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ANALYSIS OF CRACKED CORE SPRAY INJECTION LINE PIPING FROM THE
QUAD CITIES UNITS 1 AND 2 BOILING WATER REACTORS

by

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ANALYSIS OF CRACKED CORE SPRAY INJECTION LINE PIPING FROM THE
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ABSTRACT

Elbow assemblies and adjacent piping from the loops A and B core spray injection lines of Commonwealth Edison Company's Quad Cities Units 1 and 2 Boiling Water Reactors have been examined in order to determine the nature and causes of coolant leakages and flaw indications detected during hydrostatic tests and subsequent ultrasonic inspections. The elbow assemblies were found to contain multiple intergranular cracks in the weld heat-affected zones. The cracking was predominantly axial in orientation in the forged elbow and wedge components, whereas mixed axial and circumferential cracking was seen in the wrought piping pieces. In at least two instances, axial cracks completely penetrated the circumferential weld joining adjacent components. Based upon the observations made in the present study, the failures were attributed to intergranular stress corrosion cracking caused by the weld-induced sensitized microstructure and residual stresses present; dissolved oxygen in the reactor coolant apparently served as the corrosive species. The predominantly axial orientation of the cracks present in the forged components is believed to be related to the banded microstructure present in these components. The metallographic studies reported here are supplemented by x-radiography, chemical analysis and mechanical test results, determinations of the degree of sensitization present, and measurements of weld metal delta ferrite content.

SUMMARY

Elbow assemblies and adjacent piping from the loops A and B core spray injection lines of Commonwealth Edison Company's Quad Cities Units 1 and 2 Boiling Water Reactors have been examined in order to determine the nature and causes of coolant leakages and flaw indications detected during hydrostatic tests and subsequent ultrasonic inspections. The results of this investigation may be summarized as follows:

1. The coolant leakage in the Unit 2 loop A core spray injection line was found to be due to cracks at the inner surface of the elbow region, at least three of which apparently penetrated to the outer surface. Similarly, ultrasonic flaw indications in the remaining Quad Cities core spray lines were related to multiple cracking at the inner surfaces of the corresponding elbow regions.
2. A total of approximately 40 cracks were detected at the inner surface of the Unit 2 loop A elbow assembly, and similarly large numbers of cracks were seen in the other three assemblies. All of the cracks were located in the vicinity of the circumferential welds joining the elbow, wedge, and pipe pieces.
3. Except for some circumferential cracking seen in the Unit 2 loop B elbow, almost all of the cracks detected in the forged elbow and wedge pieces from the four core spray lines were predominantly axial in orientation. Both circumferential and axial cracking were seen in the wrought pipe pieces.
4. In the Unit 2 loop A assembly, virtually all of the cracks were located in the forged elbow and wedge components, and those cracks found in the pipe material appeared to have initiated in the wedge or elbow material. Similarly in the Unit 1 loop B assembly, cracking in the elbow and wedge pieces predominated. In the remaining two assemblies, extensive cracking was present in the wrought pipe material as well as the forged piece.
5. The base metal cracks were intergranular and more-or-less branched in all cases, and are apparently due to intergranular stress corrosion cracking. Unusually pronounced crack branching and surface checking was present in the weld heat-affected zones (HAZs) in the Unit 1 loop B elbow assembly.

6. In two instances, axial cracks that had initiated in the forged elbow or wedge material were found to have penetrated completely across the adjacent circumferential weld. In another instance, a subsurface crack had apparently grown completely through the weld metal to join two inner-surface cracks in the wedge and elbow material, respectively.
7. The chemical compositions of selected base metal samples from the Unit 2 loop A elbow, wedge, and pipe were found to conform to the specifications for Type 304 stainless steel. The carbon level in a weld metal sample from the wedge-to-elbow weld was within the required range for Type 308 stainless steel.
8. Room temperature tensile tests were conducted on axial and transverse base metal specimens from the Unit 2 loop A pipe and elbow material. These tests indicated a modest difference in properties among the axial and transverse pipe specimens and the axial elbow specimen. However, the transverse elbow specimen displayed noticeably higher tensile and yield strengths than the remaining three specimens.
9. The delta ferrite content in a section of weld metal containing a through-weld crack was found to be between 5.2 and 6.3 percent, which is within the normal range.
10. A qualitative test for sensitization based on ASTM Procedure A 262, Practice A determined that the Unit 2 loop A elbow, wedge, and pipe materials in the weld HAZ were heavily sensitized, but relatively little sensitization was indicated in samples away from the weld.
11. Microhardness measurements on samples from Unit 2 loop A detected the presence of a slight to moderate increase in hardness near the machined inner surface in the vicinity of the weld.
12. The forged elbow and wedge material from all four core spray lines exhibited a pronounced banded microstructure with a significant amount of delta ferrite strung out in the axial direction. Bands of apparent compositional variations in the austenite matrix were associated with the delta ferrite stringers. The axial cracks were generally parallel to the banded features of the microstructure, and the prevailing crack orientation is believed to have been influenced by banded compositional variations in the austenite matrix.

Section 1

INTRODUCTION

Commonwealth Edison Company's Quad Cities Nuclear Power Plant, located near Cordova, Illinois, consists of two essentially identical but independent 800-MWe boiling water reactor (BWR) units and turbine-generator systems located in a common building. Both BWRs began commercial operation in 1972. On March 8, 1980, during a pressure test of the Unit 2 reactor vessel, water was observed to be leaking from the loop A core spray injection piping in the region near the junction of this piping with the reactor pressure vessel. An ultrasonic inspection of the entire core spray piping system located within the primary containment was subsequently conducted. This inspection indicated the presence of several cracks near welds at the leaks in loop A, and suggested that cracks were also present at similar locations in loop B. Several months later, cracking was detected ultrasonically at similar locations in the Unit 1 loops A and B core spray lines. All four lines were replaced, and selected components from the failed lines were provided to Argonne National Laboratory (ANL) for failure analyses.

The layout of the Units 1 and 2 loop A core spray injection lines is shown schematically in Figure 1-1. The piping is 10-inch Schedule 80 ASTM A 312, grade TP 304 (Type 304 stainless steel) seamless pipe, and the elbows are A 403, grade WP 304 (Type 304 stainless steel) schedule 80 forgings. Type 308 stainless steel filler metal was used in the welds. Of particular interest to the present investigation are the 90° elbow and adjacent 15° wedge located between the reactor pressure vessel and the first manual isolation valve. In Unit 2 loop A, ultrasonic inspection revealed crack indications at all three welds joining these forgings to each other and to the adjacent piping. Crack indications were also detected ultrasonically at the welds joining the first manual isolation valve to another 90° elbow immediately adjacent to it.

The layout of the Units 1 and 2 loop B core spray injection lines is not greatly different from that shown in Figure 1-1 for loop A. However, in the loop B lines the positions of the 90° elbow and 15° wedge between the pressure vessel wall and

Figure 1-1. Schematic representation of the loop A core spray injection line in the Quad Cities Units 1 and 2 boiling water reactors.

the manual isolation valve are reversed in that the wedge is nearer the vessel. Cracks were detected ultrasonically in the B loops at essentially the same locations as indicated in Figure 1-1 for Unit 2 loop A.

During reactor operations, the manual isolation valve and testable check valve shown in Figure 1-1 are normally open, and the core spray isolation valve is normally closed. Since the core spray inlets to the pressure vessel are below the level of the reactor coolant water, that portion of the core spray lines up to the core spray isolation valve is normally filled with more or less stagnant coolant water. At the cracked elbow and wedge welds, the water temperature is estimated

to range from 204 to 260°C (400 to 500°F) under normal operating conditions, and the pressure is about 6.9 MPa (1000 psi).

The present report describes the results of analyses performed on components from the cracked Quad Cities core spray lines. The first components to be analyzed, from Unit 2 loop A, received the most comprehensive examination, and the results obtained from that examination will be emphasized in the present report. Observations from subsequent analyses of components from the remaining three failed lines will be included where appropriate.

Section 2

COMPONENT REMOVAL, SHIPPING, AND DECONTAMINATION

The piping regions from Unit 2 loops A and B that included the 90° elbow and 15° wedge pieces were selected for detailed failure analysis. These two 105° elbow assemblies were removed from the core spray line by making circumferential cuts approximately 8 inches away from the pipe-to-elbow and pipe-to-wedge welds, respectively. The elbow assembly from loop A was partly decontaminated at the plant before it was shipped to ANL, but the loop B assembly was shipped in the nondecontaminated condition. The cracked weld regions between the manual isolation valve and the adjacent 90° elbow for the Unit 2 loops were not sent for examination.

Smaller pieces of the same components from the cracked Unit 1 core spray lines were obtained several months later. Only the region surrounding the circumferential elbow-to-pipe weld was obtained from loop A, and the region adjacent to the two circumferential welds at either end of the 15° wedge from loop B were examined.

The first two components to be received at ANL were the Unit 2 loops A and B elbow assemblies. The loop A assembly was immediately subjected to a thorough decontamination procedure to facilitate subsequent handling and examinations, but the loop B assembly was initially placed into storage in the as-received condition. Several months later, when the Unit 1 loops A and B components were received, all of the remaining components were decontaminated. In all cases, decontamination was accomplished by first immersing the components in a caustic permanganate solution at 93°C (200°F) to oxidize the surface residue, after which this residue was dissolved in a phosphoric acid solution. However, this technique was found to be only partly successful in removing the surface contamination. A "bright dip" solution of acetic, nitric, phosphoric, and hydrochloric acid was then swabbed over the surface in order to chemically remove a thin surface layer. This approach was found to be more successful, and the radioactivity of the components was finally reduced to about 7.2×10^{-9} C/kg·s (100 mR/h) as compared to levels in excess of 7.2×10^{-8} C/kg·s (1 R/h) in the as-received condition. Two views of the decontaminated Unit 2 loop A elbow assembly are shown in Figures 2-1 and 2-2.

Figure 2-1. View of decontaminated elbow and wedge assembly from Unit 2 loop A before initial sectioning.

Figure 2-2. Alternate view of decontaminated Unit 2 loop A elbow and wedge assembly.

Section 3

INITIAL SECTIONING

After decontamination, all of the failed core spray line components except that from Unit 2 loop B were sectioned to permit a more detailed examination of the cracking present at the inner surface in the vicinity of the welds. The sectioning of the Unit 2 loop A elbow assembly is typical: The 15° wedge was first removed from the assembly by making a pair of circumferential cuts through the elbow and pipe material, respectively, approximately 64 to 76 mm (2-1/2 to 3 inches) away from the circumferential welds to the wedge. A similar pair of cuts was made at the other end of the assembly on either side of the circumferential elbow-to-pipe weld. The resulting circular rings were then split axially through the 6 and 12 o'clock positions to produce the four semicircular pieces on which the ensuing examinations were performed. (The clock positions around the circumference of these semicircular pieces are defined looking toward the reactor pressure vessel, with the 12 o'clock position originally oriented upward in the installed position in the plant.) The locations of the above cuts are shown as the dashed lines in Figure 3-1.

The Unit 1 components were sectioned in a similar manner, i.e., circumferential cuts were made parallel to and approximately 64 to 76 mm (2-1/2 to 3 inches) to each side of the circumferential welds of interest, and the resulting rings containing these welds were split lengthwise. However, the Unit 1 components were split axially through the 3 and 9 o'clock positions rather than the 6 and 12 o'clock positions. In the case of the Unit 2 loop B assembly, excessive piping material at the pipe side of the elbow-to-pipe and wedge-to-pipe welds was removed by circumferential cutting. However, the remaining elbow assembly was not split lengthwise, since it was needed intact for subsequent ultrasonic inspection by another laboratory.

Figure 3-1. Diagram of elbow and wedge assembly with initial sections indicated by dashed lines.

Section 4

DYE PENETRANT EXAMINATION

A macroscopic examination of the weld region at the inner surfaces of the pieces described above was performed with Spotcheck type SKC-NF dye penetrant (Magnaflux Corp., Chicago). The surfaces were first cleaned with alcohol, acetone, and a special dye penetrant cleaner. The dye penetrant was then applied and the excess removed, and a developer was subsequently applied to reveal the presence of cracks through the bleed-out of retained dye penetrant. Figures 4-1 through 4-4 show the appearances of the inner surfaces of the four Unit 2 loop A pieces after this procedure. Numerous cracks are indicated in the regions near the welds, and in almost every case the cracks are oriented in the axial direction. The only exceptions are (1) an irregular crack on the elbow side of the wedge-to-elbow weld at approximately the 8 o'clock position (see Figure 4-1), and (2) a pair of circumferential cracks at the inner surface on the elbow side of the wedge-to-elbow weld at the 6 o'clock position. These latter cracks are not readily visible in the photograph shown in Figure 4-1, but are shown with more clarity in Figure 4-5. The dye penetrant revealed no cracks in the weld metal itself or on the pipe side of the welds. The cracks tend to be concentrated to either side of the wedge-to-elbow weld.

An axial strip was cut from the semicircular sample shown in Figure 4-2 before the dye penetrant inspection was performed. This strip, which included approximately the 5:30 to 6 o'clock positions, was removed during initial sectioning to permit a preliminary metallographic examination of an axial crack on the wedge side of the wedge-to-elbow weld. Thus, the semicircular piece shown in Figure 4-2 includes only the 12 o'clock to approximately 5:30 positions.

A dye penetrant examination was also performed at the outer surface of the above wedge and adjacent welds in an attempt to locate the leaking cracks. Unfortunately, the relatively rough surface at the exterior of the pipe, particularly at the interface between the weld bead and the adjacent base metal, greatly hindered the inspection. Relatively faint surface indications were found at several locations along the weld-metal/base-metal interface at the outer surface; at least

Figure 4-1. Inner surface of Unit 2 loop A elbow assembly near elbow-to-wedge and wedge-to-pipe welds in region from 6 o'clock (RHS) through 9 o'clock to 12 o'clock (LHS) after dye penetrant examination.

Figure 4-2. Same as Figure 4-1 but in the region from 12 o'clock (RHS) through 3 o'clock to approximately 5:30 (LHS).

Figure 4-3. Inner surface of Unit 2 loop A elbow assembly near elbow-to-wedge weld in region from 6 o'clock (RHS) through 9 o'clock to 12 o'clock (LHS) after dye penetrant examination.

Figure 4-4. Same as Figure 4-3 but in the region from 12 o'clock (RHS) through 3 o'clock to 6 o'clock (LHS).

Figure 4-5. Circumferential cracks revealed by dye penetrant at 6 o'clock position on elbow side of wedge-to-elbow weld from Unit 2 loop A.

three of these indications may correspond to leaking cracks. Figure 4-6 shows one of these outer-surface indications at approximately the 6:30 position on the wedge side of the weld, probably corresponding to the darker of the two inner-surface cracks seen in this region in Figure 4-1. A second possible leaking crack is shown in Figure 4-7; this indication apparently corresponds to the nonaxial crack on the elbow side of the weld near the 8 o'clock position in Figure 4-1. The third indication (Figure 4-8) appears to match up with an elbow-side crack at approximately the 10 o'clock position in Figure 4-1. It should be noted that the outer-surface indications shown in Figures 4-6 and 4-8 agree reasonably well with the positions of the leaks observed in the field (see previous discussion), but the indication at the 8 o'clock position (shown in Figure 4-7) does not correspond to the location of a reported leak. Similarly, a reported leak near the 10 o'clock position on the wedge side of the weld does not appear to have been confirmed here.

Figure 4-6. Outer surface of Unit 2 loop A near wedge-to-elbow weld, showing dye penetrant indication (arrow) on wedge side of weld at approximately 6:30 position.

Figure 4-7. Outer surface of Unit 2 loop A near wedge-to-elbow weld, showing dye penetrant indication (arrow) on elbow side of weld at approximately 8 o'clock position.

Figure 4-8. Outer surface of Unit 2 loop A near wedge-to-elbow weld, showing dye penetrant indication (arrow) on elbow side of weld at approximately 10 o'clock position.

Similar dye penetrant examinations were performed on the inner surface of the Unit 1 loop A and B components, and the results are shown in Figures 4-9 through 4-12. As in the case of the Unit 2 loop A elbow assembly, numerous cracks were detected in the heat-affected zones (HAZs) of the circumferential welds. For the Unit 1 loop A pipe-to-elbow weld (Figures 4-9 and 4-10), the cracking in the forged elbow material is again predominantly axial, but the cracking across the weld in the adjacent wrought piping material is almost entirely circumferential. The Unit 1 loop B examination included both the pipe-to-wedge and wedge-to-elbow welds. The rough inner surface of this component resulted in a badly stained and mottled background, but axial cracking is again visible in the weld HAZs, particularly in the forged wedge and elbow material (Figures 4-11 and 4-12). No circumferential cracking is observed in the piping material in this component.

A slightly different dye penetrant examination procedure was employed for the Unit 2 loop B elbow assembly, since it was necessary to preserve the weld regions intact for subsequent automated ultrasonic inspection at EG&G-Idaho under another program. Therefore, the assembly was sectioned circumferentially through approximately the midpoint of the elbow region so that one of the resultant pieces contained the entire pipe-to-elbow weld and the second piece contained the

Figure 4-9. Inner surface of Unit 1 loop A elbow assembly near elbow-to-pipe weld in region from 3 o'clock (RHS) through 6 o'clock to 9 o'clock (LHS) after dye penetrant examination.

Figure 4-10. Same as in Figure 4-9 but in the region from 9 o'clock (RHS) through 12 o'clock to 3 o'clock (LHS).

Figure 4-11. Inner surface of Unit 1 loop B elbow assembly near elbow-to-wedge (top) and wedge-to-pipe welds in region from 3 o'clock (LHS) through 6 o'clock to 9 o'clock (RHS) after dye penetrant examination.

Figure 4-12. Same as Figure 4-11 but in the region from 9 o'clock (LHS) through 12 o'clock to 3 o'clock (RHS).

elbow-to-wedge and wedge-to-pipe welds. The inner surfaces of these two pieces were then examined by means of dye penetrant techniques from the ends. Figures 4-13 through 4-15 show the dye penetrant indications seen near the elbow-to-wedge and wedge-to-pipe welds. Both axial and circumferential cracking in the HAZs is apparent, and the cracking is again most heavily concentrated in the elbow and wedge components. Less cracking is seen near the pipe-to-elbow weld (Figures 4-16 through 4-19), and again both the axial and circumferential modes are present. In this weld region, the elbow and pipe material are cracked to about the same extent.

Figure 4-13. View of the inner surface of the Unit 2 loop B elbow assembly from the elbow end after dye penetrant examination. That portion of the elbow-to-wedge weld (lower weld in photograph) extending from about the 3:15 o'clock position (bottom right) to the 6:45 o'clock position (top) is shown. The wedge-to-pipe weld is above (behind) the elbow-to-wedge weld.

Figure 4-14. Same as Figure 4-13 except for that portion of the elbow-to-wedge weld (to right in photograph) extending from the 10:30 o'clock position (top) to the 1:45 o'clock position (bottom).

Figure 4-15. Same as Figure 4-13 but viewed from the pipe end. That portion of the elbow-to-wedge weld (upper weld in photograph) extending from about the 7:45 o'clock position (left) to the 10:30 o'clock position (lower right) is shown.

Figure 4-16. View of the inner surface of the Unit 2 Loop B elbow assembly from the pipe end after dye penetrant examination. The pipe is to the bottom in the photograph, and that portion of the pipe-to-elbow weld extending from about the 11:30 o'clock position (right) to the 2:15 o'clock position (left) is shown.

Figure 4-17. Same as Figure 4-16 (pipe to right in photograph) except for that portion of the pipe-to-elbow weld extending from the 2:30 o'clock position (top) to the 4:45 o'clock position (bottom).

Figure 4-18. Same as Figure 4-16 (pipe to bottom in photograph) except for that portion of the pipe-to-elbow weld extending from the 7:45 o'clock position (top right) to the 10:00 o'clock position (bottom left).

Figure 4-19. Same as Figure 4-16 (pipe to bottom in photograph) except for that portion of the pipe-to-elbow weld extending from the 10:45 o'clock position (right) to the 1:15 o'clock position (left).

Section 5

X-RADIOGRAPHY

The dye penetrant examinations just described were supplemented by x-radiography of all of the weld regions. In several cases, additional flaws or extensions of cracks seen with dye penetrant were detected. The most thorough radiographic inspection was performed on the Unit 2 loop B assembly, and some of the more important results obtained will be summarized here.

Figure 5-1 shows the radiograph obtained from the central region of the elbow-to-wedge and wedge-to-pipe weld area of Unit 2 loop A, shown previously in Figure 4-1. The crack seen at the bottom center of the picture corresponds to the one made visible by dye penetrant toward the wedge side of the wedge-to-pipe weld at approximately the 9 o'clock position (Figure 4-1). However, Figure 4-1 suggests that the crack stops at the weld fusion line, whereas Figure 5-1 indicates that this crack penetrates the weld metal and extends into the pipe material on the other side.

The remaining suspected flaws identified by radiography were not as clear-cut as the crack shown in Figure 5-1, and did not reproduce well in the photographic prints. These additional possible flaws are shown by dotted lines in the sketch of Figure 5-2. Three of them represent extensions of cracks already detected by use of dye penetrant. Two of these cracks may extend through the weld metal, as indicated in Figure 5-2; one is seen in the wedge-to-elbow weld at about the 11 o'clock position and the other in the wedge-to-pipe weld at approximately the 11:30 position. A faint indication of a possible crack on the pipe side of the wedge-to-pipe weld at about the 11 o'clock position was also detected in the radiographs.

Figure 5-1. Radiograph of central portion of Unit 2 loop A specimen shown in Figure 4-1.

Figure 5-2. Diagram indicating how Unit 2 loop A specimen was sectioned for metallography. Flaws seen by x-radiography that were not revealed using dye penetrant are indicated by dotted lines, the dashed lines indicate where cuts were made, and the metallographic sections are denoted by the letters C-C through F-F. Also shown is the strip of material between approximately the 5:30 and 6:00 o'clock positions from which sections A-A and B-B were taken.

Section 6
CHEMICAL ANALYSES

After the above examinations and procedures were completed, chemical analysis samples were taken from the Unit 2 loop A pipe, elbow, and wedge material. The results of these analyses are presented in Table 6-1. The compositions of all three samples to fall within the specified values for Type 304 stainless steel for all of the elements analyzed. Additional emission spectroscopy analyses were performed to check for the possible presence of such elements as Ti, Nb, V, Mo, Zr, and Pb. None of these elements was found to be present in significant quantity.

An additional chemical analysis for carbon only was performed on a weld metal sample taken from the wedge-to-elbow weld at approximately the 9 o'clock position. This sample was taken from the center of the weld pass at the outer surface to reduce the likelihood of dilution by the surrounding base metal. The carbon content of this sample was found to be 0.064 wt %, which is below the maximum allowable for Type 308 stainless steel.

Table 6-1
COMPOSITIONS OF PIPE, WEDGE, AND ELBOW SAMPLES FROM
UNIT 2 LOOP A COMPARED WITH SPECIFICATIONS FOR
TYPE 304 STAINLESS STEEL (WT %)

	<u>Pipe Sample</u>	<u>Wedge Sample</u>	<u>Elbow Sample</u>	<u>Type 304 Stainless Steel</u>
C	0.046	0.074	0.058	0.08 max
Cr	18.96	18.62	18.67	18-20
Ni	10.36	10.34	10.46	8-12
Mn	1.62	1.78	1.80	2.0 max
Si	0.46	0.41	0.43	1.0 max

Section 7

METALLOGRAPHY

As noted above, the Unit 2 loop B elbow assembly was sent intact to EG&G-Idaho for ultrasonic inspection under another program after dye penetrant and radiographic inspections were performed at ANL. However, the remaining three elbow assemblies were retained and subsequently sectioned for metallographic examination. The most thorough examination was performed on the Unit 2 loop A assembly, and in particular on the semicircular region shown in Figures 4-1 and 5-1. Consequently, most of the following discussion is devoted to the metallographic observations made on samples from this piece of piping. Sectioning was accomplished as indicated by the dashed lines in Figure 5-2; the locations of the metallographic sections A-A through F-F are also shown in Figure 5-2.

The first metallographic sections examined were sections A-A and B-B through an axial crack on the wedge side of the wedge-to-elbow weld between about the 5:30 and 6 o'clock positions. These two sections were taken in the radial direction through the pipe wall at two locations along the crack length. The circumferential weld parallel to the two sections has a V-groove configuration tapering outward toward the outer surface, and section A-A is sufficiently close to the weld that it intersects the weld metal approximately midway through the thickness of the section. Thus, the inner surface of section A-A consists of wedge base metal very near the wedge-to-elbow weld, and the outer surface consists of weld metal. Section B-B cuts entirely through base metal ~13 mm (~0.5 in.) away from the weld at the inner surface, but is presumably still within the HAZ.

Two cracks were detected in section A-A, both of which initiated at the inner surface and penetrated approximately halfway through the wall thickness at this point. The base metal portions of the two cracks exhibited the branched intergranular propagation mode commonly associated with intergranular stress corrosion cracking (IGSCC), and some oxide was present in portions of the cracks (see Figure 7-1). Both cracks penetrated ~1.5 to 2.0 mm (~60 to 80 mils) into the weld metal before stopping, as shown in Figure 7-2. It should be noted that the crack seen in Figure 7-2 appears to be discontinuous in the weld metal; however, the visible

Figure 7-1. Intergranular cracking observed in metallographic section A-A.

Figure 7-2. Penetration of cracking in section A-A into weld metal at wedge-to-elbow weld.

crack segments probably link up above and below the plane of the polished section. One of the two cracks seen in section A-A was also observed in section B-B, where its appearance was similar to that shown in Figure 7-1. The depth of the crack seen in section B-B was about 60% of the wall thickness.

The two circumferential cracks detected in the elbow material immediately above the wedge-to-elbow weld in the 6 o'clock position were examined metallographically in section C-C. The larger of these two cracks, which was closer to the weld, is shown in Figure 7-3. The crack is again intergranular and highly branched, but follows a much more tortuous path than the axial cracks observed in sections A-A and B-B. In addition, large voids are observed where entire grains have apparently fallen out during sample preparation. A higher-magnification view of a portion of this crack (Figure 7-4) reveals that corrosion product, probably oxides, is present in the crack as well as in some of the voids. The crack seen in Figure 7-3 extends about one-third of the way through the wall thickness from the inner surface, and apparently stops at the weld metal in this section.

The second circumferential crack seen in section C-C is shown in Figure 7-5. This crack extends for about 3.3 mm (130 mils), or about 20% of the way through the wall thickness, and again displays a highly complex nature. Both of these circumferential cracks, like the axial cracks seen in section A-A and B-B, appear to have been caused by IGSCC.

The circumferential section D-D shown in Figure 5-2 was also examined metallographically. This section was taken at the pipe side of the adjacent wedge-to-pipe weld, and is near enough to the tapering weld metal region that it intersects the weld metal approximately halfway through the section thickness. Thus, the inner surface of this section is pipe material and the outer surface is weld metal. Section D-D was chosen for examination because the dye penetrant check did not reveal any flaws in this location, but the radiographic examination indicated that a surface crack on the wedge side of the weld, which was seen with dye penetrant, extended into the pipe material in this region.

Figure 7-6 shows a low-magnification photomicrograph of the crack found in section D-D. This micrograph clearly indicates that the crack intersects the inner surface, even though it was not seen with dye penetrant. The crack path is intergranular, and some branching is evident. The overall crack depth in this section is about 10.2 mm (400 mils), or about two-thirds of the wall thickness,

Figure 7-3. Low-magnification view of the larger of two circumferential cracks observed in section C-C.

Figure 7-4. Higher-magnification view of the crack shown in Figure 7-3.

Figure 7-5. Low-magnification view of smaller circumferential crack present in section C-C.

Figure 7-6. Low-magnification view of axial crack present in section D-D.

and the crack penetrates approximately 2.8 mm (110 mils) into the weld metal before stopping. The crack again appears to be the result of IGSCC.

The radiographic results suggest that the present crack may have completely penetrated the circumferential wedge-to-pipe weld. However, this has not been confirmed here. In addition, a smaller second crack on the pipe side of the weld, to the right of the present crack (see Figure 5-2), was indicated by radiography. An attempt was made to include this crack in section D-D, but it could not be found in the prepared metallographic section. It is possible that this smaller crack, if actually present, was lost in one of the saw cuts.

The crack examined metallographically in section E-E is of particular interest. The radiograph shown in Figure 5-1 indicates rather clearly that this crack completely penetrates the wedge-to-pipe weld, even though the dye penetrant examination revealed it to be present at the surface on the wedge side only. The metallurgical sections to be discussed here were obtained by mounting the specimen with the inner surface containing the crack parallel to the face of the mount, so that the plane of the polish in the prepared section was approximately parallel to the inner surface of the wedge and pipe. The mounted specimen was then ground down to a level at which the weld bead was exposed across the entire plane of the polish, but the base metal to each side was still slightly below this plane. This level was arbitrarily defined to be zero depth into the specimen, and the various metallographic sections discussed below were taken at several depths below this reference plane.

Figure 7-7 shows a metallographic section obtained at a depth of 0.7 mm (26 mils) below the reference plane. An intergranular crack is visible in the wedge material only, and no cracking is seen in either the weld metal or the pipe base metal. The flaw seen in Figure 7-7 extending vertically for about 10 mm (0.4 in.) along the wedge-material/weld-metal interface appears to be a region of lack of fusion in this circumferential weld. This identification of this flaw is based upon the fact that it lies exactly on the weld-metal/wedge-material interface over most of its length, although near the bottom of Figure 7-7 it appears to have extended into the weld metal as a crack. The axial crack in the wedge material terminates abruptly at this lack of fusion.

Figure 7-8 shows the metallographic section obtained at a depth of 1.5 mm (61 mils) below the reference plane. The lack of fusion at the wedge/weld-metal interface is no longer visible, and the crack in the wedge material now extends

Figure 7-7. Axial crack present in section E-E approximately 0.7 mm (26 mils) below the reference plane.

Figure 7-8. Axial crack present in section E-E approximately 1.5 mm (61 mils) below the reference plane.

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somewhat into the adjacent weld metal. An intergranular crack on the pipe side of the weld is also now visible, though it does not link up with the crack in the wedge in this plane. Higher-magnification views of the cracked regions at each side of the weld are shown in Figures 7-9 and 7-10.

An interesting microstructural feature visible in the wedge material in Figure 7-8 is the presence of delta ferrite stringers extending along the axial direction. These stringers parallel the flow lines in the forged microstructure, and are not present in the pipe material, which was not forged. The stringers also parallel the axial cracks present in the wedge and elbow, and their possible influence on this cracking will be discussed below.

The metallographic section taken at a depth of 2.5 mm (100 mils) reveals one continuous crack extending from the wedge material across the weld metal and into the pipe material on the other side, as shown in Figure 7-11. The crack path in the base metal on both sides of the weld is again intergranular. In the weld metal, the crack path appears to be influenced by the alignment of the columnar structure along the directions of heat flow that occurred during solidification. A higher-magnification view of a secondary crack in the weld metal (Figure 7-12) suggests that the cracking process here is one of alternate crack extension through the austenite matrix between the delta ferrite particles and subsequent propagation along the interface between these particles and the austenite.

A final metallographic section at this location was taken at a depth of 210 mils (5.33 mm), and is shown in Figure 7-13. The weld metal region is larger here, since the V-groove weld tapers outward toward the outer surface. In addition, the cracking in the weld metal is wider and somewhat straighter in this section, and is not as discontinuous. The features of the crack are otherwise similar to those seen in the previous sections.

The final metallographic section taken from the Unit 2 loop A elbow assembly was section F-F of Figure 5-2. This section was taken normal to the pipe wall down the weld centerline between adjacent cracks in the wedge and elbow material. The purpose of this section was to determine if these adjacent cracks were interconnected through the weld metal, as had been suggested by radiographic results. Figure 7-14 shows a portion of the section obtained. The small, discontinuous, subsurface crack seen in Figure 7-14 is located ~2.5 mm (~100 mils) below the

Figure 7-9. Higher-magnification view of cracking present at wedge-material/weld-metal interface in same section shown in Figure 7-8.

Figure 7-10. Higher-magnification view of cracking present near pipe-material/weld-metal interface in same section shown in Figure 7-8.

Figure 7-11. Axial crack present in section E-E approximately 2.54 mm (100 mils) below the reference plane.

Figure 7-12. Higher-magnification view of secondary cracking present in weld metal in same section shown in Figure 7-11.

Figure 7-13. Axial crack present in section E-E approximately 5.33 mm (210 mils) below the reference plane.

Figure 7-14. Subsurface crack present in weld metal in section F-F.

specimen surface, and was clearly visible in both the unetched and etched conditions. Thus, the adjacent cracks are probably interconnected through the weld metal.

Less extensive metallographic examinations were performed on the Unit 1 loops A and B elbow assemblies. As previously noted in the discussion of the dye penetrant results, the cracking observed in the loop A assembly was predominantly axial in the forged elbow material but almost entirely circumferential in the adjacent wrought piping material. The axial cracking again paralleled the banded delta ferrite present in this microstructure, as shown in Figure 7-15. The etchant used for this micrograph, Kalling's reagent, not only preferentially attacked the delta ferrite stringers, but also brought out the banded character of the austenite matrix. The austenite regions near the δ -ferrite stringers are presumably somewhat depleted in Cr and enriched in Ni as compared to the bulk austenite, and these banded austenite regions are less heavily attacked by the etchant. These depleted-Cr austenite bands also appear to be favored regions for crack growth, and their presence in the forged microstructure may be the cause for the axial cracking tendency in these components.

Figure 7-15. Banded microstructure and axial cracking present in forged elbow material near elbow-to-pipe weld from Unit 1 loop A. The section is parallel to and immediately below the inner surface of the component. The banded microstructure has been brought out by a Kalling's reagent etch.

Again, no banding was observed in the wrought piping material from the loop A elbow assembly, and in this case the cracking tended to be circumferential rather than axial. Figure 7-16 shows the branched intergranular nature of the cracking observed in the piping. Gray particles identified as oxides based upon their appearance are again present in some of the cracks.

The Unit 1 loop B elbow assembly displayed predominantly axial cracking in both the forged and wrought components. The dye penetrant staining of the weld HAZs to each side of the circumferential pipe-to-wedge and wedge-to-elbow welds is found to be associated with profuse intergranular surface cracking in these regions. Such cracking is shown in Figure 7-17 for a region in the wedge material near the wedge-to-pipe weld. The intergranular attack is sufficiently extensive in this

Figure 7-16. Branched intergranular cracking present in wrought piping material from Unit 1 loop A.

Figure 7-17. Intergranular "checking" present near inner surface of heat-affected zone on wedge side of wedge-to-pipe weld in Unit 1 loop B elbow assembly. The surface of this sample is parallel to and approximately 0.6 mm below the original inner surface of the component.

region that entire grains have fallen out. Delta ferrite banding was again present in the forged elbow and wedge components, and this banding showed some tendency to parallel these cracks. The axial cracking observed in the forged components likewise paralleled the banded microstructure in much the same manner as has been previously described for the other forged components.

Another noteworthy feature of the Unit 1 loop B elbow assembly is the presence of an additional through-weld crack. This crack was seen at the circumferential elbow-to-wedge weld, as shown in two different parallel sections in Figures 7-18 and 7-19. These sections are parallel to and some distance below the original component inner surface. Although the extensive surface checking in the weld HAZs has largely been removed during polishing to the depths of these sections, considerable intergranular crack branching may still be seen in the HAZs.

Figure 7-18. Through-weld cracking present at circumferential elbow-to-wedge weld in Unit 1 loop B elbow assembly. The section is parallel to and approximately 0.6 mm below the original inner surface of the component; the wedge material is to the left in the micrograph.

Figure 7-19. Same region as shown in Figure 7-18 but at a depth of approximately 1.8 mm below the original inner surface.

Section 8

DELTA FERRITE DETERMINATION

In view of the extensive weld metal cracking observed in several of the metallographic sections, it was decided that a quantitative determination of the amount of delta ferrite present in the Type 308 weld metal was desirable. Metallographic section E-E from the Unit 2 loop A assembly was selected for this determination. Regions both near (within 0.25 mm or 10 mils of) and away from (more than 2.5 mm or 100 mils from) the through-weld crack were examined, and all determinations were made at selected locations on the section at the 5.3-mm (210-mil) depth (see Figure 7-9). A special etching technique, based on Kalling's reagent, was used to accentuate the delta ferrite regions in the weld metal. A Quantimet 720 image analyzer system was used to measure delta ferrite from several photomicrographs taken at a magnification of 700X; one of these is shown in Figure 8-1. Five randomly selected locations on each photomicrograph were analyzed, and the average of these five values is reported in Table 8-1 as the delta ferrite content for the region shown in that photomicrograph. No significant differences were observed in the levels present near and away from the through-weld crack. In all cases, the volume percentage of delta ferrite was within the ~4-8% range typically recommended to avoid susceptibility to weld cracking. Similar quantitative determinations of delta ferrite content were not performed for the weld metal in the Unit 1 components, but visual comparisons of the various weld microstructures did not indicate any unusually low or high delta ferrite levels in any of the metallographic sections examined.

Table 8-1

DELTA FERRITE LEVELS OBSERVED IN SECTION E-E FROM
UNIT 2 LOOP A IN REGIONS NEAR AND AWAY FROM
THROUGH-WELD CRACK

Region	Distance from Through-Weld Crack		Delta Ferrite Content (vol. %)
	mm	mils	
1	<0.25	<10	5.8
4	>2.5	>100	6.3
5	>2.5	>100	5.9
8	<0.25	<10	5.2
9	<0.25	<10	5.9

Figure 8-1. High-magnification view of typical delta ferrite distribution present in weld metal of section E-E (same section shown in Figure 7-13).

Section 9

MICROHARDNESS MEASUREMENTS

Before the core spray piping and elbow sections were welded together, the inner surfaces of these pieces were machined near the weld regions. As a result of this machining operation, slight deformation could be visually observed in the first 1-2 grain layers from the prepared surfaces. A series of microhardness readings was therefore taken to determine the extent and depth of this surface deformation. The readings were taken on elbow material from Unit 2 loop A near the 6 o'clock position adjacent to the elbow-to-wedge weld, with hardness measured as a function of distance from the machined inner surface. For comparison purposes, a similar series of readings was taken on this same specimen near the inner surface but away from the machined region. All readings were taken using a 50-g weight and a diamond pyramid (Vicker's) indenter.

The hardness data obtained are summarized in Table 9-1. Only a modest increase in hardness is observed near the machined surface as compared with the inner-surface region away from the weld. The depth of the affected region appears to be of the order of 0.25 to 0.5 mm (10 to 20 mils).

Table 9-1

MICROHARDNESS DATA OBTAINED ON ELBOW MATERIAL AT AND AWAY FROM THE WELD PREP AREA, AS A FUNCTION OF DISTANCE FROM THE INNER SURFACE

At Weld Prep Area			Away from Weld Prep Area		
Distance from Inner Surface		Vicker's Hardness (kg/mm ²)	Distance from Inner Surface		Vicker's Hardness (kg/mm ²)
mm	mils		mm	mils	
0.10	4.0	147	0.06	2.4	124
0.12	4.6	138	0.07	2.9	113
0.13	5.1	135	0.09	3.7	113
0.16	6.2	135	0.19	7.4	112
0.18	7.1	124	0.22	8.5	95
0.19	7.5	124	0.25	10.0	113
0.21	8.1	124	0.44	17.3	107
0.23	9.2	107	0.51	20.0	102
0.25	10.0	112	0.57	22.3	104
0.43	17.1	122			
0.44	17.3	118			
0.45	17.6	101			

Section 10

TENSILE TESTS

Room temperature tensile tests were conducted on specimens of Unit 2 loop A pipe and elbow material oriented both parallel to the pipe axis (axial specimens) and perpendicular to the axis (transverse specimens). The test specimens were ~102 mm (4 in.) long and ~2.5 mm (~100 mils) thick with a 25.4-mm (1-in.) gauge length. The specimen geometry and testing procedure conformed to the requirements of ASTM Standard E-8 (1).

The tensile-test results are summarized in Table 10-1. A relatively modest difference in tensile properties is seen between the axial and transverse pipe specimens. In addition, the axial specimen from the forged elbow exhibits about the same properties as the two pipe specimens. However, the transverse specimen from the elbow is noticeably stronger than the axial specimen, indicating a possible directionality in properties in the forged microstructure. It is somewhat surprising that the room temperature tensile strength is greater in the transverse direction, since virtually all of the IGSCC observed in the failed component occurred approximately normal to this direction. It thus appears that either (a) the service plus residual stresses present in the failed core spray line were substantially greater in the transverse (hoop) direction than in the axial direction, or (b) the susceptibility to IGSCC in a given direction cannot be directly related to room-temperature tensile properties.

Table 10-1

SUMMARY OF TENSILE-TEST DATA OBTAINED ON PIPE AND ELBOW MATERIAL
FROM UNIT 2 LOOP A

	Yield Strength		Ultimate Tensile Strength		Total Elongation (%)
	MPa	psi	MPa	psi	
Pipe, Axial	270	39,200	565	82,000	54.0
Pipe, Transverse	236	34,300	556	80,600	66.0
Elbow, Axial	253	36,700	574	83,200	56.5
Elbow, Transverse	303	44,000	644	93,400	57.9

Section 11

SENSITIZATION DETERMINATION

A simple qualitative test for the presence of sensitization in the Unit 2 loop A austenitic stainless steel pipe, elbow, and wedge material was performed as described in ASTM Procedure A 262, Practice A (2). Under this procedure, the sample to be tested is electroetched in a solution of 10% oxalic acid in water at a current density of 1 A/cm² for a period of 90 seconds. The degree of sensitization in the sample is revealed by the extent to which it is attacked by this etching procedure. Samples in and away from the weld HAZ were tested.

As expected, the samples from the weld HAZ were found to be heavily sensitized, but little sensitization was indicated in the samples away from the weld regions. Figure 11-1 shows an etched sample of wedge material from the HAZ of the wedge-to-pipe weld. The heavily attacked "ditch" structure along the grain boundaries is apparent. In contrast, relatively little attack was noted, for example, in the sample of elbow material taken away from the weld region (Figure 11-2).

Figure 11-1. Heavily attacked microstructure observed in wedge material near wedge-to-pipe weld after etching according to ASTM Procedure A 262, Practice A.

Figure 11-2. Lightly attacked microstructure observed in elbow material away from heat-affected zone after etching according to ASTM Procedure A 262, Practice A.

Section 12

DISCUSSION

Based upon the above observations, it seems reasonable to conclude that the cracking observed in the Quad Cities Units 1 and 2 elbow assemblies is due to IGSCC. The principal corrosive species was probably dissolved oxygen in the semistagnant reactor coolant water present at the inner surface of the core spray lines, although recent studies have indicated that other anions such as Cl^- and SO_4^{-2} can play an important role in inducing IGSCC. The fact that cracks were present only at the weld regions indicates that the sensitized microstructure and probable residual welding stresses present in these regions contributed to the failure. Any welding residual stresses present would, of course, be supplemented during normal operation by a tensile hoop stress of about 55 MPa (8000 psi) owing to the nominal 6.9-MPa (1000-psi) internal pressure contained by the piping.

Failure of this piping due to IGSCC is not in itself a unique occurrence; at least 190 incidents of IGSCC in U.S. and foreign BWRs have been reported during a six-year period ending in 1980, (3) and a number of others have occurred since that time. However, two aspects of the present failures distinguish them from the sorts of IGSCC failures typically observed in BWR piping systems. The first of these is the overwhelmingly axial orientation of the cracking observed in most of the failed components. Approximately 40 cracks were detected by various means at the inner surface of the Unit 2 loop A elbow assembly, and all of these cracks were axial with the exception of the two circumferential cracks seen in Figure 4-5 and the mixed circumferential and oblique crack seen in Figure 4-1. Axial cracking also predominated in the forged elbow and wedge components from the Unit 2 loop B assembly as well as the Unit 1 assemblies, although circumferential and mixed axial and circumferential cracking were commonly observed in some of the piping material. The second distinguishing feature of the present failures is the fact that, in at least two and probably three instances, a crack has completely penetrated a weld metal region. These two aspects of the present failure will be addressed briefly here.

In the IGSCC failures seen to date in BWR recirculation piping, cracking is typically observed to take place in a weld HAZ and to propagate circumferentially around the pipe in this zone at a more-or-less constant distance from the weld fusion line. However, axial cracks have been seen in, for example, the Type 304 stainless steel steam-to-isolation condenser piping from the Dresden Unit 1 BWR (4). In the case of the IGSCC failures in BWR core spray lines, both axial and circumferential cracking have been found. Cracks seen in the safe-end reducer and spool piece from the Peach Bottom Unit 3 BWR (5) and in a furnace-sensitized safe end from the Nine Mile Point reactor (6) were almost entirely circumferential in character. However, in the Vermont Yankee A and B loop core spray lines, both axial and circumferential cracks were found near several welds located between the pressure vessel and the first manual isolation valve (7). Mixed axial and circumferential cracks were also found near welds in the 10-inch core spray lines of the Dresden Unit 2 BWR (8). In this case, the cracks tended to be concentrated in the furnace-sensitized Type 316 stainless steel safe ends and safe-end extensions (dutchmen), all of which were forgings. A single axial crack has also been detected in the safe end of one of the core spray lines in the Tsuruga BWR in Japan (9). However, the author is not aware of any instances in which the axial cracking of BWR components was as pronounced as in the present case.

A number of observations made in the present study suggest that the axial cracking seen here is related to the banded microstructure present in the forged elbow and edge pieces. First of all, the axial cracks observed are heavily concentrated in the forged elbow and wedge material, just as the axial cracks seen in the Dresden Unit 2 core spray line were located primarily in the forged safe ends and safe-end extensions. Secondly, the axial cracks in the elbow and wedge closely parallel the banding that is present (see Figures 7-8 and 7-15). The presence of delta ferrite stringers implies that the forging temperature may have been somewhat in excess of the maximum 1149 to 1260°C (2100 to 2300°F) commonly recommended (10). However, austenitic stainless steels containing delta ferrite have been found to possess increased resistance to stress corrosion cracking in aqueous solutions (11), and so the mere presence of delta ferrite in the forged microstructure does not explain the cracking seen here. It appears more likely that compositional variations present in the banded austenite (as revealed by the Kalling's reagent etch of Figure 7-15) may have influenced the cracking direction, with the cracks propagating preferentially along regions somewhat depleted in Cr.

It is also reasonable to expect that the state of residual stress present in the failed components would influence the orientation of the IGSCC cracks present. However, a detailed study of residual stresses requires considerable time and effort in instrumenting and machining the samples of interest, and such a study was determined to be beyond the scope of the present investigation.

The final point to be considered here is the propagation of at least two stress corrosion cracks completely through the Type 308 weld metal. Devine (12,13) has analyzed the problem of intergranular cracking in duplex austenite plus delta ferrite weld metal structures, and has developed quantitative criteria for assessing the susceptibility of these alloys to such cracking. He assumes that cracking in duplex microstructures is contingent upon sensitization of the austenite-austenite grain boundaries, and that a critical amount and distribution of delta ferrite is required to prevent this sensitization by causing preferential carbide precipitation at the austenite/delta-ferrite phase boundaries. The key parameter in Devine's criteria is S_v , the amount of austenite/delta-ferrite boundary area per unit volume of alloy. For Type 308 weld metal, Devine predicts that complete immunity to sensitization should be attained at an S_v value of 2900 cm^{-1} for an alloy with 5 percent delta ferrite and a carbon content of 0.064 wt %. Alloys with S_v levels somewhat below these critical values should be highly resistant but not totally immune to sensitization. The S_v value of about 2250 cm^{-1} for the cracked Type 308 weld metal shown in Figure 7-10 (carbon content = 0.064 wt %) places it somewhat below Devine's critical level for complete immunity to sensitization, although considerable resistance to sensitization would still be expected. This appears to be consistent with the situation actually observed for the welds examined here in that most but not all cracks were stopped before they penetrated the weld metal.

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Section 13

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