TSP 2 and 3: Crack Opening After Burst Test

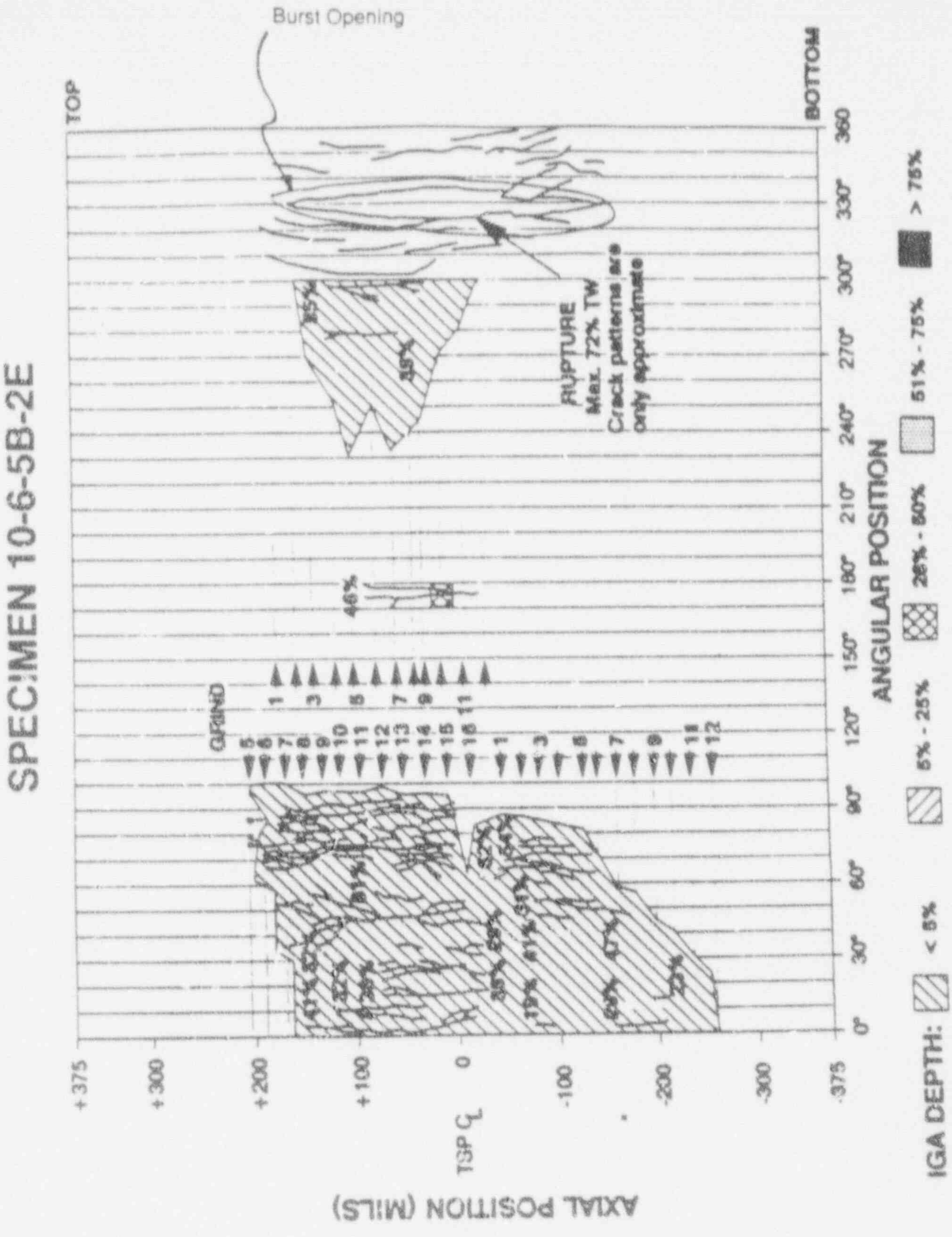



Figure 6-11. Catawba-1 Pulled Tube R10C6, TSP-2: Incremental Grind and Polish Results

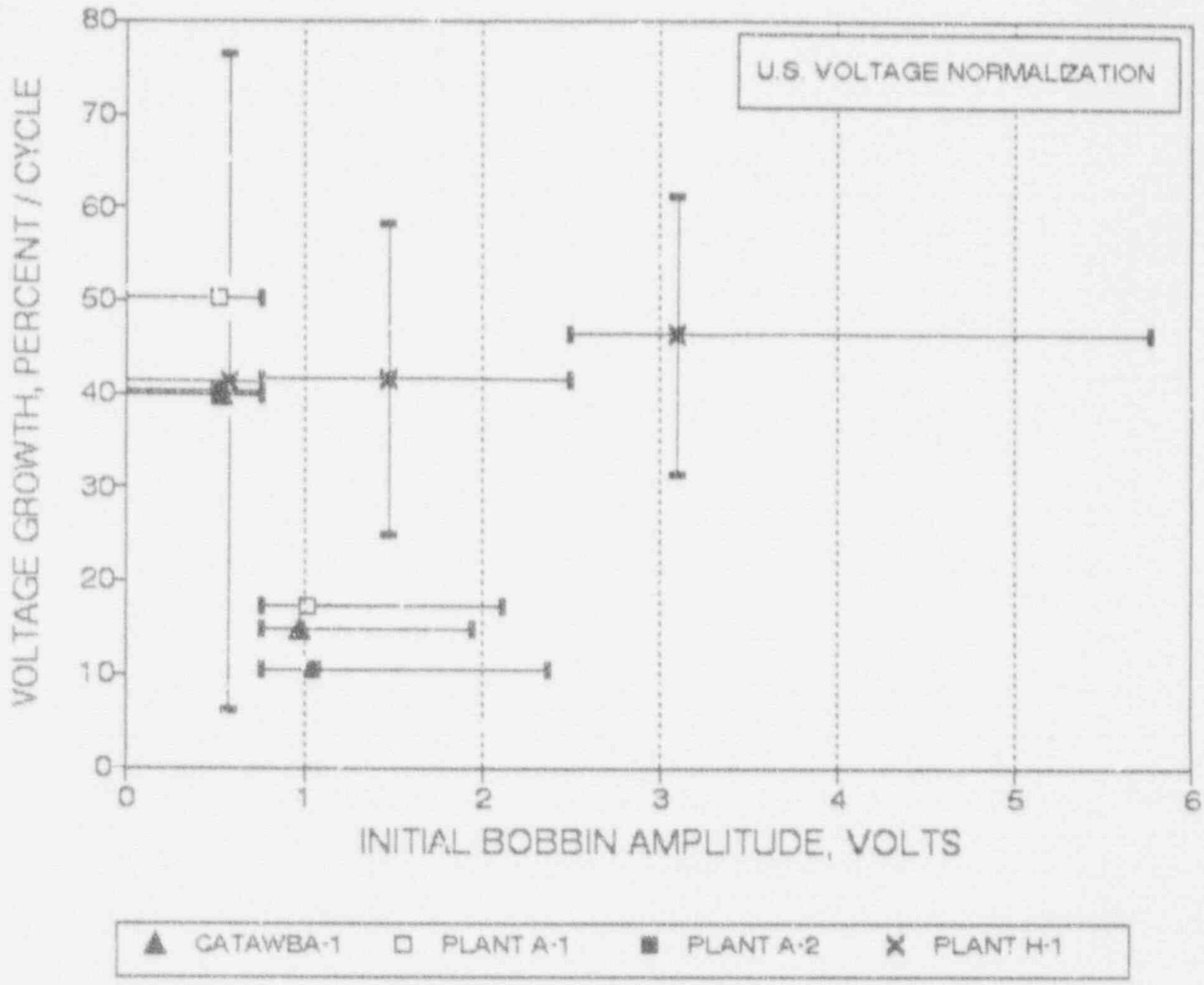



Figure 6-12. Average Percent Voltage Growth Rates for Catawba-1, Plant A and Plant H-1

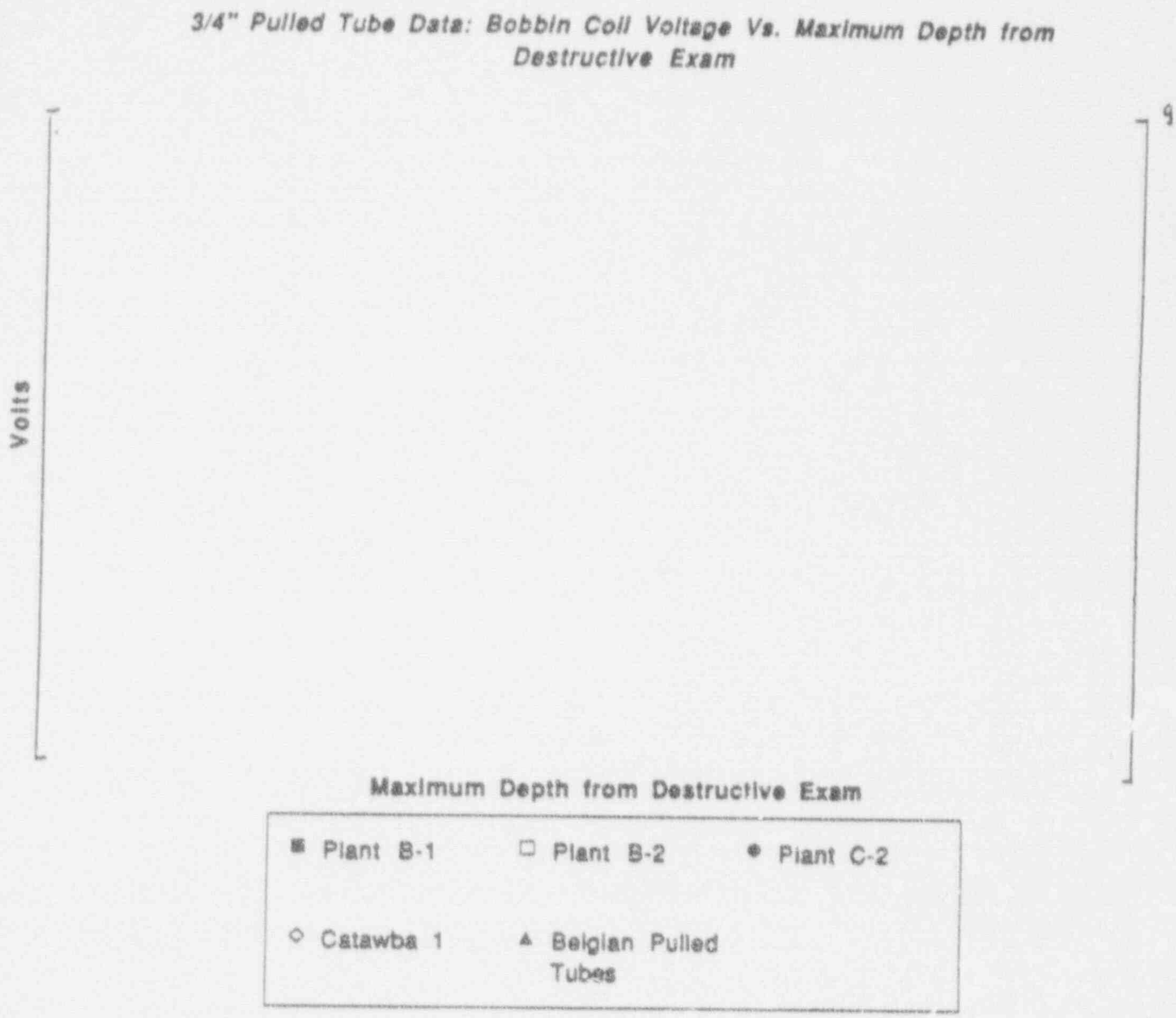



Figure 6-13. 3/4 Inch Pulled Tube Data: Bobbin Coil Voltage versus Maximum Depth from Destructive Examination

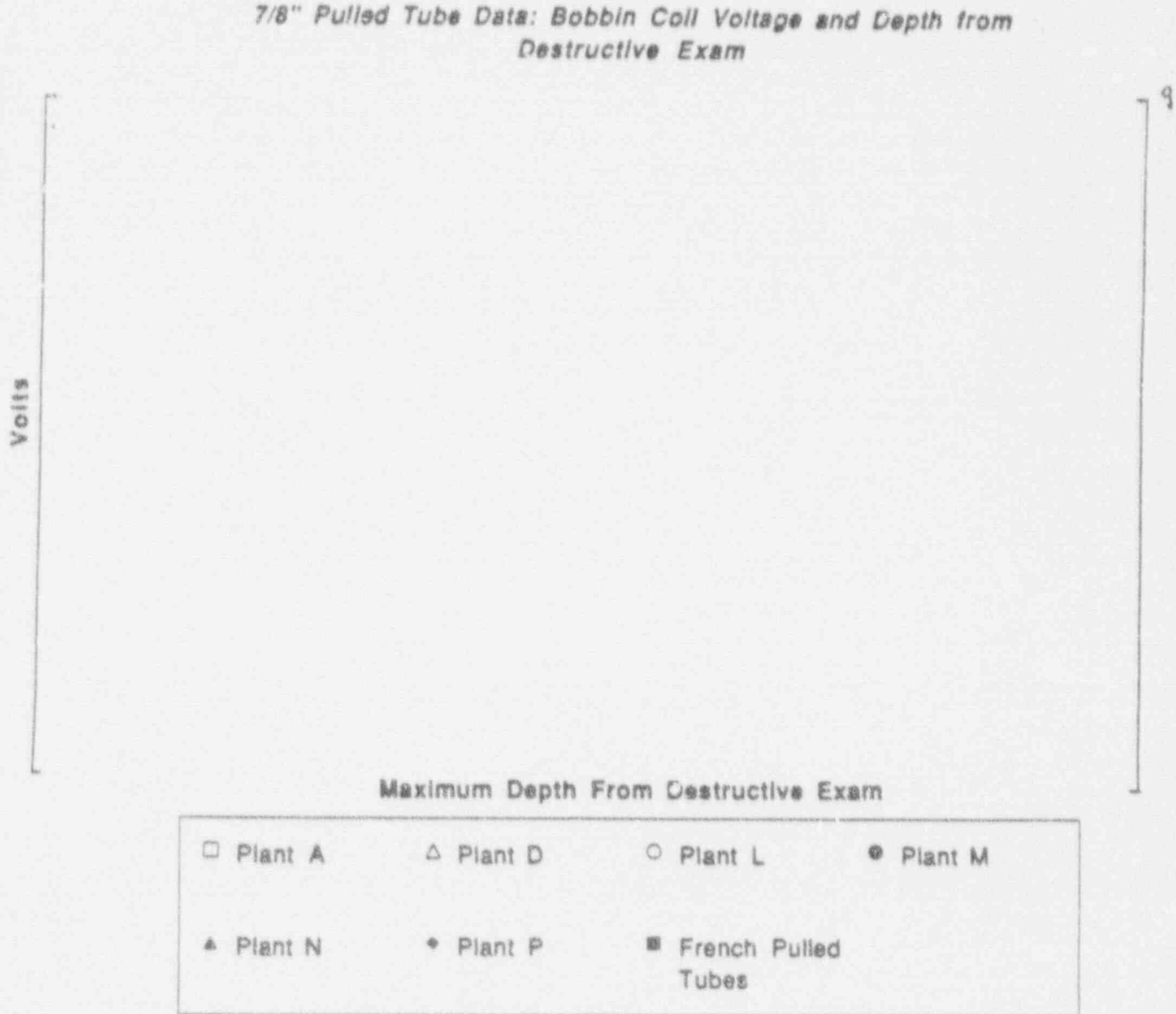



Figure 6-14. 7/8 Inch Pulled Tube Data: Bobbin Coil Voltage versus Maximum Depth from Destructive Examination

*3/4" and 7/8" Pulled Tube Data: Bobbin Coil Voltage Vs. Maximum Depth from Destructive Exam*

[9]

Volts

Maximum Depth from Destructive Exam

■ 3/4" Pulled Tubes ○ 7/8" Pulled Tubes

Note: 7/8" voltages decreased by factor of 1.36 to correspond to 3/4" tubing.

Figure 6-15. 3/4 Inch and 7/8 Inch Pulled Tube Data: Bobbin Coil Voltage versus Maximum Depth from Destructive Examination

## Section 7

## LEAK RATE AND BURST CORRELATIONS

### 7.1 Introduction

This section utilizes the model boiler (Section 4) and pulled tube (Section 6) data to develop correlations of burst pressure vs voltage and SLB leak rate vs voltage. The correlations are considered to be preliminary pending resolution of the Belgian voltage normalization (Section 5.7) and review/concurrence on the 3/4 inch tubing database and correlation methods by the EPRI APC Task Team. The EPRI Task Team provides an additional independent review of the available database and an industry concurrence on the APC methodology. This process leads to a consistent methodology, particularly for the correlations, in developing plant specific APC submittals. The 3/4 inch database and methodology have not yet been reviewed by the Task Team. The methods for the SLB leak rate correlation are in the process of being revised to enhance the statistical methodology together with the physics of the correlation. The SLB leak rate correlations presented in this section are a preliminary step in evolving the enhanced correlations.

### 7.2 Summary of Data Base for 3/4 Inch Tubing

The data base developed in Sections 4 to 6 is summarized in Table 7-1 for both the model boiler specimens and the pulled tubes. Data points not used in the correlations, such as zero leakage points with <90% actual crack depth, are specifically addressed by footnotes. Destructive examination crack lengths in this table are preliminary pending more detailed examination of the data.

### 7.3 Burst Pressure vs. Voltage Correlation

The data set of 3/4 X 0.043 inch tubing contains 57 possible burst pressure versus bobbin voltage data points from model boiler (MB) samples and pulled tube intersections. Of the pulled tube data, the voltage amplitudes of samples from the Belgian Plant E-4 are adjusted by a factor of 1.5 to put them on a comparable basis with U.S. voltage normalization. The conservatism of the 1.5 factor is discussed further in Section 5 of this report. In addition, some of the pulled tube burst samples from Catawba-1 (not listed in Table 7-1) do not in our judgment reflect the characteristics of a tube that has experienced burst or in fact had burst in regions outside of the degraded region (see discussion in Section 6.6). For these reasons, not all of the Catawba-1 data are utilized in the recommended correlation. However, to provide a basis for judging the sensitivity of the correlation to these data, correlations are provided in the following that include these data (see Table 6-4 for values).

The burst pressures of all the room temperature data are normalized to the mean of the flow stress, 77 ksi, for the mill annealed Alloy 600 tubing at room temperature (WCAP-12522). A second order regression analysis is performed on the data to obtain a best fit and the associated error of the estimate. Based on the standard error, prediction interval methodology is applied to establish the lower 95% and 99% probability intervals (one-sided). These lines are then ratioed to reflect the effect of operating temperature and lower tolerance limit (LTL) strength properties (WCAP-12522).

Pressure ratios at beginning of cycle (BOC) and end of cycle (EOC) relative to $3\Delta P_{NO}$ and $\Delta P_{SLB}$ are used in Section 10 to define pressure margin ratios and to provide comparisons with 7/8 inch tubing. This section develops burst pressure/voltage values to support analyses described in Section 10. Interim plugging criteria comparable with that approved previously for 7/8 x 0.050 inch tubing is accomplished with a burst capability at the lower 95% probability of 5290 psi for Catawba at BOC and verification of 3750 psi capability ($3\Delta P_{NO}$) at EOC (1.4 $\Delta P_{SLB}$ is enveloped), using 90% cumulative probability values of EC error and degradation growth. In addition, verification of end of cycle $\Delta P_{SLB}$ capability (2650 psi) is required with the lower 99% probability (LTL) curve and with maximum EOC voltage.

Recommended Correlation

The burst data of Section 7.2 provide a total of 57 data points that have been scaled per the above discussion and used to develop a correlation between bobbin coil voltage and burst pressure. The scaled data used in the correlation for 3/4 inch tubing are listed in Table 7.2

A higher order regression analysis of this data has been performed providing an equation for the mean curve using a second order polynomial equation. The equation for burst pressure (BP) as a function of volts (v) obtained is:

[ ]g

The coefficient of correlation for this regression fit is 0.87 and the error of the BP estimate is 1.13. A -95% prediction interval is established using the expression:

[ ]g

where,

[

]g

The recommended burst pressure versus bobbin voltage correlation is shown in Figures 7-1 through 7-3. In Figure 7-1, the voltages (4.1 volts and 10.95 volts, respectively) corresponding to 3 $\Delta P_{NO}$ (3750 psi) and $\Delta P_{SLB}$ (2650 psi) are presented. These voltages represent the values that would form the basis for an alternate plugging criteria. The EOC voltage value of 4.1 volts results in an EOC burst pressure capability that meets R.G. 1.121. Margin to burst of cracked tubing (throughwall cracking in the limit) is a direct function of crack length, applied pressure, flow stress and radius to thickness ratio. With the others remaining equal, the applied pressure then dictates margin. Consequently, the most limiting case will envelope all other cases and demonstrating that the most limiting case is satisfied envelopes all other cases. 3 $\Delta P_{NO}$ is limiting and enveloping since it is greater than 1.4 $\Delta P_{SLB}$.

Figure 7-2 illustrates the burst strength of 5290 psi corresponding to the BOC amplitude of 1.0 volt, and 4740 psi corresponding to the 90% cumulative probability EOC voltage of 1.66 volts. The 4740 psi EOC capability exceeds 3750 psi (limiting and enveloping case) by a wide margin. At the maximum EOC voltage, 2.53 volts, a burst capability of 3580 psi is illustrated for a lower 99% probability in Figure 7-3. Therefore, the probability of rupture due to 2650 psi is (much) less than $1X10^{-2}$. The computed EOC probability of rupture at 2650 psi is $1.1X10^{-5}$. It can be noted that the 2.53 volt maximum EOC voltage corresponds to 99.94% cumulative probability of the Monte Carlo projected EOC voltage distribution.

Sensitivity to Catawba Data

The first assessment of sensitivity with regard to treatment of the burst pressures of the Catawba pulled tube intersections is to eliminate the 10 to 15% increase applied to the three data points incorporated in the recommended correlation described above.The equation of BP as a function of V for this data set is:

[ ]a

The coefficient of correlation for this fit is 0.86 with a standard error of 1.15. Figures 7-4 through 7-6 provide results that correspond to Figures 7-1 through 7-3, respectively. The EOC allowable voltage at 3750 psi is 3.76 volts versus 4.1 volts and the 2650 psi EOC voltage allowable is 10.6 volts versus 10.95 volts. The conclusions regarding EOC burst capability at 1.66 volts and 2.53 volts remain unchanged. However, the BOC voltage providing 5290 psi burst strength drops to 0.88 volt.

The second assessment of sensitivity to Catawba data is performed including what are judged to be unreliable data. The Catawba-1 pulled tube data added to the above data set are:

| Bobbin volts | Burst pressure (ksi) |
|---|---|
| 1.82 | 4.23 |
| 0.10 | 9.40 |
| 1.48 | 5.00 |
| 1.57 | 5.74 |

The resulting equation for BP is:

[ ]a

The coefficient of correlation for this fit is 0.83 with a standard error of 1.25. This is shown in Figures 7-7 through 7-9. The result of including these "unburst" data is to unrealistically reduce the BOC voltage corresponding to 5290 psi to 0.6 volt. Other requirements regarding EOC voltage are still satisfied although with smaller margins. The judgment that the correlation resulting from including these data is unrealistic is further reinforced by the trend analysis in the following subsection wherein it is shown that very small changes in throughwall crack length (less than 0.03 inch) are associated with the voltage range of 0.1 to 1.0 volt. Consequently, a likewise very small change in burst capability would be expected (less than 500 psi) for the same crack morphology over the same voltage range.

Trends Between 3/4 Inch and 7/8 Inch Correlations

To obtain additional insight into the difference between the 3/4 inch (lower structural voltage limit) and 7/8 inch voltage/burst correlations, a very preliminary assessment has been performed of expected differences based on crack length correlations. Relations between voltage and throughwall crack length were estimated using preliminary crack length data (See Figures 7-10 and 7-11). Although average crack lengths are more relevant to burst capability than throughwall lengths, only the throughwall data were immediately available for this trend analysis. For the present application, the use of throughwall crack lengths leads to an overestimate of burst capability but the trends between 3/4 inch and 7/8 inch tubing should be representative of the expected trends. Existing (Belgian and Westinghouse) correlations for burst pressure vs uniform throughwall crack length (Figure 7-12) were then combined with the voltage/crack length relations to obtain voltage/burst pressure correlation estimates for both 3/4 inch and 7/8 inch tubing. The resulting, preliminary correlations, Figures 7-13 and 7-14, indicate a steeper slope (decreasing burst pressure) with increasing voltage for 3/4 inch tubing and lower burst pressures at a given voltage (>2.0 volts) for 3/4 inch tubing. These trends are the same as found for the direct correlation of bobbin voltage measurements to burst pressure as presented at the August 28 meeting with the NRC staff. The principal contributor to the trends is the lower burst pressures of 3/4 inch tubing at a given crack length as augmented by somewhat higher voltages (factor not considered reliable from current data) at a given crack length for 7/8 inch tubing. These preliminary results indicate that the general differences found between the 3/4 inch and 7/8 inch voltage/burst correlations should be expected based on crack length considerations.

## 7.4 SLB Leak Rate vs. Voltage Correlation

Recommended Correlation

The regression analysis techniques for the 3/4 inch tube data are consistent with those performed for the 7/8 inch tubing and described in WCAP-12871, Rev. 2. The resulting mean and upper and lower 95% probability lines (one-sided) are shown in each of the following plots. Also presented is a curve representing the arithmetic (numerical) average of an assumed log-normal distribution of leak rate at each value of voltage. Figure 7-15 utilizes the non-leaker data at 0.0001 l/hr. as done in WCAP-12871, Rev. 2, for 7/8 inch tubing. However, based on the discussion presented below, the recommended regression solution, presented in Figure 7-16, utilizes the non-leaker data at 0.001 l/hr.

The correlation is established utilizing linear regression analysis of the logarithms of the corresponding leak rates and voltages thereby establishing a leakage rate model of the form:

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where,

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Prediction intervals for leakage rate at a given voltage are then established to statistically define the range of potential leakage rates.

The SLB leakage rate data from 32 model boiler specimens used to establish the recommended correlation for 3/4 inch tubing are listed in Table 7.3. Linear regression analysis of the logarithms of this data results in the following mean leakage rate correlation:

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The coefficient of correlation for this regression fit is 0.65 and the error c ..e estimate is 1.31. A prediction interval is established using the expression:

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where,

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Sensitivity to Plant E-4 Data

As should be noticed, the set of data evaluated in Figures 7-15 and 7-16 does not include the Plant E-4 data. They are excluded since both leak rate (taken at room temperature) and voltage must be adjusted and consensus has not been reached on either adjustment. To assess the potential sensitivity of the correlation, the regression analysis of Figure 7-16 was repeated with the Plant E-4 data added. The voltage and leak rates were included at values recommended by the supplier of the data, Laborelec, and the voltage values further factored by 1.5 as was the case with the recommended burst correlation. As seen in Figure 7-17, the mean regression equation and the 95% prediction intervals are not changed significantly. If, however, the Plant E-4 data are included in the regression analysis without the additional 1.5 factor on voltage, leak rates at a given voltage are approximately doubled (Figure 7-18). The factor of 1.5 is expected to be conservative as discussed in Section 5.

SLB Leak Rate vs. Voltage Trends

An evaluation has been completed that provides results supporting the recommended correlation methodology employed for SLB leak rate versus bobbin voltage. Of concern to some reviewers has been the use of non-leaking, degraded tubes in the correlation. Our reasoning for including them is to establish a log-log slope on the order 4, similar to leak rate versus crack length curves, even though the selection of leak rate at 0.0001 was arbitrary (yet consistent with the accuracy of the leak rate measuring instrumentation/method).

The evaluation establishes leak rate versus voltage from:

1) Formulation of throughwall crack length (L) versus voltage (v) correlation from available data using regression analysis $\{L = f_1(v)\}$.

2) Calculation of leak rate (Q) as a function of L using the CRACKFLO computer code. Formulate relationship (simplified) of Q as a function of L through regression analysis of

CRACKFLO predictions $\{Q = f_2 (L)\}$.

3) Development of correlation between Q and V from the above. Substitite the formulation $L = f_1 (v)$ into $Q = f_2 (L)$ to get $Q = f_3 (v)$. Compare $Q = f_3 (v)$ to test data.

The result of the first step is shown in Figure 7-10 which illustrates the mean of the regression formulation provided in the title of the figure. This is the same correlation described in Section 7.3. This crack length correlation is considered preliminary as additional crack lengths for other specimens are being obtained and the existing data is being verified. The CRACKFLO code for calculating leak rate from throughwall axial cracks (WCAP-12871, Rev. 2) is utilized to provide predictions of SLB leak rate as a function of crack length. For simplicity, these solutions are then fit via regression analysis by two equations to improve the accuracy of the correlation and to eliminate further CRACKFLO calculations. Figure 7-19 provides the fit utilized below Log(0.25) and Figure 7-20 the fit utilized at Log(0.25) and above.

Combining the crack length versus voltage and SLB leak rate versus crack length equations results in an equation that estimates SLB leak rate as a function of voltage. A comparison of CRACKFLO predictions to measured magnitudes is shown in Figure 7-21. The mean of predicted values is greater than the measured values over a range of 0.003 gpm and higher. Thus, applying CRACKFLO directly results in an assumption that predicted equals measured and is conservative in that CRACKFLO overpredicts measured leak rates. Thus, as Figure 7-22 indicates, the calculated mean is higher than the bulk of the data as reflected by the regression fit mean also plotted. Note the nearly equal magnitude of slope. This slope is obtained by including non-leakers in the correlation but at 0.001 l/hr. rather than 0.0001 l/hr. as had previously been done. Use of 0.001 l/hr. is recommended in lieu of 0.0001 l/hr. since the slope agrees with the alternate method and since regression analysis of the data excluding the non-leakers would result in a lower slope.

## 7.5 Bounding SLB Leak Rate vs. Voltage

This section documents the development of bounding leakage under steam line break conditions. The leak rate database includes both the 7/8 inch and the 3/4 inch diameter tubes. The database consists of 74 model boiler specimens and 93 pulled tube intersections. The voltage amplitudes from Plant E-4 pulled tubes were not adjusted to account for the differences in voltage normalization used for the data acquisition in Belgium and for the APC database (in the U.S). The data from 7/8 inch tubing is at 400/100 kHz differential mix with the 20% holes in the ASME standard normalized to 2.75 volts in the mix. Similarly, the 3/4 inch tubing data is at 550/130 kHz differential mix with the 20% holes in the ASME standard normalized to 2.75 volts.

In order to combine the data from the 7/8 inch and 3/4 inch specimens, a conversion factor equal to the square of the diameter ratios is applied. This factor results from the fact that the ASME standard hole size is the same for 3/4 and 7/8 inch tubing. Thus, to convert the 7/8 inch data to the same basis as the 3/4 inch data, the voltage amplitudes from the 7/8 inch data (at 400/100 kHz) were divided by the factor 1.36. The results were then combined with the 3/4 inch database.

As per the detailed discussion in Section 6.6, the Catawba-1 pulled tube R5C112 (TSP-3) would not leak at SLB condition had it not been damaged during the tube pull operations. Therefore, for

this specimen (and only for this specimen) the post pull amplitude of 5.06 volts rather than the prepull value of 1.82 volts is used in this context. This tube had an SLB leak rate of 0.56 l/hr.

The leak rates were, in most (131 of 167) cases, the direct result of measurements in the laboratory under SLB conditions. In other (36) cases, laboratory data on leak rate measurement was not available and the likelihood of leak rate was inferred from crack morphology (throughwall depth and length) obtained from destructive examination.

The data was classified into leaking and nonleaking specimens. Frequency distribution of voltage amplitudes (corresponding to the 3/4 inch data normalization) in each classification was determined. This is shown in Figure 7-23 as a stacked bar chart. The number of leaking specimens in each voltage range out of the total number in that range is also shown listed at the top of each bar in the figure.

The ratio of the number of leaking specimens in a voltage range (bin) to the total number of specimens in the bin was calculated from the above frequency distribution of voltage amplitudes. This result, probability of leakage, within each voltage range is plotted as a bar chart in Figure 7-24.

Instead of classifying the data into leakers and nonleakers, a second classification was made with a leakage threshold of 1.0 l/hr (specimens leaking at rates less than 1.0 l/hr and those leaking at a higher rate). For each of these classifications, frequency distribution of voltage amplitudes was determined. Probability of leak rate above 1.0 l/hr was calculated for each voltage range as was done for the 0.0 leakage threshold. The frequency distributions and the probability distribution are displayed in Figures 7-25 and 7-26, respectively.

The above results (Figures 7-23 through 7-26) were developed using data from both the 7/8 and 3/4 inch diameter tubing. If the 7/8 inch data is excluded and only the SLB leak rate data from 3/4 inch tubing is used, the results are not changed significantly. This is displayed in Figures 7-27 through 7-30.

For the 3/4 inch tubes, the data supports no leak under SLB conditions for indications up to 2.0 volts (bobbin data for 550/130 kHz mix with 20% hole ASME standard normalized to 2.75 volts) and small leak rate (< 1 l/hr, if any) in the voltage range of 2.0 to 3.5 volts. Table 7-4 summarizes the bounding SLB leak rates determined from the pulled tube and model boiler database for voltage ranges up to 3.5 volts for 3/4 inch diameter tubes. Recommendations for bobbin signals above 3.5 volts are also included in the table. The table also shows the low voltage indications which contribute to the threshold voltage values of 2.0 volts and 3.5 volts. It may be noted that if the voltage amplitudes for the Plant E-4 data were factored up to account for the differences in European and U.S. voltage normalizations, then the threshold voltage for low (< 1.0 l/hr) leak rate would increase to 4.2 volts.

Table 7-4 summarizes the lowest voltage indications having leakage <1.0 l/hr. and the lowest having >1.0 l/hr. The lowest voltages with <1.0 l/hr. help to define a threshold for leakage. The smallest voltage having a measurable leak rate is >2.0 volts (R46C73) based on reducing the 7/8 inch tubing voltage of 2.81 volts by a factor of 1.36 for the approximate 3/4 inch tubing voltage. As discussed above, Catawba-1 tube R5C112 has not been applied for the leakage threshold as the post-pull voltage of >5 volts should be associated with the leakage due to expected damage to the indication during the tube pull. The lowest voltage of 1.9 volts (R5C61 from Plant B-1) found for a throughwall crack with no leakage (pressurization during burst test) is consistent with about a 2.0 volt threshold for leakage. EPRI report TR-100407 also

uses the 7/8 inch R46C73 to define a leakage threshold for SLB conditions. The EPRI report scales the 2.8 volts to a BOC estimate of 1.9 volts and suggests 1.5 volts as a BOC estimate. For this Catawba-1 assessment, the threshold applied is for EOC volts and applies the same basis as the EPRI report. The threshold for leakage >1.0 liter/hour is about 3.5 volts from Table 7-4. However, the Belgian tube R33C96 bobbin voltage of 3.54 volts should be increased by a factor of at least 1.5 to >5 volts. Thus no indications below about 4 volts have been identified with a leak rate >1.0 liter/hr. in model boiler or pulled tubes. For Catawba-1, a threshold >3.5 volts for leakage >1.0 liter/hr does not significantly influence the SLB leakage as the largest projected EOC indication is about 2.53 volts.

The threshold for SLB leakage can be assessed by evaluating the lowest bobbin voltages resulting in leakage at SLB conditions and by evaluating the throughwall crack length generally required for measurable leakage. If the throughwall crack length associated with measurable leakage can be defined, the voltage vs crack length relationship of Section 7.3 above can be used to assess the voltage threshold for leakage. The crack length method for estimating a voltage threshold for leakage provides a more physical insight into the threshold estimate.

It can be noted that significant efforts were applied in the 3/4 inch tubing model boiler specimen preparation to obtain the lowest voltage associated with leakage. In the model boilers, leakage is monitored by sensing for lithium which provides a leakage sensitivity of about $3X10^{-3}$ l/hr. Upon detection of any leakage, the model boilers were shutdown and the tube (typically 4 to 6 TSPs) was removed for NDE inspection. TSP intersections with bobbin indications above about 1 volt were removed from the tube for further NDE, leak and burst testing. The smallest bobbin voltage from this program having a measurable leak rate in the leak test facility (capability to measure down to $10^{-3}$ to $10^{-4}$ l/hr) was 4.24 volts (No. 601-1). It is possible that a specimen at 2.79 volts (No. 595-2, throughwall crack length = 0.17 inch) was detected in the model boilers with no measurable leakage in the leak test facility.

As discussed above, the leakage threshold can be assessed by examining crack length data. Table 7-5 shows specimen throughwall crack lengths for no leakage, leakage <1.0 liter/hr. and between >1.0 and 6.0 liter/hr. No leakage has been found for throughwall cracks up to 0.17 inch. With the exception of 601-1, leakage <1 liter/hr occurs for crack lengths of 0.11 to 0.27 inch.

Specimen 601-1 had a 0.05 inch throughwall corrosion crack with a thin ligament suspected to have partially opened at SLB conditions. This specimen had no leakage at operating condition pressure differential and 0.33 liter/hr. at SLB conditions. For this type of indication (above APC repair limit), voltage is a better indicator of leakage potential than even throughwall crack length or total crack length (0.29 inch). Overall, the data of Table 7-5 indicate that throughwall crack lengths >0.1 inch are generally required for SLB leakage. Small leakers, such as 601-1 could result at small crack lengths but voltages significantly exceeding EOC voltages for an IPC with a 1.0 volt repair limit. The Table 7-5 data indicate a throughwall crack length of about 0.14 inch for leakage >1.0 liter/hr.

From Figure 7-10, it is seen that a crack length of 0.1 inch, as an estimated no leakage threshold corresponds to a bobbin voltage of 3.0 volts. A crack length of about 0.14 inch for leakage >1.0 liter/hr. corresponds to about 4 volts. Thus, the leakage thresholds from crack length trends support the leakage thresholds obtained above from voltage considerations only. Overall, the data support no leakage below about 2 volts, leak rate of less than 1 l/hr below about 4 volts, and leakage greater than 1 l/hr above about 4 volts at EOC.

Table 7-1

**Leak Rate & Burst Strength Database for 3/4 Inch Tubing**

| No. | Specimen | Bobbin Amplitude (volts) | Leak Rate (l/hr) N. O. ΔP | Leak Rate (l/hr) SLB ΔP | Burst Pressure (psi) | Preliminary Destructive Exam. Length (inch) Maximum | Preliminary Destructive Exam. Length (inch) Thruwall* |
|---|---|---|---|---|---|---|---|

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* Maximum depth of penetration is shown when crack is not throughwall, or when throughwall length is not available.

Table 7-1 (Continued)

**Leak Rate & Burst Strength Database for 3/4 Inch Tubing**

| No. | Specimen | Bobbin Amplitude (volts) | Leak Rate (l/hr) N. O. ΔP | Leak Rate (l/hr) SLB ΔP | Burst Pressure (psi) | Preliminary Destructive Exam. Length (inch) Maximum | Preliminary Destructive Exam. Length (inch) Thruwall* |
|---|---|---|---|---|---|---|---|

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Notes:

* Maximum depth of penetration is shown when crack is not throughwall, or when throughwall length is not available.

1. Tested at room temperature.
2. Belgian voltages with the cross calibration factor of 1.5 (rather than 1.809).
3. Leak rates measured at room temperature conditions and analytically adjusted to operating conditions by Laborelec.
4. Not measured at 550/130 kHz. Voltage renormalized from 300 kHz data.
5. Observed during burst test at room temperature.
6. Burst pressures from Table 6-7 including adjustments to mean flow stress, and, for Catawba-1 data, for burst testing methods.

Table 7-2

**Burst Pressure Data Used to Develop the Recommended Correlation**

| Bobbin amplitude (volts) | Burst pressure (ksi) |
|---|---|
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Table 7-2 (Continued)

**Burst Pressure Data Used to Develop the Recommended Correlation**

| Bobbin amplitude (volts) | Burst pressure (ksi) |
|---|---|
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* Plant E-4 data

Table 7-3

**SLB Leak Rate Data Used to Develop the Recommended Correlation**

| Bobbin amplitude (volts) | Leak Rate (l/hr) |
| --- | --- |

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Table 7-4

**Summary of Bounding SLB Leak Rates for 3/4 Inch Tubing Voltage Ranges**

| Voltage Range | Bounding SLB Leak Rate | Limiting Indications for Leakage |
|---|---|---|
| ≤ 2.0 volts | 0.0 l/hr | Tube R46C73 from Plant A-2: 2.06 volts (2.81 volts for 7/8 inch tube), 0.17 l/hr |
| 2.0 to 3.5 volts | 1.0 l/hr | Tube R33C96 from Plant E-4: 3.54 volts (1), 1.5 l/hr<br>Model boiler specimens:<br>558-1 (7/8"): 4.79 volts, 4.08 l/hr<br>600-3 (3/4"): 4.25 volts, 44.4 l/hr<br>601-1 (3/4"): 4.24 volts, 0.33 l/hr<br>604-1 (3/4"): 4.93 volts, 5.00 l/hr |
| 3.5 to 4.2 volts | 10 l/hr | Based on NRC recommendation for IPC implementation (D. C. Cook) |
| > 4.2 volts | If projected EOC amplitude for indications in 3/4 inch tube exceeds 4.2 volts, additional evaluation on bounding SLB leak rate will be required | |

1) Utilizes minimum voltage increase in renormalizing Belgian data to APC normalization. Final renormalization factor is expected to significantly increase voltage.

Table 7-5

Dependence of SLB Leakage on Throughwall (TW) Crack Length

| TW - No Leakage | | | TW - <1 lit[illegible]r | | | TW >1 liter/hr. & < 6 l/hr | | |
|---|---|---|---|---|---|---|---|---|
| No. | Bobbin Volts | TW Length | No. | Bobbin Volts | TW Length | No. | Bobbin Volts | TW Length |

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Notes:

1. Bathtub flaw (thin OD ligament) reasonably expected to open crack at SLB $\Delta P$.

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Figure 7-1. Recommended Correlation for Burst Pressure versus Bobbin Voltage

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Figure 7-2. Recommended Correlation for Burst Pressure versus Bobbin Voltage

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Figure 7-3. Recommended Correlation for Burst Pressure versus Bobbin Voltage

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Figure 7-4. Sensitivity Correlation for Burst Pressure versus Bobbin Voltage. Includes Unadjusted Catawba-1 Pulled Tube Data.

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Figure 7-5. Sensitivity Correlation for Burst Pressure versus Bobbin Voltage. Includes Unadjusted Catawba-1 Pulled Tube Data.

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Figure 7-6. Sensitivity Correlation for Burst Pressure versus Bobbin Voltage. Includes Unadjusted Catawba-1 Pulled Tube Data.

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Figure 7-7. Sensitivity Correlation for Burst Pressure versus Bobbin Voltage. Includes Both Unadjusted and Unreliable Catawba-1 Pulled Tube Data.

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Figure 7-8. Sensitivity Correlation for Burst Pressure versus Bobbin Voltage. Includes Both Unadjusted and Unreliable Catawba-1 Pulled Tube Data.

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Figure 7-9 Sensitivity Correlation for Burst Pressure versus Bobbin Voltage. Includes Both Unadjusted and Unreliable Catawba-1 Pulled Tube Data.

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Figure 7-10. Crack Length versus Bobbin Voltage for 3/4 Inch Tubing

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Figure 7-11. Crack Length versus Bobbin Voltage for 7/8 Inch Tubing

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Figure 7-12. Burst Pressure versus Crack Length

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Figure 7-13. Trend Analysis for Predicting Burst Pressure versus Bobbin Voltage for 3/4 Inch Tubing.

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Figure 7-14. Trend Analysis for Predicting Burst Pressure versus Bobbin Voltage for 7/8 Inch Tubing.

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Figure 7-15. SLB Leak Rate versus Bobbin Voltage with Non-leakers at 0.0001 l/hr for 3/4 Inch Tubing.

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Figure 7-16. Recommended Correlation for SLB Leak Rate versus Bobbin Voltage for 3/4 Inch Tubing (with Non-leakers at 0.001 l/hr)

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Figure 7-17. Sensitivity Correlation for SLB Leak Rate versus Bobbin Voltage for 3/4 Inch Tubing (with Non-leakers at 0.001 l/hr). Includes Plant E-4 Data with Voltages Factored by 1.5.

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Figure 7-18. Sensitivity Correlation for SLB Leak Rate versus Bobbin Voltage for 3/4 Inch Tubing (with Non-leakers at 0.001 l/hr). Includes Plant E-4 Data without the 1.5 Factor on Voltages.

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Figure 7-19. SLB Leak Rate versus Crack Length from CRACKFLO Code

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Figure 7-20. SLB Leak Rate versus Crack Length from CRACKFLO Code

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Figure 7-21. Measured versus Predicted SLB Leak Rate Using CRACKFLO Code

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Figure 7-22. Trend Analysis for Predicting SLB Leak Rate versus Bobbin Voltage

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Figure 7-23. Frequency Distribution of Leakers and Nonleakers (at SLB Conditions) versus Bobbin Voltage for 3/4 Inch Voltage Normalization

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Figure 7-24. Probability Distribution of SLB Leakage versus Bobbin Voltage

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Figure 7-25. Frequency Distribution of Specimens for SLB Leak Rate Threshold of 1 l/hr versus Bobbin Voltage for 3/4 Inch Voltage Normalization

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Figure 7-26. Probability of SLB Leak Rate > 1 l/hr versus Bobbin Voltage

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Figure 7-27. Frequency Distribution of Leakers and Nonleakers (at SLB Conditions) versus Bobbin Voltage for 3/4 .nch Data

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Figure 7-28. Probability Distribution of SLB Leakage versus Bobbin Voltage for 3/4 Inch Tubing

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Figure 7-29. Frequency Distribution of Specimens for SLB Leak Rate Threshold of 1 l/hr versus Bobbin Voltage for 3/4 Inch Tubing

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Figure 7-30. Probability of SLB Leak Rate > 1 l/hr versus Bobbin Voltage for 3/4 Inch Tubing

Section 8

# ACCIDENT CONDITION CONSIDERATIONS

This section deals with accident condition loadings in terms of their effects on tube deformation and on tube burst pressure. The most limiting accident conditions relative to these concerns are seismic (SSE) plus loss of coolant accident (LOCA) for tube deformation, and seismic plus steamline/feedline break (SLB/FLB) for tube burst capability.

For the combined SSE + LOCA loading condition, the potential exists for deformation of tubes and subsequent loss of flow area and postulated in-leakage. In-leakage is a potential concern, as secondary to primary leakage may affect the Catawba Unit 1 emergency core cooling system (ECCS) analysis.

Relative to tube burst strength, tube bending stress is induced at the TSP intersections during postulated accident conditions. This bending stress is tensile on one side and compressive on the other, and is oriented in the axial direction. The compressive stress has the potential to open axial cracks and to reduce the burst capability of the cracked tube due to the crack opening.

## 8.1 Tube Deformation Under Combined LOCA + SSE

For the combined SSE + LOCA loading condition, the potential exists for yielding of the tube support plate in the vicinity of the wedge groups, accompanied by deformation of tubes and subsequent loss of flow area and a postulated in-leakage. Tube deformation alone, although it impacts the steam generator cooling capability following a LOCA, is small and the increase in PCT is acceptable. Consequent in-leakage, however, may occur if axial cracks are present and propagate throughwall as tube deformation occurs. This deformation may also lead to opening of pre-existing tight through wall cracks with consequent in-leakage following the event. In-leakage is a potential concern, as secondary to primary leakage may affect the ECCS analysis as a result of the potential for steam binding in the tubes during the core reflood.

### 8.1.1 SSE Analysis

Seismic loads result from motion of the ground during an earthquake. The SSE excitation of the steam generators is defined in the form of acceleration response spectra at the steam generator supports. To perform the non-linear time history analysis, it is necessary to convert the response spectrum input into acceleration time history input. Acceleration time histories for the nonlinear analysis are synthesized from El Centro Earthquake motions, using a frequency suppression/raising technique, such that the resulting spectrum in each of the orthogonal axes closely envelopes the original specified spectrum in the corresponding axis. The resulting three orthogonal time histories of the earthquake are then applied simultaneously at each steam generator support to perform the analysis.

The analysis is performed using the WECAN finite element computer program. The mathematical model consists of three-dimensional lumped mass, beam, and pipe elements as well as general matrix input to represent the specific steam generator piping stiffnesses. The TSP-shell interaction is represented by a rotating, concentric gap-spring dynamic element, using impact damping to account for energy dissipation at these locations. The mathematical model with selected node numbers is shown in Figure 8-1. The primary loop piping and the lower column

support stiffnesses are input as 6x6 matrices. The upper and lower lateral support restraints are represented by compression-only (single-acting) spring elements, with the shell flexibility included for the upper support stiffnesses. At the lower elevation, the support structure is connected to a relatively rigid channel head-foot combination. In modeling the tube bundle internals-to-shell interface, the TSP local shell stiffness, obtained from detailed finite element analyses, is also included. The local shell stiffness at the top TSP location is higher than at lower TSP locations because of its proximity to the upper lateral supports.

The tube bundle geometry is shown in Figure 8-2, with the tube baffles and support plates identified. The flow baffles (E, F, J, K, N, P) are typically not included in the seismic model, both due to the difficulty in representing them accurately in the model, and also because it is conservative in terms of tube stresses to exclude them from the model. If the baffles were included in the model, it is anticipated that contact impact loads for the lower plates would be distributed among the various plates and baffles resulting in reduced loads. However, it is difficult to estimate these loads, due to the flexible nature of the partition plate which forms one of the support members for these plates. For the flow baffles, it is concluded to be conservative to use the loads developed for the support plates (C/D, G/H, L/M).

Seismic loads for this analysis are taken from an analysis of a similar model steam generator, and have been determined to be conservative by comparing the spectra and TSP loads from three different plants, all having similar steam generator geometries. Results from the bounding analysis show the flow distribution baffle (plates A/B in Figure 8-2) to not experience seismic impact loads. Thus, it is judged that there will not be any tubes at the flow distribution baffle location that are potentially susceptible to in-leakage.

For reasons that will be discussed later, tube deformation calculations are performed for three TSP groupings. Discussions of the groupings along with the resulting TSP loads is contained in Section 8.1.3.

### 8.1.2 LOCA Analysis

LOCA loads are developed as a result of transient flow, and temperature and pressure fluctuations following a postulated primary coolant pipe break. Based on the prior qualification of the Catawba steam generators for leak before break requirements for the primary piping, the limiting LOCA event is either the accumulator line break or the pressurizer surge line break. However, bounding LOCA load calculations for Catawba for the accumulator or pressurizer surge lines are not available. As a conservative approximation, the available LOCA loads for the primary piping breaks are used to bound the smaller pipe breaks. The large pipe break loads have been shown for other model steam generators to be several times larger than the smaller pipe breaks, and thus, it is judged that these loads form a conservative basis for the small pipe breaks for Catawba.

As a result of a LOCA event, the steam generator tubing is subjected to the following loads:

1) Primary fluid rarefaction wave loads.

2) Steam generator shaking loads due to the coolant loop motion.

3) External hydrostatic pressure loads as the primary side blows down to atmospheric pressure.

4) Bending stresses resulting from bow of the tubesheet due to the secondary-to-primary pressure drop.

5) Bending of the tube due to differential thermal expansion between the tubesheet and first tube support plate following the drop in primary fluid temperature.

Loading mechanisms (3) through (5) above are not an issue since they are a non-cyclic loading condition and will not result in crack growth, and/or result in a compressive membrane loading on the tube that is beneficial in terms of negating cyclic bending stresses that could result in crack growth.

8.1.2.1 LOCA Rarefaction Wave Analysis

The principal tube loading during a LOCA is caused by the rarefaction wave in the primary fluid. This wave initiates at the postulated break location and travels around the tube U-bends. A differential pressure is created across the two legs of the tube which causes an in-plane horizontal motion of the U-bend. This differential pressure, in turn, induces significant lateral loads on the tubes.

The pressure-time histories input to the structural analysis are obtained from transient thermal-hydraulic (T/H) analyses, using the MULTIFLEX computer code. A break opening time of 1.0 msec of full flow area, simulating an instantaneous double-ended rupture is assumed to obtain conservative hydraulic loads. The fluid-structure interaction effect due to the flexibility of the divider plate between the inlet and outlet plenums of the primary chamber is included in the analysis. Pressure time histories are calculated for two tube radii, identified as the average and maximum radius tubes. A plot showing the tube representation in the T/H model is provided in Figure 8-3. Typical primary pressure time-histories following a LOCA are shown in Figure 8-4 for nodes 8-15 (in Figure 8-3) on the cold leg of the largest radius U-bend. For the structural evaluation, the tube loads result from the hot-to-cold leg &P. Plots showing the hot-to-cold leg &P for the maximum and average radius tubes are provided in Figures 8-5 and 8-6, respectively.

For the rarefaction wave induced loadings, the predominant motion of the U-bends is in the plane of the U-Bend. Thus, the individual tube motions are not coupled by the anti-vibration bars. Also, only the U-bend region is subjected to high bending stresses. Therefore, the structural analysis is performed using single tube models limited to the U-bend and the straight-leg region over the top two TSP's. The node and element numbering for a typical single tube model is shown in Figure 8-7

The tube structural model consists of three-dimensional straight and curved pipe elements. The mass inertia is input as effective material density and includes the weight of the tube, weight of the primary fluid inside the tube and the hydrodynamic mass effects of the secondary fluid. Damping coefficients are defined to realize a maximum damping of 4% at the lowest and highest significant frequencies of the structure.

To account for the varying nature of the tube/TSP interface with increasing tube deflection, three sets of boundary conditions are considered. For the first case, the tube is assumed to be laterally supported at the TSP, but is free to rotate. This is designated as the "continuous" condition, as the finite element model for this case models the tube down to the second TSP. As the tube is loaded, it moves laterally and rotates within the TSP. After a finite amount of rotation, the tube will become wedged within the TSP and is no longer able to rotate. The second set of

boundary conditions, therefore, considers the tube to be fixed at the top TSP location, and is referred to as the "fixed" case. Continued tube loading causes the tube to yield in bending at the top TSP and eventually a plastic hinge develops. This represents the third set of boundary conditions, and is referred to as the "pinned" case.

For the average radius tube, only the continuous case is analyzed. Results for the continuous case analysis indicate that both the tube rotations and moments at the TSP nodes are small compared to those required to cause the locking-in or plastic hinge, respectively, at the support locations. Since the main objective in analyzing the average radius tube is to determine the maximum reaction load on the TSP due to the overall response of the tube bundle, the continuous configuration is the most appropriate for the average radius tube analysis. In addition to the pressure induced bending loads, the rarefaction wave analysis also includes the membrane stresses due to the primary-to-secondary &P. Each of the dynamic solutions results in a force time history acting on the TSP. These time histories show that the peak responses do not occur at the same time during the transient. However, it is assumed for this analysis that the maximum reaction forces occur simultaneously. Using these results, a TSP load corresponding to the overall bundle is then calculated. A summary of the resulting TSP forces is provided in Section 8.1.3.

8.1.2.2 LOCA Shaking Loads

Concurrent with the rarefaction wave loading during a LOCA, the tube bundle is subjected to additional bending loads due to the shaking of the steam generator caused by the break hydraulics and reactor coolant loop motion. However, the resulting TSP loads from this motion are small compared to those due to the rarefaction wave induced motion.

To obtain the LOCA induced hydraulic forcing functions, a dynamic blowdown analysis is performed to obtain the system hydraulic forcing functions assuming an instantaneous (1.0 msec break opening time) double-ended guillotine break. The hydraulic forcing functions are then applied, along with the displacement time-history of the reactor pressure vessel (obtained from a separate reactor vessel blowdown analysis), to a system structural model, which includes the steam generator, the reactor coolant pump and the primary piping. This analysis yields the time history displacements of the steam generator at its upper lateral and lower support nodes. These time-history displacements formulate the forcing functions for obtaining the TSP loads due to LOCA shaking of the steam generator.

To evaluate the steam generator response to LOCA shaking loads, the computer code WECAN is used. The model used is similar to the one used for the seismic analysis, discussed previously. The steam generator support elements are removed, however, as the LOCA system model accounts for their influence on the steam generator response. Input to the WECAN model is in the form of acceleration time histories at the tube/tubesheet interface. These accelerations are obtained by differentiation of the system model displacement time histories at this location. Acceleration time histories for all six degrees of freedom are used. Past experience has shown that LOCA shaking loads are small when compared to LOCA rarefaction loads. For this analysis, these loads are obtained from the results of a prior analysis for a Model D steam generator.

8.1.3 Combined Plate Loads

A summary of the resulting LOCA and seismic loads is provided in Table 8-1. In combining loads, the LOCA shaking and LOCA rarefaction loads are combined algebraically, while LOCA and SSE loads are combined using the square root of the sum of the squares. The TSP loads, which are

reacted by wedge groups located at their periphery, are divided into three groups based on the wedge group arrangements for the plates. The number of wedge groups varies in number, size, and orientation among the various plates. The wedge group orientation for plates C/D and G/H is shown in Figure 8-8, and for plates Q-T in Figure 8-9. The wedge group sizes and locations for the remaining plates are combinations of plates C/D and G/H. Typically, the wedge groups are symmetrical about the centerline of the bundle, and also hot-leg to cold-leg. TSP C/D and G/H are two cases where hot-to-cold leg symmetry does not exist.

Relative to wedge group size for the Catawba steam generators, the wedge groups are comprised of either two or three wedges, each two inches wide. Thus, the overall wedge group size is either 4 or 6 inches. The wedge group size is important, because it affects the local distribution of load into the neighboring tubes.

In reacting the load among the various wedge groups, a cosine distribution is assumed among the wedges that are loaded. Typically, only half of the wedge groups are loaded at any given time. In determining the distribution of load for seismic and LOCA loads, the directionality of the load is considered. LOCA loads are uni-directional, in that they only act in the plane of the U-bend. Seismic loads on the other hand are random, and can act in any direction. Calculations are performed to determine load factors for the various plates, grouping the TSP by commonality of their wedge group locations. The load factors are not a function of the wedge group size, only of location.

Applying these load factors to the overall TSP loads in Table 8-1, loads for each of the wedge groups are determined. A summary of the individual wedge loads is provided in Table 8-2.

8.1.4 Tube Deformation

In estimating the number of deformed tubes, the results of TSP crush tests for Model D steam generators are used. The deformation criteria for establishing a tube as being susceptible to in-leakage has been defined to be [ ]a,c. In reporting the crush test results, tube deformations were reported for various deformation magnitudes. This is the smallest deformation reported. Although test data is not available for leak rate as a function of tube deformation, it is judged that deformation levels of this magnitude will not result in significant in-leakage.

Using the crush test data, a correlation is developed between elastic plate load and the number of tubes that would have a deformation of [ ]a,c or greater. It is this correlation, summarized in Table 8-3, that is used to approximate the number of affected tubes. Summaries of the number of potentially affected tubes for each of the wedge groups are provided in Tables 8-4 through 8-7. 8.1.5 Tube Maps / Summary Tables for Potentially Affected Tubes Catawba is a four-loop plant. The numbering scheme used by Duke Power in identifying tube rows and columns is the same for all four loops. The reference configuration used in identifying tube locations is shown in Figure 8-10. As shown in the figure, the nozzle and tube column 1 are located at 0 .

Maps showing the location of the potentially susceptible tubes are provided in Figures 8-11 through 8-21. Tabular summaries of the tubes that are potentially susceptible to collapse and subsequent in-leakage are summarized in Tables 8-8 through 8-13.

Identification of the potentially susceptible tubes is based on the crush test results. The wedge / tube configurations considered in the tests are not identical to those for the Catawba steam

generators. As such, it is not possible to identify exactly the tubes that might be limiting at each wedge group. Thus, due to the uncertainties involved, there are more tubes identified at each wedge group as being limiting than estimated in the calculations.

Finally, Table 8-14 provides an index of the applicable tables and figures identifying the potentially susceptible tubes for each TSP.

## 8.2 Tube Deformation Under Combined SLB + SSE

Since the tube support plates provide lateral support to tube deformation that may occur during postulated accident conditions, tube bending stress is induced at the TSP intersections. This bending stress is distributed around the circumference of the tube cross section, tension on one side and compression on the other side, and is oriented in the axial (along the tube axis) direction. Axial cracks distributed around the circumference will therefore either experience tension stress that tends to close the crack or compressive stress that tends to open the crack. The compressive stress has the potential then to reduce the burst capability of the cracked tube due to the crack opening.

Test results are summarized in Table 8-15 that demonstrates that an outer diameter bending stress on the order of the yield strength of the tube material is required before any significant effect is realized in the burst pressure capability of a cracked tube (WCAP-7832-A). A tube with through wall slots (Figure 8-22) was tested under combined beam bending and internal pressure to achieve the burst pressures listed. The 0.8 inch long through wall slots were oriented on the compressive and tensile sides and on the bending neutral axis. The neutral axis and tensile side burst results are almost identical and within normal data scatter of the burst pressure without bending stress.

Burst capability during accident conditions is required to be at least 2650 psi, the maximum primary to secondary pressure differential following the SLB or FLB. Regulatory Guide 1.121 requires that SSE be combined with these events. Therefore, tube bending stresses from SSE at the TSP elevations must be combined with the SLB/FLB pressure differential to establish that burst capability meets SLB/FLB requirements. Rather than retest burst capability with combined bending stress, it is sufficient to establish that the SSE maximum tube bending stress at any TSP elevation is less than the tube material yield strength at operating temperature based on the test results of Table 8-15.

Based on the results of the seismic analysis judged to be conservative for Catawba, discussed in Section 8.1.1, the maximum tube bending stress occurs at the top TSP and has a magnitude of 34.07 ksi for tubes with end of life wall thinning due to general erosion and corrosion. For the loser TSPs, the tube bending stress is 6.59 ksi. The yield strength of 3/4 x 0.043 inch mill annealed tubing at 650 $^{O}$F is 39 ksi using 95% confidence / 95% probability, lower tolerance limit properties (WCAP-12522). Burst capability is therefore not affected by the SSE bending stress.

Table 8-1

**Summary of LOCA Plus Seismic TSP Loads**
**Catawba Unit 1 Steam Generators**
**Steam Generator Inlet Break**

[ ] a

Table 8-2

Summary of TSP Wedge Loads
Catawba Unit 1 Steam Generators

a

Table 8-3

Number of Tubes with $\Delta D > 0.030$ Inch Versus Load
Catawba Unit 1 - Model D Steam Generator

[ ]a

Table 8-4

Number of Tubes with ΔΓ > 0.030 Inch
Catawba Unit 1 Steam Generators
Steam Generator Inlet Break
TSP C/D, L/M

[ ]a

Table 8-5

Number of Tubes with $\Delta D$ > 0.030 Inch
Catawba Unit 1 Steam Generators
Steam Generator Inlet Break
TSP E, F, G/H, J, K, N, P

[ ]a

Table 8-6

Number of Tubes with ΔD > 0.030 inch
Catawba Unit 1 Steam Generators
Steam Generator Inlet Break
TSP Q, R, S

[ ] a

Table 8-7

Number of Tubes with $\Delta D$ > 0.030 inch
Catawba Unit 1 Steam Generators
Steam Generator Inlet Break
TSP T

[ ]a

Table 8-8

Summary of Tubes Excluded from IPC
Catawba Unit 1 Steam Generators
TSP C/D

[ ] a

Table 8-9

Summary of Tubes Excluded from IPC
Catawba Unit 1 Steam Generators
TSP G/H

[ ]a

Table 8-10

Summary of Tubes Excluded from IPC
Catawba Unit 1 Steam Generators
TSP L/M

[ ]a

Table 8-11

Summary of Tubes Excluded from IPC
Catawba Unit 1 Steam Generators
TSP E, F, J, K, N, P

[ ] a

Table 8-12

Summary of Tubes Excluded from IPC
Catawba Unit 1 Steam Generators
TSP O, R, S

[ ]a

Table 8-13

Summary of Tubes Excluded from IPC
Catawba Unit 1 Steam Generators
TSP T

a

Table 8-14

Summary of Tables and Figures for TSP Row / Column Identification

| TSP | Summary Tables | Tube Map Figures |
|---|---|---|
| C | 8-8 | 8-11 |
| D | 8-8 | 8-12 |
| E | 8-11 | 8-17 |
| F | 8-11 | 8-17 |
| G | 8-9 | 8-13, 8-14 |
| H | 8-9 | 8-15, 8-16 |
| J | 8-11 | 8-17 |
| K | 8-11 | 8-17 |
| L | 8-10 | 8-11 |
| M | 8-10 | 8-17 |
| N | 8-11 | 8-17 |
| P | 8-11 | 8-17 |
| Q | 8-12 | 8-18, 8-19 |
| R | 8-12 | 8-18, 8-19 |
| S | 8-12 | 8-18, 8-19 |
| T | 8-13 | 8-20, 8-21 |

Table 8-15

Combined Bending and Internal Pressure Burst Tests

on Tubes with Through Wall Slots

a

[ ]a

Figure 8-1. Seismic Model Representation of Steam Generator

a

Figure 8-2. Tube Bundle Geometry

[a]

Figure 8-3. Thermal / Hydraulic LOCA Tube Model

[ ][a]

Figure 8-4. LOCA Pressure Time Histories, Maximum Radius Tube Nodes 8-15

[ ][a]

Figure 8-5. LOCA Pressure Time History, Hot-to-Cold Leg Pressure Differential, Maximum Radius Tube

[ ][a]

Figure 8-6. LOCA Pressure Time History, Hot-to-Cold Leg Pressure Differential, Average Radius Tube

a

Figure 8-7. Structural LOCA Tube Model

[a]

Figure 8-8. Wedge Group Orientation, Plates C/D, G/H

[a]

Figure 8-9. Wedge Group Orientation, Plates Q-T

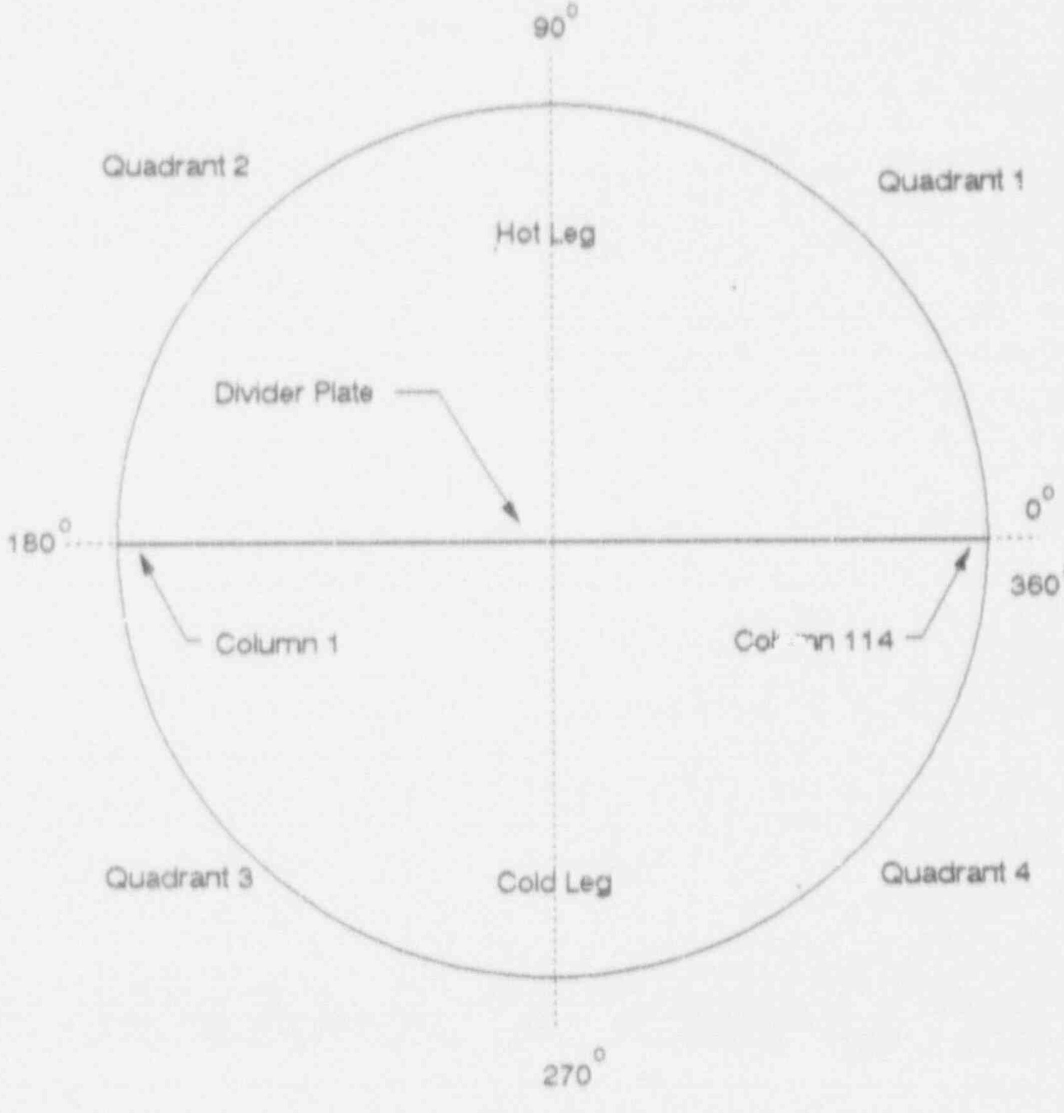



Figure 8-10. Reference Configuration for Tube Identification Looking Down on Steam Generator, Catawba Site Specific Convention

[ ][a]

Figure 8-11. Tubes Excluded from IPC, TSP C,L - Quadrant 1

a

Figure 8-12. Tubes Excluded from IPC, TSP D - Quadrant 4

[ ]a

Figure 8-13. Tubes Excluded From IPC, TSP G - Quadrant 1

a

[ ]

Figure 8-14. Tubes Excluded from IPC, TSP G - Quadrant 2

a

Figure 8-15. Tubes Excluded from IPC, TSP H - Quadrant 3

a

Figure 8-16. Tubes Excluded from IPC, TSP H - Quadrant 4

[ ][a]

Figure 8-17. Tubes Excluded from IPC, TSP E, F, J, K, M, N, P - Quadrant 4

a

Figure 8-18. Tubes Excluded from IPC, TSP Q, R, S - Quadrant 1

[ ] a

Figure 8-19. Tubes Excluded from IPC, TSP Q, R, S - Quadrant 2

[ ]a

Figure 8-20. Tubes Excluded From IPC, TSP T - Quadrant 1

[ ]a

Figure 8-21. Tubes Excluded from IPC, TSP T - Quadrant 2

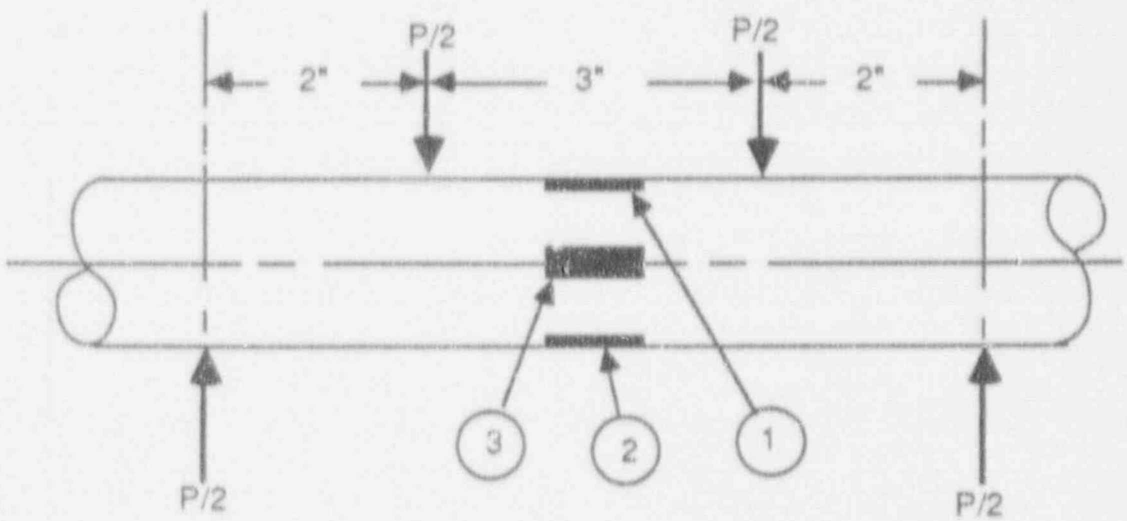



Figure 8-22. Externally Applied Bending Load and Locations of Through Wall Slots

## Section 9

## CATAWBA UNIT 1 INSPECTION RESULTS

### 9.1 Inspection Scope

For the end of cycle 6 inspection (1EOC6-'92) 100% of the support plate intersections in each steam generator, both hot leg and cold leg, were inspected with bobbin probes - 0.610 inch diameter for the hot leg and 0.630 inch diameter for the cold leg. All intersections exhibiting possible flaw indications were recorded notwithstanding the amplitude of the signal. Eddy current (EC) frequencies used for analysis of the bobbin data were as follows: 550 kHz - prime inspection frequency; 400 kHz for continuity with prior inspections; 130 kHz for support plate suppression in mixing; and 35 kHz for support plate location. The Duke Power EC guidelines for Catawba Unit 1 used each of the flaw sensitive frequencies (550 kHz, 400 kHz, 130 kHz) along with several mix channels for flaw detection. Measurements of possible ODSCC voltages were performed in the 550 kHz/130 kHz differential mix channel to provide consistency with the industry data base, as described in Section 5.

RPC (rotating pancake coil) inspection was performed for all possible support plate bobbin indications equal to or greater than 1.0 volt, as well as on a substantial fraction of the possible indications below 1.0 volt. All bobbin indications 1.0 volt or greater in amplitude, which were confirmed as flaws with the RPC probe, were designated for repair; those which were unconfirmed and those less than 1.0 volt whether tested or not are the subject of this report.

### 9.2 Summary of Inspection Results

As a result of the hot leg bobbin inspection program, 6941 support plate indications possibly reflecting ODSCC were identified. Table 9-1 shows the distribution of the TSP indications among the four steam generators. The amplitude distribution of these indications was such that less than 5% exceeded 1.0 volt. Prior outage tube removal operations (1EOC5) had established the probable nature of these indications as ODSCC, similar in character to the degradation documented at Plants A-1, A-2, L, D-1 and C-2. The distribution of the indications relative to elevation in the tube bundle, shown in Table 9-2, confirmed the pattern of greatest incidence at the lower hot leg support plates which has been typical of support plate ODSCC observed in other plants. Figure 9-1 illustrates the data in histogram format.

The 1H level is a flow distribution baffle with enlarged tube holes which directs increased flow past the tube surface; the concentration of aggressive species is limited compared to the nominal support plate crevice geometry. This explains why the number of indications are low at the 1H location.

RPC testing was performed on all indications greater than 1.0 volt and a substantial fraction of those 1.0 volt or less. The results of this program are tabulated in Table 9-3. To satisfy the interim plugging criteria commitments, an augmented RPC program was conducted over and above the confirmatory testing of all support plate bobbin flaw indications ≥1.0 volt. This program contained two elements, as follows:

1) Support plate dent indications ≥5.0 volts,
2) Support plate non-flaw residuals (artifacts) with amplitudes greater than 1.0 volt.

These signal categories were tested to provide confidence that axial cracking indications ≥1.0 volt were not being mashed by interferences. Table 9-4 provides for each steam generator the number of such locations/tubes which were examined; none of these intersections - 136 dents, 2 artifacts - exhibited ODSCC indications consistent with bobbin indications ≥1.0 volt, nor was any circumferential cracking noted. Small axial indications observed were placed on the tube repair list.

Except for steam generator C, very low fractions of the bobbin indications examined with RPC probes exhibited the patterns associated with axial ODSCC. The Zetec 3-coil MRPC probes used incorporate a pancake coil, an axially wound coil preferentially sensitive to circumferential cracking and a circumferentially-wound coil preferentially sensitive to axial cracking.

The observed distribution of the bobbin indication relative to support plate elevation coupled with the generally low RPC confirmation rate supports the evaluation that significant support plate ODSCC is found only on hot leg side of the tube bundle. Cold leg indications were considered independently of the IPC criteria; disposition was made in conformance with the usual Tech. Spec. plugging criteria.

## 9.3 Cross Calibration of ASME Standards

In order to reduce the uncertainty associated with the bobbin voltage amplitudes from the current (1992) inspection results, the calibration standards used during the inspection were cross calibrated against the reference laboratory standard used in the APC data acquisition. This was accomplished as described below.

A new ASME standard (AS-015-91) was first eddy current tested in the laboratory along with the reference laboratory standard (AS-009-91) used for the APC data acquisition. The former is called the transfer standard. The test was performed usnig a Zetec 610 ULC probe and was repeated ten times (ten separate passes through the standards). The test results indicated that for the 550/130 kHz mix, when the 20% holes in the reference laboratory standard was set to 2.75 volts, the corresponding reading for the 20% holes in the transfer standard was 3.22 volts. The transfer standard was then shipped to the Catawba site and each of the ASME standards used during the 1992 inspection was calibrated against the transfer standard. These tests were also repeated ten times.

The results of the cross calibration for the various ASME standards are listed in Table 9-5. Using this data, correction factors were developed for each ASME standard. The listing of ASME standards used for the various eddy current data tapes in each steam generator during the 1992 inspection are summarized in Table 9-6. The appropriate correction factor was applied to each TSP indication based on which ASME standard was used during the data acquisition for that tube. The bobbin coil eddy current voltage amplitudes developed in this manner formed the basis for the assessment of TSP indications.

## 9.4 1992 Inspection Results at TSP Elevations

The eddy current data analysis guidelines applied for the evaluation of indications at TSP elevations are described in Appendix A. Further, the bobbin amplitudes were multiplied by the appropriate correction factors developed from the cross calibration of the ASME standards as discussed in Section 9.3 above. Thus:

1) The TSP indication distributions were developed based on eddy current results at the 550/130 kHz differential mix, since this data is available from the current (1992) inspection. This frequency mix is consistent with the APC database.

2) The eddy current data analysis was performed by normalizing the 550/130 kHz mix signal for the 20% holes in the ASME standards to 2.75 volts.

There were a total of 6941 indications in the population: 713 in steam generator A, 781 in B, 1970 in C, and 3477 in D. With the exception of one 3.55 volt indication in steam generator C, all indications were less than 3 volts in amplitude. A frequency distribution of the TSP indications in all generators is shown in Figure 9-2. A cumulative probability distribution is also shown in the figure. It shows that over 97% of the indications are less than 1 volt in amplitude and 76% below 0.5 volt. The average signal amplitude of all indications is 0.38 volt. The frequency distribution for each of the four steam generators is shown in Figures 9-3 through 9-6.

## 9.5 Voltage Growth Rates

For the 1992 outage, data analysis had first been performed using analysis guidelines typically used for depth based plugging criteria. In order to apply voltage based plugging criteria, the data from indications at tube support plates (TSP) were reanalyzed using guidelines consistent with the application of voltage based plugging criteria (APC). The specific guidelines used for this reanalysis is described in Appindix A. The evaluation described below was performed using the reanalysis results.

The voltage growth rate evaluation was performed using the results of 541 TSP indications. These indications were selected by Duke Power based on their (largest) amplitudes from the original analysis. Inclusion of all TSP indications in the growth rate evaluation would have added over a week to the initiation and completion of this critical task. Since the largest amplitude indications from the current outage were used for this analysis, the calculated growth rates (averages and 90 and 99 percentiles) are likely to be very conservative. The 541 indications were made up of 90, 117, 197 and 137 from steam generators A, B, C and D, respectively.

In order to determine growth rates, voltage amplitudes of an indication during successive inspections should be compared. Therefore, the eddy current data for these 541 indications from the 1991 inspection were reanalyzed using the same guidelines (Attachment A) so as to get a consistent set. The existing APC database for 3/4 inch diameter tubes uses eddy current results from 550/130 kHz differential mix. In order to accommodate this, the current (1992) Catawba-1 eddy current inspection was performed at frequencies including 130, 400 and 550 kHz. However, the 1991 Catawba-1 inspection did not utilize the 550 or 130 kHz frequency. The closest frequency mix available was 400/100 kHz. This frequency mix was therefore used for the 1991 data. For the growth estimation therefore, it was decided to use the 400/130 kHz mix from the current inspection.

To convert the signal amplitudes at 400/100 kHz to an equivalent result at 550/130 kHz, a conversion factor was used. This correlation was developed from the eddy current test results of Catawba-1 pulled tubes performed in the past. The data and the excellent regression fit are shown in Figure 5-3. The correlation is:

$$V(550/130) = 1.094 * V(400/100) + 0.143 \qquad (9\text{-}1)$$

where V (550/130) and V (400/100) are signal amplitudes at the two corresponding frequencies.

This correction is applied to both the 1992 data (400/130 kHz) and the 1991 data (400/100 kHz). The voltage growth was determined for each of the 541 indications.

The above correction factor (Equation 9-1) is an overcompensation for the 1992 results since this data is at 440/130 rather than 400/100 kHz. Comparison of current results from a sample of 96 indications from steam generator C of Catawba-1 (see Figure 9-7) suggests a factor of:

$$V(550/130) = 1.038 * V(400/130) - 0.047 \quad (9\text{-}2)$$

In order to account for this, the calculated growth rates were reduced by a factor of 0.95, this being the ratio of the coefficients in the above equations (1.038/1.094).

This was substantiated independently by data obtained on an ASME standard using the three mixes. This data is listed in Table 5-2. In each case, the mix channel was normalized to 2.75 volts for the 20% holes and data taken for the other machined flaws in the standard. The results show increasing voltage amplitudes for the 400/100, 400/130, and 550/130 kHz, in that order. Further, the magnitude of the difference is comparable to the 5% value used.

The resulting growth rates are plotted against beginning of cycle (BOC) amplitudes in Figure 9-8. A frequency distribution of the growth rates is shown in Figure 9-9. This figure also shows a cumulative distribution function. With the exception of one indication with a growth rate of 2.7 volts, all indications had voltage growths less than 2 volts. Indeed, only 10 of the 541 indications (less than 2%) had growth rates exceeding 1 volt.

The average growth rate for all indications in the growth rate study was 0.18 volt during the cycle. It may be noted from Figure 9-8 that, in general, the indications with larger BOC amplitudes had loser growth rates. To assess this further, the growth rate averages were determined separately for indications with BOC amplitudes below and above 0.75 volt. The average growth for indications with BOC amplitudes below 0.75 volt was 0.21 volt/cycle. The average growth for BOC amplitudes at or above 0.75 volt was 0.14 volt/cycle, considerably smaller. These results as well as some other statics are summarized in Table 9-7.

The 1991-92 operating cycle (Cycle 6) consisted of 0.80 effective full power years (EFPY) of operation. Per Duke Power the next operating cycle is planned to be 0.96 EFPY. Therefore, growth rate projection for the next cycle is obtained using prorating the Cycle 6 growth rates by the ratio of the EFPYs (0.96/0.80). A frequency distribution of the EFPY adjusted growth projections (for Cycle 7) is shown in Figure 9-10. A cumulative distribution function is also shown in the figure.

Growth rate during Cycle 5 was determined using reanalyzed signal amplitudes of TSP indications in tubes plugged during 1991. The reanalysis was performed using the eddy current analysis guidelines shown in Appendix A. 158 tubes had been plugged for TSP indications during the 1991 outage. Eddy current results from two consecutive inspections are needed to estimate growth rates. NDE results from both 1990 and 91 were available for only 126 of these indications.

These data (both 1990 and 1991) were taken at 400/100 kHz mix. The adjustment factor obtained from the laboratory NDE of the Catawba-1 pulled tubes (Equation 9-1) was applied to convert the above signal amplitudes to equivalent 550/130 kHz voltages. Growth rates were then calculated as the difference between the 1991 and 1990 values. The average growth rate for the cycle was 0.10 volt, lower than the 0.18 volt calculated for the last cycle. These results are summarized in Table 9-7. Although the average was smaller, the standard deviation of 0.35 volt was comparable to the 0.36 volt obtained for the 1991-92 cycle. The resulting average percent growth rate is 13% for cycle 5. The growth rates were higher for indications with BOC amplitudes smaller than 0.75 volt compared to those with BOC amplitudes greater than or equal to 0.75 volt. This is consistent with what has been observed at other domestic plants. A frequency distribution of the voltage growth rates during Cycle 5 is shown in Figure 9-11. The upper ends of the voltage ranges are shown in the abscissa. Also a cumulative frequency distribution in percentage is shown in the figure as a curve with the scale shown on the right hand side.

As discussed above, only one intersection (tube R12 C111 at 2H in steam generator C) had growth rate exceeding 2 volts during Cycle 6. Further evaluation of this indication was performed as described below. This indication had amplitudes of 3.39 volts in the 400/130 kHz and 3.44 volts in the 550/130 kHz mix channels. Converting the 400/130 kHz value using Equation 9-2 results in a value of 3.47 volts at 550/130 kHz. This agrees with the actual measured value of 3.44 volts. The ASME standard with serial number 50415 was used during the bobbin coil testing of this tube in 1992 (see Table 9-6). Using the correction factor of 1.033 applicable for this standard results in a corrected 1992 amplitude of 3.55 volts. Resizing of the 1991 data for this indication performed during 1992 resulted in an amplitude of 0.78 volts at the 400/100 kHz test frequency. Since bobbin testing at the 550 kHz frequency was not performed during the 1991 inspection, the 400/100 kHz data was ussed along with Equation 9-1 to obtain the voltage for 1991. This resulted in an amplitude of 1.00 volts at the 550/130 kHz mix. During 1991, the ASME standard 50290 was used for this tube. This ASME standard has a correction factor of 1.236. Thus the corrected amplitude for this indication from 1991 is 1.24 volts. This results in a growth rate of 2.31 volts (3.55-1.24) during Cycle 6. This is the largest growth observed at any TSP intersection during Cycle 6. This also reveals that the growth rates for most intersections (particularly in steam generator C) are somewhat lower than calculated above without the detailed accounting for the correction factors in ASME standards. The projected maximum growth rate for Cycle 7, using the adjustment based on EFPY ratios between Cycles 7 and 6, is then 2.77 volts.

Table 9-1

**Catawba Unit 1**

**EOC-6 Hot Leg Support Plate Bobbin Indications**

| Steam Generator | Total TSP Indications | Indications ≥1.0 volt |
|---|---|---|
| 1A | 713 | 6 |
| 1B | 781 | 7 |
| 1C | 1970 | 100 |
| 1D | 3477 | 57 |
| Total | 6941 | 170 |

Table 9-2

**Catawba Unit 1**

**Distribution of Indications Over Support Plates Elevations**

| Hot Leg TSP Elevation | Steam Generator 1A | 1B | 1C | 1D | Total |
|---|---|---|---|---|---|
| 1H | 1 | 0 | 1 | 0 | 2 |
| 2H | 196 | 155 | 548 | 469 | 1368 |
| 3H | 139 | 218 | 445 | 1002 | 1804 |
| 4H | 109 | 185 | 474 | 839 | 1607 |
| 5H | 60 | 102 | 197 | 347 | 706 |
| 6H | 52 | 40 | 154 | 493 | 739 |
| 7H | 110 | 43 | 134 | 266 | 553 |
| 8H | 46 | 38 | 17 | 61 | 162 |
| Total | 713 | 781 | 1970 | 3477 | 6941 |

Table 9-3

**Catawba Unit 1**

**EOC6 RPC Test Results at TSP Locations**

| Steam Generator | RPC Examined | RPC Confirmed |
|---|---|---|
| 1A | 50 | 5 |
| 1B | 223 | 7 |
| 1C | 896 | 263 |
| 1D | 1358 | 130 |
| Total | 2527 | 405 |

Table 9-4

**Number of Tubes Examined During EOC-6 Augmented RPC Program**

| | SGA | SGB | SGC | SGD |
|---|---|---|---|---|
| Dents | | | | |
| BOB | | | | |
| Tubes | 14 | 16 | 43 | 5 |
| Ind | 16 | 67 | 47 | 6 |
| MRPC | | | | |
| Tubes | 4 | 58 | 38 | 4 |
| Ind | 4 | 64 | 42 | 5 |
| Artifacts (R36) | | | | |
| BOB | | | | |
| Tubes | 0 | 0 | 2 | 0 |
| Ins | 0 | 0 | 2 | 0 |
| MRPC | | | | |
| Tubes | 0 | 0 | 2 | 0 |
| Ind | 0 | 0 | 2 | 0 |

Table 9-5

Cross Calibration of ASME Standards Against the Transfer Standard

| | PROBE | 590 | | 610 MULC | | 610 SFRM | | 630 MULC | |
|---|---|---|---|---|---|---|---|---|---|
| | Standard | 1 | P1 | 1 | P1 | 1 | P1 | 1 | P1 |
| TAPE 1 | AS-01591 | 4.560 | 3.246 | 4.[illegible]0 | 3.236 | 4.560 | 3.241 | 4.560 | 3.244 |
| | Z-9617 | 3.316 | 2.377 | 3.382 | 2.389 | 3.329 | 2.345 | 3.374 | 2.386 |
| TAPE 2 | 50390 | 4.287 | 2.994 | 3.980 | 2.783 | 4.032 | 2.806 | 4.112 | 2.871 |
| | 50391 | 3.954 | 2.760 | 3.844 | 2.710 | 3.853 | 2.670 | 3.786 | 2.636 |
| | 50392 | 4.408 | 3.131 | 4.125 | 2.939 | 4.039 | 2.829 | 4.055 | 2.869 |
| | 50415 | 4.229 | 3.141 | 3.992 | 2.841 | 3.916 | 2.749 | 3.971 | 2.815 |
| | 50416 | 3.985 | 2.839 | 3.852 | 2.736 | 3.885 | 2.750 | 3.797 | 2.714 |
| | 50417 | 4.469 | 3.178 | 4.365 | 3.134 | 4.293 | 3.067 | 4.199 | 3.004 |
| | 50418 | 4.180 | 2.967 | 3.895 | 2.746 | 3.840 | 2.675 | 3.831 | 2.690 |
| | 50419 | 3.823 | 2.661 | 3.607 | 2.566 | 3.619 | 2.507 | 3.617 | 2.562 |
| | AS-01591 | 4.561 | 3.183 | 4.560 | 3.224 | 4.560 | 3.207 | 4.560 | 3.256 |

1: 550 Hz
P1: 550/130 Hz Mix

Table 9-6

**Catawba Unit-1, 1992 Inspection**

**ASME Standards Used and Corresponding Calibration Corrections**

| Steam Generator | ASME Standard | Tapes Numbers Calibrated Using the ASME Standard | Calibration Correction |
|---|---|---|---|
| A | 50391 | 1 to 37 | 0.9855 |
| A | 50417 | 39 to 84 | 1.1396 |
| B | 50415 | 50 to 85 | 1.0331 |
| B | 50417 | 1 to 49 | 1.1396 |
| B | 50418 | 86 | 0.9985 |
| C | 50415 | 1 to 48 | 1.0331 |
| C | 50417 | 49 | 1.1396 |
| C | 50418 | 50 to 86 | 0.9985 |
| D | 50391 | 38, 39, 41 | 0.9855 |
| D | 50416 | 39, 41 to 50, 52 to 80, 82, 83 | 0.9949 |
| D | 50417 | 84, 85 | 1.1396 |
| D | 50419 | 1 to 37, 40, 51, 86, 87 | 0.9258 |

Table 9-7

Catawba Unit 1 Growth Rate Statistics

| | Number of Indications | Average BOC Volts | Growth Rate Average | Growth Rate Std. Dev. | Percent Growth | Projected 92-93 (1) Growth Rate |
|---|---|---|---|---|---|---|
| **Cycle 6 (1991-92)** | | | | | | |
| | Total Population of Bobbin Indications | | | | | |
| Entire Sample | 6941 | 0.55 | 0.01 | 0.23 | 2 | 0.02 |
| BOC Ranges: | | | | | | |
| $V_{BOC}$ < 0.75 volt | 5846 | 0.48 | 0.03 | 0.19 | 6 | 0.05 |
| $V_{BOC}$ ≥ 0.75 volt | 1095 | 0.92 | -0.16 | 0.33 | -17 | -0.15 |
| $V_{BOC}$ ≤ 1.00 volt | 6699 | 0.53 | 0.01 | 0.21 | 2 | 0.03 |
| | Pleliminary Study of 541 Largest Bobbin Indications | | | | | |
| Entire Sample | 541 | 0.71 | 0.18 | 0.36 | 27 | 0.19 |
| BOC Ranges: | | | | | | |
| $V_{BOC}$ < 0.75 volt | 318 | 0.53 | 0.21 | 0.31 | 40 | 0.21 |
| $V_{BOC}$ ≥ 0.75 volt | 223 | 0.96 | 0.14 | 0.41 | 15 | 0.15 |
| $V_{BOC}$ ≤ 1.00 volt | 471 | 0.64 | 0.18 | 0.31 | 28 | 0.19 |
| **Cycle 5 (1990-91)** | | | | | | |
| Entire Sample (2) | 126 | 0.74 | 0.10 | 0.35 | 13 | |
| BOC Ranges: | | | | | | |
| $V_{BOC}$ < 0.75 volt | 78 | 0.55 | 0.20 | 0.24 | 37 | |
| $V_{BOC}$ ≥ 0.75 volt | 48 | 1.06 | -0.07 | 0.42 | -7 | |
| $V_{BOC}$ ≤ 1.00 volt | 101 | 0.62 | 0.18 | 0.27 | 29 | |

Notes:

1. Projected from the 1991-92 growth rate based on 0.80 EFPY for the 1991-92 cycle versus 0.956 EFPY for the next cycle. Negative voltage changes were not factored up.
2. Tubes plugged during the 1991 outage.

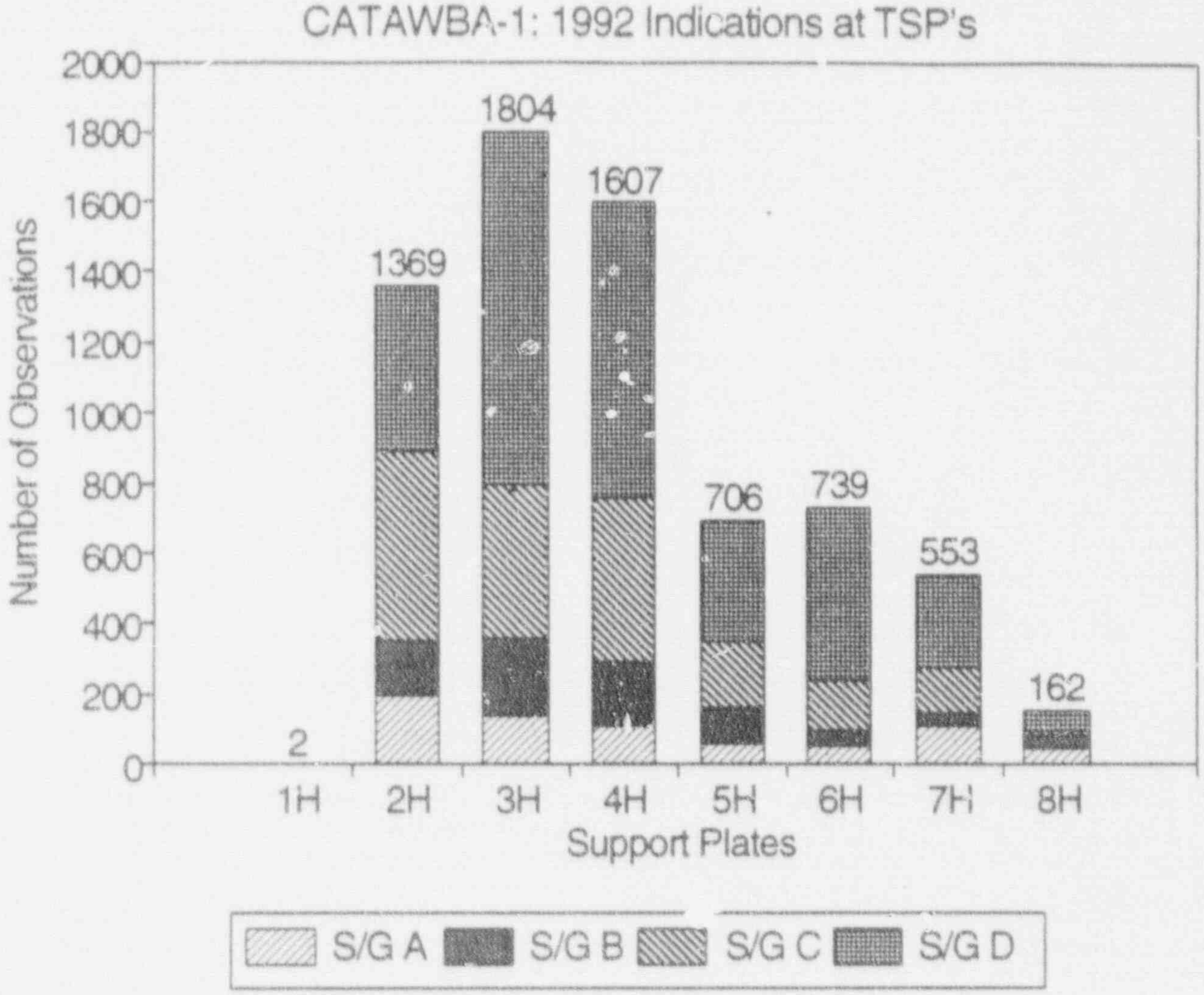



Figure 9-1. Distribution of Indications with TSP Elevation/Location

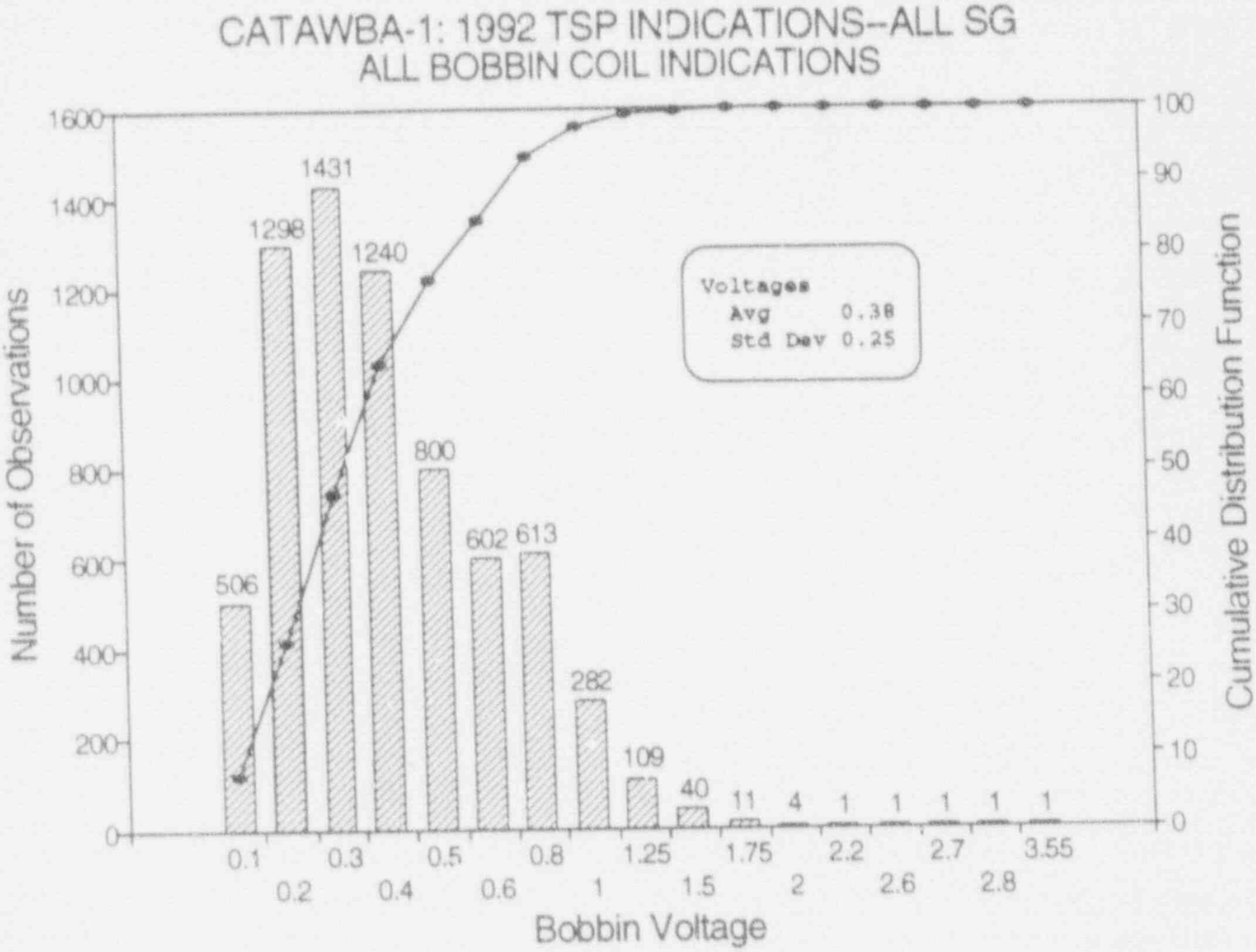



Figure 9-2. Frequency Distribution of TSP Indication Voltage Amplitudes in All S/Gs

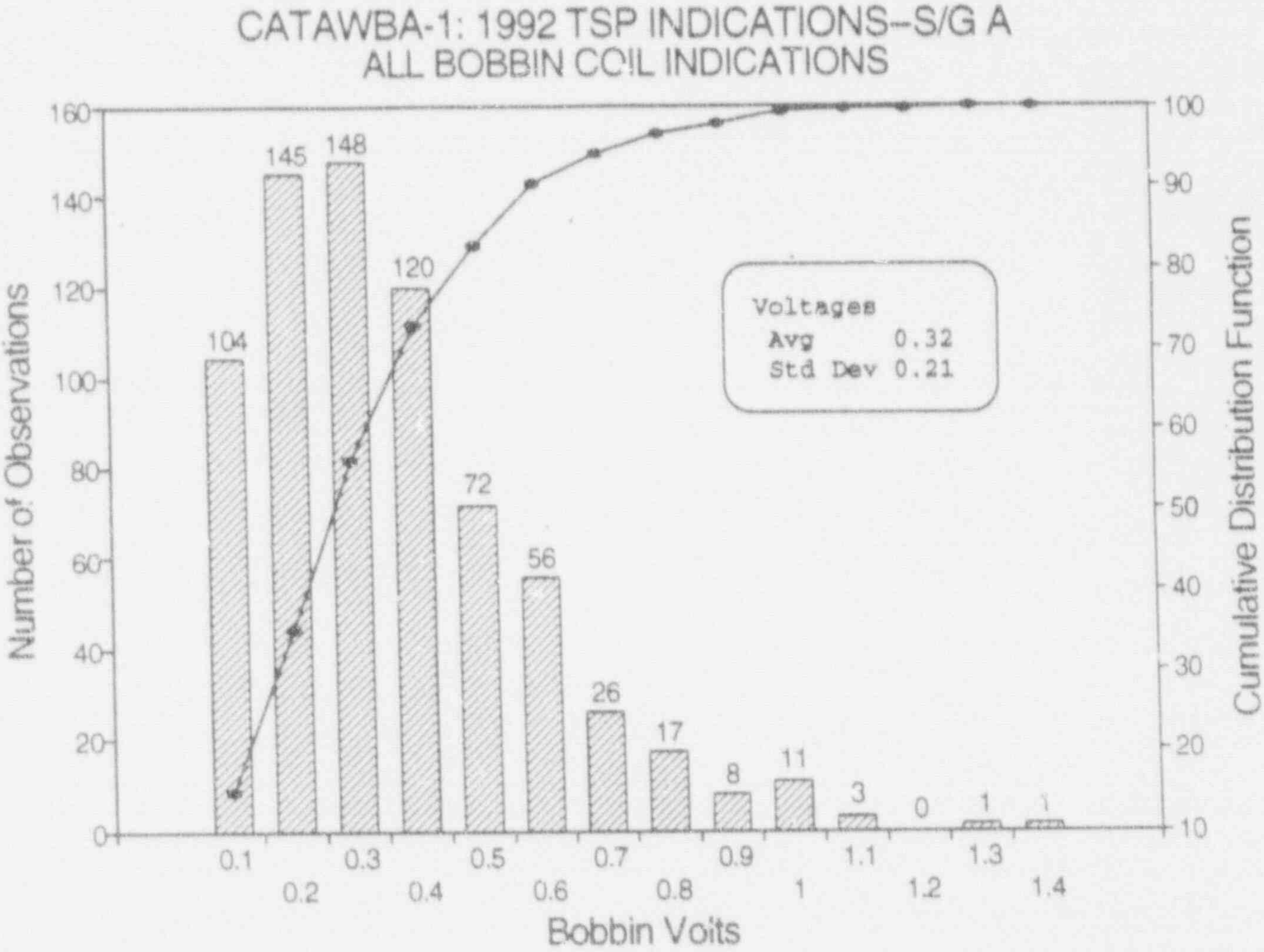



Figure 9-3. Frequency Distribution of TSP Indication Voltage Amplitudes in S/G-A

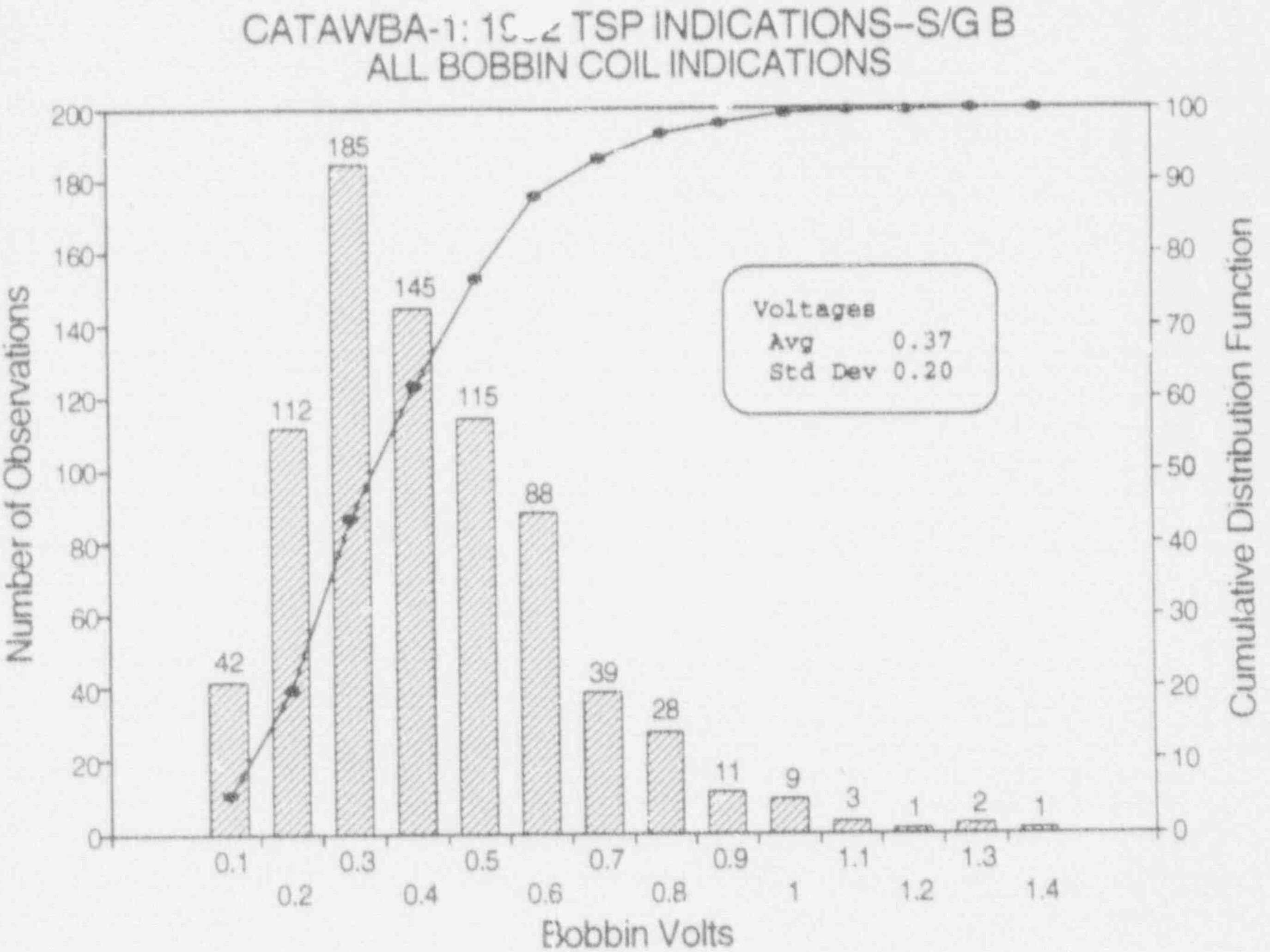



Figure 9-4. Frequency Distribution of TSP Indication Voltage Amplitudes in S/G-B

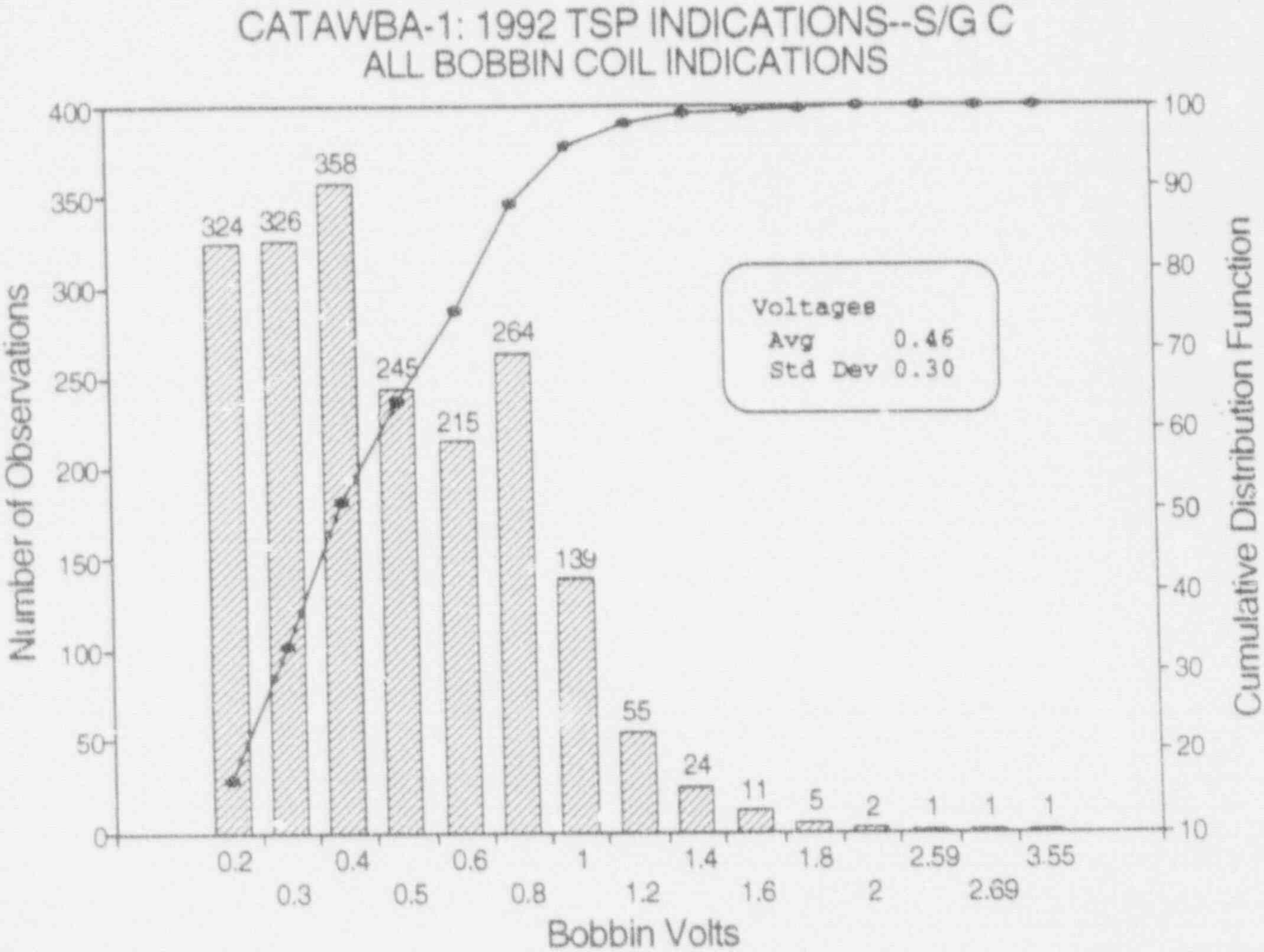



Figure 9-5. Frequency Distribution of TSP Indication Voltage Amplitudes in S/G-C

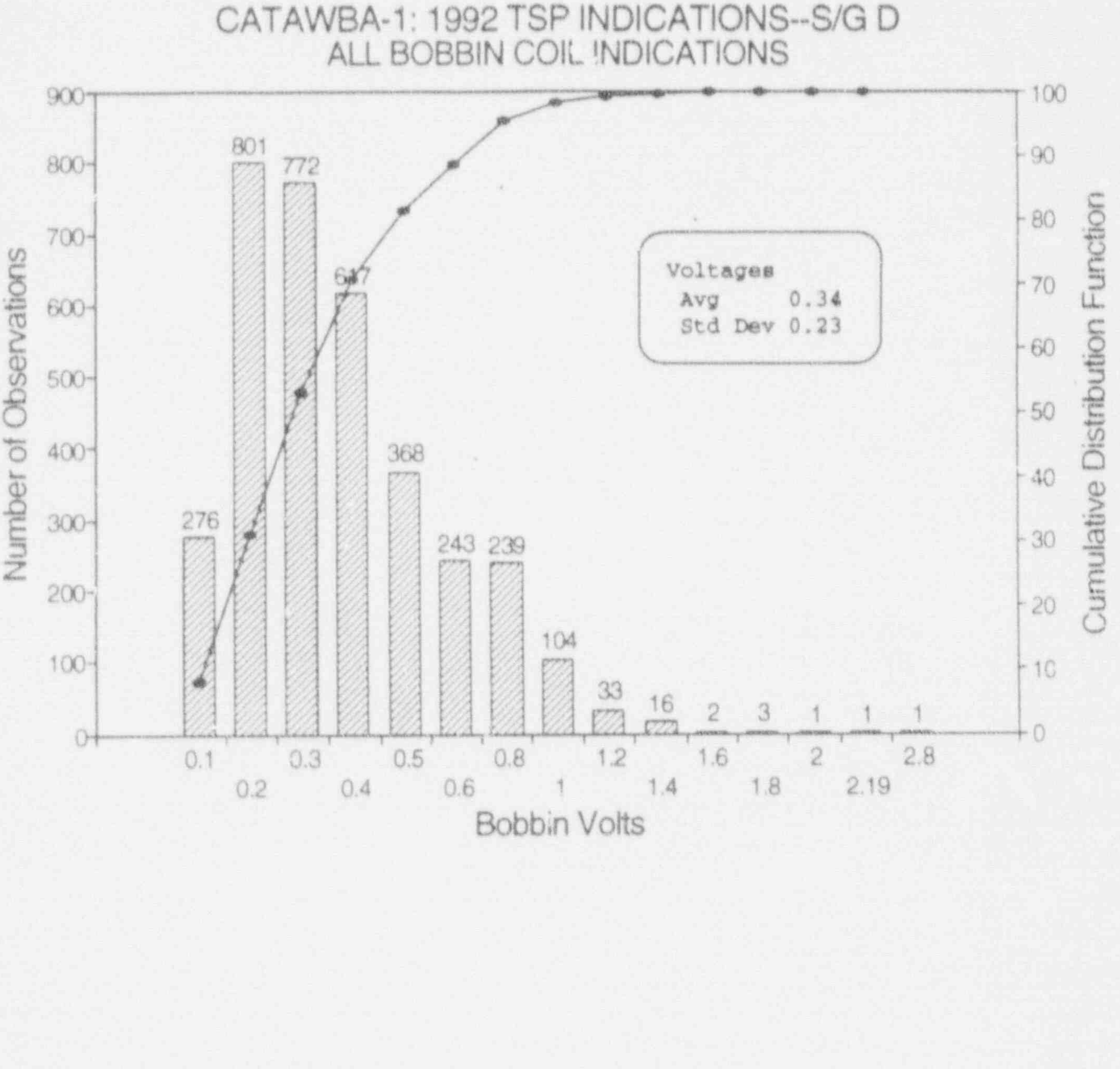



Figure 9-6. Frequency Distribution of TSP Indication Voltage Amplitudes in S/G-D

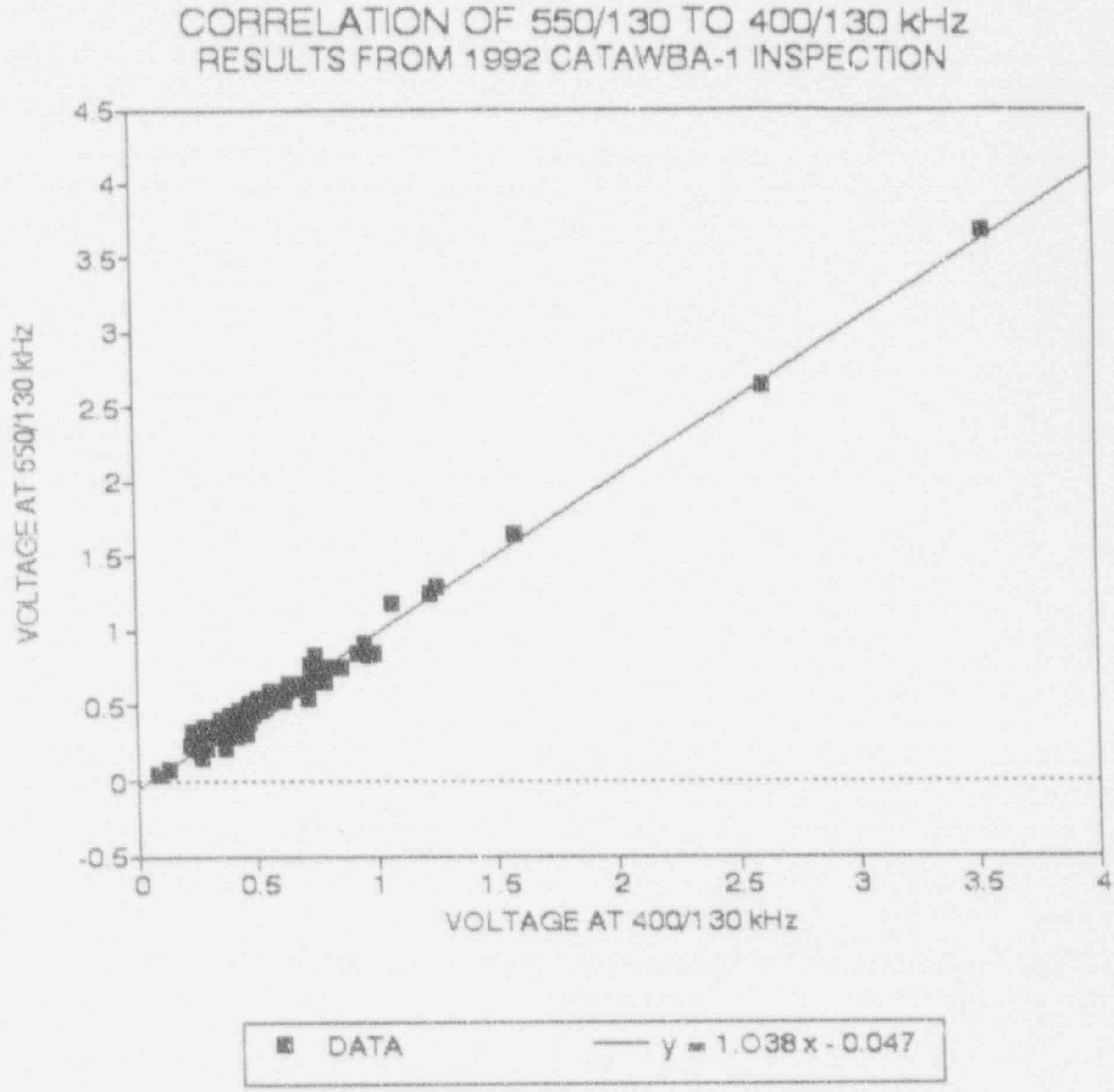



Figure 9-7. Correlation of Voltage Amplitudes Between 550/130 kHz and 400/130 kHz Using a Sample of 96 TSP Indications in S/G-C from the 1992 Outage

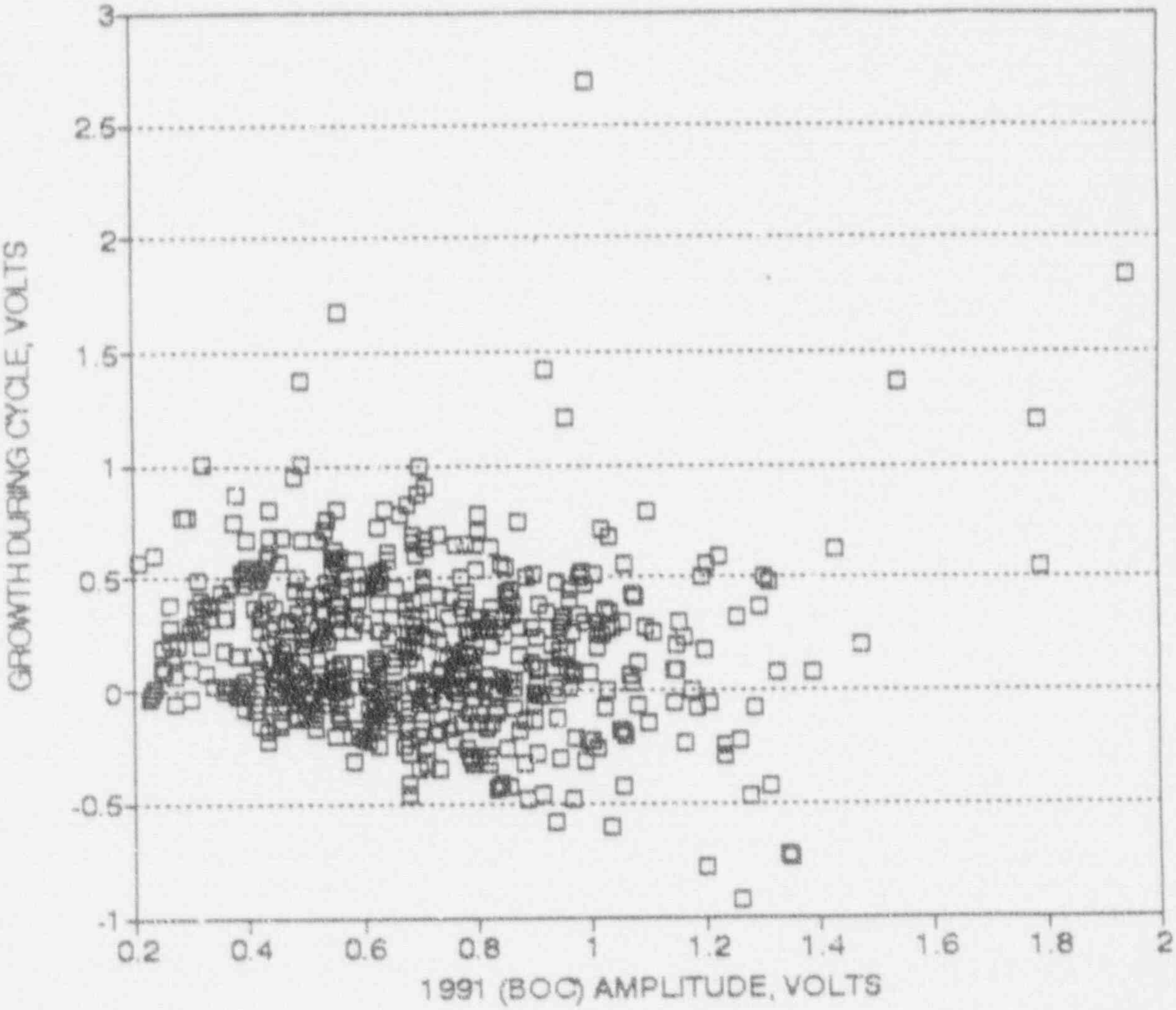



Figure 9-8. TSP Indication Voltage Growth Rates During Cycle 6 versus BOC Voltages for a Sample of 541 Largest Indications from 1992 Inspection

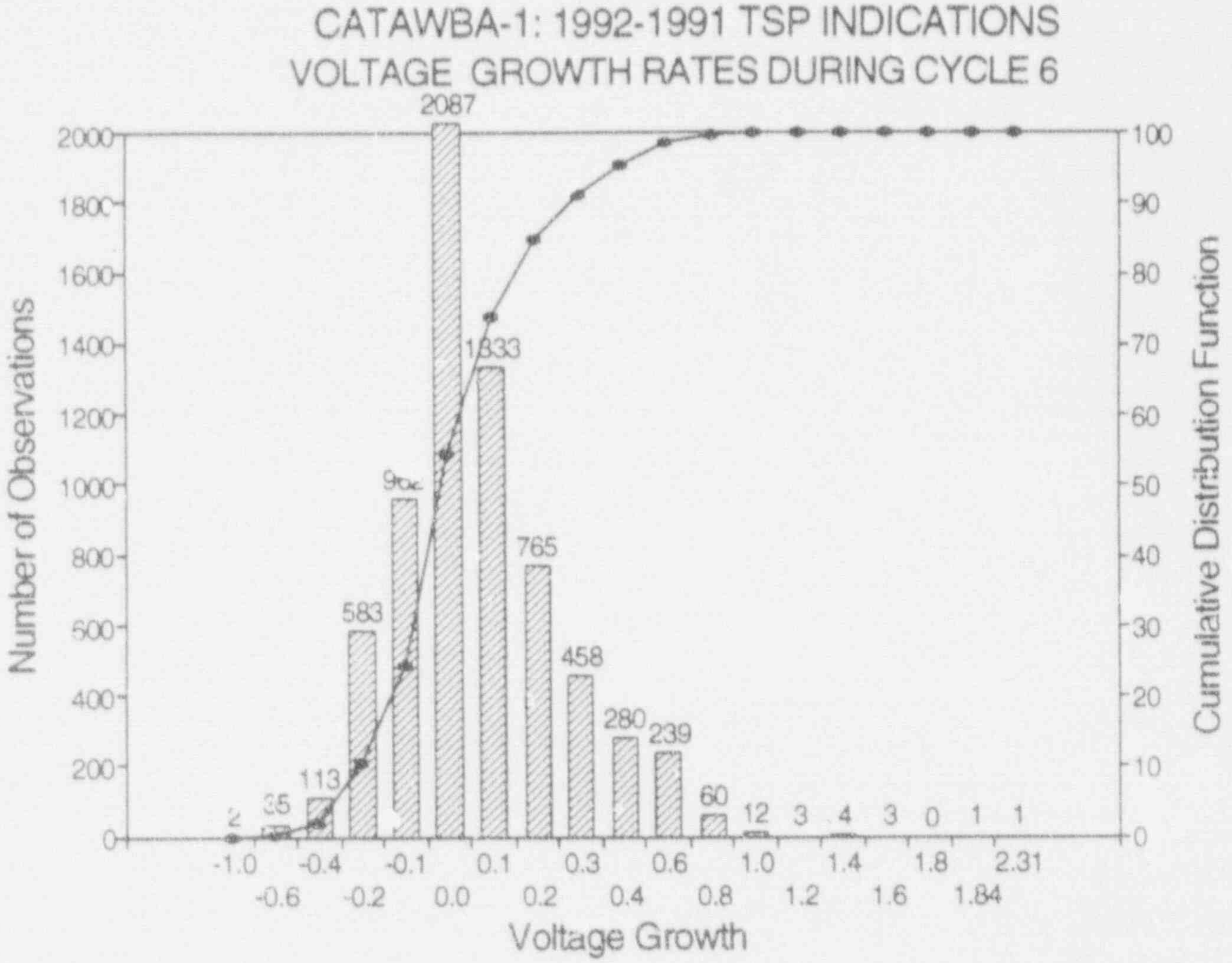



Figure 9-9. Frequency Distribution of TSP Indication Voltage Growths During Cycle 6 (All S/Gs)

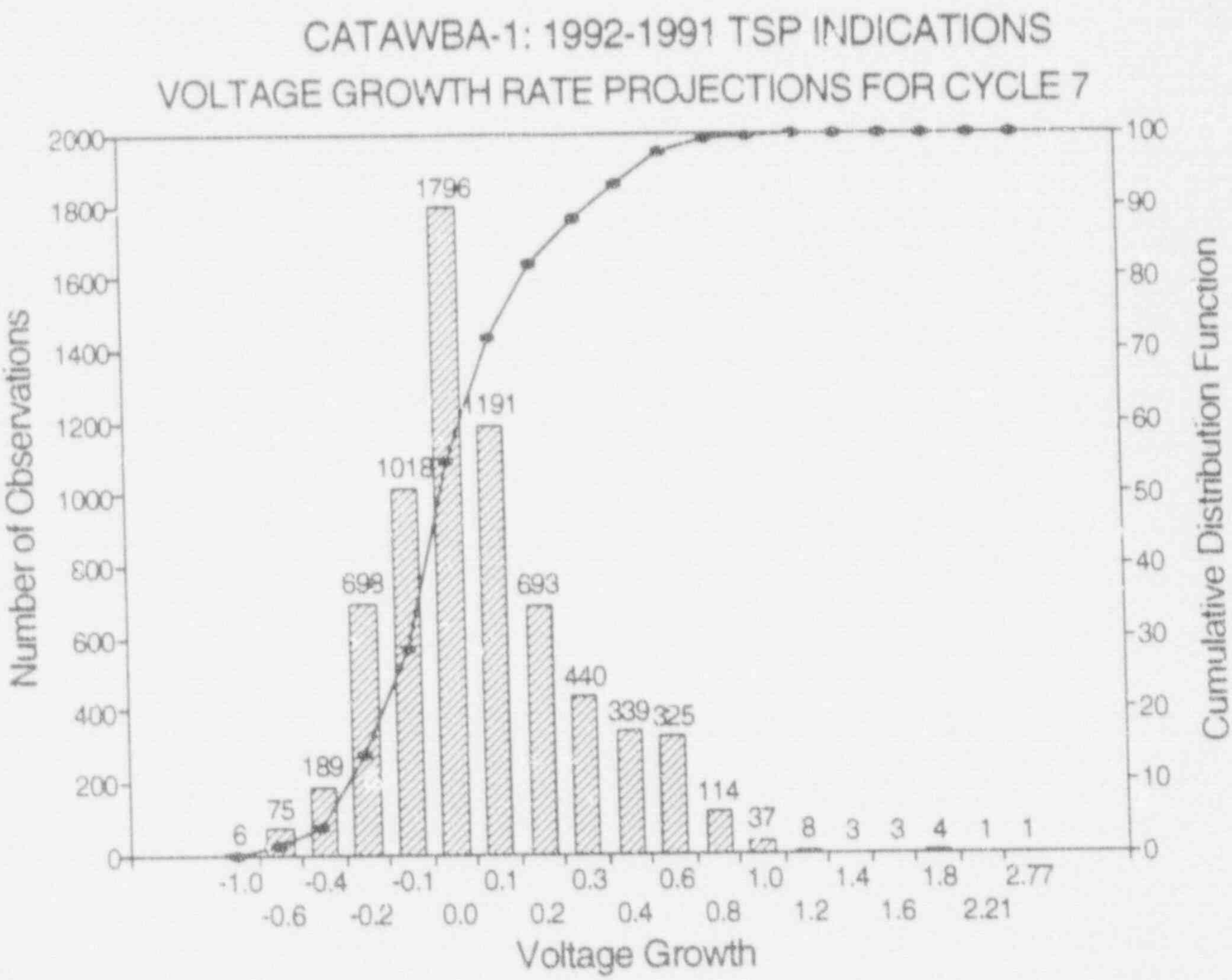



Figure 9-10. Frequency Distribution of TSP Indication Voltage Growth Projections for Cycle 7 Using EFPY Ratios and Cycle 6 Results (All S/Gs)

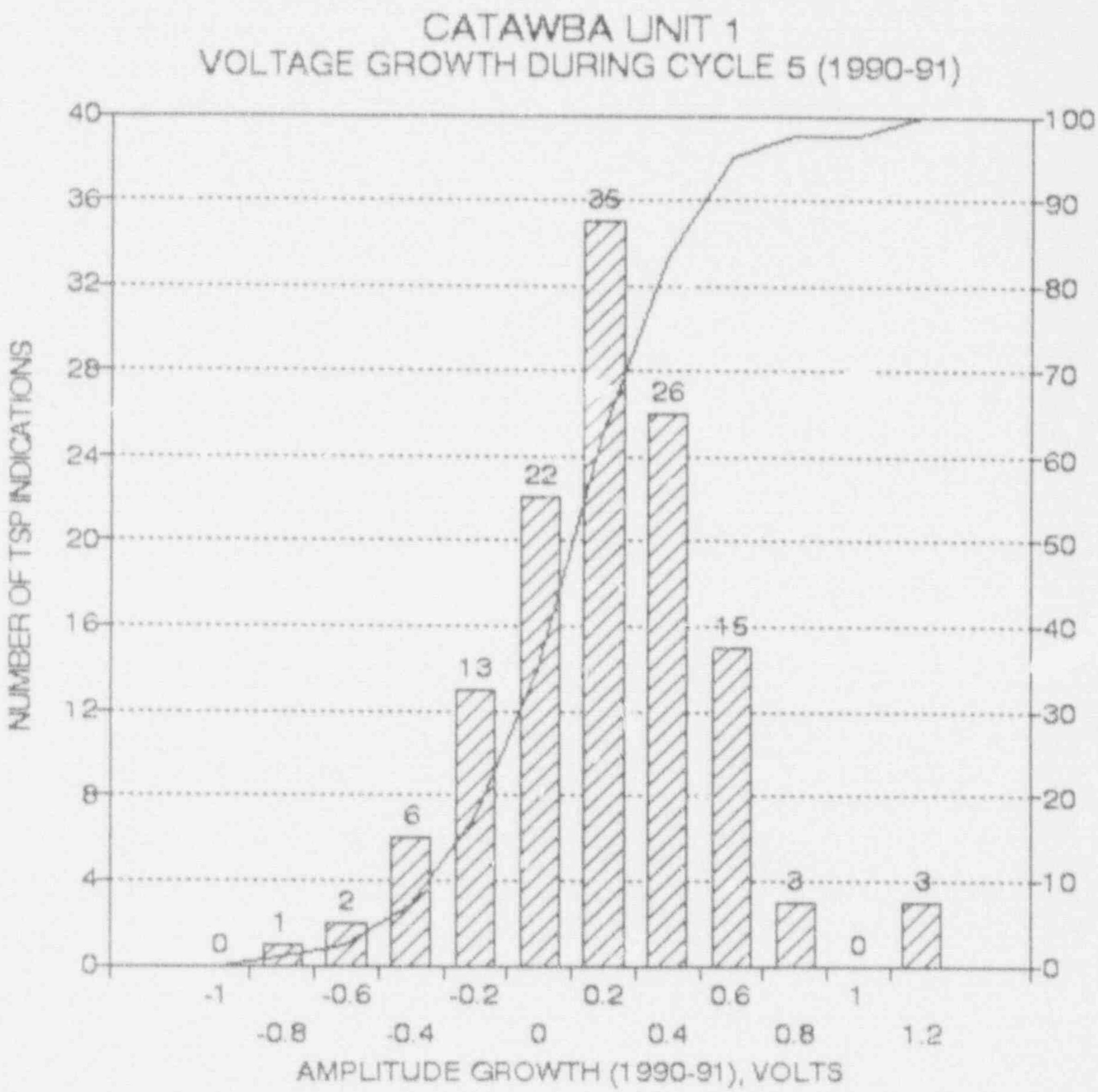



Figure 9-11. Frequency Distribution of TSP Indication Voltage Growths During Cycle 5 (All S/Gs)

## Section 10

## CATAWBA UNIT 1 IPC EVALUATION

### 10.1 Introduction

This section provides the tube integrity evaluation performed for the Catawba-1 IPC to demonstrate margins against R.G. 1.121 criteria. The Catawba-1 IPC are given in Section 10.2 including the tube repair basis, inspection requirements and operating leak rate limit. An equivalent Catawba-1 voltage repair limit for full implementation of an APC is developed in Section 10.3. This limit is applied to the IPC as the upper limit for leaving bobbin coil flaws in service even if not confirmed by RPC inspection. The Monte Carlo analysis methods used in this section are generally described in Section 10.4 and are used to project the EOC voltage distribution given in Section 10.5. This section also develops the maximum expected EOC 7 bobbin voltage. Sections 10.6 and 10.7 provide the tube burst margin assessment and the SLB leakage evaluation. Development of the operating leak rate limit is given in Section 10.8, and the principal conclusions of the Catawba-1 IPC evaluation are summarized in Section 10.9.

### 10.2 Catawba-1 Interim Plugging Criteria (IPC)

The Catawba-1 Interim Plugging Criteria (IPC) follow the precedent approved by the NRC for application to J. M. Farley and D. C. Cook-1 steam generators. The IPC include the tube repair basis, inspection requirements and operating leak rate limit as described below:

Tube Repair Basis

- o Bobbin coil indications having flaw voltages greater than 1.0 volt and confirmed as flaws by RPC inspection shall be repaired.
- o Bobbin coil indications having flaw voltages greater than 2.5 volts shall be repaired independent of RPC confirmation of a flaw.
- o Projected leakage for a postulated steam line break (SLB) event at end of cycle (EOC) conditions shall be less than 1.0 gpm for the most limiting S/G. Bobbin coil flaw indications inspected by RPC and found to have no RPC indication do not need to be included in the leakage analyses.
- o Tubes identified as subject to significant deformation at a TSP elevation under a postulated LOCA + SSE event shall be excluded from application of the IPC at that TSP location.

Inspection Requirements

- o The inspection shall include 100% bobbin coil inspection of all hot leg intersections and cold leg intersections down to the lowest TSP for which the IPC is to be applied.
- o All bobbin coil flaw indications above 1.0 volt and below 2.5 volts shall be inspected by RPC to evaluate for detectable RPC indications and, for indications, to support ODSCC as the degradation mechanism.

- o Eddy current analysis guidelines shall be consistent with guidelines utilized in prior NRC submittals supporting APC for ODSCC at TSPs.

- o An RPC sampling program of at least 100 TSP intersections will be performed emphasizing intersections with greater than 5 volt (bobbin coil) dents and including some intersections with artifact bobbin indications or indications with unusual phase angles.

Operating Leak Rate Limit

- o The normal operating leak rate requiring plant shutdown shall be limited to 0.1 gpm (150 gpd) per S/G.

The remainder of Section 10 demonstrates that the IPC provide significant margins against the tube integrity criteria of R.G. 1.121. The 1992 Catawba-1 inspection satisfied the above inspection requirements including the RPC sampling plan as described in Section 9.1. The operating leak rate limit is developed in Section 10.8.

## 10.3 Equivalent Catawba-1 APC Repair Limit

The equivalent APC voltage repair limit for full implementation of alternate plugging criteria (APC) is utilized in the IPC to establish the maximum bobbin coil flaw voltage indication to be left in service even if not confirmed by RPC inspection. The tube repair criteria are developed to preclude freespan tube burst if it is postulated that TSP displacement would occur under accident conditions. No analyses for the Model D3 S/Gs in Catawba-1 have been performed for SLB conditions to determine if significant TSP displacement would occur to uncover the tube degradation occurring within the TSPs under normal operating conditions. If significant TSP displacement does not occur, the constraint provided by the TSPs would prevent tube burst and the principal repair criteria would be based on limiting leakage rather than free span burst.

The equivalent APC repair limit is developed to provide R.G. 1.121 tube burst margins. The lower IPC repair limits incorporate additional margins against R.G. 1.121. For the equivalent voltage repair limit, the voltage structural requirement for burst capability at three times normal operating pressure differential ($3\Delta P_{NO}$) is reduced by allowances for NDE uncertainties in the voltage measurements and by voltage growth between inspections as described below.

EOC Voltage Limit for Structural Requirement

The recommended correlation between burst pressure and bobbin voltage, as adjusted for temperature and minimum material properties, is developed in Section 7.3. At the lower 95% prediction interval, a bobbin voltage of 4.1 volts establishes the structural requirement for $3\Delta P_{NO}$ (3750 psi) tube burst capability as shown on Figure 7-1.

Allowance for NDE Uncertainty

The Catawba-1 NDE uncertainties for bobbin voltage measurements are developed in Section 5.8.2. NDE uncertainties at +90% cumulative probability are applied to develop the tube repair limits. For the final Catawba-1 uncertainty evaluation given in Table 5-8, the NDE

uncertainty of 90% cumulative probability is 22% of the voltage measurement. This uncertainty is applied at the tube repair limit voltage to develop the equivalent APC repair limit.

Allowance for Crack Growth

Voltage growth rates for the Catawba-1 S/Gs are developed in Section 9.5 and summarized in Table 9-7. The voltage growth rate average over the entire BOC voltage range is 27% for the largest 541 EOC indications. When averaged over only BOC indications greater than 0.75 volts, the growth rate is15% for the 541 largest EOC indications. These results show that the Catawba-1 growth rates, as a percentage of BOC voltage levels, tend to decrease with increasing BOC volts. This trend is consistent with other domestic plants as shown in Figure 6-12. The data from European plants indicate that percent growth may be approximately independent of amplitude. It is thus conservative to assume that percentage growth is independent of amplitude and to use overall average growth from Catawba-1 operating experience for the growth rate allowance in the plugging limits. The Catawba-1 average growth of 27% is conservatively increased to 42% to established the equivalent APC repair limit.

Equivalent APC Repair Limit

Table 10-1 summarizes the development of the equivalent APC repair limit based on reducing the structural voltage limit of 4.1 volts by allowances for growth and NDE uncertainties. The resulting equivalent APC repair limit is 2.5 volts. For IPC applications, the equivalent APC repair limit is used to define an upper bobbin flaw voltage limit for leaving unconfirmed RPC indications in service rather than as the tube repair limit.

## 10.4 Monte Carlo Methodology

Monte Carlo sampling is the primary methodology applied for projecting EOC voltage distributions. The Monte Carlo method permits combining any number of distributions to obtain a frequency or cumulative probability distribution of EOC voltages. A maximum EOC voltage can then be defined that properly reflects the number of indications left in service by integrating the tail of the frequency distribution to one complete indication (or evaluating the cumulative probability distribution at (N-1)/N where N is the number of indications left in service).

The Monte Carlo methods for EOC voltages applied in this report includes the following steps:

1. Establish frequency distribution of indications vs voltage (0.05 volt intervals applied) for BOC indications (≤1.0 volt) left in service.

2. Define cumulative probability or normal distributions for voltage growth and NDE uncertainties (probe wear, analyst variability).

3. For each BOC voltage interval, randomly sample growth and NDE uncertainty distributions and, for each sample, add to mid-interval voltage value to obtain one EOC voltage sample.

4. Weight each EOC sample by the number of indications in the BOC voltage interval.

5. Repeat steps 3 and 4 for each BOC voltage interval to obtain one sample of the EOC voltage frequency distribution.

6. Repeat steps 3 to 5 above 100,000 times, order distributions and divide by 100,000 to obtain overall frequency.

7. Integrate frequency distribution of step 6 over voltage intervals to obtain a histogram of EOC indications.

8. Determine maximum EOC voltage by integrating tail of frequency distribution of step 7 to one complete tube.

If SLB leak rate is desired from the Monte Carlo process, the first 3 steps above are the same and are followed by:

4a. At each EOC voltage sample, randomly sample SLB leak rate distribution (mean ± uncertainties) to obtain a sample leak rate.

5a. Weight each SLB leak rate sample by number of indications in the BOC voltage interval.

6a. Repeat steps 3, 4a and 5a for each BOC voltage interval and sum weighted leakage for each interval over all intervals to obtain one sample of total EOC leakage per S/G.

7a. Repeat steps 3 to 6a above 100,000 times and develop leak rate per S/G into a cumulative probability distribution.

8a. Evaluate result of 7a at 90% cumulative probability to obtain reference SLB leak rate per S/G.

The tube burst probability is obtained similarly to the SLB leakage with the burst pressure vs voltage distribution sampled at step 4a and no summation is made at step 6a.

It can be noted that the maximum EOC voltage, as defined by step 8 above, increases as the number of indications left in service increases when all distributions are fixed. This results as the maximum voltage moves to a higher cumulative probability as the number of indications increase.

It is important in applying the Monte Carlo process that the cumulative probability distribution for voltage growth be developed from a sample representative (in approximate number and voltage range) of the distribution of indications left in service. For example, if the growth distribution is developed only over a small sample of the largest indications and applied to a large population including a range of indications, excessive conservatism can result. This results as the growth distribution for only the largest EOC indications would overestimate the probability of large growth values. This is shown by sensitivity analyses in Section 10.5.

### 10.5 Projected EOC Voltage Distribution

The most limiting S/G for tube integrity (tube burst, SLB leakage) considerations is between S/Gs C and D. S/G D has been found to have an RPC confirmation rate for bobbin indications of about 10% based on RPC testing of about 1350 indications. This indicates that the bobbin calls result from very short and shallow degradation or are false bobbin calls. Both bobbin and RPC probes are expected to approach 100% detectability (see Plant L WCAP-13129) for significant

flaw lengths (greater than about 0.2") having average depths greater than 40-50%. Thus indications not detected by both bobbin and RPC probes would not be expected to challenge tube integrity over one operating cycle. This EC detection consideration forms the basis for application of RPC inspection for resolving distorted bobbin signals in applying the 40% depth repair limits. S/G C has had an average confirmation rate of about 30%. Since S/G C has about 2000 bobbin indications compared to about 3500 in S/G D, S/G C would be expected to have about 70% more RPC confirmed or significant indications than S/G D. In addition, the average bobbin voltage growth rate during Cycle 6 in S/G D is negative while positive in S/G C. This negative average growth in S/G D may be another clue that the S/G D indications are small or marginal. Based on these considerations, S/G C is the most limiting S/G and is used for reference tube integrity assessments and sensitivity studies. An assessment is also provided for S/G D based on all bobbin indications less than or equal to one volt for a general comparison with S/G C. The results of this analysis confirm that S/G C is more limiting.

In S/G C, about 45% of the bobbin indications were RPC inspected. RPC confirmed indications having bobbin voltages >1.0 volt have been repaired. Of 1871 bobbin indications less than or equal to 1.0 volt in S/G C, 793 were RPC tested and 229 (29%) were confirmed as flaws. The remaining 564 bobbin indications found to be NDD can be ignored for the reference tube integrity assessment. As noted above, the indications not found by RPC are either too small or are false bobbin calls and would not be a challenge to tube integrity. Thus the reference S/G C assessment is based on BOC indications left in service as the sum of indications not RPC tested plus those confirmed by RPC with bobbin voltages less than or equal to 1.0. The total number of indications left in service for this reference case is 1307. For consistent Monte Carlo analyses, it is necessary that the growth rates be developed from a population comparable to the BOC indications left in service. Therefore, the growth rates for the reference analyses were also based on 1992 S/G C RPC confirmed indications plus indications not RPC tested in 1992. The growth rates include RPC confirmation of bobbin indications >1.0 volt which were repaired and not included in the BOC 7 indications left in service. Growth rates for 1991 to 1992 were increased by the ratio of 0.96 EFPY potential Cycle 7 operation to the actual 0.80 EFPY operation for Cycle 6. All growth rates used for EOC 7 projections include this adjustment for the potentially longer Cycle 7 operation.

As a sensitivity analysis for comparison with the above reference analysis, a calculation was carried out based on leaving in service at BOC 7 only S/G C RPC confirmed indications having bobbin voltages less than or equal to one volt (229 indications). Growth rates were derived from the S/G C population of tubes having 1992 RPC confirmed indications. This assessment of the most limiting BOC indications might be expected to yield the maximum EOC voltage.

For additional sensitivity analyses, the more common practice previously used for APC applications (7/8" tubing, WCAP-13464 and WCAP-12871) was also performed for S/Gs C and D. These analyses assume all bobbin indications in a S/G less than the repair limit of >1.0 volt are left in service at BOC 7. The number of BOC 7 indications are 1871 for S/G C and 3420 for S/G D. The growth rate applied is the growth distribution obtained for the total population of TSP indications in all S/Gs during Cycle 6, adjusted to the potentially longer Cycle 7. For comparisons of burst pressure margin ratios between Catawba-1 and a typical plant with 7/8 inch diameter tubing (WCAP-13464), the more limiting S/G C results are utilized. S/G C has the higher RPC confirmation rate which is more typical of the prior 7/8 inch experience given in WCAP-13464.

Based on the above, four analyses are performed: 1) the S/G C reference model with RPC confirmed (<1.0 volt) and not tested by RPC at BOC 7; 2) the S/G C model with only RPC

confirmed (<1.0 volt) indications at BOC 7; 3) the more common S/G C model including all bobbin indications below the repair limit at BOC 7; and 4) S/G D including all bobbin indications below the repair limit. For each of these models, Monte Carlo analyses (as described in Section 10.4) were performed to project EOC 7 bobbin voltages distributions. The BOC 7 distributions, growth rates and EOC 7 distributions are shown in Figures 10-1 to 10-4. The EOC 7 results for models 1 to 4 are, respectively, 2.34, 2.53, 2.24 and 2.33 maximum EOC 7 voltages and 2, 3, 2, and 3 for the the number of indications above the SLB leakage threshold of 2.0 volts.

For deterministic tube burst margin assessments, the estimated EOC 7 voltages based on a 1.0 volt indication left in service and increased by allowances for growth and NDE uncertainties are also required. The deterministic assessments utilize allowances at +90% cumulative probability for comparisons with $3\Delta P_{NO}$ tube burst capability and at +99% for comparisons with SLB burst requirements. EOC 7 voltages for the +90% and +99% allowances are given in Table 10-2 for the reference case and for the S/G C, all bobbin indication case. The S/G C result for all bobbin indications left in service is used in Section 10.6 for comparisons with typical results for a plant with 7/8" tubing. The Monte Carlo analysis results for maximum EOC voltages are included in Table 10-2 for comparison with the deterministic assessments. It is seen that there is little difference (≤0.1 volt) between the two deterministic analyses for projecting EOC 7 voltages. Also the sum of +99% cumulative probabilities is within 0.15 volt of the Monte Carlo results. It can be noted that the sum of +99% probability levels has a net confidence on the order of 99.8% for the present application. The reference case Monte Carlo maximum voltage corresponds to 99.92% for the Monte Carlo EOC 7 voltage cumulative probability distribution.

The above reference and sensitivity results indicate that the maximum EOC 7 voltage for indications <1.0 volt left in service would be in the range of 2.34 (reference case) to 2.53 (RPC confirmed case) volts and can be bounded by 2.53 volts. For tube burst margin assessments in Section 10.6, 2.53 volts is applied as the maximum EOC voltage.

Table 10-2 also includes the preliminary analysis results reported at the Catawba-1 NRC meeting of August 28, 1992 (WCAP-13496). This calculation utilized all S/G D BOC 7 indications less than or equal to 1.0 volt as left in service (same as Case 4 above). The growth rate distribution applied was that obtained for the largest 541 indications identified in the 1992 inspection. The use of the small sample of 541 large growths overestimates the probability of large growth when applied to the total population of 3420 indications left in services in S/G D. For example, the largest 20 growth indications having increases >1.0 volts in Figure 10-3 are the same 20 indications in the largest 541 population. The probability of the largest 20 in the 541 indication subset of growths is about 3.7% but would only be 0.3% of the total population. Thus the use of the small population of large growths for the larger population leads to a (0.037-0.003) * 3420 = 116 indication overestimate of growths greater than about 1.0 volt. The result is to over estimate the large voltage indications at EOC 7. This result is seen by the 3.28 maximum voltage and 33 indications above 1.8 volts for the preliminary assessment compared to the Figure 10-4 result of a maximum EOC 7 voltage of 2.33 volts and 5 indications above 1.8 volts. Thus the preliminary EOC 7 projections were excessively conservative compared to the more consistent analyses of this report. The preliminary analyses were intended to be conservative to establish the feasibility of a 1.0 volt IPC for Catawba-1 although the degree of conservatism could not be assessed prior to completing the final 1992 inspection voltages and associated growth rates.

10.6 Tube Burst Margin Assessment

Application of the equivalent APC repair limit developed in Section 10.3 would result in meeting R.G. 1.121 criteria at EOC conditions. The objective of the IPC repair limit is to establish additional margins beyond that included in the equivalent APC repair limit.

The limiting R.G. 1.121 criterion for Catawba-1 is to satisfy the $3\Delta P_{NO}$ tube burst margin requirement. Thus the additional IPC margins can be expressed as burst pressure margin ratios relative to $3\Delta P_{NO}$. That is, the ratios of BOC and EOC burst pressures to $3\Delta P_{NO}$. The burst margin ratios are developed adding +90% cumulative probability on growth and NDE uncertainties to the 1.0 volt repair limit and evaluating the resulting voltages at the lower 95% prediction interval of the burst/voltage correlation (Figures 7-1 to 7-2 for tube burst capability.) These uncertainty levels provide that only a few, if any, indications would exceed $3\Delta P_{NO}$ at EOC conditions. It is necessary to establish higher confidence levels to prevent tube burst at $\Delta P_{SLB}$. The burst margin ratios relative to $\Delta P_{SLB}$ are therefore developed applying +99% cumulative probability on growth and NDE uncertainties to the 1.0 volt repair limit and the lower 99% prediction interval of the burst/voltage correlation (Figure 7-3) for tube burst capability. In addition, the burst margin ratios relative to $\Delta P_{SLB}$ are provided for the maximum projected EOC voltage of 2.53 volts (Section 10.5).

Table 10-3 summarizes the tube burst margin assessment relative to $3\Delta P_{NO}$ for Catawba-1. At +90% cumulative probability on allowances for growth and NDE uncertainties, the projected EOC volts are 1.56 for the limiting S/G C based on all bobbin indications $\leq$1.0 volts left in service (Figure 10-3 data). For the reference case (Figure 10-1 data) based on RPC confirmed plus not tested indications <1.0 volts left in service, the projected EOC volts is 1.66. These two cases yield EOC burst pressure capability of 4810 and 4740 psi. The EOC burst pressure margin ratios relative to $3\Delta P_{NO}$ are 1.28 and 1.26 or substantial margins against this R.G. 1.121 criterion. At BOC, the burst margin ratio is 1.41.

A typical case for the 1.0 volt IPC applied to 7/8 inch diameter tubing is also shown in Table 10-3. It is seen that the Catawba-1 burst margin ratios are essentially the same as the 7/8 inch tubing example. For a 1.0 volt IPC, the BOC burst margin ratios are comparable for the two tubing sizes which shows that the 1.0 volt IPC establishes essentially equivalent margins between 3/4 and 7/8 inch tubing. While the 1.4 margin ratios are the same for this particular case, it should be recognized that variations about 1.4 will result for plants with different steam pressures and the 1.4 ratio may be somewhat modified upon updating the burst/voltage correlation for 3/4 inch tubing. The EOC burst margins should not be compared for assessing equivalency of the 1.0 volt IPC limit between tubing sizes as modest changes in growth distributions can significantly alter the tube size comparison. It is necessary for IPC margin demonstration that the EOC margin ratio exceed unity to show that R.G. 1.121 is satisfied with some margin. For full implementation of the equivalent APC repair limits, the EOC burst margin ratio relative to $3\Delta P_{NO}$ would be expected to be near unity.

The tube burst margin ratio assessment relative to $\Delta P_{SLB}$ is given in Table 10-4. The Catawba-1 results are the growth rate developed for all bobbin indications (Figure 10-3) and for the maximum projected EOC 7 voltage of 2.53 volts. The EOC margin ratios were found to be 1.35 to 1.41 for Catawba-1. This demonstrates substantial margin against burst at SLB for EOC 7 conditions. As a supplemental demonstration of burst margins, the probability of tube burst at

$\Delta P_{SLB}$ was calculated for S/G C (Figure 10-1 data) using Monte Carlo methods and found to be about 1.1 X $10^{-5}$. Thus large margins against burst at SLB conditions are provided by the Catawba-1 IPC. It can be noted from Table 10-4 that both 3/4 and 7/8 inch tubing provide large margins against $\Delta P_{SLB}$ although the 7/8 inch margin ratios are somewhat higher than that for 3/4 inch tubing.

The above assessment shows that the Catawba-1 IPC repair limit of >1.0 bobbin coil voltage provides significantly large margins against R.G. 1.121 structural criteria for tube burst. These assessments utilized the recommended voltage/burst correlation of Figure 7-1. Section 7, Figures 7-4 to 7-9 provide sensitivity of the correlation to various conservative assumptions on finalization of the 3/4 inch burst data. For all of these conservative correlations, the EOC voltages of Tables 10-3 and 10-4 provide burst pressure margin ratios above unity against $3\Delta P_{NO}$ and $\Delta P_{SLB}$, respectively. The correlation of Figure 7-7 based on including the unreliable Catawba-1 burst data provides the lowest burst pressure capability for all sensitivity correlations examined including use of the Belgian data without any voltage adjustment for cross calibration of ASME standards. With this correlation, the burst pressure margin ratios are 1.13 relative to $3\Delta P_{NO}$ and 1.15 relative to $\Delta P_{SLB}$ using the methodology of Tables 10-3 and 10-4. Thus the R.G. 1.121 criteria would be satisfied by the Catawba-1 IPC repair limits even under the most limiting assumption on effects of current burst data uncertainties on the voltage/burst correlation.

## 10.7 SLB Leak Rate Assessment

The IPC require that potential leakage under SLB conditions at EOC 7 be less than 1 gpm. This section provides the results of the leak rate analyses to demonstrate that this requirement is satisfied for the Catawba-1 IPC repair limit of >1.0 bobbin coil volt. The methods of analysis are consistent with the guidelines provided in the SER for the D. C. Cook-1 IPC. These guidelines recommend SLB leak rate analyses based on Monte Carlo analyses using a SLB leak rate vs bobbin voltage correlation and a separate analysis using EOC voltage distributions that consider tails of the growth distribution together with a more deterministic leak rate calculation based on a bounding, stepwise change in leak rate with voltage. The results of these two analyses are provided in this section. In addition, the results of sensitivity analyses for SLB leak rates are provided.

The results of applying the two SLB leak rate analysis methods are given in Table 10-5. This table also provides the source of the input data (Tables, Figures) applied to calculate the leakage. The BOC voltage distribution for the reference SLB leak rate analysis is that of Figure 10-1 and includes all RPC confirmed indications and indications not inspected by RPC that have bobbin voltages <1.0 volts. The EOC voltage distribution is shown also in Figure 10-1. For the deterministic assessment, the SLB leak rate relation applied (Table 7-4) leads to no leakage for EOC indications below the leakage threshold of 2.0 volts and a leak rate of 1.0 liter/hr per indication between 2.0 and 3.5 volts. No EOC indications are expected to approach the 3.5 volt limit for a 1.0 liter/hr leak rate and only about 2 indications are projected above the leakage threshold of 2.0 volts. Thus the deterministic method leads to an EOC 7 SLB leak estimated at 2 liter/hr or <0.01 gpm.

The Monte Carlo analysis utilizes the same input data as the deterministic analysis except that the continuous EOC voltage distribution is applied to the SLB leak rate correlation of Figure

7-16 (including uncertainty distribution). The 2.0 volt threshold for SLB leakage is applied in the Monte Carlo analysis. If the EOC voltage sample being evaluated is less than 2.0 volts, it is assigned zero leakage and the Figure 7-16 distribution is sampled for EOC volts >2.0. At 90% cumulative probability of the Monte Carlo SLB leak rate distribution, the EOC 7 leakage is projected to be approximately zero. Thus both the deterministic and Monte Carlo methods project negligible SLB leakage at EOC 7.

To assess the sensitivity of SLB leakage to the input data, a number of alternate cases were run with both the Monte Carlo and deterministic models applied for the leak rate calculation. The four BOC voltage distributions of Figures 10-1 to 10-4 were assessed as the reference case and Cases 3, 5 and 6. All of these cases show essentially no SLB leakage (≤0.01 gpm) for both the deterministic and Monte Carlo analysis methods. These cases apply the 2.0 volt SLB leakage threshold. Supplemental cases applying a 1.8 volt leakage threshold also yielded zero gpm leakage by Monte Carlo and <0.022 gpm by the deterministic model. Case 2 which applies the SLB leakage correlation including the Belgian data without a voltage adjustment yields the same Monte Carlo results of zero leakage as obtained for the reference as Cases 3, 5 and 6. Thus the SLB leakage is insignificantly dependent on the input data a ong as a leakage threshold is included in the analyses. Leakage thresholds <1.8 volts were not evaluated.

As bounding sensitivity cases, the unrealistic assumption of no leakage threshold was applied for cases 1 and 4. Cases 1 and 4 use the S/G C BOC voltage distributions of Figures 10-1 and 10-2. Even under the no threshold assumption, the S/G C leakage is bounded by 0.67 gpm (Case 1) for the recommended SLB leak rate correlation of Figure 7-16.

Given that a leakage threshold of >2.0 volts (Section 7.5) for a measurable or quantifiable leak rate is supported by all model boiler and pulled tube data, it is concluded that the SLB leak rate for Catawba-1 at EOC 7 is expected to be nearly zero gpm and is conservatively within the allowable limit of 1.0 gpm.

## 10.8 Operating Leakage Limit

R.G. 1.121 acceptance criteria for establishing operating leakage limits are based on leak before break (LBB) consideration such that plant shutdown is initiated if the leakage associated with the longest permissible crack is exceeded. The longest permissible crack is the length that provides a factor of safety of 3 against bursting at normal operating pressure differential. As noted above, a voltage amplitude of [ ]g volts for typical ODSCC cracks corresponds to meeting this tube burst requirement at the lower 95% confidence level on the burst correlation. Alternate crack morphologies could correspond to [ ]g volts so that a unique crack length is not defined by the burst pressure to voltage correlation. Consequently, typical burst pressure versus through wall crack length correlations are used below to define the "longest permissible crack" for evaluating operating leakage limits.

The CRACKFLO leakage model has been developed for single axial cracks and compared with leak rate test results from pulled tube and laboratory specimens. Fatigue crack and SCC leakage data have been used to compare predicted and measured leak rates. Generally good agreement is obtained between calculation and measurement with the spread of the data being somewhat greater for SCC cracks than for fatigue cracks. Figure 10-5 shows normal operation leak rates including uncertainties as a function of crack length.

The through wall crack lengths resulting in tube burst at 3 times normal operating pressure

differentials (3750 psi) and SLB conditions (2650 psi) are about [ ]a, respectively, as shown in Figure 10-6. Nominal leakage at normal operating conditions for these crack lengths would range from about [

]a would cause undue restrictions on plant operation and result in unnecessary plant outages, radiation exposure and cost of repair. In addition, it is not feasible to satisfy LBB for all tubes by reducing the leak rate limit. Crevice deposits, presence of small ligaments and irregular fracture faces can, in some cases, reduce leak rates such that LBB cannot be satisfied for all tubes by lowering leak rate limits.

An operating leak rate of 150 gpd (~0.1 gpm) will be implemented in conjunction with application of the tube plugging criteria. As shown in Figure 10-5, this leakage limit provides for detection of [

]a. Thus, the 150 gpd limit provides for plant shutdown prior to reaching critical crack lengths for SLB conditions at leak rates less than a -95% confidence level and for 3 times normal operating pressure differentials at less than nominal leak rates.

The tube plugging limits coupled with 100% inspection at affected TSP locations provide the principal protection against tube rupture. The 150 gpd leakage limit provides further protection against tube rupture. In addition, the 150 gpd limit provides the capability for detecting a rogue crack that might grow at much greater than expected rates and thus provides additional protection against exceeding SLB leakage limits.

## 10.9 Conclusions

Based on the above evaluation of the Catawba-1 IPC repair limit of >1.0 bobbin volt, it is concluded that:

- o R.G. 1.121 criteria for tube integrity are conservatively satisfied at EOC 7 for an IPC repair limit of 1.0 bobbin volt.

- o At EOC 7, burst pressure capability (expressed as margin ratios relative to $3\Delta P_{NO}$ and $\Delta P_{SLB}$) is expected to have ratios of about 1.25 relative to $3\Delta P_{NO}$ at 90% cumulative probability levels and about 1.35 relative to $\Delta P_{SLB}$ at 99% cumulative probability levels. A burst pressure margin ratio of 1.4 relative to $3\Delta P_{NO}$ for Catawba-1 at BOC conditions is comparable to typical values for plants with 7/8 inch diameter tubing with an IPC repair limit of 1.0 volt. Thus the two tubing sizes can be considered to have equivalent margins for IPC repair limit of 1.0 volt.

- o Potential SLB leakage at EOC 7 is expected to be negligible (~0.01 gpm) as supported by both Monte Carlo and deterministic evaluations including sensitivity analyses.

- o The maximum EOC 7 bobbin voltage indication resulting from indications left in service below the repair limit is projected to be about 2.53 volts.

- o The operating leak rate limit of 150 gpd implemented with the IPC satisfies R.G. 1.121 guidelines for leak before break. This limit provides for plant shutdown prior to reaching critical crack lengths for SLB conditions at a -95% confidence level on leak rates and for $3\Delta P$ conditions at less than nominal leak rates.

rates and for $3\Delta P$ conditions at less than nominal leak rates.

## Table 10-1

**Equivalent APC Repair Limits to Satisfy Structural Requirements**

| Item | Volts | Basis |
|---|---|---|
| Maximum Voltage Limit to Satisfy Tube Burst Structural Requirement | 4.10 | Burst Pressure vs. Voltage Correlation at -95% confidence level (Fig. 7-1) |
| Allowance for NDE Uncertainty | -0.55(22%)[(1)] | From Table 5-8, 22% uncertainty at 90% cumulative probability. |
| Allowance for Crack Growth Between Inspections | -1.05(42%)[(1)] | Table 9-7 shows average growth/cycle of 27%. Allowance conservatively increased to 42% of Tube Plugging Limit. |
| | ——— | |
| Equivalent APC Repair Voltage Limit | 2.50 | |
| o Acceptable Limit to Meet Structural Requirement | | |

Note:

1. Voltage percentage allowances for NDE and growth rate/cycle applied to Equivalent APC Repair Voltage Limit of 2.5 volts.

Table 10-2

**Maximum EOC Voltage Sensitivity Assessment**

| Cumulative Prob. | | 99% Cumulative Prob. | Monte Carlo | 90% |
|---|---|---|---|---|
| BOC Volts | | 1.00 | 1.00 | 1.00 |
| NDE Uncertainty | | 0.22 | 0.42 | --- |
| BOC + NDE Unc. Volts | | 1.22 | 1.42 | --- |
| Reference Case | | | | |
| S/G C:RPC Confirmed + RPC Untested | | | | |
| o | Growth | 0.44 | 0.78 | --- |
| o | EOC Maximum Volts | 1.66 | 2.20 | 2.34(1) |
| Case for Comparison of Burst Margin Ratios with Typical 7/8 Inch Tubing REsults | | | | |
| S/B C:RPC Confirmed Only | | | | |
| o | Growth | 0.34 | 0.79 | --- |
| o | EOC Maximum Volts | 1.56 | 2.21 | 2.24 |
| Preliminary Assessment | | | | |
| S/G D:All BOC Bobbin, Largest 541 Ind. Growth, Preliminary NDE Unc. | | | | |
| o | Growth | 0.62 | 1.4 | --- |
| o | EOC Maximum Volts | 1.78 | 2.81 | 3.28 |

Note:

1. Maximum EOC volts based on integrating EOC distribution to one indication (typically >0.999 cumlative probability)

Table 10-3

**Catawba-1 Tube Burst Margin Assessment for $3\Delta P_{NO}$**

| | Catawba-1:3/4" Tubing | 7/8" Tubing Example[1] |
|---|---|---|
| BOC Volts | 1.0 | 1.0 |
| Allowances @ [illegible]% Cum.Prob. | | |
| o Voltage Growth | 0.34 | 0.60 |
| o NDE Uncertainty | 0.22 | 0.16 |
| | ——— | ——— |
| EOC Volts (+90%) | 1.56 (1.66)[2] | 1.76 |
| Tube Burst Capability (psi) | | |
| o $3\Delta P_{NO}$ Requirement | 3750 | 4380 |
| o Capability at -95% Pred.Int.: | | |
| At BOC = 1.0 volt | 5290 | 6200 |
| At Projected EOC Volts | 4810 (4740)[2] | 5660 |
| Burst Capability Ratios to $3\Delta P_{NO}$ | | |
| o At BOC = 1.0 volt | 1.41 | 1.41 |
| o At Projected EOC volts | 1.28 (1.26)[2] | 1.29 |

Note:

1. Example for 7/8" Tubing for Plant A-2, WCAP-13464.
2. Reference analysis results.

Table 10-4

**Catawba-1 Tube Burst Margin Assessment for SLB Conditions**

| | Catawba-1 3/4" Tubing | 7/8" Tubing Example[1] |
| --- | --- | --- |
| BOC Volts | 1.0 | 1.0 |
| Allowances @ +99% Cum.Prob. | | |
| o Voltage Growth | 0.79 | 2.0 |
| o NDE Uncertainty | 0.42 | 0.25 |
| EOC Volts (+99%) | 2.19 | 3.25 |
| Maximum Projected at EOC Volts | | |
| o Monte Carlo | 2.53 | --- |
| Tube Burst Capability (psi) | | |
| o $\Delta P_{SLB}$ Requirement | 2650 | 2650 |
| o Capability at -99% Pred.Int.: | | |
| At +99% EOC volts | 3730 | 4420 |
| At Maximum EOC Volts | 3580 | --- |
| Burst Capability Ratios to $\Delta P_{SLB}$ | | |
| o At +99% EOC volts | 1.41 | 1.67 |
| o At Maximum EOC volts | 1.35 | --- |

Note 1. Example for 7/8" Tubing for Plant A-2, WCAP-13464

Table 10-5

**SLB Leak Rate Assessment for EOC7**

| | "Deterministic" Assessment | Monte Carlo Assessment |
|---|---|---|
| Inputs to Leak Rate Analysis | | |
| o BOC Voltage Distribution | Figure 10-1 | Figure 10-1 |
| - RPC Confirmed or not inspected with BOC bobbin volts ≤1.0 volt | | |
| o NDE Uncertainties | Table 5-8 | Table 5-8 |
| - Monte Carlo Distributions | Final Values | Final Values |
| o Voltage Growth | Figure 10-1 | Figure 10-1 |
| - Distribution for all RPC confirmed or not RPC inspected | | |
| o EOC Voltage Distribution | Figure 10-1 | Continuous Distribution Consistent with Figure |
| o SLB Leak Rate Correlation | | |
| - Threshold Voltage for Leakage | 2.0 | 2.0 |
| - Correlation | Table 7-4 Discrete Step Changes | Figure 7-16 Continuous from Regression Analysis |
| Projected EOC 7 SLB Leak Rate | <0.01 gpm | 0.0 gpm |

Table 10-6

## SLB Leak Rate Sensitivity Assessment

| | S/G C | | | | | | S/G D |
|---|---|---|---|---|---|---|---|
| | Reference | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 |
| Inputs to Leak Rate Analysis | | | | | | | |
| o BOC Voltage Distribution | Fig.10-1 | Ref. | Ref. | Fig.1[illegible] | Ref. | Fig.10-3 | Fig. 10-3 |
| | RPC+Uninsp. | | | RPC Only | | All <1.0v | All <1.0v |
| o NDE Uncertainties | Table 5-8 | Ref. | Ref. | Ref. | Ref. | Ref. | Ref. |
| o Voltage Growth | Fig.10-1 | Ref. | Ref. | Fig.10-2 | Case 3 | Fig.10-3 | Fig.10-4 |
| | SG C RPC+Unt. | | | SG C RPC | | All S/G | All S/G |
| o EOC Voltages | Fig.10-1 | Ref. | Ref. | Fig.10-2 | Case 3 | Fig.10-3 | Fig.10-4 |
| - Continuous Dis.for M.C. | | | | | | | |
| o SLB Leakage Correlation | | | | | | | |
| - Threshold Volts | 2.0 | 0.0 | 2.0 | 2.0 | 0.0 | 2.0 | 2.0 |
| Monte Carlo Corr. | Fig.7-16 | Ref. | Fig.7-18 | Ref. | Ref. | Ref. | Ref. |
| Monte Carlo EOC-7 | | | | | | | |
| o Maximum EOC Voltage | 2.34 | 2.34 | 2.34 | 2.53 | 2.53 | 2.24 | 2.33 |
| o SLB Leak Rate-gpm | 0.00 | 0.67 | 0.00 | 0.00 | 0.41 | 0.00 | 0.00 |
| "Deterministic" EOC-7 | | | | | | | |
| o No.Ind. >Leak Threshold | 2 | N.A. | 2 | 3 | N.A. | 2 | 3 |
| o SLB Leak Rate-gpm | <0.01 | N.A. | <0.01 | 0.01 | N.A. | <0.01 | 0.01 |

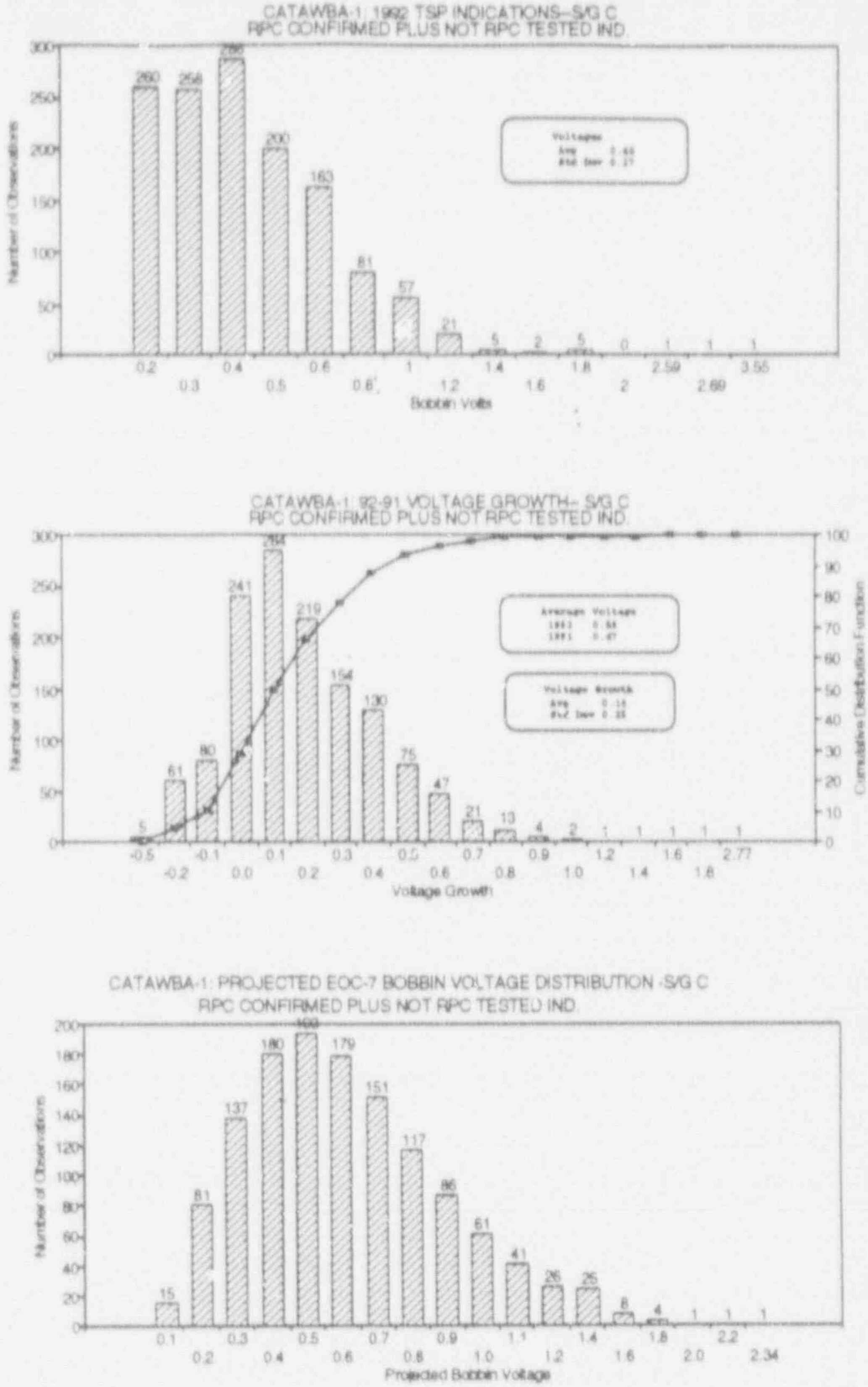



Figure 10-1. Steam Generator C EOC 7 Voltage Distribution Based on RPC Confirmed and Not Tested Indications

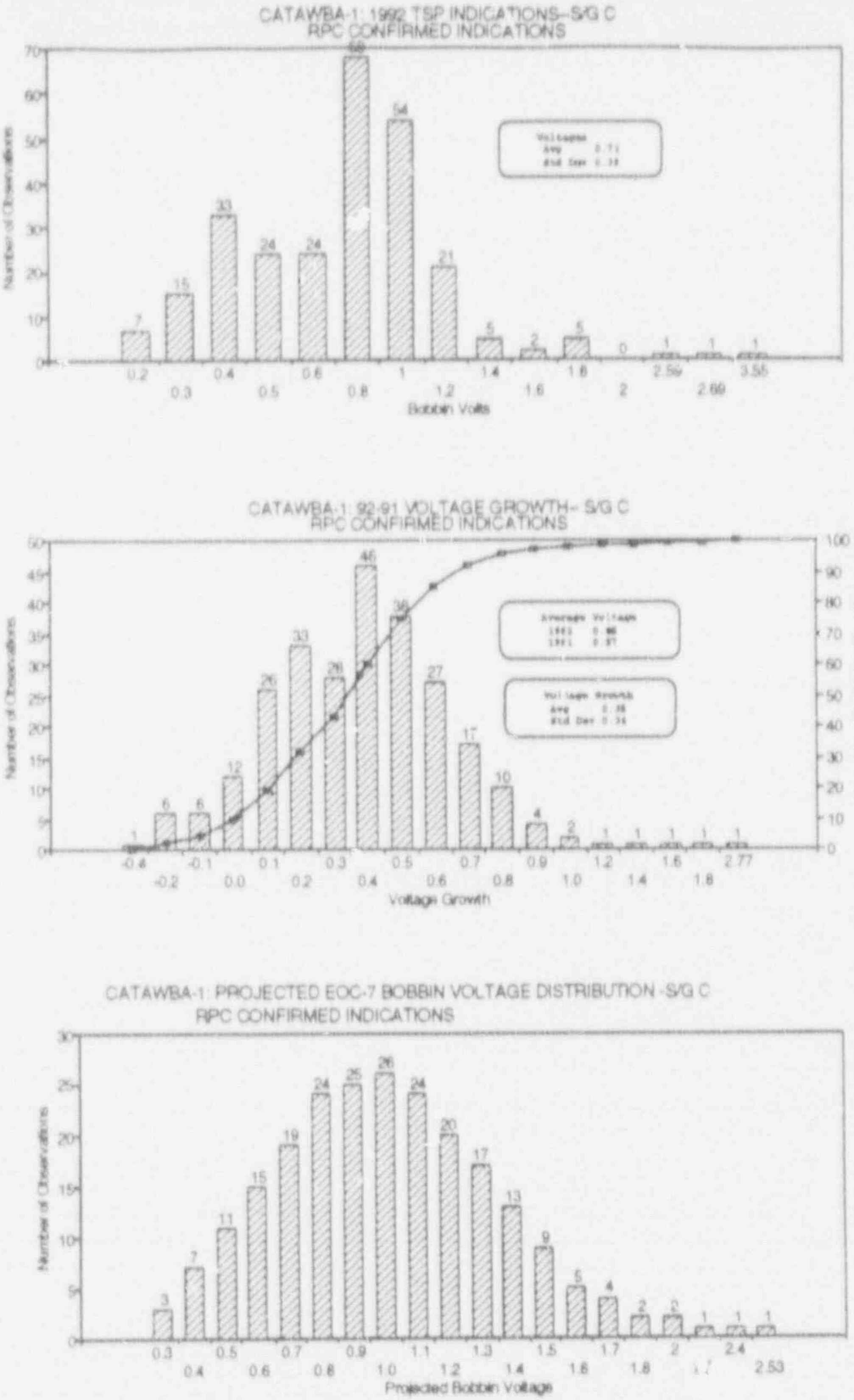



Figure 10-2. Steam Generator C EOC 7 Voltage Distribution Based on RPC Confirmed Indications

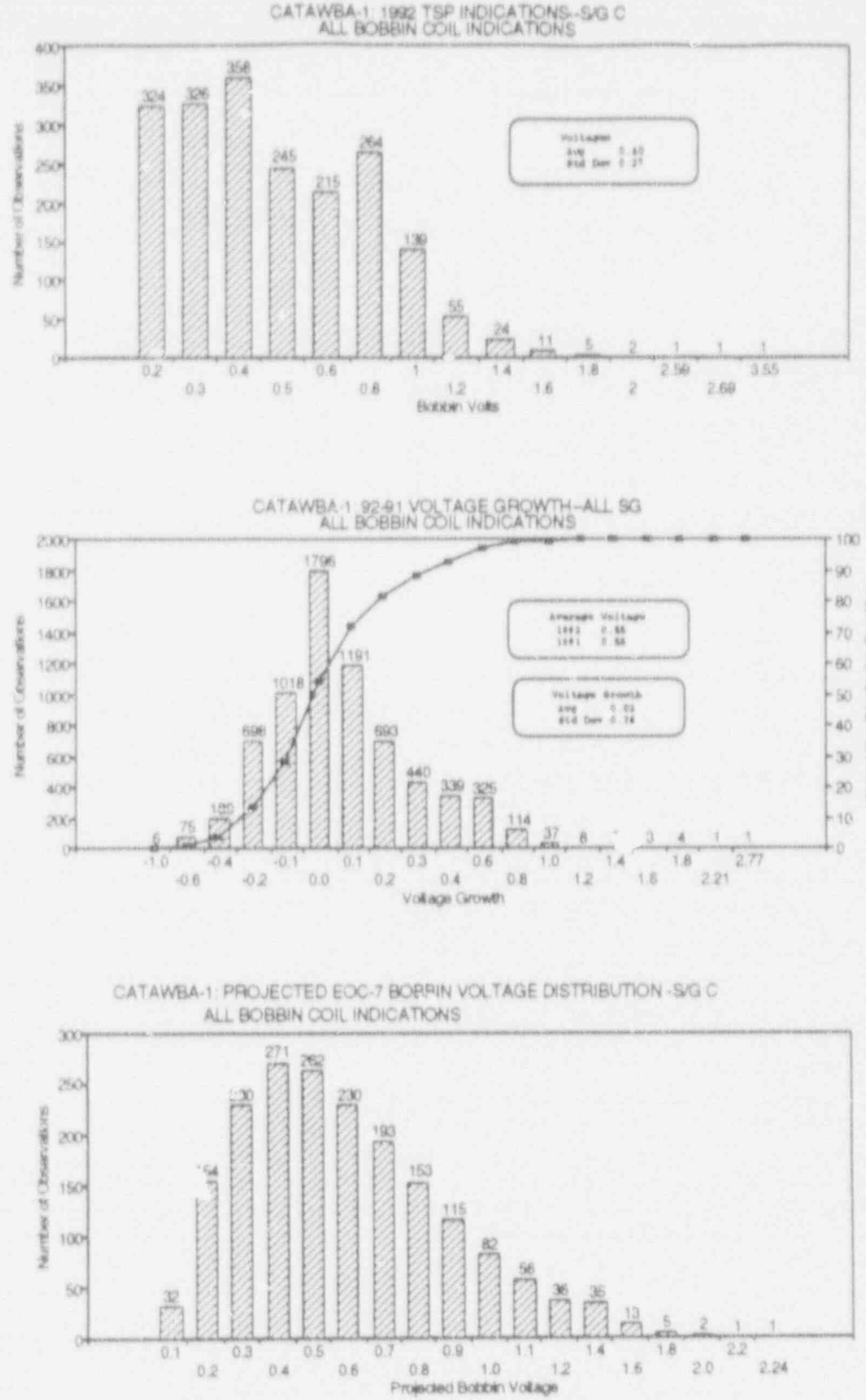



Figure 10-3. Steam Generator C EOC 7 Voltage Distribution Based on All Bobbin Coil Indications

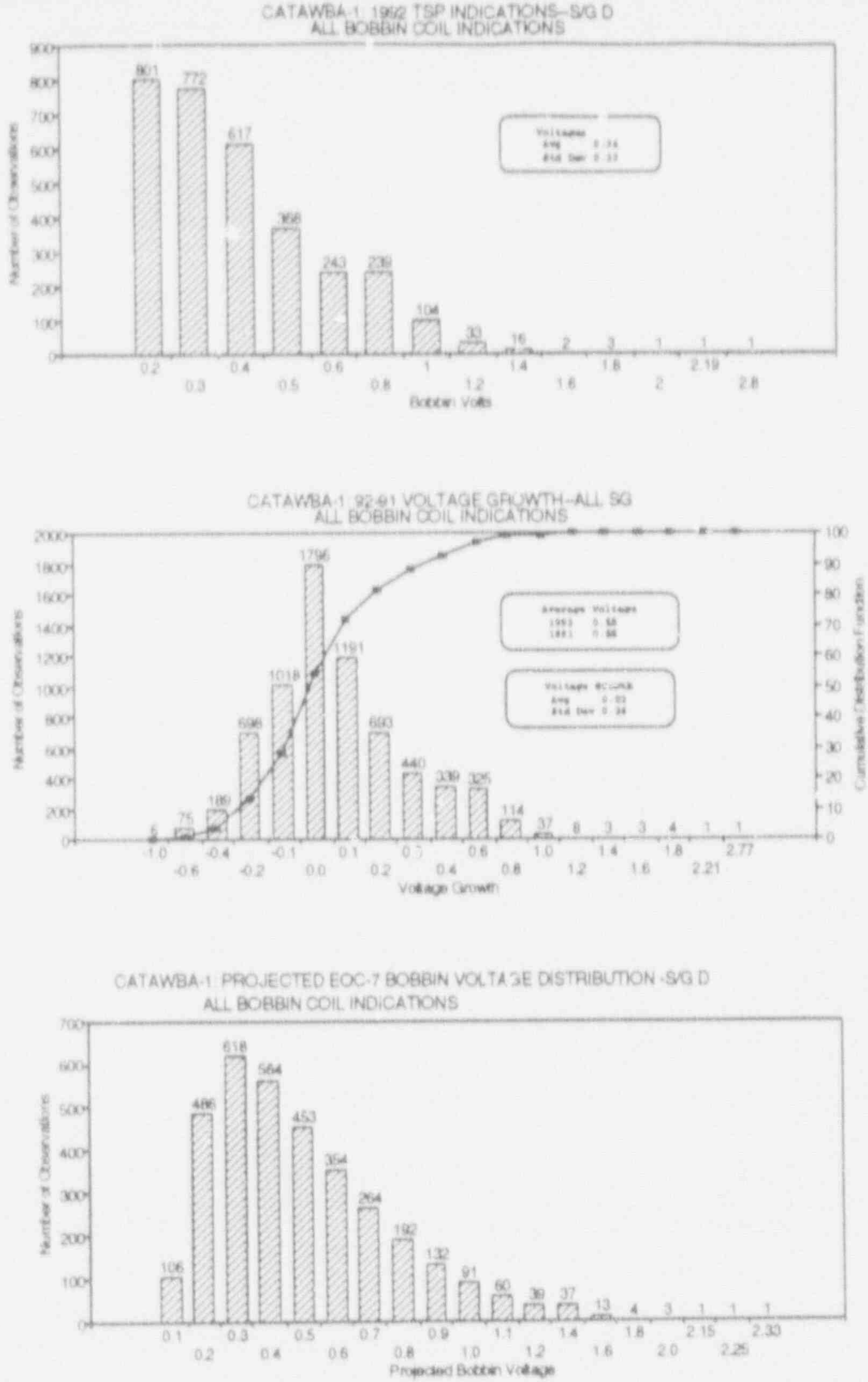



Figure 10-4. Steam Generator D EOC 7 Voltage Distribution Based on All Bobbin Coil Indications

[a]

Figure 10-5. Leak Rate Under Normal Operating Conditions versus Crack Length for 3/4 Inch Tubing

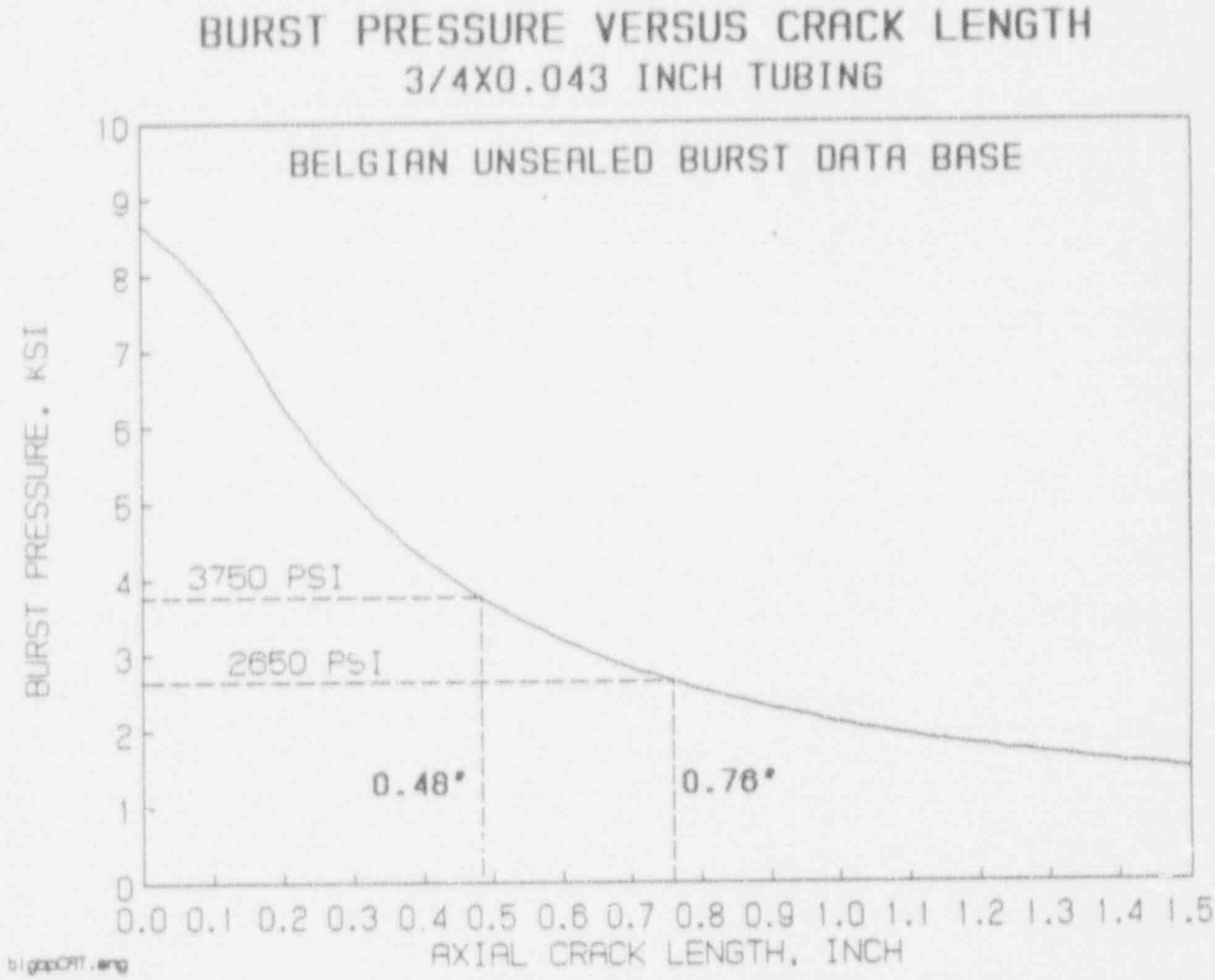



Figure 10-6. Burst Pressure versus Crack Length for 3/4 Inch Tubing

## Appendix A

### Catawba Nuclear Station, Unit 1
### Hot Leg Tube Support Re-sizing Analysis Guidelines and
### Hot Leg Tube Support Re-sizing Analysis Guidelines for Growth Trending

This appendix summarizes the guidelines used for re-analysis of the hot leg tube support plate (HL TSP) calls from the Catawba Unit 1, EOC-6 bobbin coil inspection program. The initial eddy current data analysis was performed in accordance with "Eddy Current Analysis Guidelines, Catawba Nuclear Station Unit 1", Revision 2, dated 7/9/92. Following the initial inspection program, the guidelines presented in this appendix were used to obtain voltage values consistent with Westinghouse recommendations for measuring bobbin voltages for ODSCC degradation at HL TSPs. This appendix also includes guidelines used to obtain ODSCC growth trending information.

The following pages show the HL TSP re-sizing analysis guidelines and the guidelines for growth trending. Figures A-1 through A-13 are provided to support the application of these guidelines.

Hotleg Tube Support

Re-sizing Analysis Guidelines

Technical Approval: ______________________ Date 8/13/92
NDE Level III, Eddy Current

NPD Concurrence: ______________________ Date 8/13/92
Support Engineer, Nuclear Services

Revision 0 - 08/12/92

# Catawba Nuclear Station

## Unit 1

## Hot Leg Tube Support
## Re-sizing Analysis Guidelines

1.0 Introduction:

Catawba Unit 1 is implementing a Hot Leg Tube Support voltage criteria for dispositioning Hot Leg TSP indications. This will require Re-sizing of all reported H/L TSP indications using a 550/130 KHz differential mix.

All analysts will be trained in Re-sizing TSP indications and the use of the resolution mode prior to analyzing data.

These guidelines are in addition to the present Catawba Unit 1 Guidelines Rev. 2 dated 7/9/92.

2.0 Mixes:

Only one additional mix will be required for Re-sizing, a 550/130 KHz differential mix (Mix-5) shall be established as the primary H/L TSP suppression mix. This mix shall be accomplished by using the drilled TSP in the calibration standard.

3.0 Normalization:

The voltage of the 550/130 KHz differential mix channel will be set at 2.75 volts on the four 20% flat bottom holes, and saved/stored to all other channels.

4.0 Re-sizing

To assure that a proper voltage is obtained only the ODSCC signal will be sized and not the TSP residual. This shall be accomplished by reviewing the TSP using the 550/130 KHz mix differential channel and setting the measurement "BALLS" so only the indication signal is being sized using P/P volts If the ODSCC signal cannot be distinguished from the mix residual then the 550 or 400 KHz differential channel can be used to set the P/P voltage then flip to the 550/130 KHz mix to report the indication. Insure that the P/P voltage points go from one edge of the indication to the other edge. All indications shall be reported off of Mix 5 550/130 KHz differential mix. (reference pictures attached for correct sizing.)

5.0 Reporting:

- Re-sizing will be accomplished using the 1st Re-eval mode.

- Only tube supports will be Re-sized and the call will be entered into the report using the 1st Re-eval.

- A final report by tape will be used to determine what tubes have TSP calls. Only the tubes with TSP calls need review.

6.0 Graphic Printouts:

New graphic printouts will be required. A graphic of the reporting channel 400/130 XY Liss and D-8 shall be made. The D-8 shall be comprised of channels 1, 3, [illegible] d Mix 1 on top and 2, 4, 6 and Mix 5 on the bottom. The D-8 shall be auto scaled in order to maintain a constant representation of the indications being reported.

7.0 Data Flow:

- A sign off tape log will be maintained. When a tape is complete it will be signed off by the analyst.

- New get shells will be printed by the analyst once the tape is complete. This data will be printed and saved.

- Prior to turning in the new get shell and new pictures, the analyst will compare his get shell to the first final report to ensure he has identified all TSP calls.

- All get shells and new pictures will be put into a folder and put into a box marked Re-Eval in the lead analyst cube.

8.0 Lead and Resolution Analyst Responsibilities:

- Compare original get shell to new get shell. Make corrections as required.

- Review all pictures to ensure the indications are reported correctly. If not, resolve as required.

- Send new get shells to Duke Power to be loaded into the data base.

Hotleg Tube Support

Re-sizing Analysis Guidelines
For Growth Trending

Technical Approval: James M. Buzman Date 8/13/92
NDE Level III, Eddy Current

NPD Concurrence: DB Mayes Date 8/13/92
Support Engineer, Nuclear Services

Revision 0 - 08/12/92

Catawba Nuclear Station

Unit 1

Hot Leg Tube Support
Re-sizing Analysis Guidelines
For Growth Trending

1.0 Introduction:

Catawba Unit 1 is implementing a Hot Leg Tube Support growth trending study for dispositioning Hot Leg TSP indications. This will require Re-sizing of all reported H/L TSP indications using a 400/130 KHz differential mix.

All analysts will be trained in re-sizing TSP indications prior to analyzing data.

These guidelines are in addition to the present Catawba Unit 1 Guidelines, Rev. 2 dated 7/9/92.

2.0 Mixes:

Mix 1 will be used for growth trending. This mix is a 400/130 KHz differential mix. This mix shall be accomplished by suppressing the drilled TSP in the calibration standard.

A 550/130 kHz differential mix (Mix 5) shall be established as an additional H/L TSP suppression mix. This mix shall be accomplished by suppressing the drilled TSP in the calibration standard.

3.0 Normalization:

The voltage of the 400/130 KHz differential channel will be set at 5.75 volts P/P on the four 20% flat bottom holes, and saved/stored to all other channels.

4.0 Re-sizing

To assure that a proper voltage is obtained only the ODSCC signal will be sized and not the TSP residual. This shall be accomplished by reviewing the TSP using the 400/130 KHz differential mix channel and setting the measurement "BALLS" so only the indication signal is being sized using P/P ensuring that the P/P voltage points go from one edge of the indication to the other edge and that the maximum voltage is displayed. If the ODSCC signal cannot be distinguished from the mix residual then the 550 or 400 KHz differential channel can be used to set th P/P voltage. Then, flip to the 400/130 KHz differential mix to report the indication. All indic ions shall be reported off the 440/130 KHz differential mix (reference Figures 1 thru 13 for correct sizing).

5.0 Reporting:

- Re-sizing will be accomplished using the 2ND_RESIZE window.

- Only tube support intersections with existing calls shall be resized.

- A listing of existing calls will be provided to determine which tubes have TSP calls.

- The analyst shall visit only those tubes with existing TSP calls and resize the indications at those intersections.

6.0 Graphic Printouts:

New graphic printouts will be required. A graphic of the reporting channel 400/130 XY Liss and D-8 shall be made. The D-8 shall be comprised of channels 1, 3, 5 and Mix 1 on top and 2, 4, 6 and Mix 5 on the bottom. The D-8 shall be auto scaled and refreshed in order to maintain a constant representation of the indications being reported.

7.0 Data Flow:

- A sign off tape log will be maintained. When a tape is complete it will be signed off by the analyst.

- The analyst shall print a build report for each cal group.

- Prior to turning in the results and new pictures, the analyst will compare his build report to the first final report to ensure he has identified all TSP calls.

- All build reports and new pictures will be sent to Duke Power at McGuire.

8.0 Resolution Analyst Responsibilities:

- Compare original report to the build report. Make corrections as required.

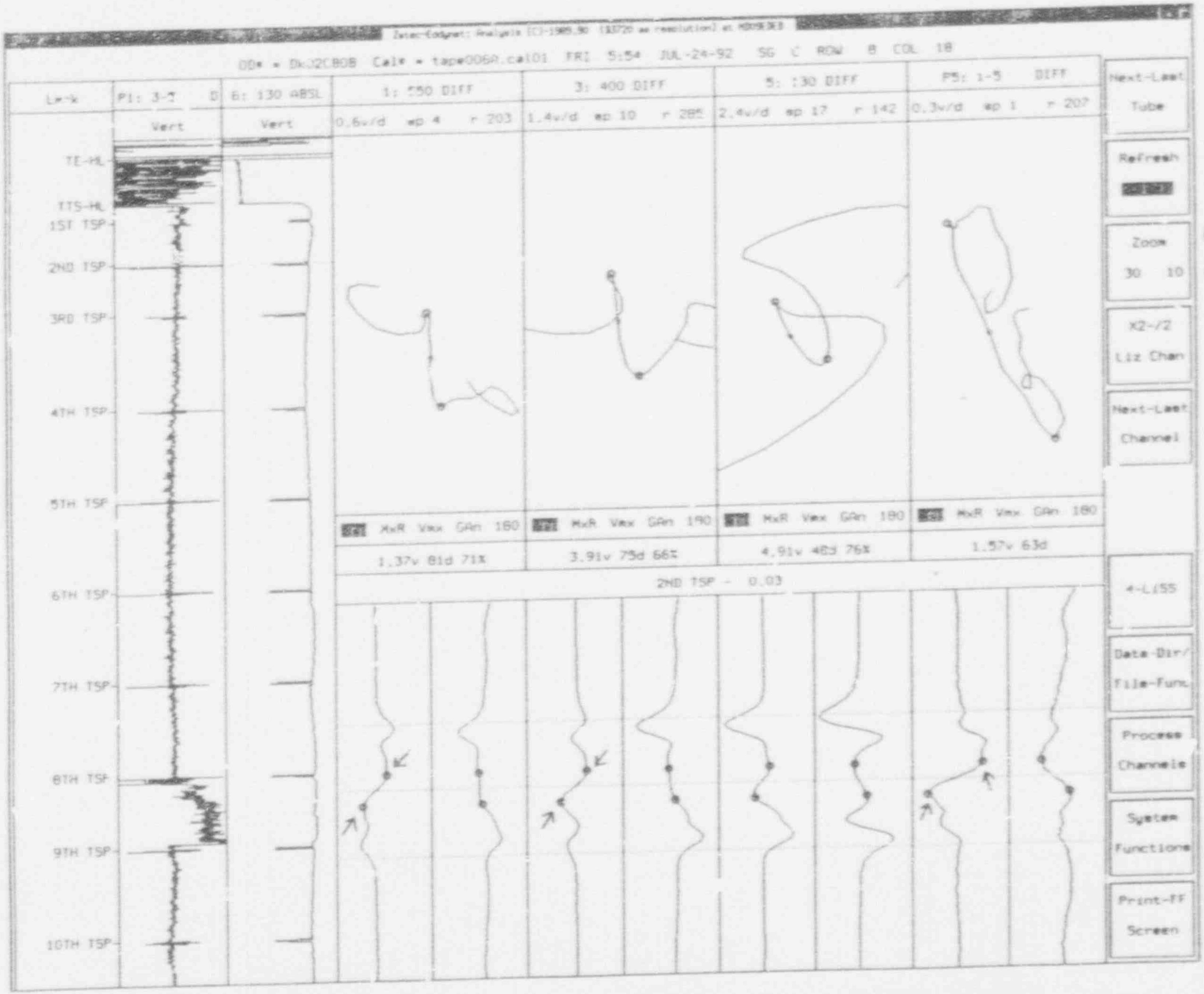
- Review all pictures to ensure the indications are reported correctly. If not, resolve as required.

- Print/Save get_shells under 2nd Re-size.

- Mark the get_shells as "2ND RESIZE" and turn in to Data Management in the "2ND RESIZE" box.

- Put pictures in the "2ND RESIZE" TO BE FILED BOX.

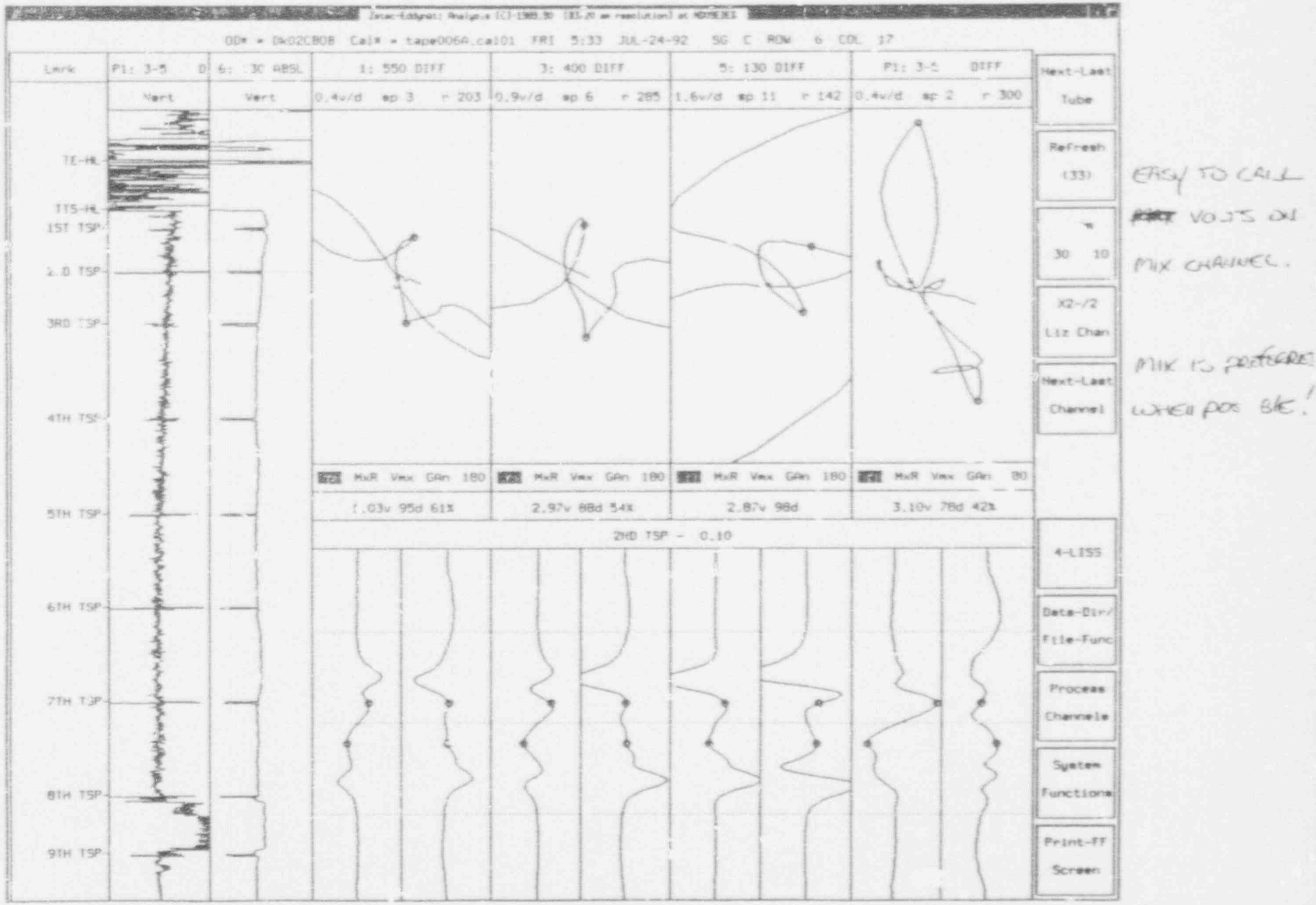
Figure A-1




GOOD BALLS

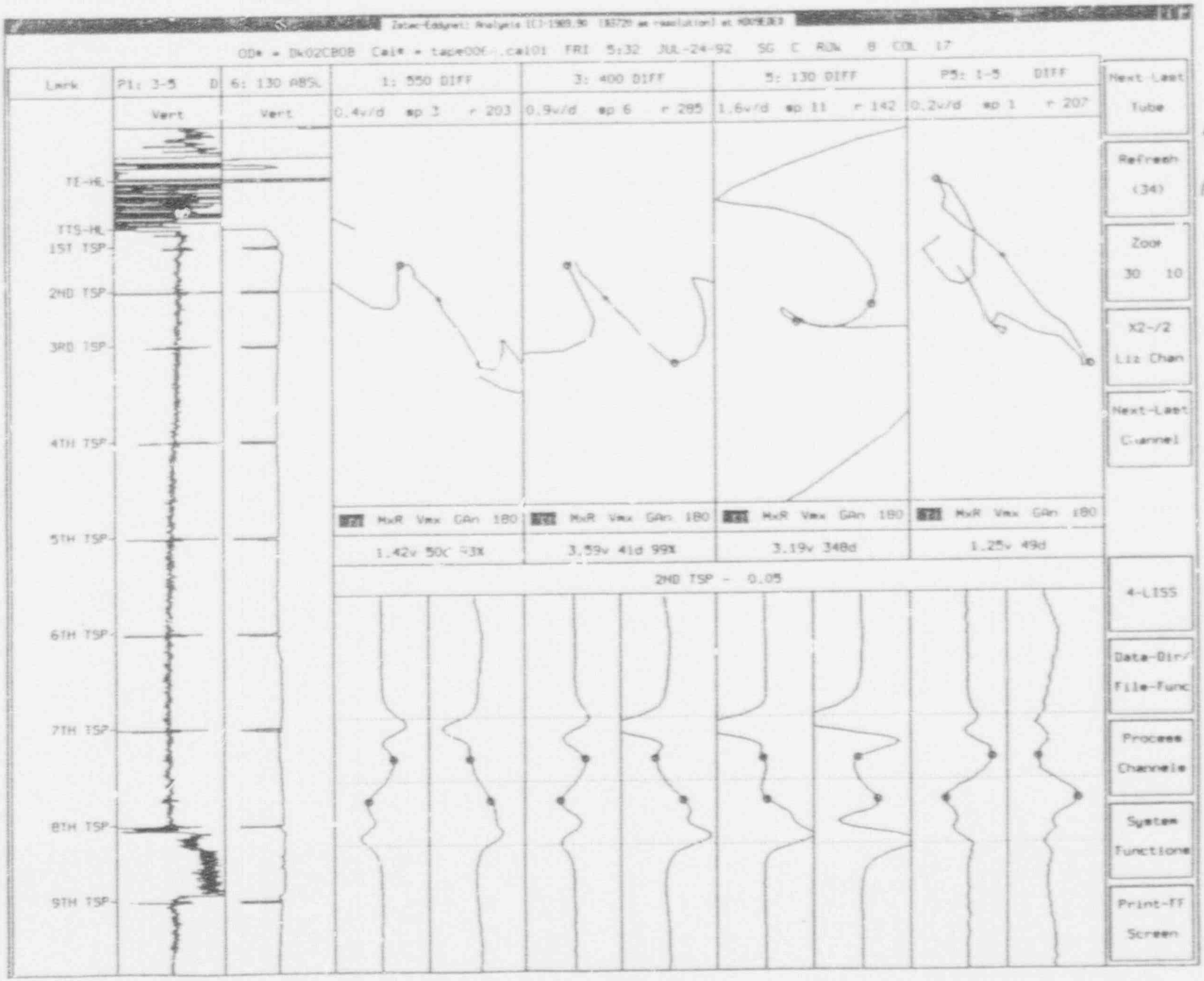
MAXIMIZED ON RAW AND MIX.

# Figure A-2



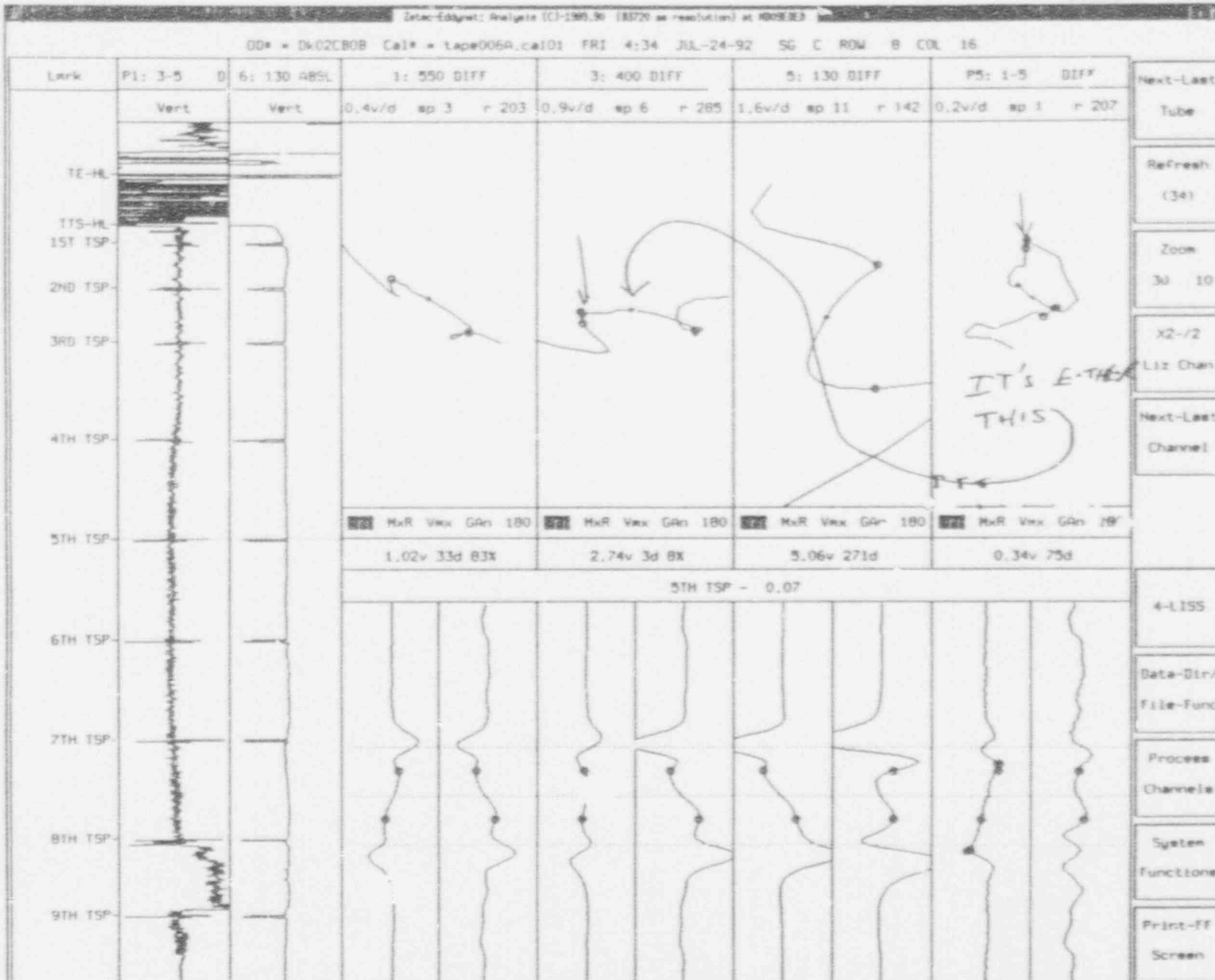
ODF = Dk02CB08 Cal# = tape006A.cal01 FRI 5:33 JUL-24-92 SG C ROW 6 COL 17
Lmrk
P1: 3-5 D
6: 130 ABSL
1: 550 DIFF
3: 400 DIFF
5: 130 DIFF
P1: 3-5 DIFF
Vert
Vert
0.4v/d sp 3 r 203
0.9v/d sp 6 r 285
1.6v/d sp 11 r 142
0.4v/d sp 2 r 300
TE-HL
TTS-HL
1ST TSP
2ND TSP
3RD TSP
4TH TSP
5TH TSP
6TH TSP
7TH TSP
8TH TSP
9TH TSP
MxR Vmx GAn 180
MxR Vmx GAn 180
MxR Vmx GAn 180
MxR Vmx GAn 90
1.03v 95d 61%
2.97v 88d 54%
2.87v 98d
3.10v 78d 42%
2ND TSP - 0.10
Next-Last Tube
Refresh (33)
30 10
X2-/2 Liz Chan
Next-Last Channel
4-LISS
Data-Dir/ File-Func
Process Channels
System Functions
Print-FF Screen
EASY TO CALL
VOLTS ON
MIX CHANNEL.
MIX IS PREFERRED
WHEN POSSIBLE!

Figure A-3




EASY TO CALL
MAY VOLTS ON
MIX CHANNEL!

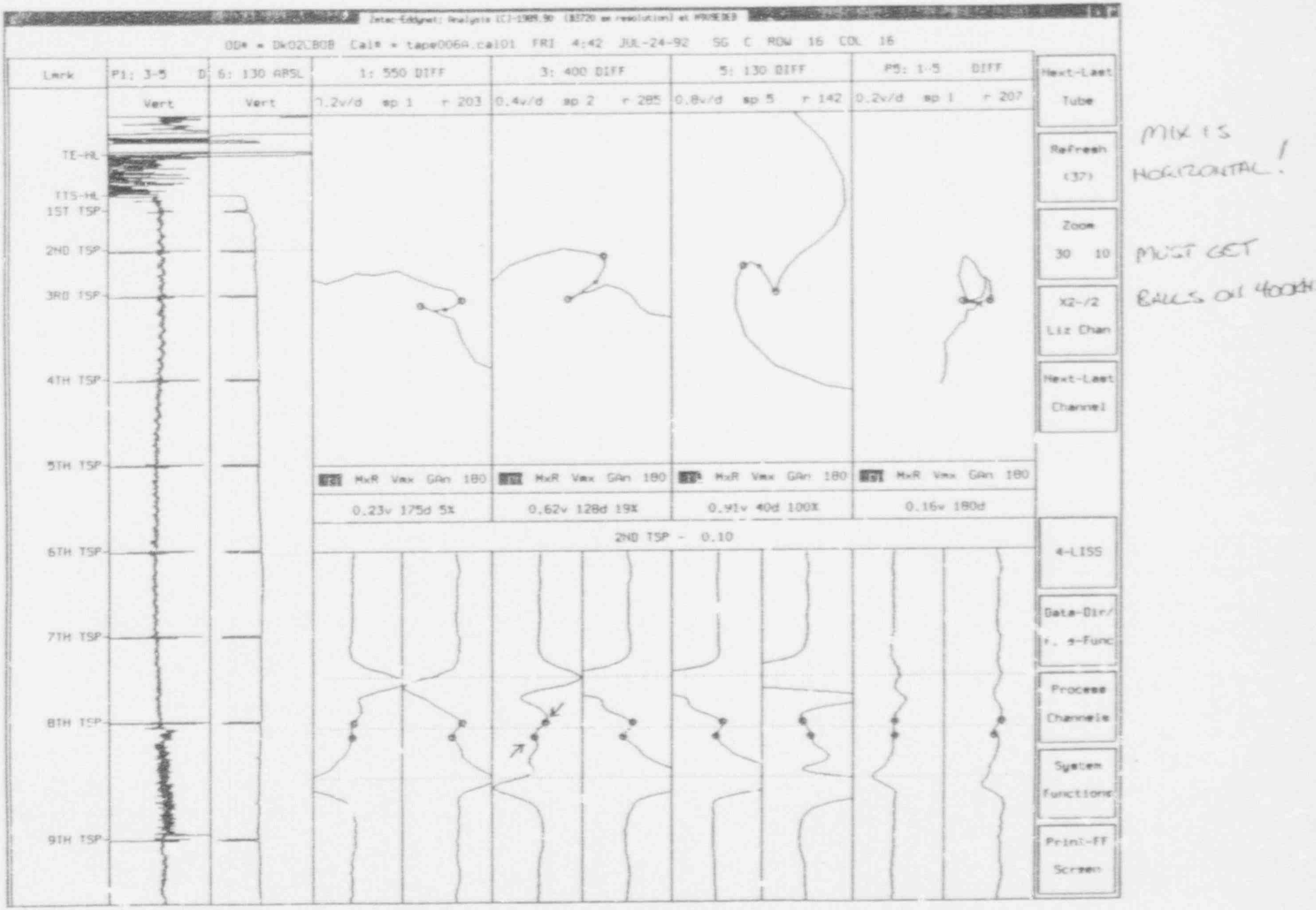
Figure A-4




BALLS CAN BE SET ON 400KHZ OR MIX

MUST INSURE BALLS ARE ON ENTIRE SIGNAL

Figure A-5



OD# = DK02CB08 Cal# = tape006A.cal01 FRI 4:42 JUL-24-92 SG C ROW 16 COL 16
Lmrk
P1: 3-5 D 6: 130 ABSL
Vert
Vert
1: 550 DIFF
3: 400 DIFF
5: 130 DIFF
P5: 1-5 DIFF
0.4v/d sp 2 r 285
0.8v/d sp 5 r 142
0.2v/d sp 1 r 207
TE-HL
TTS-HL
1ST TSP
2ND TSP
3RD TSP
4TH TSP
5TH TSP
6TH TSP
7TH TSP
8TH TSP
9TH TSP
MxR Vmx GAn 180
0.23v 175d 5%
0.62v 128d 19%
0.91v 40d 100%
0.16v 180d
2ND TSP - 0.10
Next-Last Tube
Refresh (37)
Zoom 30 10
X2-/2 Liz Chan
Next-Last Channel
4-LISS
Process Channels
System functions
Print-FF Screen
MIX IS HORIZONTAL!
MUST GET BALLS ON 400kH

Figure A-6

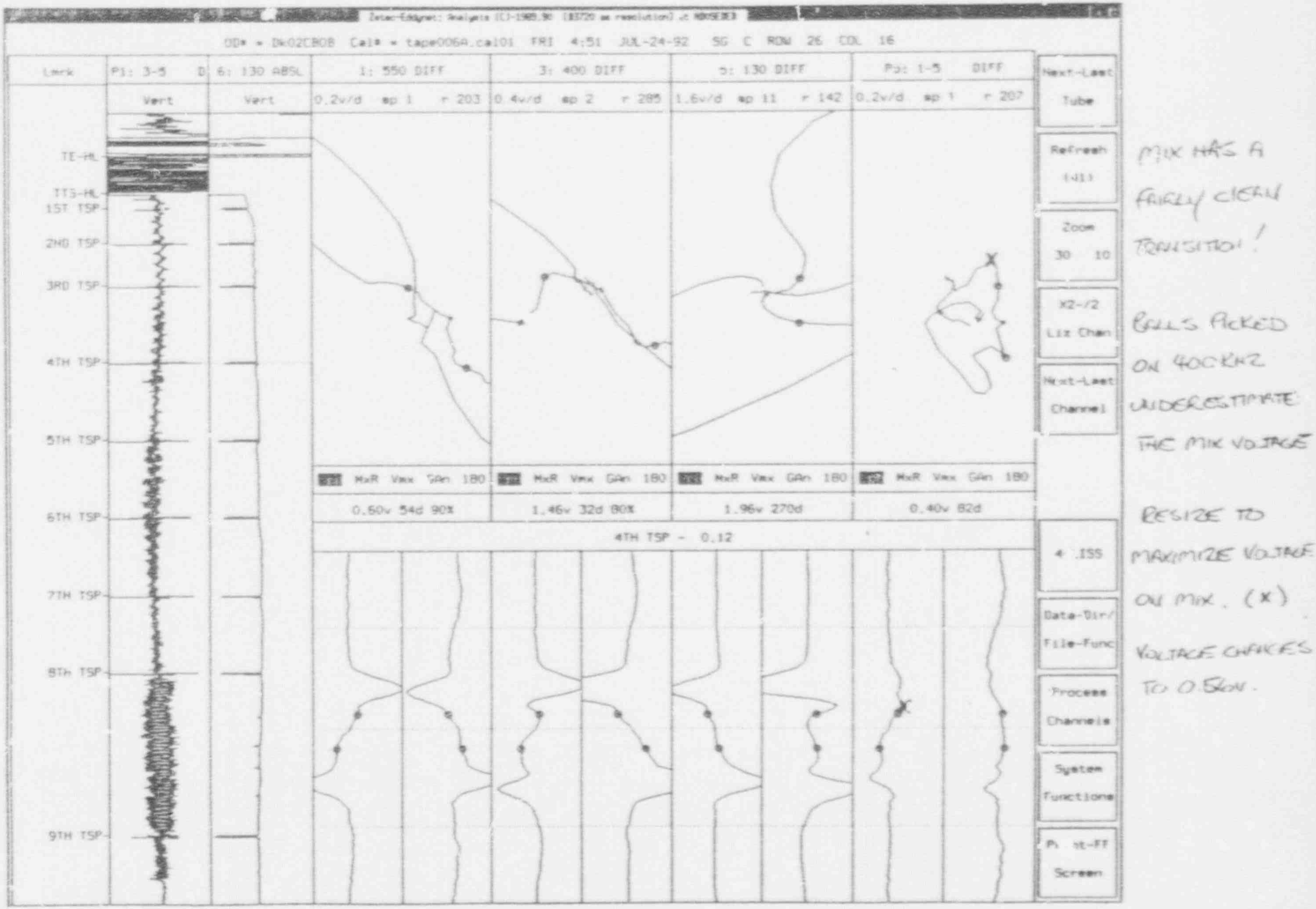
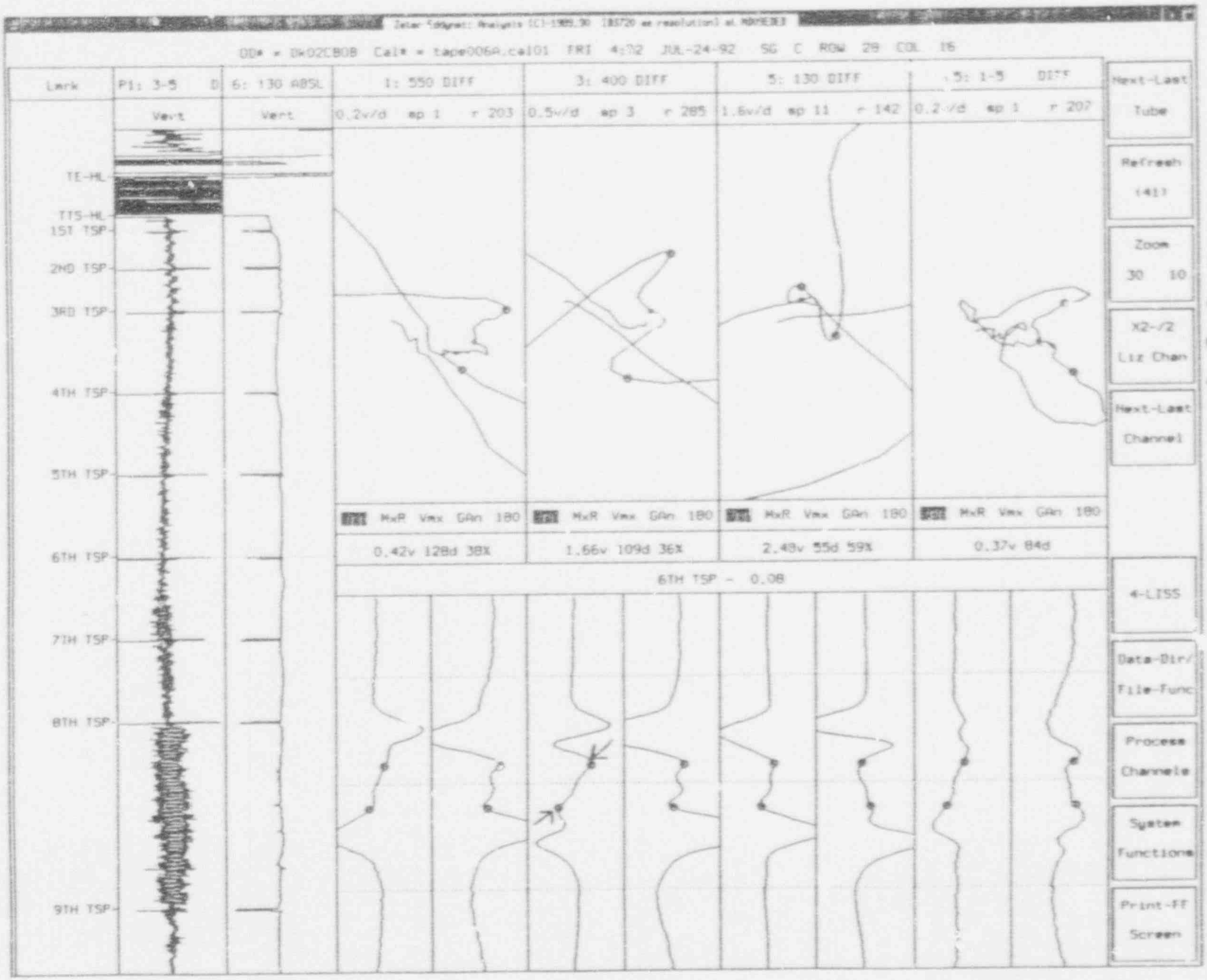

Zetec-Eddynet: Analysis (C)-1988.90 (8372) as resolution) .c KOXSEDED
OD# = DK02CB08 Cal# = tape006A.cal01 FRI 4:51 JUL-24-92 SG C ROW 26 COL 16
Lmrk
P1: 3-5 D
6: 130 ABSL
1: 550 DIFF
3: 400 DIFF
5: 130 DIFF
P3: 1-5 DIFF
Vert
Vert
0.2v/d sp 1 r 203
0.4v/d sp 2 r 285
1.6v/d sp 11 r 142
0.2v/d sp 1 r 207
TE-HL
TTS-HL
1ST TSP
2ND TSP
3RD TSP
4TH TSP
5TH TSP
6TH TSP
7TH TSP
8Th TSP
9TH TSP
MxR Vmx GAn 180
0.60v 54d 90%
1.46v 32d 80%
1.96v 270d
0.40v 82d
4TH TSP - 0.12
Next-Last Tube
Refresh
Zoom 30 10
X2-/2 Liz Chan
Next-Last Channel
Data-Dir/ File-Func
Process Channels
System Functions
Screen
MIX HAS A FAIRLY CLEAN TRANSITION!
BALLS PICKED ON 400KHZ UNDERESTIMATE THE MIX VOLTAGE
RESIZE TO MAXIMIZE VOLTAGE ON MIX. (X) VOLTAGE CHANGES TO 0.56V.

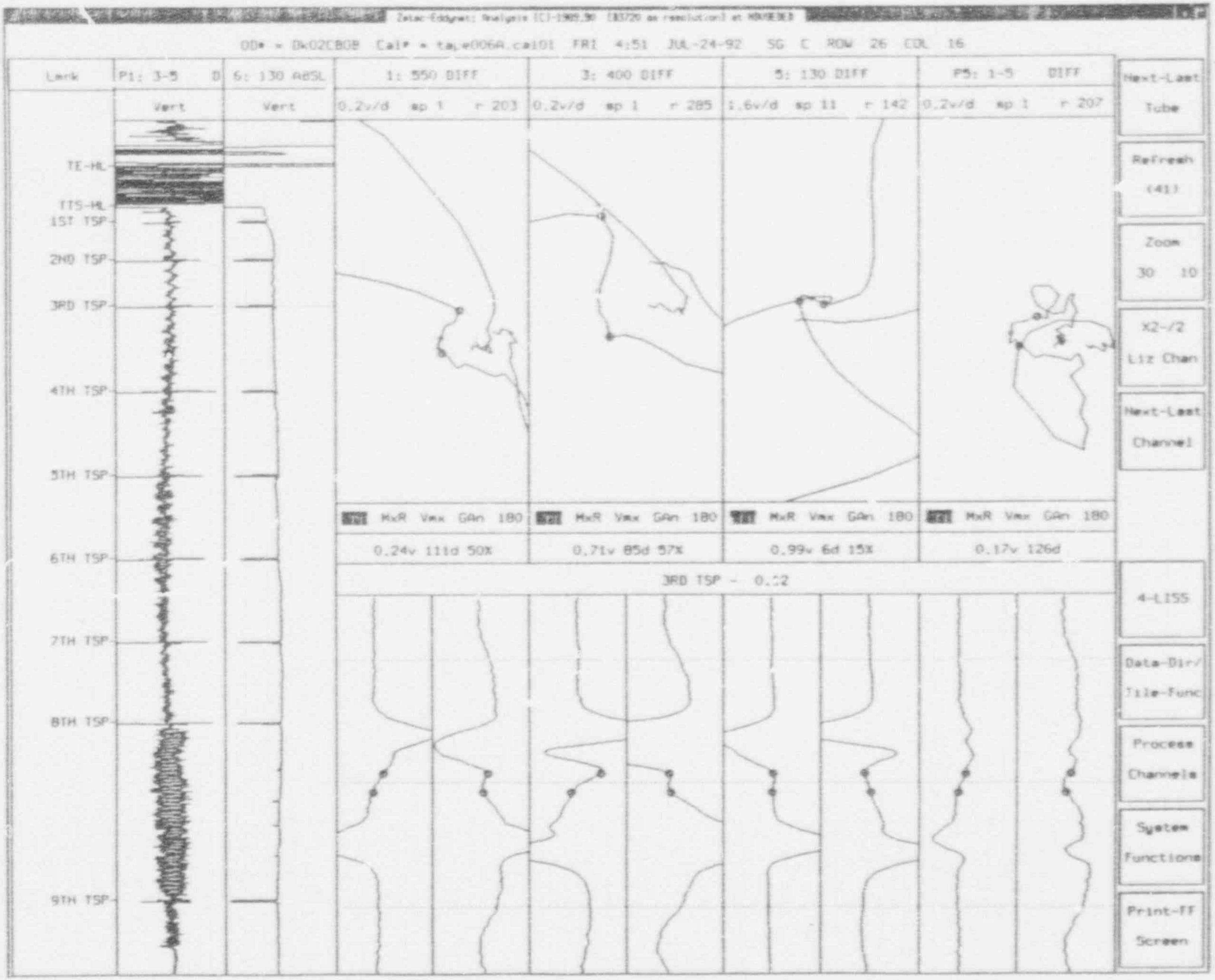
Figure A-7




MIX RESIDUAL HAS NO GOOD TRANSITION.

400KHZ HAS TWO GOOD POINTS ON VERT EXPANDED CHART.

Figure A-8

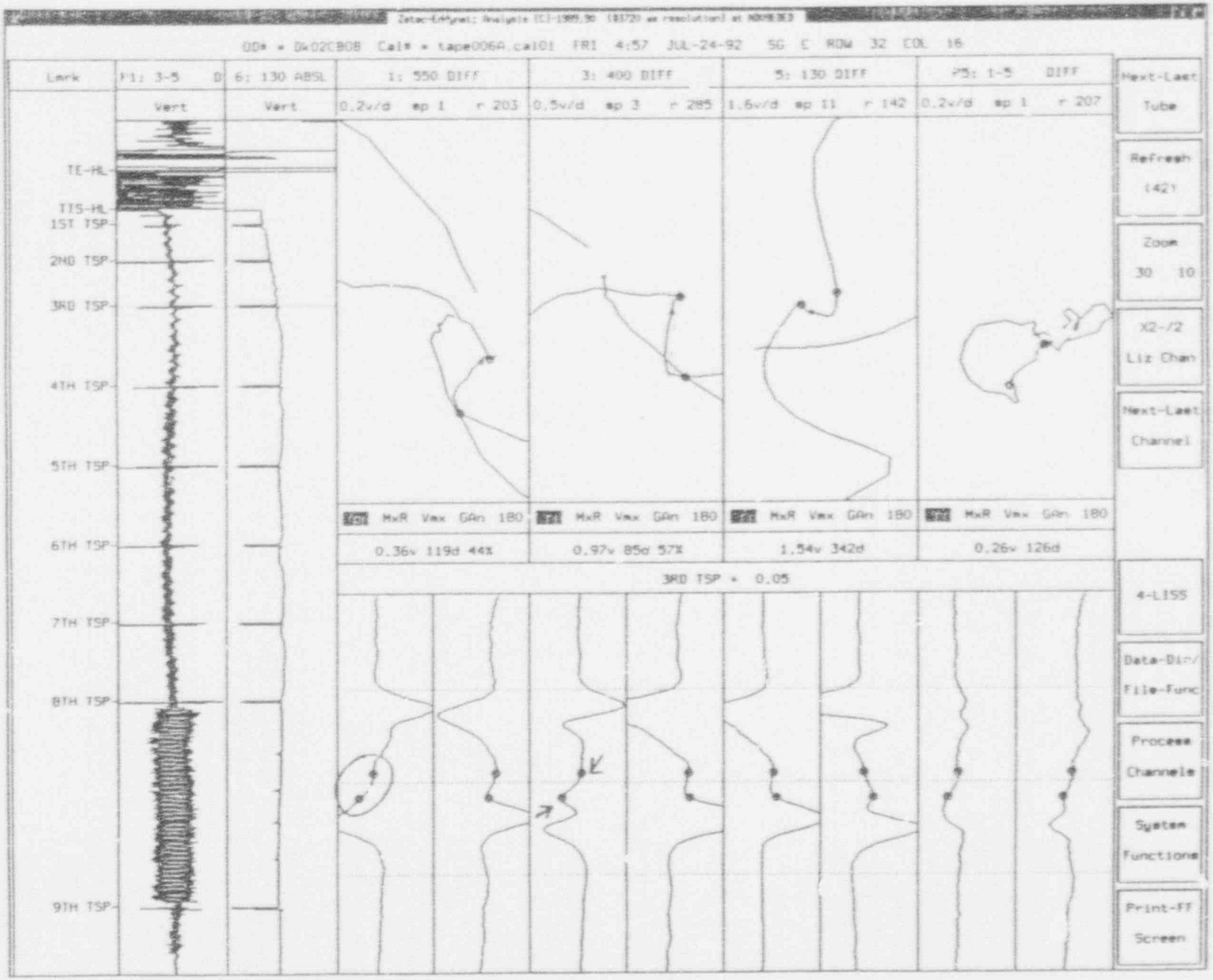



MIX RESIDUAL HAS NO FLAW TRANSITION.

BALLS BEST PICKED ON 400KHZ LISSAJOU

NO GOOD POINTS TO PICK ON 400 OR 550 EXPANDED STRIP

Figure A-9

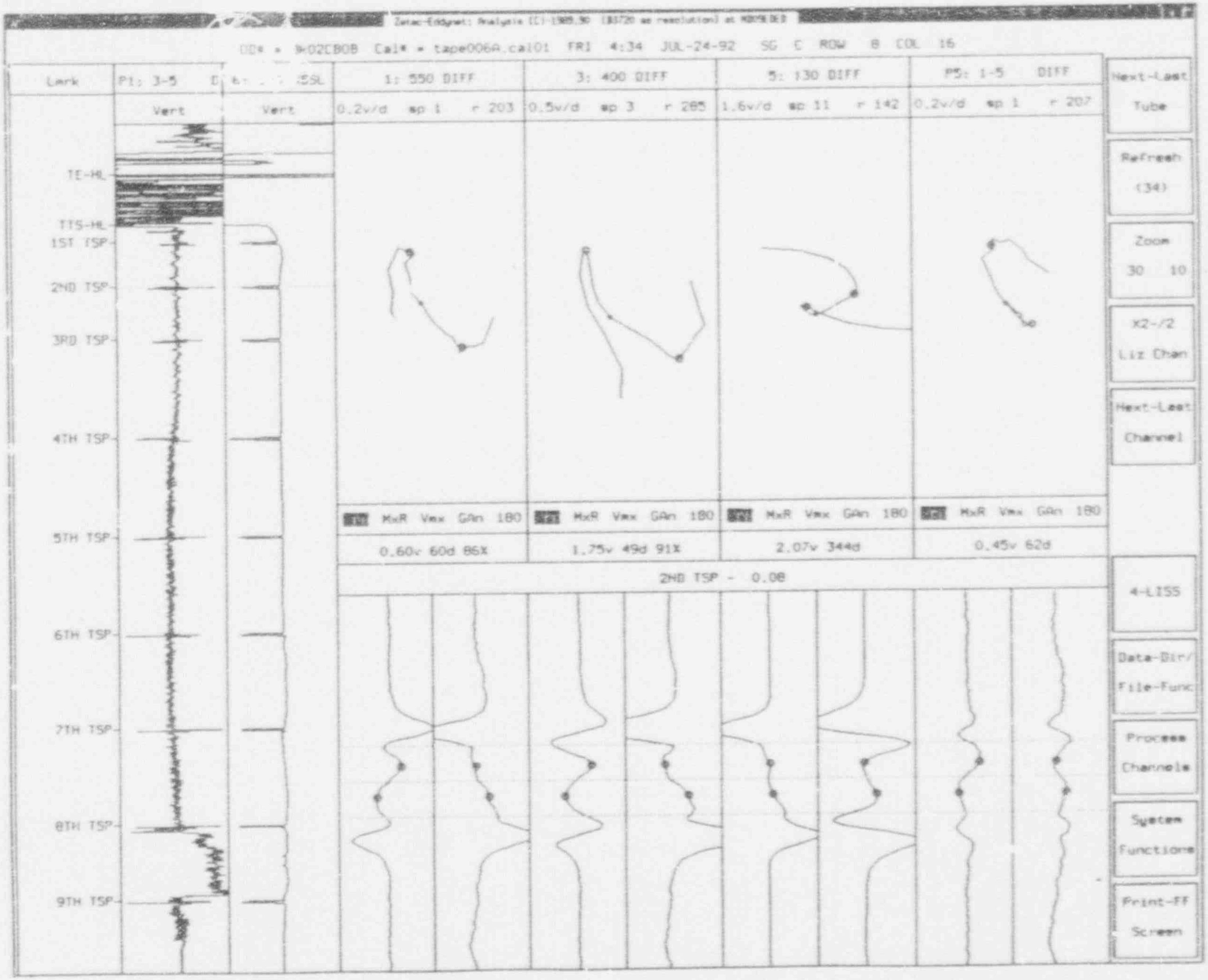



MIX RESIDUAL
HAS NO GOOD
TRANSITION.

MAXIMIZE BALL
ON 400KHZ.

NO GOOD POINTS
ON 550KHZ
VERT EXPANDED
CHART.

Figure A-10




GOOD CALLS ON MIX LISS MAXIMIZED ON RAW AND MIX.

Figure A-11

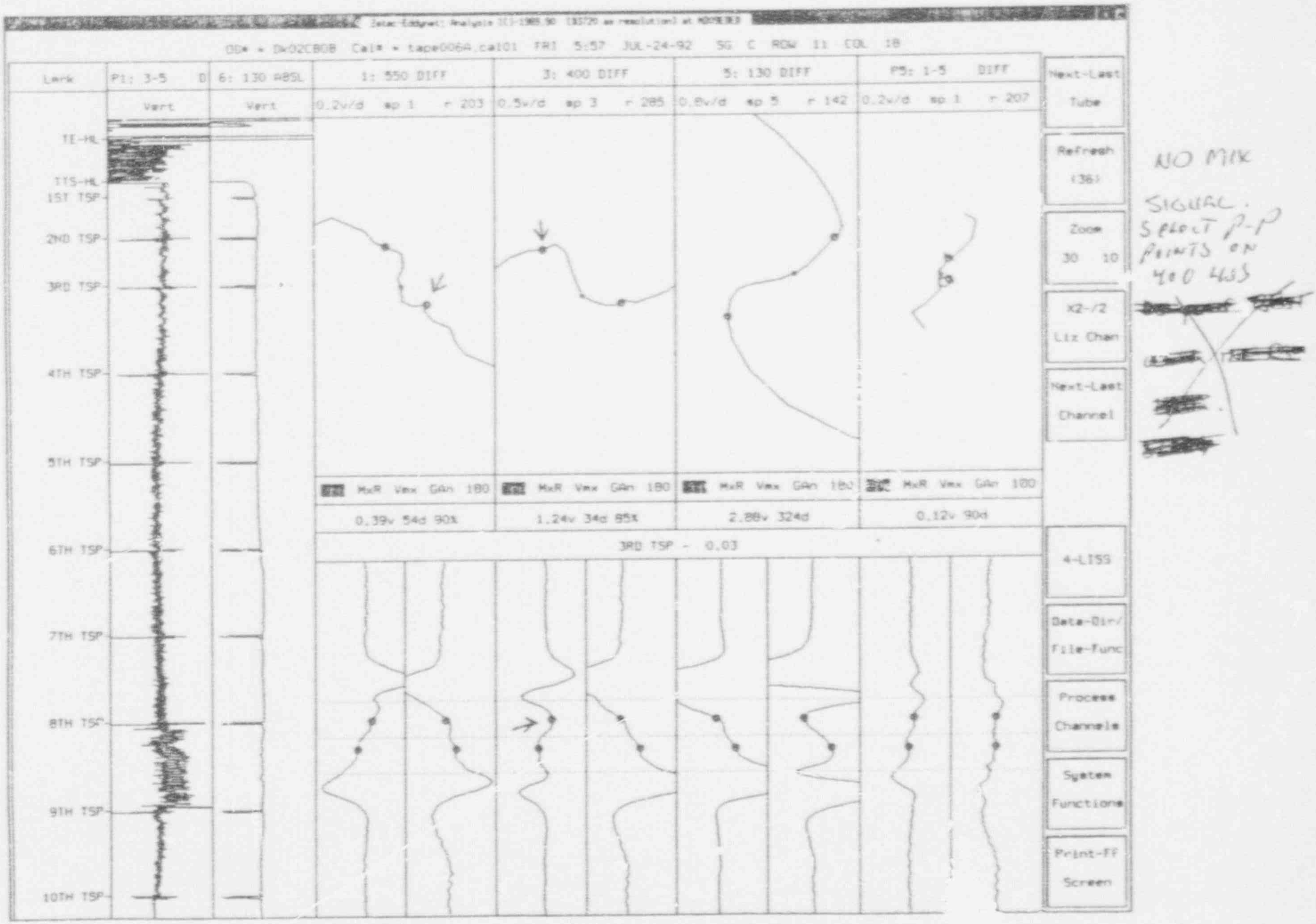
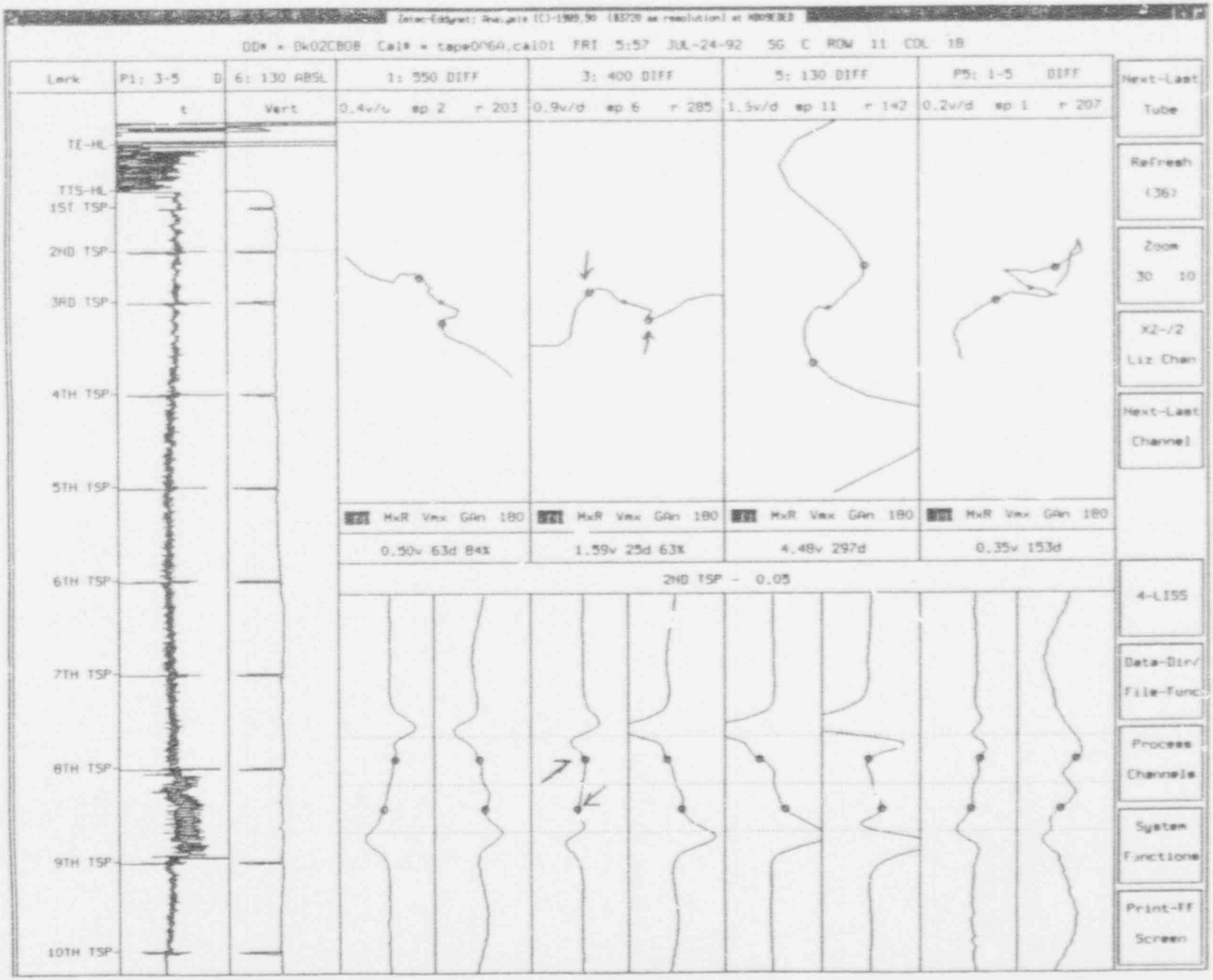
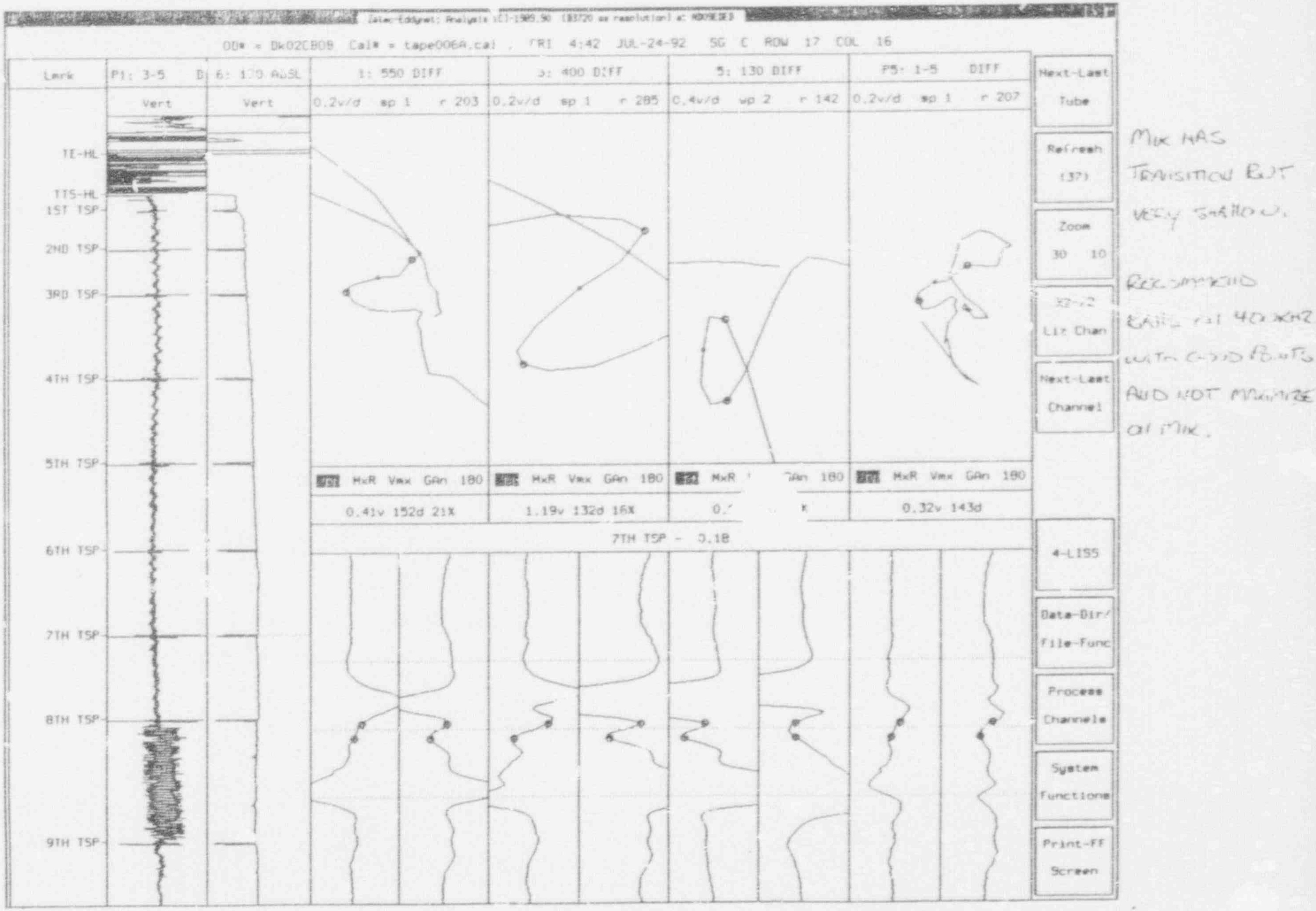

OD# = Dw02CB0B Cal# = tape006A.cal01 FRI 5:57 JUL-24-92 SG C ROW 11 COL 18
Lmrk
P1: 3-5
Vert
6: 130 ABSL
Vert
1: 550 DIFF
0.2v/d sp 1 r 203
3: 400 DIFF
0.5v/d sp 3 r 285
5: 130 DIFF
0.8v/d sp 5 r 142
P5: 1-5 DIFF
0.2v/d sp 1 r 207
TE-HL
TTS-HL
1ST TSP
2ND TSP
3RD TSP
4TH TSP
5TH TSP
6TH TSP
7TH TSP
8TH TSP
9TH TSP
10TH TSP
MxR Vmx GAn 180
0.39v 54d 90%
1.24v 34d 85%
2.88v 324d
0.12v 90d
3RD TSP - 0.03
Next-Last Tube
Refresh (36)
Zoom 30 10
X2-/2 Liz Chan
Next-Last Channel
4-LISS
Data-Dir/ File-Func
Process Channels
System Functions
Print-FF Screen
NO MIK
SIGNAL. SELECT P-P POINTS ON 400 LISS

Figure A-12




NO MIX SIGNAL
GET GAINS on
400KHZ.

Figure A-13


OD# = Dk02CB09 Cal# = tape006A.cal , FRI 4:42 JUL-24-92 SG C ROW 17 COL 16
Lmrk
P1: 3-5
Vert
Vert
1: 550 DIFF
0.2v/d sp 1 r 203
400 DIFF
0.2v/d sp 1 r 285
5: 130 DIFF
0.4v/d wp 2 r 142
P5: 1-5 DIFF
0.2v/d sp 1 r 207
TE-HL
TTS-HL
1ST TSP
2ND TSP
3RD TSP
4TH TSP
5TH TSP
6TH TSP
7TH TSP
8TH TSP
9TH TSP
MxR Vmx GAn 180
0.41v 152d 21X
1.19v 132d 16X
0.32v 143d
7TH TSP - 0.18
Next-Last Tube
Refresh (37)
Zoom 30 10
Liz Chan
Next-Last Channel
4-LISS
Data-Dir/ File-Func
Process Channels
System Functions
Print-FF Screen
MIX HAS TRANSITION BUT VERY SHALLOW.
AND NOT MAXIMIZE
OF MIX.