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April 14, 2000

Re: Indian Point Unit No. 2
Docket No. 50-247

Document Control Desk
US Nuclear Regulatory Commission
Mail Station P1-137
Washington, DC 20555-0001

Subject : Root Cause Evaluation For Steam Generator Tube Rupture Event of February 15, 2000

Enclosed please find the evaluation summarizing the technical assessment of the cause of the leaking tube, Row 2 - Column 5 in 24 Steam Generator. This evaluation summarizes the following:

1. Actions taken to identify the source of the leak
2. Visual inspections from both the primary and secondary sides of the tube to characterize the crack in the tube
3. Visual inspections of the steam generator secondary side structure to identify potential contributing factors to the tube cracking
4. Review of the eddy current data from both the current and the 1997 inspections
5. Preliminary results of modified eddy current analysis methods, including the use of a high frequency probe
6. Results of a study of probe restrictions at the top of the Tube Support Plate (TSP), and direct measurement of flow slot hourglassing at the top of the Tube Support Plate (TSP)
7. Review of the manufacturing history regarding tube ovalization
8. Preliminary results of a stress analysis to assess the sensitivity of row 2, row 3, and row 4 to potential straight leg deformation resulting from TSP hourglassing
9. Review of industry experience with regard to low row U-bend cracking and leakage events

Con Edison concludes that the source of the leakage was Primary Water Stress Corrosion Cracking (PWSCC) at approximately the apex of R2 - C5, about 2.4 inches long. Significant contributing factors for this leak were masking of the indication in the 1997 inspection by noise related to deposits and tube geometry, and increased stress in row 2 due to TSP flowslot deformation because of denting.

Because eddy current data acquisition and analysis is currently ongoing, the enclosed evaluation does not address all of the recently identified degradation mechanisms. Con Edison intends to provide a complete evaluation of other degradation mechanisms identified during the current outage in the Condition Monitoring and Operational Assessment (CMOA). Furthermore, we intend to provide additional information regarding Outside Diameter Stress Corrosion Cracking (ODSCC) above the top of the tubesheet location, and PWSCC at the row 2 U-bend in our response to the NRC's Request for Additional Information dated March 24, 2000, and the CMOA.

No new regulatory commitments are being made by Con Edison in this correspondence.

Should you or your staff have any concerns regarding this matter, please contact Mr. John McCann, Manager, Nuclear Safety & Licensing.

Very truly yours,

Attachment

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<u>ATTACHMENT</u>

Root Cause Evaluation For Steam Generator Tube Rupture Event of February 15, 2000

Consolidated Edison Company of New York, Inc.
Indian Point Unit No. 2
Docket No. 50-247
April 2000

Root Cause Evaluation

1.0 Introduction

On February 15, 2000, with the plant operating at approximately 99% power, Indian Point 2 experienced primary to secondary leakage of approximately 75 to 100 gpm. The initial indication of leakage was an N-16 alarm. Plant operators identified the source of the leak to be in SG-24 and took appropriate actions to isolate the leak and bring the plant to a cold shutdown condition.

This report summarizes the technical investigation of the primary to secondary steam generator leakage event that occurred at Indian Point 2. It is the objective of this report to establish the mechanism by which the leakage occurred, based on the examination of the SG performed after the plant achieved cold shutdown, on a review of the operating experience of Indian Point 2 and a review of previous industry experience. A corrective action plan, which has already been partially implemented as described herein, is also described in this report.

This report will be followed by a separate report, the Condition Monitoring and Operational Assessment (CMOA) required by NEI 97-06, that evaluates the structural integrity of the SG tubes and tube support plates, and justifies continued operation of the SGs for a period of time based on accepted industry criteria. The CMOA will address the issues of detection, growth and measurement uncertainties for the degradation that led to the R2C5 leakage as well as for other degradation mechanisms identified in the Indian Point 2 steam generators. The CMOA report will be issued prior to restart of the plant.

2.0 Summary

The observed leak was due to a crack at the apex of the R2C5 U-bend. The crack is due to primary water stress corrosion cracking (PWSCC). This conclusion is based on review of the prior eddy current inspection data, prior industry experience and predictions of the tube stress that show the maximum stresses are consistent with ID crack initiation at the tube extrados. The characteristics of the crack are the same as those on tubes with PWSCC that were removed from other plants' SGs and destructively examined. Denting at TSP6 (top TSP) appears to have contributed to the row 2 cracking at Indian Point 2. The majority of TSP intersections are dented, based on a review of the current eddy current inspection data. The cumulative denting manifests itself as hourglassing in the flowslot region. Hourglassing found in the flow slots at TSP6 results in pinching (reducing the distance between the straight legs of the tubes) of the u-bends and elevated hoop stress at the ID of the extrados of the tube near the apex. The increased hoop stress increases the potential for PWSCC at the ID of the row 2 u-bend extrados.

Retrospective examination of the R2C5 data from the 1997 inspection showed an anomalous indication. Expert review of the data concurred that the flaw would not have been called by accepted EC practices in 1997, due to background noise in the signal related to geometry effects and deposits including copper. Once identified, using current sizing practices, the 1997 R2C5 flaw signal was sized in the range of 63-71% average depth, and 92% maximum depth. Thus, the principal cause of the leakage was the inability to detect the indication in 1997 inspection due to noise in the signal; growth of the indication between 1997 and 2000 is moderate and is not the principal root cause of the leakage.

The first reported PWSCC in the low row u-bends at Indian Point 2 was discovered during the steam generator inspection in 1997 when one row-2 tube (R2C67) was plugged. All row 1 tubes, which are more susceptible to PWSCC than the row 2 tubes, were preventively plugged prior to plant startup. The 1997 Steam Generator Inspection was conducted in accordance with industry guidelines; however, retrospective review of the 1997 data showed that background noise in the eddy current signal masked the flaw in R2C5. The same review indicated the presence of a second flaw in the U-bend of R2C69 that was also not reported in 1997. The crack in R2C5 is estimated to be approximately 2.4 inches long, located at the extrados of the tube near the apex. Application of current sizing methods indicated that the R2C5 flaw had an average depth in the range of approximately 63-71%, and a maximum depth of 92% in 1997. NDE sizing of the current outage R2C69 indication shows that this indication satisfies all structural criteria at the time of the year 2000 inspection. NDE sizing of the 1997 outage data for R2C69, although less reliable than the 2000 data, shows only moderate growth occurred over the 540 EFPD of operation. Assessments of the U-bend PWSCC growth rates for Indian Point 2 show low to moderate growth. Modest growth for row 2 u-bend PWSCC is also supported by industry experience for which there have been no significant operating SG leakage prior to the Indian Point 2, R2C5 indication. A complete summary of the u-bend indications, sizing of the indications and a discussion of growth rates of the indications will be included in the CMOA report. -

Overall, the principal cause of the leakage event is the lack of detection of the PWSCC indication at the U-bend apex of R2C5. (A second concern is the growth rate of the PWSCC indications in the low row u-bends which is moderate.) The degradation mechanisms for the row 2 crack is axial PWSCC with the potential for row 2 cracking enhanced by the flowslot hourglassing resulting from generally dented tube conditions at TSP6. The lack of detection of the crack is attributable to masking of the flaw in the 1997 inspection. Masking of the flaw was due to signal distortion (noise) caused by deposits (magnetite, copper) on the tube and, potentially, ovalization of the tube. A reduction in the noise level obtained by inspection with a high frequency probe, as discussed below, tends to indicate that the deposits were the principal contributor to the lack of detection of the R2C5 flaw in1997.

Improvements in the analysis techniques in 2000 were made relating to more stringent noise criteria, setup changes and use of data from the strip charts to identify potential indications. Application of these improvements resulted in the identification of two additional row 2 flaws in the 2000 inspection that were subsequently also identified in the 1997 data. For the 2000 inspections, the conventional mid-range Plus Point probe low row U-bend examinations were supplemented with a high frequency, 800 kHz Plus Point probe. The use of a higher frequency focuses the test on the inner surface of the tubes and, therefore performs in a manner less sensitive to the effects of OD deposits. The design of the high frequency probe may also result in improved surface riding capability, thus reducing signal noise due to tube geometry effects. Additional flaws were detected through use of the high frequency Plus Point probe; these will be summarized in the CMOA.

Indian Point 2 has a history of denting that has been observed since early in the plant's operation. Evaluation of the restricted tubes reported in the 1997 and 2000 inspections indicate that the denting mechanism is continuing at a slow rate. The cumulative effect of denting was confirmed by measurements of the row 1 leg spacing at TSP 6 of flow slot N1 near the leaking tube which showed hourglassing of the flow slot adjacent to R2C5 of approximately 0.47 inch Hourglassing results in additional bending of the u-bends and has been shown by analysis to contribute to the conditions that lead to PWSCC. The effect of hourglassing on the tubes decreases with increasing row number, due to the greater flexibility of the larger bend radii tubes.

3.0 IP-2 Steam Generator Summary of Inspection History

The Indian Point 2 SGs are Westinghouse Model 44 units that were put into service in 1973. The steam generator tubes are 0.875-inch diameter tubes utilizing Alloy 600 mill annealed material. The Row 1 U-bends were plugged prior to SG operation. No stress relief by heat treatment of the R2 U-bends was performed at Indian Point 2.

Denting was reported in 1978; however, no tubes required plugging as a result of the denting. In 1979, a small number of tubes were plugged due to denting; however, no defects were reported. In subsequent inspections, until 1984, additional tubes were plugged for denting; however, no defects were reported. In 1984, in addition to denting, a number of tubes were plugged due to sludge pile pitting. This pattern of plugging due to denting and pitting and preventive plugging to address industry issues (e.g., NRC GL 88-02) continued without observed cracking mechanisms until 1993 when primary water stress corrosion cracking (PWSCC) was reported in the roll transition zone (RTZ). In 1995, PWSCC at the RTZ continued to be observed and repairs were made under F*, and additional tubes were plugged due to restrictions (the result of denting). In 1997, additional PWSCC was reported in the RTZ, and ODSCC and PWSCC at the support plate intersections and PWSCC at the apex of a single row-2 U-bend were reported for the first time.[1]

4.0 Location of Leaking Tube and Defect

After isolation of SG24 and cooldown of the plant, SG 24 was drained, and a re-fill of the SG secondary side was initiated using the Auxiliary Feedwater Pump at a rate of approximately 25–30 gpm, equivalent to a water level increase in the tube bundle of approximately 1 inch /minute. Water entered the SG through the feedring. At a water level estimated at several inches above the first tube support plate (TSP), drippage at a rate of approximately 2 drops per second was observed from both the hot leg (HL) and the cold leg (CL) of the R2C5 tube. This implied a defect that would affect both legs of the SG, which typically would be interpreted as a flaw at the apex of the U-bend. The water level was reduced in the SG while the drippage from R2C5 was assessed.

Concurrent HL and CL flaws at TSP1 of a size to support the reported leak rate of 75-100 gpm were not considered likely. Further, since the observed rate of drippage was negligible compared with the expected rate of leakage at ambient conditions that would be equivalent to a leak of approximately 75-100 gpm at operating conditions, the fill of the SG was resumed. (The expected room temperature leak rate equivalent to an operating condition leak rate of 75-100 gpm was calculated to be in the range of 3-10 gpm, depending on the elevation of the flaw.) No drippage was observed from R2C5 during this fill until the level of the water was above the elevation of TSP2, when some drips of water were again observed from tube R2C5.

At a water level of approximately 60% of the wide range level sensor, equivalent to about 16 inches above the top of the uppermost TSP (TSP6), a steady stream of water was observed to be leaking from

[1] Personal communication J.R. Maris to S.M.Ira; 2/19/00 (e-mail)

both the HL and CL of tube R2C5. The SG fill was continued to a level of 75% of the wide range level sensor, or approximately 75 inches above the top of TSP6, an elevation that is approximately 1 foot above the apex of the outer row of tubes in the tube bundle. No leakage was observed from any other tubes during the SG fill.

4.1 Evaluation of Tube Condition at TSP1

To evaluate the drippage from R2C5 during the first fill of the SG, the eddy current (EC) data for the tube were examined to determine if a flaw existed at either, or both, of the HL and CL TSP1 intersections. A significant flaw would be required for leakage to occur at the observed rate. A flaw of this size would be clearly identified by the EC test. The EC data from the 1997 inspection were reviewed, and the data from the current inspection were analyzed for indications at TSP1. No indications were found; thus, it is concluded that no leakage is possible at this location.

The observed drippage was considered the result of condensation resulting from a chimney effect through the failed tube, R2C5. If the tube is assumed open at the apex, consistent with the observed crack, condensation results from cooling of the moist air drawn through the tube that is also open at the tubesheet. The condensed water is believed to be the source of the drippage observed at the tube ends.

4.2 Primary Side Visual Examination

Visual examination of R2C5 was performed by inserting a Welch-Alyn fiberscope into the tube from the CL to beyond the apex of the U-bend. A crack was located approximately at the apex of the U-bend. Figure 1 shows a photomontage of the crack. The length of the crack was estimated at approximately 2.5 inches tip to tip by marking the lead of the probe at the tube end when the crack was first visible and at the point when the crack was no longer visible.

The key characteristics of the crack apparent from the visual examination were:

- The crack is principally axially oriented, based on comparison of the crack with the axially oriented probe marks at the intrados and extrados of the tube. These marks occur on the intrados and extrados of the tube ID when the probe is being pushed or pulled through the tube due to the inherent stiffness of the probe, and thus provide a reasonable reference for up and down in the tube. The photomontage does suggest that there is an oblique component to the crack, that is, the crack appears to be "dog-legged"; however, it is not possible to determine conclusively that this is the case from only the photomontage. Comparison of the photomontage with the photograph of a similar tube leakage event at Doel-2 (Figure 9, see below) shows that the characteristics of the crack are quite similar.
- The crack appears to be the coalescence of several cracks that were separated by ligaments. This pattern of corrosion cracks is consistently observed and results from crack initiation as short microcracks (<0.1 inch long) that grow to coalesce and form the longer macrocracks. It is postulated that the ligaments separating the individual cracks failed, causing a "zipper"-like effect and rupture of additional ligaments. At least five ligaments that apparently spanned the crack width prior to tearing can be seen in Figure 1.
- The scaled maximum crack opening width is 2% of the tip-to-tip length of the crack, or about 50 mils.

The observed leak rate trends of the plant can provide insight into the morphology of the crack. For the postulated case that the crack observed in the visual inspection was due to coalescence of two or more cracks separated by ligaments, the expected total leakage prior to tearing of any ligaments would be the sum of several small leaks. As ligaments between separate cracks begin to tear, the combined cracks lead to larger leaks due to the sudden increase in crack opening area. Ultimately, if a "zipper"-like effect occurs because the tube strength has been reduced by coalescence of several cracks, with tearing of ligaments between multiple cracks, the total leak rate would be expected to rapidly increase prior to shutdown of the plant. In addition to ligaments between axial cracks, shallow wall thickness ligaments at the tube OD may have torn to contribute to the large leakage event. The presence of ligaments prior to the large leakage event is essential to rationalize the very low (a few gpd) or no leakage from this crack prior to tearing the large opening shown in Figure 1.

Although the N-16 monitor alarm signaled the leak, the recorder was out of operation at the time of the alarm. Consequently, the short-term leak rate data just prior to the shutdown are not available. However, the longer-term leak rate over a period of a year (1999) is available and shown in Figure 2. The trend of the long-term leak rate, although not conclusively verifying the postulated mechanism of coalescence of cracks, is consistent with that hypothesis. The low leakage indicated on Figure 2 may have been due to R2C5 or may have resulted from other sources in the SG, such as-tube plugs.

4.3 Secondary Side Visual Inspection

Visual inspection of R2C5 and TSP 6 from the secondary side was initiated to verify the R2C5 tube condition and to evaluate the condition of the TSP 6 flow slots with respect to hourglassing. The objectives of the inspection were to confirm the location of the crack at the apex of the tube, provide a verification of the orientation of the crack, and to estimate the length of the crack in the tube. Further, the objectives of the secondary side visual inspection were to measure the presence (if any) and extent of hourglassing of the TSP 6 flow slots on at least the nozzle side of the TSP to establish a suspected contributing mechanism and to provide boundary condition input to structural analyses. A 2-inch diameter inspection port was installed in SG21 and SG24 (similar ports already existed on SGs 22 and 23) at an elevation between the intrados of the Row 1 tubes and the top of TSP6, aligned with the flow slots in the TSP. Inspection was performed by inserting a fiberscope into the region between the Row 1 tubes and the TSP6 and into the space between the tube columns and rows. Video records were made of these inspections.

Verification of the crack properties (location, orientation, length, etc) proved unsuccessful. Although a probe was inserted into the space between the Column 6 and Column 7 tubes to view the apex of R2C5, the crack was not discernible in the video images of the side of Column 5. However, it was confirmed that the space between the R2C5 tube and the R3C5 tube was unobstructed. (Preliminary eddy current test results indicated the presence of a possible foreign object at his location. The confirmed absence of a foreign object indicates that the eddy current signal is likely related to a variation in the deposit on the OD of the R3C5 tube.)

Measurements of the "pinching" of the U-bend legs were made by measuring the row 1 leg spacing. Direct measurement of the flow slot dimensions is impractical since the flow slots were flame cut in the TSP, a process that leaves the cut surface rough and does not provide an accurate dimensional reference. Since significant denting has occurred at Indian Point 2, the tubes are tight within the TSP; thus, leg spacing measurements provide the best estimate of flow slot dimensional changes. Since the row 1 tubes were plugged prior to operation, these tubes may not be dented at the TSP; however, the clearance between the tube and the TSP is sufficiently small that the row 1 leg spacing measurement provides an accurate assessment of the flow slot condition. Measurements were made by passing a gauge of known length between the row 1 tubes, and observing if the gauge would pass between all of the tubes adjacent to flowslot 1 (1st flowslot from TSP periphery, nozzle side). The tube spacing adjacent to the flow slot is a "hard spot" which represents the non-hourglassed condition. The process was repeated near the middle of the flow slot, which represents the maximum flow slot closure. Thus the difference between the longest gauge and the shortest gauge that passed all of the tubes represents the estimate of the flowslot closure.

The row 1 design nominal leg spacing is 3.50 inches (twice the bend radius minus the tube diameter). A measurement taken at the tube column located at the TSP ligament between flow slots 1 and 2 (column 78) showed a spacing of 3.47 inches, 0.03 inch less than the theoretical spacing. The minimum leg spacing measured within the span of the first flow slot was approximately 3.03 inches, indicating hourglassing of approximately 0.47 inch.

5.0 Eddy Current Evaluations

The Indian Point steam generator examination program for the 2R13 refueling outage in the spring of 1997 included:

- Tube support plate (TSP), top of tubesheet (TTS), sludge pile, tubesheet crevices and expanded tube roll transitions examinations with the Cecco probe
- Freespan straight leg and U-bend examinations of 100% of all active tubes with the bobbin probe
- Plus Point examinations of all indications, except AVB wear, resulting from the Cecco and/or bobbin probe data analyses
- Plus Point examinations of all restricted TSPs not examined by the Cecco probe
- Retests with reduced diameter probes of tubes with restrictions
- Pancake/bobbin examination of all tubesheet expansion zone bobbin/Cecco indications within 1.25" below the roll transition (i.e., the F* region).
- Rotating pancake coil examination of all rolled plugs
- Plus Point examinations of the small radius U-bends in 100% of active row 2 and 3 tubes

Results of the low row U-bend examination program in 1997 identified degradation in one row 2 tube, R2C67, in steam generator 24. The Plus Point eddy current inspection identified PWSCC on the tube extrados at the U-bend apex with a length of approximately 0.4". This tube was removed from service by plugging. No other U-bend degradation was reported. Nothing was reported by either the primary or secondary analysis team in R2C5 in steam generator 24.

Subsequent to the identification of R2C5 in steam generator 24 as the tube responsible for the leakage event on February 15, 2000, a re-review was conducted of the 1997 eddy current data for that tube. Initial review of the 1997 data supported the NDD findings. The R2C5 data from the 1997 inspection were also reviewed by several experienced, qualified data analysts and industry experts who concurred with this conclusion. The signal included an anomaly in the data that, upon further detailed analysis of the signal, proved to be an indication of a flaw that developed into the leak. However, background noise was apparent on the Plus Point C-scan plot due to tube geometry and the presence of deposits (Figure 3). The irregularities (offsets) in the ridges shown on Figure 3 can occur as a result of the probe rattling in the tube. The noise levels seen in Figure 3 would not typically permit the signal to be identified as an indication. This conclusion was consistent with that reached in the 1997 interpretation of the data.

The re-review of 1997 eddy current results was extended to Plus Point data from all row 2 and 3 u-bends in all four steam generators. One additional indication, not reported in the 1997 inspection, was found. The indication, typical of PWSCC on the extrados at the tube apex, was reported in R2C69. This particular indication, although relatively small, was not reported in 1997 for the reasons stated.

Further investigation of the 1997 R2C5 data resulted in a number of changes to the analysis process intended to improve the capability to identify the form of degradation responsible for the leakage. All primary, secondary and resolution analysts received training on the following changes, incorporated into the analysis guidelines as a training supplement for the 2000 U-bend inspection program:

- More stringent criteria were established for data quality
- The analysis setup process was changed to achieve better resolution of the 20% ID calibration notch
- Supplementary instructions were developed for use of information available in the eddy current strip chart displays to assist in identification of degradation of the low row U-bends

When the supplementary criteria were applied, two additional indications were detected during the 2000 inspection program. The two indications, typical of PWSCC, were found on the extrados at the tube apex, in R2C72 of steam generator 24 and in R2C89 of steam generator 21. The 1997 eddy current data for these tubes were re-reviewed with the changes in the analysis guidelines described above and both were detected.

Even with the enhancements to the analysis guidelines, background noise and extraneous signals associated with geometric effects (ovality) and deposits resulted in a number of tubes being classified as difficult to interpret. For the 2000 inspections, the conventional Plus Point low row U-bend examinations were supplemented with a high frequency, 800 kHz Plus Point probe.[2] The use of a higher frequency focuses the test on the inner surface of the tubes and, therefore performs in a manner less sensitive to the effects of deposits for detection of PWSCC. Figure 4 is a comparison of data for the mid range and high frequency probes for tube R2C69 that shows that the signal noise is substantially eliminated by use of the high frequency probe. The row 2 and row 3 tubes in the SGs were re-tested using the high frequency probe. The use of the high frequency probe proved successful in mitigating the effects of the data noise, and the improved detection resulted in the identification of several more indications in the row 2 tubes in the steam generators.

Further analysis of the 1997 data for R2C5 indicated that the flaw initiated at the ID of the tube (i.e., PWSCC) and was approximately 2.4 inches in length, located at the extrados of the tube and

[2] Prior to its use on the IP-2 U-bends, the 800 KHz, high frequency +Point probe was qualified for use in the low row u-bends by tests performed by EPRI, Westinghouse and Con Edison.

approximately centered at the apex of the tube. Based on a depth profile developed from the 1997 data using available sizing techniques for PWSCC[3], the average depth of the flaw was between about 63% and 71%, and the maximum depth of the flaw was about 92%. The detailed evaluation of this flaw will be included in the Condition Monitoring report to be issued for the 2000 inspection.

Additional testing and evaluations of the leaking tube, R2C5, were performed to characterize the flaw. The tube was re-tested using a bobbin probe, which confirmed the length of the crack and its location at the apex of the tube. A standard U-bend +Point test was attempted to establish the length of the crack and verify its extrados position. A short data segment from the CL confirmed the crack to be at the extrados of the tube. Subsequently, another test with a smaller diameter +Point probe with tracking shoes fixed in place to minimize the diameter was successfully completed. This test confirmed the length of the crack at about 2.44 inches, approximately centered at the apex extrados of the U-bend.

6.0 Denting Assessment

Denting at the TSPs had been the major cause of plugging at Indian Point 2 until approximately 1989.[4] Although only 22 tubes have been plugged since 1989 due to tube restrictions, twenty of these were plugged in 1997 (total in all 4 SGs) due to restrictions at, or above, TSP6. The 1997 examination was the first 100% examination since startup; thus the noted plugging in 1997 is believed to be result of the larger inspection sample in 1997. The other two tubes were plugged, one each, in 1995 and 1991.

Denting at the TSPs causes large in-plane forces in the TSPs that can lead to "hourglassing" of the flow slots. There are six flow slots, 15 inches long and 2.75 inches wide, spaced uniformly across the TSP, separated by "hard spots", that are 4 inches long. At TSP6, the u-bends bridge over the flow slots. "Hourglassing" describes the condition where the sides of the flow slots are deformed toward the centerline of the slots by the in-plane forces resulting from denting. This condition has been monitored at Indian Point 2 for a number of years, with significant hourglassing documented at the lower TSPs. Hourglassing at the top TSP causes the u-bend straight legs to be pinched, leading to increased stresses in the U-bends (see Section 8). As discussed in section 4.3 above, measurements made along the first flow slot (adjacent to the columns 2 through 14) showed the row 1 leg spacing at the "hard spot" between flow slots 1 and 2 to be 0.03 inch less than nominal (may be within measurement accuracy limits) and the minimum row 1 leg spacing approximately at the center of the flow slot 1 span to be approximately 0.47 less than the nominal row 1 leg spacing. Thus, these measurements confirm that hourglassing has occurred at the top TSP.

Denting also leads to constriction of the tubes that are reported as "restrictions" to particular probe sizes during the EC examination of the SGs. A study of the tube restrictions was performed based on the 1997 and 2000 inspection data, both 100% inspections. All four steam generators were examined and the results from the SG judged most active, SG 24, are shown in Figure 5. The diagrams on Figure 5 show reported restrictions of 0.640" and smaller for TSP6, summarized by probe type. In these

[3] WCAP-15128, Rev 2; EPRI ETSS 96703
[4] ALTRAN Technical Report No. 00603-TR-001, Rev 0; March 2000.

diagrams, positively numbered rows indicate hot leg; negatively numbered rows indicate cold leg. Column numbering is as indicated, right to left, from the nozzle side to the manway side.

A qualitative review of Figure 5 indicates that the number of restrictions is increasing. The following observations are made:

- There are more restrictions reported in the 2000 inspection than in the 1997 inspection for the 0.640" CECCO probe.
- The reported restrictions are distributed approximately equally between the bundle periphery and along the flow slots. No restrictions to the 0.640" CECCO probe were reported in the interior of the bundle.
- The restrictions reported adjacent to the TSP flow slots show that most of the denting is located near the flow slots.
- The restrictions occur predominantly on the hot leg of the TSP.

These observations are consistent with a general conclusion that the denting process is continuing at a slow rate. The rate of denting progression cannot be quantified from the increased number of restrictions since there is no available correlation between restrictions and denting. Also, variations between inspections on probe restrictions can occur due to differences in probe types, probe pushers and tolerances on probe length and diameter. However, the restriction study leads to the qualitative conclusion that, if additional restrictions are observed for the same probe type, it is reasonable to conclude that denting is continuing.

7.0 Tubing Manufacturing Summary

It has been documented in the literature that bending of the U-bends results in ovalization of the tube cross- section. The degree of ovalization depends on the specific bending process utilized for the low row u-bends. Various techniques have been employed to minimize the ovalization of the low row u-bends; the Westinghouse bending process that utilized a ball mandrel and concave die for the R1 and R2 U-bends is well documented and supported by ovalization data[5]. The U-bends for Indian Point 2 were manufactured by Huntington Alloys. A review of manufacturing techniques indicated that the bending process employed by Huntington Alloys also utilized a ball mandrel for bending the row 1 and row 2 tubes. Ovalization data for similar u-bends manufactured by Huntington Alloys are available from examination of U-bends removed from the Turkey Point 4 SGs in 1976[6]. The average ovalization at the u-bend apex of the tubes removed is: R1 - 13.9% (10 tubes), R2 - 10.0% (12 tubes), R3 – 5.0% (1 tube). For comparison with the data from Doel 2 discussed below, for which 24 Row 1 tubes were found to have minor inside diameters more than 0.058 inches less than nominal, the tubes removed from Turkey Point 4 had an average decrease in the outside diameter of 0.057 inch for Row 1 tubes and 0.037 inch for the Row 2 tubes.

These data demonstrate the expected reduction in tube ovality with increasing row number and associated increasing bend radius. This reduction in ovality for the higher numbered rows significantly increases the time to cracking for the higher row numbers.

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[5] S. Yashima, et al; "Stresses of Steam Generator U-Tubes Affecting Stress Corrosion Cracking"; ASME 82-NE-5
[6] Westinghouse 77-7D2-SGEXM-R2; Examination of U-bends form Turkey Point 4 Steam Generator B; July 1977.

8.0 Stress Evaluations

Stress analysis of the low row u-bends, R2, R3 and R4, was initiated with the objective to evaluate the sensitivity of the tube stresses to pinching of the straight legs resulting from hourglassing of the TSP flowslots. An analysis was performed, as described below, that assumed no residual stresses resulting from the bending process. A second analysis, to be included as part of the Condition Monitoring and Operational Assessment Report, seeks to establish the residual stress condition due to bending and ovalization on the tubes prior to imposing various leg spacing boundary conditions. The objective of the analyses is to evaluate if the predicted stresses are consistent with the observed cracking, i.e., PWSCC, and its location at the apex of the U-bend. Further, it is the objective of these analyses to estimate the comparative stresses and, therefore, sensitivity to cracking of the row 2, row 3 and row 4 tubes for the condition monitoring and operational assessments.

Finite element (FE) models of the U-bend tubes in Rows 2, 3 and 4, above the upper most tube support plate (TSP #6), were developed. The FE model contains 1080 3D brick elements with elastic-plastic large strain and large displacement capabilities. A bilinear stress-strain law is assumed with kinematic unloading and a 2Sy Bauschinger effect. These models are being used to make a comparison of the relative structural responses of the aforementioned tubes to the service loads and potential hourglass motion of the TSP into the adjacent flow slot. The service loads consist of internal primary side pressure, external secondary side steam pressure, the through wall temperature gradient and the thermal interaction of the tube with the TSP. The TSP hourglass motions are expected to be sufficient to cause stresses in tube that exceed the expected elevated temperature yield strength of the tube. Figure 6 shows preliminary results of the FE calculated hoop stress on the inner surface of the tubes at the U-bend extrados at the apex of the tube. The maximum hoop stress at other locations along the u-bend axially removed from the apex is less than the stress at the apex, but follow the same trend as shown for the apex.

Figure 6 shows that for a model that assumes no residual stresses in the tube, a stress plateau is reached, that is, the stress exceeds the yield strength, when the leg spacing at the TSP is reduced by approximately 0.15 inch. The maximum stress for the row 2 tubes is approximately 37ksi, and is respectively lower for the R3 (30 Ksi) and R4 (27 Ksi) tubes for the same assumed leg pinching, however, the yield point is reached with only a small increase in the straight leg pinching. For the same degree of flowslot hourglassing, the row 3 straight leg pinching is estimated to be about 85% of that for the row 2 tube in the same column.

The results of this analysis support the observation that the leak is due to PWSCC at the apex of the tube, since the point of maximum predicted stress is at the inside surface of the tube wall at the extrados of the tube at the apex of the tube. The preliminary stress results also indicate that the row 3 tubes are expected to be less susceptible to PWSCC due to the larger TSP displacement required to reach the maximum stress condition and due to the lower stress in the row 3 tubes compared to the row 2 tubes.

9.0 Industry Operating Experience with Low Row U-bends

The objective of this section is to summarize some of the major milestones that occurred relative to low row U-bend operating experience. Although it is believed that the major points are discussed, there has been no attempt to be exhaustive relative to the details of field, laboratory, engineering, regulatory or operational experience.

9.1 Crack and Leak Experience

U-Bend related leakage has occurred in two forms. One of these involves a rapid increase in leak rate (minutes) and the other a very controlled leak occurring at a low level and increasing over a relatively long period of time (months).

The rapid leakage event is characterized by the Surry 2, row 1 U-Bend tube rupture event of September 15, 1976, (Figure 7), which is described in NUREG/CR-6365[7]. The NRC estimate of leakage for this event was 330 gpm, in contrast to the 80 gpm reported by the plant operator. The source of the leak was attributed to high stresses from dent related hourglassing of the top TSP flow slots and the resultant strain placed on the U-bend. Stress corrosion cracking had occurred from the primary side at both the top and bottom (extrados and intrados) of the U-bend (Figure 8). The leak occurred at the top (extrados). The sudden, high leak rate occurred because an approximately four-inch long crack network had formed over the entire top of the U-bend. The leakage from this network was low because the individual through-wall sections of the crack were each relatively short, and, although several through-wall sections may have been leaking, the combined leak rate was still very small. The essentially parallel cracks however, overlapped each other and were separated by ligaments of sound metal that continued to decrease in cross section as the cracks grew in length and branched into a three-dimensional network. This resulted in the burst resistance of the network decreasing without a substantial increase in the leak rate. At the time that the network could no longer contain the normal pressure differential, the crack network opened over about a four-inch length, resulting in the large increase in leak rate.

A second example of large leakage, also described in NUREG/CR-6365, is a 135gpm leak in a Row 1 U-bend in SG-B at Doel Unit 2 (a Belgian plant), which occurred on June 25, 1979. The leaking crack was characterized as a "relatively long axial crack". Ovalization of the tube was identified as the cause of the cracking. The reported reduction of the nominal ID for 24 of the inner row tubes, measured by pushing various size ball bearings through the tubes, was greater than 0.058 inch. Figure 9 is a photograph of the crack in the ruptured tube.[8]

Other cases of denting related cracking have been observed at dented TSP locations and in certain "sludge piles" formed from iron shot that subsequently corroded and deformed the tube above the tubesheet.

The slowly progressing leak rate leakage is typified by the degradation observed at the Trojan power plant (Figure 10). In this case, the row 1 stress corrosion cracking occurred at the tangent point on one side of the U-Bend. This tangent point was irregular, as a result of the bending process and apparently, high residual stresses in the irregular geometry, contributed to the onset of PWSCC. Because of the local geometry, the cracks do not extend for a great distance and there is reduced potential for large,

[7] P. E. McDonald, V. N. Shah, L. W. Ward and P. G. Ellison, "Steam Generator Tube Failures; NUREG/CR-6365, INEL-95-0383, April 1996.

[8] Personal communication between Doel personnel and D.D. Malinowski at site presentation of cracking event; 1979.

sudden leakage events, such as those described for a dent related apex crack. However, the cracks still occur as a crack network, separated by ligaments of sound metal, so the possibility does exist for sudden changes in leak rate occurring as a result of crack linking. Other cases of PWSCC occurring with contributions from residual stresses associated with deformation are found in the expansion transition in the tubesheet region. The most notable of these has occurred with the French designed 'kiss-roll', which has produced cracking with A600TT material.

Although both types of U-bend cracking have been most aggressive in row 1, instances of tangent point cracking have also been observed in row 2. The bending process changed for row 3 and the irregular transition is no longer present.
NDE (eddy current) examinations have been the principal means of following degradation at the U-bend and there have been no recent tube pulls allowing the correlation of NDE and actual tube degradation as observed in operating units. Eddy current signals have been interpreted as axial, off-axial and circumferential and have been positioned at locations ranging from the tangent point to and including the apex. In addition, signals have been reported and leakage has been confirmed for both for row 1 and row 2.

Prior to this sudden tube leak in the R2C5 of SG24 at Indian Point 2, there have been no significant industry leakage events at the row-2 apex location.

9.2 Low Row U-bend Removal and Examination

The occurrence of the row 1 apex leakage resulted in a very significant industry program of low row U-bend examinations, which included tube pulls of rows 1, 2 and 3. These tube removals occurred over a fairly short period of time and successfully classified the degradation as PWSCC arising from dent related hourglassing.

Similarly, a number of tubes were removed from the Trojan plant and confirmed that PWSCC, localized to the irregular transition region, was the mechanism for the observed tangent point leakage.

9.2.1 Apex Cracking

As a result of the leakage at Surry 2, in 1976, the leaker of R1C7, SG A, was removed along with the six tubes preceding it and the subsequent two tubes. The examination of these row 1 tubes showed that the seven adjacent to the flow slot had all experienced PWSCC. Physical measurements showed that 'pinching' of the U-bend legs had occurred, contributing to the ovalization of the tubing in the U-bend region[9].

Two additional tube pull sequences followed to allow further characterization of the apex degradation phenomena and provide data out to row 3. The tubes pulled from Turkey Point 4, SG B, in the fall of

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[9] F. W. Pement, E. P. Morgan, and R. G. Aspden, "Examination of Inconel 600 Nuclear Steam Generator U-Tubes From Surry 2", Westinghouse Report 77-7D2-SGEXM-R1, July 5, 1977.

1976 provided 31 U-bends[10]. Fifteen of these were R1, fifteen were R2 and one was R3. All of the tubes were examined visually and radiographically, from three different rotations. Dimensional measurements on leg spacing were also taken. After measurement of leg spacing, seven of the tubes were placed in inventory and the others were examined, in some cases with eddy current, but in all cases with destructive examination techniques. Three of the examined U-bends showed degradation; only row 1 tubes were observed to be cracked. None of the cracking was completely through-wall and the crack networks were not well established. There was no cracking detected in the examination of the row 2 or row 3 tube.

The other tube removal sequence was performed at Surry 1, where 31 tubes were removed and characterized. Once again the cracking was only observed in the row 1 U-bends and no cracks were found in row 2 or the single row 3 tube[11].

9.2.2 Trojan

In May 1980 twenty six row 1 U-bends and three row 2 U-bends were removed from SG D at Trojan[12],[13]. One of the tubes had leaked during operation. In addition to confirming degradation for this particular tube, cracking was observed in two additional tubes. The cracks were all located at the irregular tangent point and occurred via PWSCC. The indications were axially oriented and occurred either on the extrados, or between the extrados and the intrados. Multiple crack initiation had occurred and the parallel crack network was separated by ligaments of varied dimensions.

As part of this tube examination effort, additional examination was made of some U-bend samples previously removed from Surry 1 and 2 and Turkey Point 4. These comparisons showed that the Surry 1 and Turkey Point 4 U-bends had only smooth transitions on both sides and no cracking was observed at the tangent locations. Surry 2 U-bends displayed both the smooth and opposite tangent point transitions and one of the locations evaluated displayed a PWSCC crack (Figure 11). This was on R1C7, the same tube with the apex location leak.

Some of the Trojan U-Bends were supplied to Battelle, Pacific Northwest Laboratories, for additional evaluation. This effort was sponsored by the EPRI Steam Generators Owners Group (SGOG) and was directed toward examination of eight of the 29 U-bends removed from Trojan. Residual stress analysis, dimensional measurements, metallography and microanalysis were included in the evaluation. Some iron rich deposits were identified in the mouths of some of the major cracks but no specific causative environments were identified. The results were complementary to the prior evaluations[14].

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[10] E. P. Morgan, F. W. Pement, and R. G. Aspden, "Examination of U-Bend Tubes From Turkey Point 4 Steam Generator B", Westinghouse Report 77-7D2-SGEXM-R2, July 11, 1977.

[11] E. P. Morgan, F. W. Pement, and R. G. Aspden, "Examination of U-Bend Tubes From the "A" Nuclear Steam Generator of the Surry 1 Plant", Westinghouse Report 77-7D2-SGEXM-R3, July 12, 1977.

[12] R. G. Aspden, "Evaluation of Trojan Steam Generator U-Bend Tube Samples", Westinghouse Report 81-5D9-HELEN-R1, April 13, 1981.

[13] R. G. Aspden, "Evaluation of Trojan Steam Generator U-Bend Tube Samples", Westinghouse Report 81-5D9-HELEN-R1, April 13, 1981.

[14] A.B. Johnson, Jr., R. L. Bickford, R. L. Clark, T. J. Davis and F. A. Simonen, " Steam Generator U-Bend Tube Examination" performed by Battelle, Pacific Northwest Laboratories, EPRI Report

9.3 Return to Power Actions

Following the U-bend tube rupture in 1976 at Surry 2 , the plants with extensive denting were generally operating with the requirement of interim steam generator outages. U-bends, however, were not the principal location where cracking was occurring. PWSCC was also occurring at the dented intersections in many plants and considerable effort was devoted to identifying the causative factors for denting and changing operations to reduce corrosion rates associated with denting. An interim outage of this era, therefore included an extensive inspection, generally consisting of an eddy current inspection for tube degradation and the application of measures to evaluate the progression of denting throughout the steam generator. Denting measures included flow slot hourglassing measurements (photographic), gauging with different probe sizes, bobbin coil dent signal voltage progression and profilometry. As discussed above, tube pulls and removal of a significant number of U-bends occurred to characterize the morphology of the degradation and assess the capability of the NDE techniques being applied. Tube support plate sections, with tubes in place, were removed from various plants in the United States (including Indian Point 2) and Europe. Various models that considered the distribution of the in-plane forces occurring from denting were applied to the steam generators to assist in determining the number and location of tubes to be plugged. Specialized repairs and load distribution devices, such as the flow slot blocking devices installed in the top TSP-of Surry 2, were applied on a case basis. The installation of special ports for inspection and sampling were sometimes installed, as well as other actions on a plant specific basis. Special chemical monitoring programs, such as the field measurement of hydrogen balance on the secondary side, were being applied at a number of plants and ultimately, boric acid soaks and on-line boric acid addition became a part of some plant return to power commitments. Extensive plant chemistry evaluations were common and considerable effort was devoted to modifying plant chemistry for denting control.

Extensive laboratory and field test programs and engineering evaluations, related to all aspects of denting and its consequences, were in place; not only with Westinghouse and the appropriate utilities, but in the world nuclear community. The industry was also heavily committed with an EPRI steam generator owners group program (SGOG) that was focused on SG corrosion and performance issues.

Detailed presentations to the NRC were common, as were the NRC requests for additional information.

9.4 Perspective

A principal source of the stresses required for U-bend apex location PWSCC result from flow slot hourglassing caused by denting. The forces developed through denting also deform the tube at other locations, which are also susceptible to PWSCC. The industry response to these issues, which were first observed in the mid-1970's, covered all aspects of SG design and operation.

Tube examinations of both the straight leg TSP intersections and the U-bend were performed to characterize the corrosion mechanism and provide guidance to laboratory simulation programs. A variety of remedial measures were developed for field application. These included actions related to chemistry operations, that were intended to stop the denting corrosion process, as well as U-bend thermal stress relief, which laboratory tests showed to be effective in reducing the corrosion of stressed U-bend specimens. Preventive plugging of Row 1 u-bends was frequently performed to reduce the potential for leaking indications. Inspection tools, such as improved eddy current techniques and flow slot hourglassing measurements, and preventive plugging, in anticipation of leakage in locations experiencing deformation, were regularly applied. Interim outages, to inspect the steam generators and determine the rate of denting progression, occurred at a number of the more extensively dented plants.

10.0 Conclusions

The following summarizes the observations and conclusions from the investigations and analyses performed to determine the source and cause of the leakage. The Condition Monitoring and Operational Assessment Report, to be issued prior to restart of the plant, will address the specific degradation, PWSCC, and its rate of growth in the u-bends, and actions taken to prevent future occurrences of leakage due to the degradation mechanism identified.

1) The leak occurred in R2C5 tube as the result of PWSCC at the apex of the tube. The leaking crack is approximately 2.4 inches long, based on eddy current measurements. The crack opening is estimated at approximately 0.05 inch, based on scaling of a photographic image of the crack.

   PWSCC in the low row U-bends has been observed historically in a number of plants, including Surry Units 1 and 2, Doel-2, Trojan, and Turkey Point 4 (not a comprehensive list). Low row PWSCC has been observed at plants with and without denting. For SGs with significant tube denting, the resulting hourglassing of the flow slots results in straight leg pinching of the U-bends, elevated hoop stress at the U-bend extrados, and an increased potential for cracking. The crack observed in R2C5 is consistent with previously observed U-bend apex cracking at other plants. However, the R2C5 indication is the first occurrence of significant leakage in row 2 u-bends in Westinghouse SGs.

2) Denting is continuing at a slow rate at Indian Point 2. The number of restricted tubes in the 2000 inspection is greater than in the 1997 inspection, and this implies that the denting mechanism is still active.

3) Hourglassing of TSP6 in SG24 at Indian Point 2 has occurred, based on direct measurements of the Row 1 straight leg spacing at the surface of TSP 6. In the flow slot that is adjacent to R2C5, the maximum closure measured was 0.47 inch after 27 years of service. The hourglassing at the top TSP increases the potential for PWSCC at the rows 2, 3 and 4 u-bends.

4) Overall, the cause for the R2C5 crack is axial PWSCC with the potential for cracking enhanced by increased u-bend stress resulting from hourglassing at the top TSP. This u-bend indication was not detected in the 1997 inspection of tube R2C5 due to background noise associated with tube deposits and tube geometry effects (ovality) masking the flaw.

5) Retrospective examination of the R2C5 data from the 1997 inspection showed an anomalous indication. Expert review of the data concurred that the flaw would not have been called by accepted EC practices in 1997, due to background noise in the signal related to geometry effects and deposits including copper. Once identified, using current sizing practices, the 1997 R2C5 flaw signal was sized in the range of 63-71% average depth, and 92% maximum depth. Thus, the principal cause of the leakage was the inability to detect the indication in 1997 inspection due to noise in the signal; growth of the indication between 1997 and 2000 is moderate and is not the principal root cause of the leakage.

6) A further review of the 1997 Plus Point u-bend data resulted in finding a PWSCC flaw in tube R2C69 that was not identified in 1997. NDE sizing of the 2000 data for this indication shows that the indication satisfies all structural criteria at the 2000 inspection. NDE sizing of the 1997 data for this indication shows only moderate growth over the 540 EFPD of operation.

7) PWSCC at a Row 2 u-bend was first found at Indian Point 2 in 1997. The reported tube with the indication was plugged. The Indian Point u-bends have not been heat-treated. Plants that have heat-treated rows 1 and 2 have been able to leave row 1 tubes in service. Indications have been reported in rows 1 and 2 with heat-treated tubes.

8) Based on NDE data reviews, changes were made to the analysis process intended to improve the capability to detect the degradation responsible for the leakage. These changes included:

- More stringent criteria for data quality
- The analysis setup process was changed to achieve better resolution of the 20% ID calibration notch
- Supplementary instructions for use of information available in the eddy current strip chart displays to assist in identification of degradation of the low row U-bends

Two additional indications were detected during the 2000 inspection program. The two indications, typical of PWSCC, were found on the extrados at the tube apex, in R2C72 of steam generator 24 and in R2C89 of steam generator 21. The 1997 eddy current data for these tubes were re-reviewed with the changes in the analysis guidelines described above and both were detected.

9) For the 2000 inspections, the conventional Plus Point low row U-bend examinations were supplemented with a high frequency, 800 kHz Plus Point probe designed to more critically interrogate the inner surface of the tubes and perform in a manner less sensitive to the effects of geometry and deposits. Initial results show additional detected indications in row 2 tubes that demonstrate further improvement in detectability. Three additional indications were found in the Row 2 tubes; no indications have been reported in row 3 or higher.

10) The results of the stress analysis of the low row u-bends support the observation of axial PWSCC at the tube apex. The predicted maximum hoop stress in the row 2 tubes occurs at the ID surface of the tube extrados. The maximum predicted hoop stress is reached when the leg spacing decreases approximately 0.15 inch, and is predicted not to increase significantly with further decreases in leg spacing. The row 3 and row 4 tubes exhibit the same trends, except at a reduced maximum stress level.

11) Review of industry experience with low row u-bend PWSCC indicates that row 2 indications have been reported at other operating plants, however, the occurrence has been sporadic and infrequent. A summary of the industry experience of low row u-bend cracking will be included in the CMOA.

12) A report of leakage from R2C5 at the TSP1 elevation is not correct, based on EC verification that no flaws exist at this or any nearby location on the tube. The reported leakage was several drops per minute, and this is attributed to condensation in the tube.

11.0 Corrective Action Plan

The key element in the occurrence of the leak was the inability to detect a relatively large discontinuity in the 1997 inspection, principally because of noise in the eddy current signal resulting from the geometry of the low row u-bends and the presence of deposits on the tubes. Consequently, the action plan for the operational assessment focuses on demonstrating improved ability to detect flaws in the low row u-bends. As noted above in section 5, immediate actions to this end have already been implemented. These actions are:

1) A supplement to the analysis guidelines was implemented during the 2000 inspection, which includes the action below. Implementation of these supplementary guidelines resulted in additional indications being identified.
   - More stringent criteria were established for data quality
   - The analysis setup process was changed to achieve better resolution of the 20% ID calibration notch
   - Supplementary instructions were developed for use of information available in the eddy current strip chart displays to assist in identification of degradation of the low row U-bends.
2) Qualification and use of a high frequency, 800 kHz Plus Point probe to supplement the conventional Plus Point low row U-bend examinations. All row 2 and row 3 u-bends were re-tested with the high frequency probe, and additional indications were detected.

The benefit of laboratory tests to further support the detection capability of the probes utilized for low row u-bend inspection is being evaluated. A laboratory program will be described in the CMOA report. This program is intended to develop the probability of detection as a function of crack depth and NDE sizing uncertainties for the PWSCC indications.

Required near-term actions to support restart and the operating period to the next inspections are:

1) Complete stress analysis of the low row u-bends to assess the effects of TSP deformation (hourglassing) on the relative susceptibility of the row 2, row 3 and row 4 tubes to cracking.

2) Perform additional structural evaluation to assess the effects of support plate compression and hourglassing on the u-bends, and to assess the overall integrity of the TSPs with respect to tube integrity (e.g., loss of tube support, generation of loose parts).

3) Complete a Condition Monitoring Assessment and Operational Assessment based on the current inspection data, augmented by industry experience, to assure structural integrity of the tubes and TSPs for the next operating cycle.

Figure 1 Photomontage of R2C5 U-bend Apex Crack

Photomontage of R2C5, SG24, Indian Point Unit 2 U-Bend Crack. Based on Images From the ID Video Inspection.

Figure 2 Indian Point 2 Leak Rate History

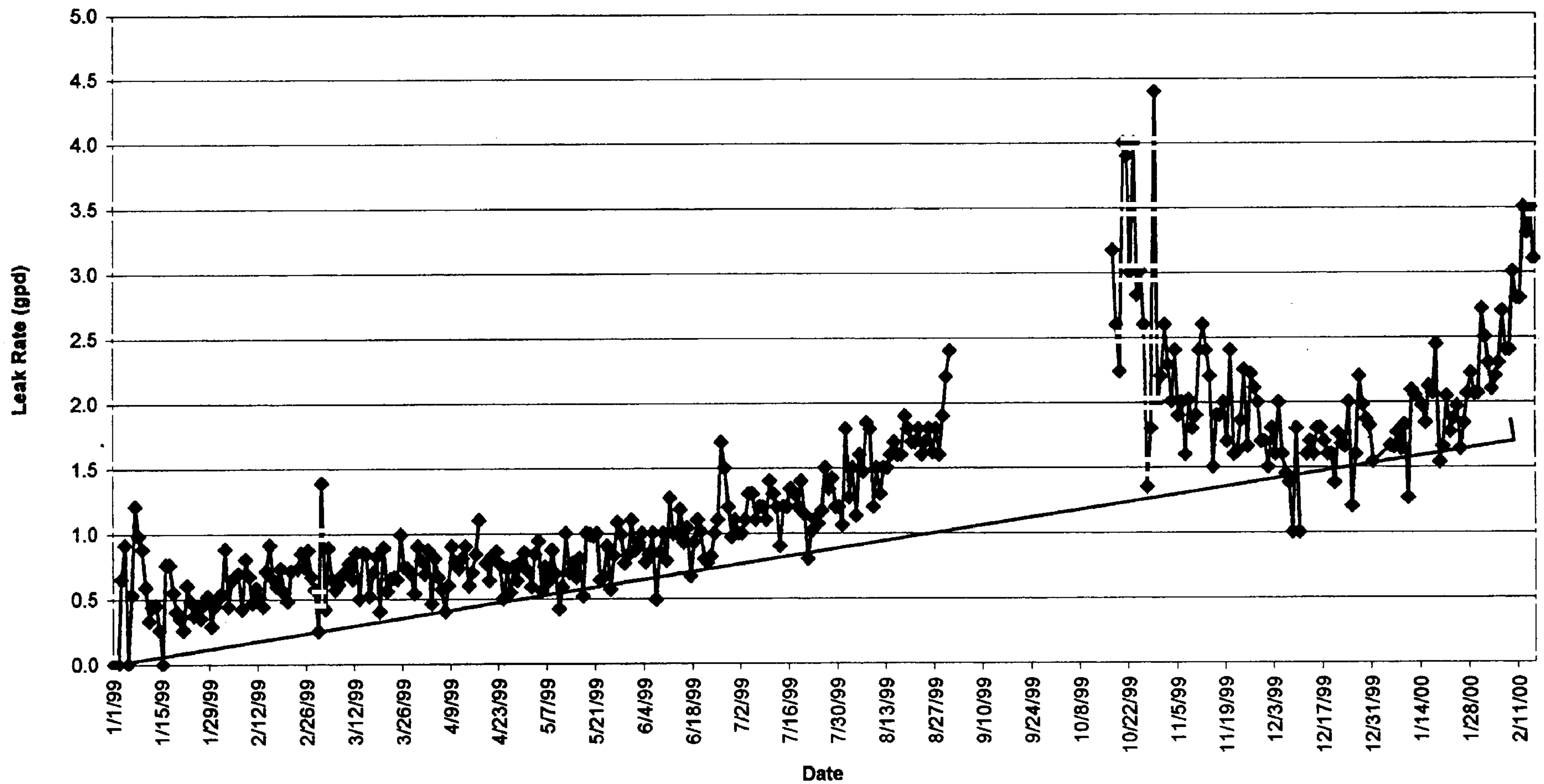


Figure 3

C-Scan of R2C5; 1997 Data

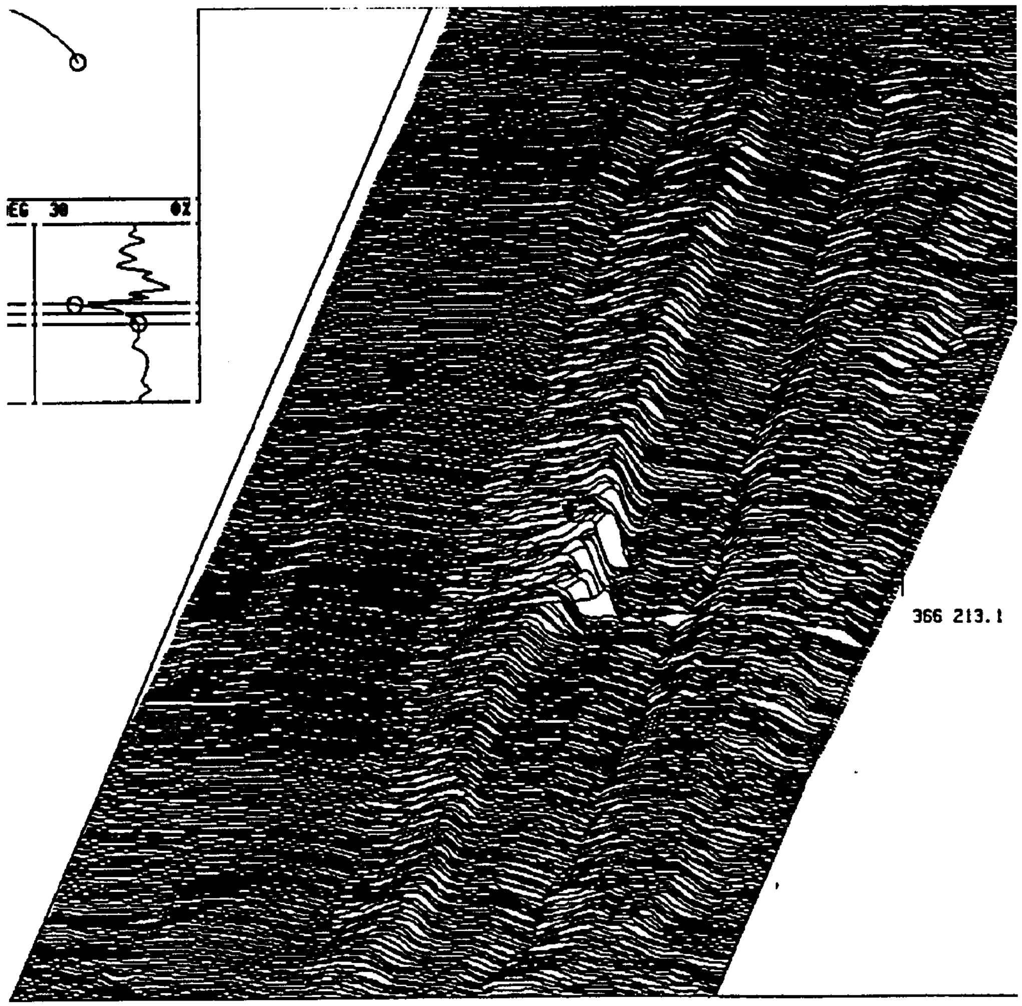
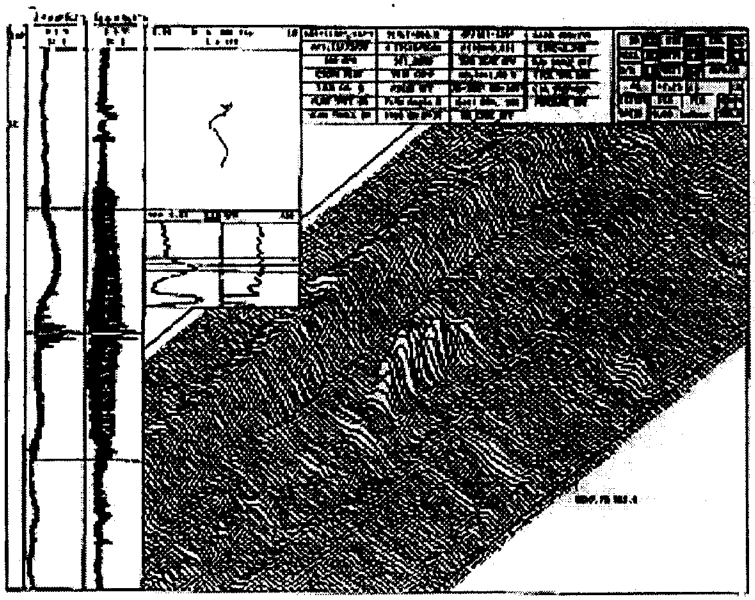
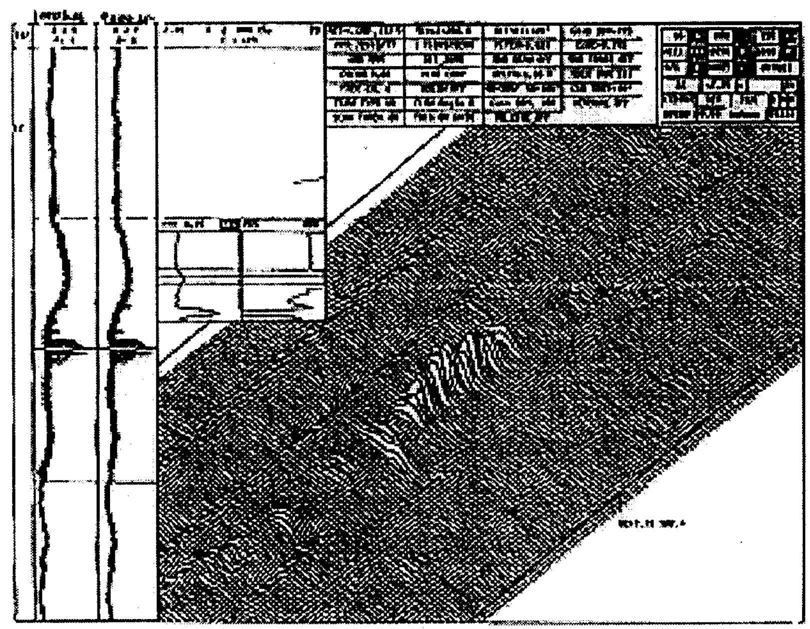


Figure 4
Comparison of Signal and Noise for Mid-Range and High Frequency Plus Point Probe



Mid-Range +Point
R2C69
2000 Data



High Frequency +Point
R2C69
2000 Data

Figure 5
SG 24, TSP6 Probe Restrictions; 1997 Data Compared to 2000 Data

Indian Point 2 S/G 24 Composite Restriction Map

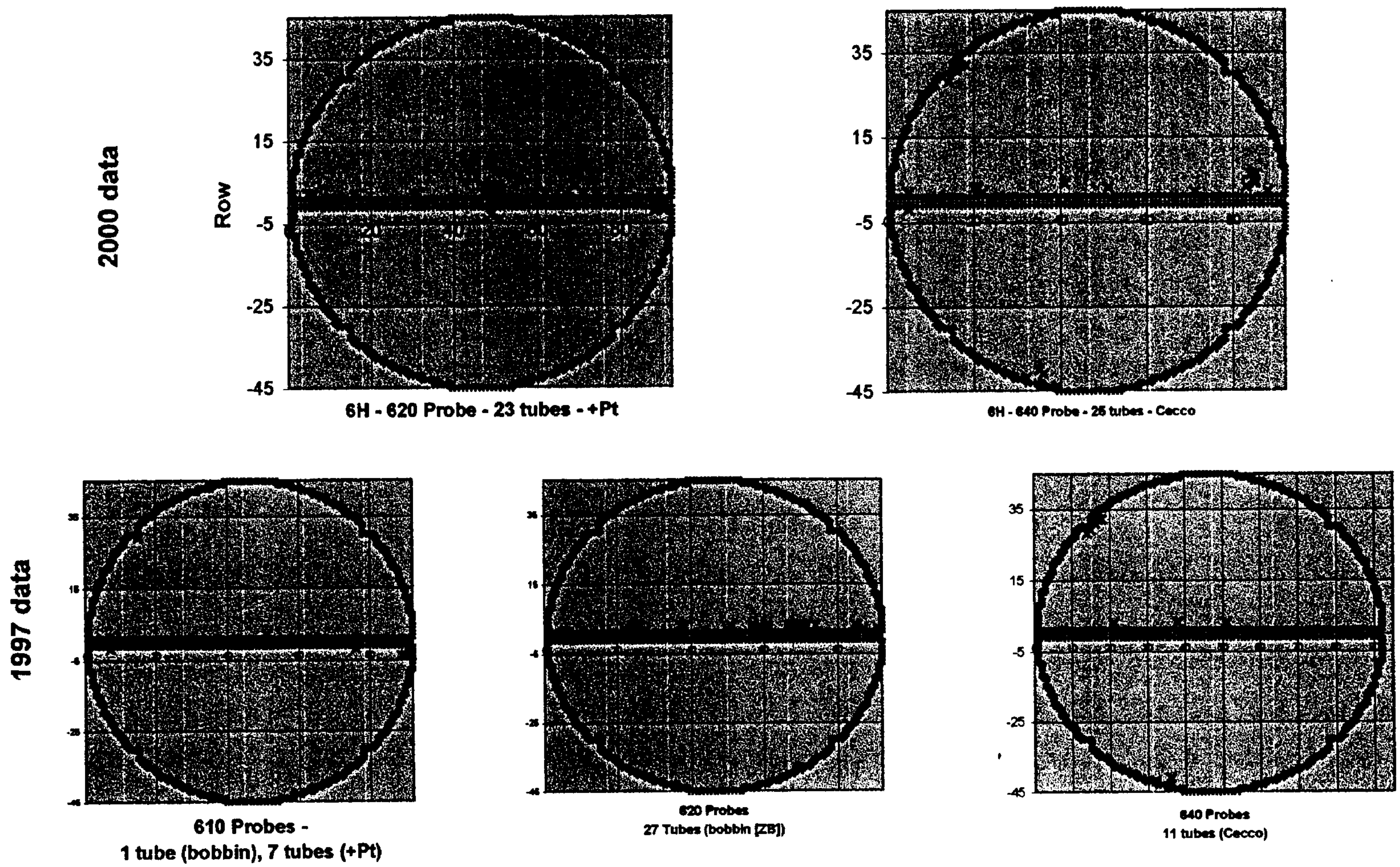
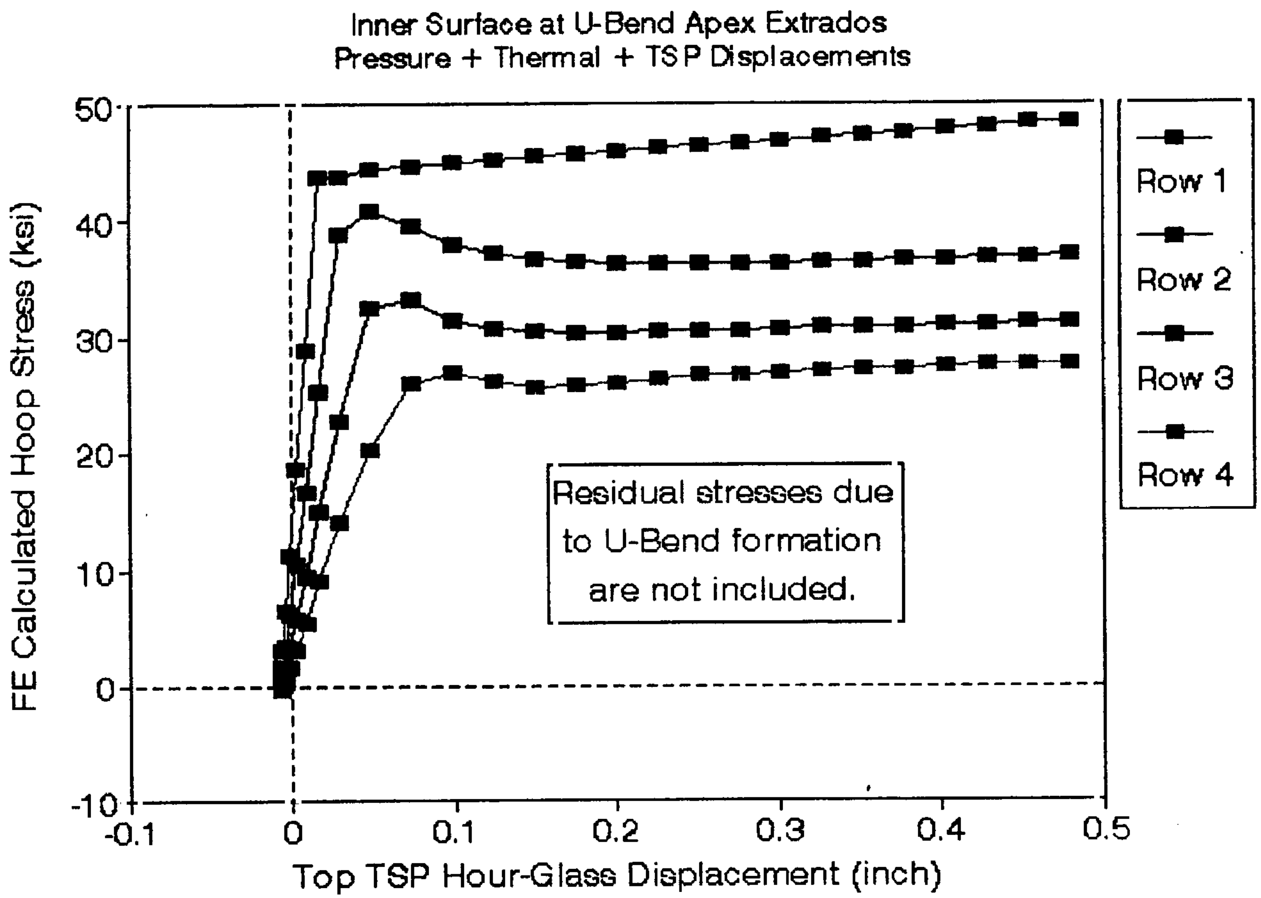


Figure 6

Finite Element Model Calculated Hoop Stresses vs Reduction in Straight Leg Spacing from Nominal Dimension



Radiography Reveals Both
Intrados and Extrados Cracking
in Surry 2 U-Bend

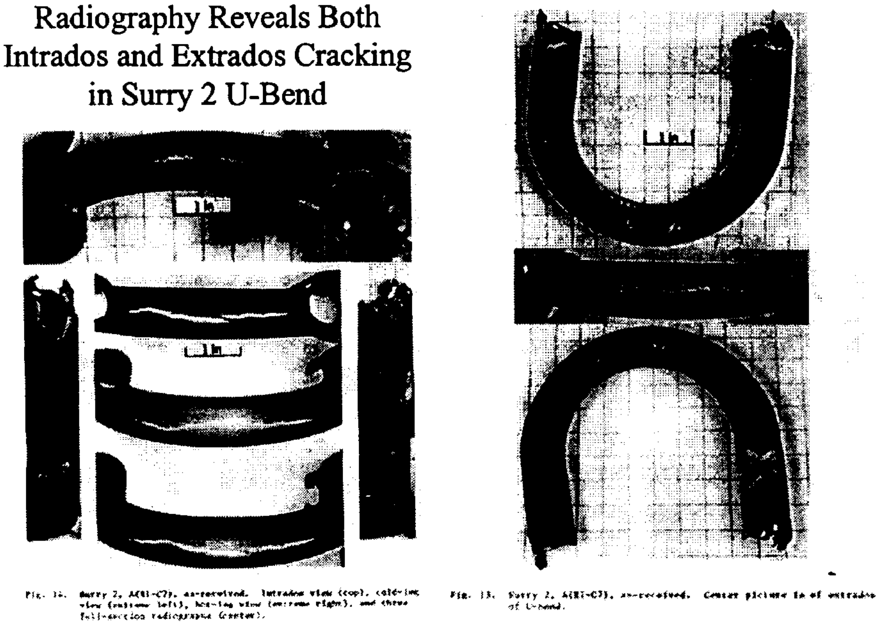


Figure 7. Apex crack location, on row 1 U-bend, which leaked in September 1976.

Metallographic Examination Confirms PWSCC
For Both U-Bend Cracking Locations

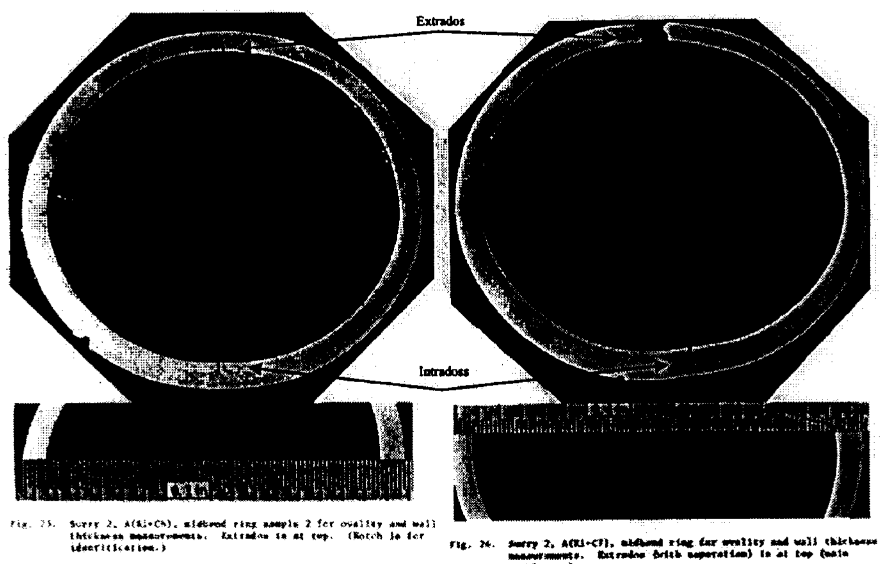


Figure 8. Cross section of row 1 U-bends for columns 6 and 7 illustrates the PWSCC crack networks on the extrados and intrados.

Figure 9. Photograph of Apex Crack in Tube R1C24, Doel Unit 2; June 1979

R1 U-Bend Cracking At Trojan Occurred at the Extrados
Tangent Point Location

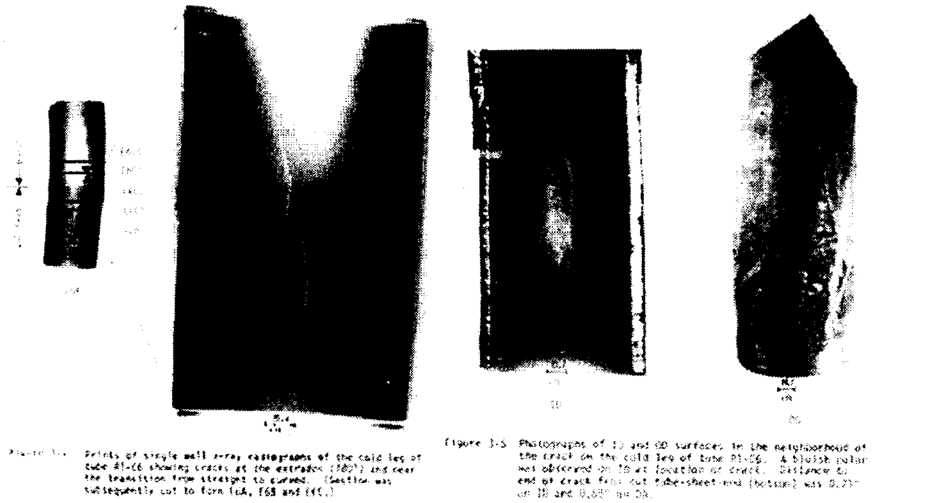
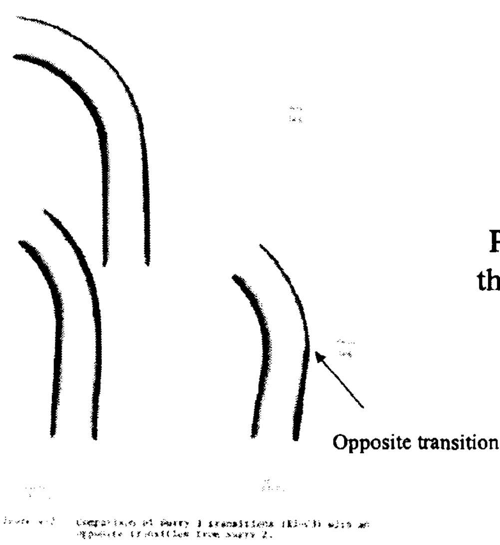


Figure 10. Radiographs, to the left of the figure, show the overall tangent point region and crack network. The visual appearance of the crack is shown to the right.



Tangent Point U-Bend
PWSCC is Influenced by
the Shape of the Transition

Figure 11. The radiographs to the left show the smooth tangent point transitions of a row 1 U-bend from Surry 1. The hot leg is shown above the cold leg. To the right is a radiograph of the irregular tangent point transition from a row 1 U-bend of Surry 2