SCOPING EVALUATION
FOR ARKANSAS NUCLEAR ONE, UNIT 1
REACTOR COOLANT PUMPS
PER THE REQUIREMENTS OF
ASME CODE CASE N-481

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1.0 INTRODUCTION

The four reactor coolant pumps ("A", "B", "C", and "D") at Arkansas Nuclear One, Unit 1 (ANO-1) were all manufactured by Byron Jackson. All four pump casings were fabricated from ASTM A351-69, Grade CF8M. The pumps have identical design, hence a single stress report was prepared for all four pumps. Inspection of the "A" and "B" pump casing welds was performed in 1986 and 1988, respectively, as part of the first 10 year Inservice Service Inspection (ISI) program. One of the requirements in the safety evaluation performed by the Office of the Nuclear Reactor Regulation (NRR) in April 1989 is that single-wall radiography (RT) should be performed in the event that any reactor coolant pumps (RCPs) are completely disassembled for maintenance, repair, or examination. During the current outage (1R10), the "D" pump was disassembled for repair due to unforeseen events; consequently, adequate plans had not been made to perform RT on this pump casing.

Because of this, ANO-1 has decided to use the alternate examination requirements for cast austenitic pump casings per ASME Code Case N-481 which was approved on March 5, 1990. Part of the requirements of this Code Case includes an evaluation to demonstrate the safety and serviceability of the pump casing. The purpose of this document is to review prior inspection results performed in 1986 and 1988 and associated fracture mechanics evaluations to determine if the safety and serviceability requirements of this Code Case, as it relates to the pump casings, will be satisfied.

2.0 1986 INSPECTION RESULTS

During the 1986 refueling outage, a volumetric RT examination was performed on the "A" RCP welds as required by the first 10 year ISI program. This program was based on the requirements of the 1974 E[illegible] through Summer 1975 Addenda of Section XI of the ASME Code. The RT exami[illegible] indicated the presence of a flaw which exceeded that allowable indication standards of IWB-3500. Since the acceptance criteria (IWB-3518) did not exist in the 1974 Edition of Section XI, the 1980 Edition was utilized. The indication is best described as a series of slag inclusions having an effective length (per ASME Section XI criteria) of 5.66 inches. The indication is located in the vertical weld which ties together the upper and lower welds of the pump casing (Figure 1-1). Radiographic parallax techniques indicate that the top of the flaw is 1.5 inches below the outside surface of the weld. The weld is approximately 2.6 inches thick is this area. Application of special UT techniques indicated that the flaw indication does not extend to the internal diameter of the pump casing. Thus, the maximum through-wall dimension of the flaw indication is less than 1.1 inches.

To determine if any flaw existed at this location prior to service, the original construction radiographs were reviewed. The review found five small inclusions that are part of the identified flaw indication of 5.66 inches in length. These inclusions on the original radiograph were determined to be acceptable per the Code during the preservice examinations. Because of the quality of the preservice radiograph in the area of the indication, equipment was brought on-site to perform computer enhancement of the area of the flaw. This process allowed the characterization of the flaw on the original film more clearly and allowed ANO-1 to determine conclusively that the current flaw indication and the original flaw were identical.

The original construction radiographs for the remaining three pumps were then reviewed, searching for any preservice flaw indications or weak areas in film density. Identified areas were then computer enhanced in an attempt to identify any unacceptable flaws that were previously unidentified. Portions of approximately 20% of all preservice radiographs were computer enhanced. From this review, "C" and "D" pumps were determined to have no unacceptable preservice flaw indications; however, the computer enhancement of the "B" pump did indicate an unacceptable flaw indication in the same general weld area as the "A" pump.

The flaw indication on the "B" pump, through the computer enhancement process, was shown as 1.5 inches in length. The original construction radiograph of this area shows a flaw of 0.625 inches in length which was acceptable per Code requirements at that time. The wall thickness in the area of the flaw indication is 3.1 inches. UT was performed in an attempt to better characterize the flaw indication. Due to the material of the pump casing (coarse-grained, statically-cast stainless) and the small size of the indication, UT was not able to specifically characterize the flaw. However, from these examinations, it was determined that the flaw size was no larger than 1.5 inches long by 1.5 inches deep.

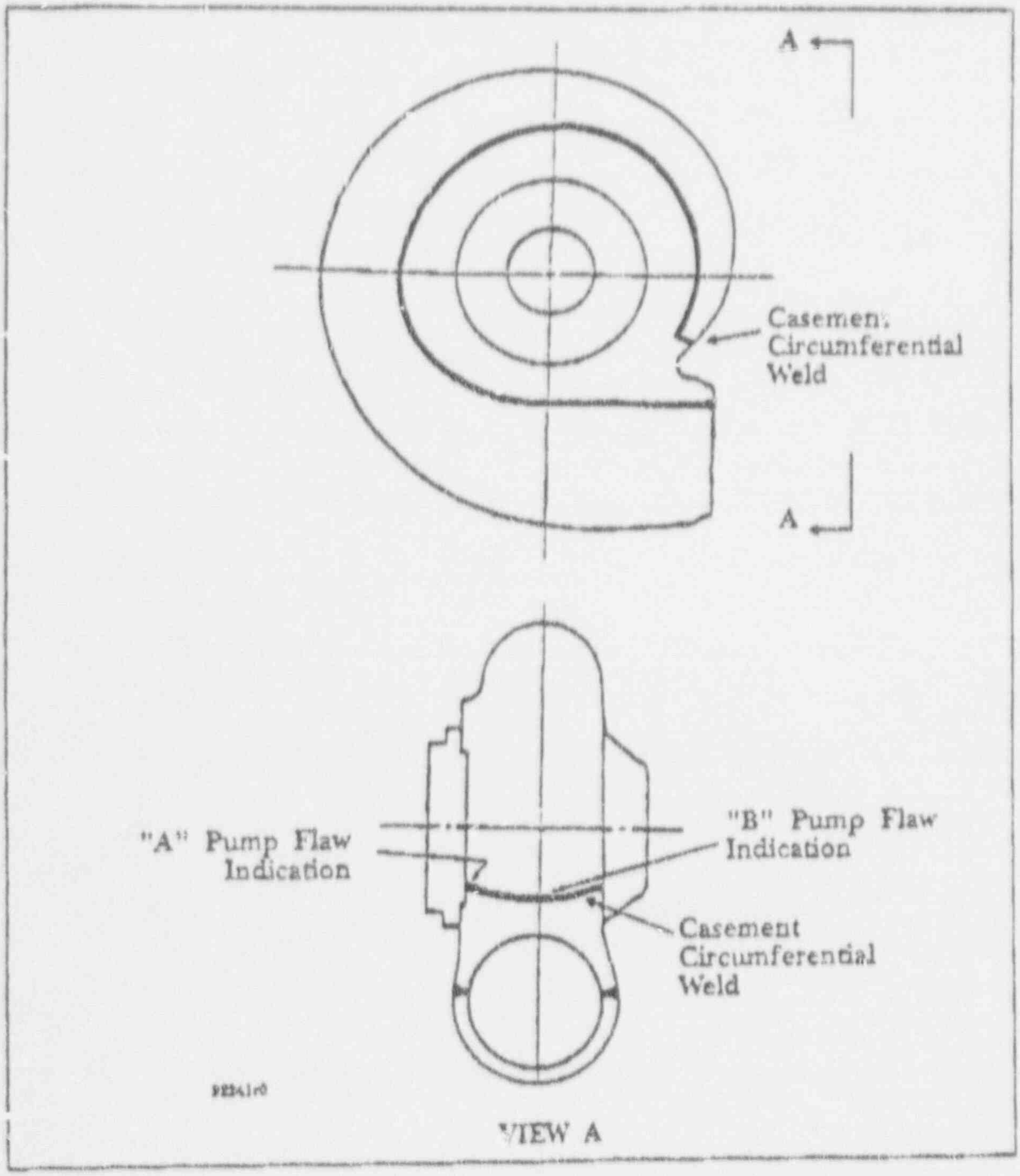


Figure 1-1. Schematic Drawing of Weld Flaw in Arkansas Nuclear One Reactor Coolant Pump, Unit 1

3.0 1986 FRACTURE MECHANICS EVALUATIONS

Because the identified indications in the "A" and "B" pump casings exceeded the ASME Section XI, IWB-3500 acceptance standards, fracture mechanics evaluations were performed in 1986 in accordance with IWB-3122.4 (1980 Edition). Conservative flaw sizes were assumed for both pump casings. For the "A" pump casing, a continuous surface flaw of 5.66 inches in length and a conservative depth of 1.1 inches to the internal diameter (ID) of the casing was assumed (UT and visual examinations performed indicated that the flaw did not extend through the ID, i.e., a surface flaw). The flat plate with a semi-elliptical surface flaw model in Appendix A of ASME Section XI was used to determine the stress intensity factor.

For the "B" pump casing, two conservative fracture mechanics models were used. The first model was a flaw having a length of 1.5 inches with a conservative through-wall depth in a center crack panel. The second model assumed a continuous semi-elliptical flaw of length 4.6 inches and 2.3 inches deep (75% through-wall) in a flat plate as in Appendix A of ASME Section XI.

Stresses at the flaw location were obtained from a more recent stress report of an identical pump casing for both normal operating and emergency/faulted conditions. These stresses, together with the above fracture mechanics models, were used to calculate the applied stress intensity factors. The applied stress intensity factors were compared with the fracture toughness of the pump casing material with consideration given to thermal aging and found to have safety factors far greater than the ASME Section XI Code allowable values. A J_{IC} value of 1171 in-lb/in^2 (which is equivalent to a K_{IC} value of about 179 ksi in$^{0.5}$) was used in the evaluation. This fracture toughness value was obtained from data of CF8A weldments with consideration given to thermal aging. For the "A" pump casing, safety factors of 5.5 and 4.8 were obtained for normal operating and emergency/faulted conditions respectively. The ASME Section XI Code safety factor for the normal operating condition is 3.16 and for the emergency/faulted condition is 1.414. For the "B" pump casing, safety factors of 7.2 and 6.6 were obtained for normal operating and emergency/faulted conditions, respectively.

Crack growth evaluations were performed using the ASME Section XI crack growth law for austenitic stainless steel in a water environment. The crack growth law was subsequently incorporated into the Code as Appendix C, 1989 Edition of Section XI. The evaluation indicated that for both pump casings, crack growth is almost insignificant considering 240 heatup and cooldown cycles (for 40-year plant life). The safety of the "A" and "B" pumps for continued operation with the observed indications was, therefore, demonstrated for the entire 40-year plant life.

4.0 1988 INSPECTION RESULTS

Since the 1986 inspection, ANO-1 with the assistance of Babcock and Wilcox (B&W), developed an ultrasonic testing (UT) procedure for the examination of the pump casing welds from the outside surface. The UT examination of the orginal flaw indications in the "A" and "B" pump casings was performed during the 1988 refueling outage utilizing the B&W automated ultrasonic data acquisition and imaging system (ACCUSONEX).

A robot was used to perform the ACCUSONEX automated scanning and to provide coordinate data for transducer location. Threshold values were utilized that just exceeded the average noise level from the pump casing material for both straight beam and angle beam measurements. Minimum detectable indications of approximately 1/8 inch through-wall and 3/4 inch in length could be detected even in areas of maximum wall thickness. The fact that the previous slag indications could not be detected with UT most likely indicates that they are very small, occupy very little volume, and are below the limit of detection for present-day UT technology.

Also, during the 1988 refueling outage, a complete volumetric examination of the "B" RCP casing welds was performed. The areas of the casing welds examined by double wall RT showed no rejectable indications. Sections of the upper and lower scroll welds near the discharge end of the pump, which could not be successfully radiographed to meet ASME Code film density requirements, along with the remainder of the vertical weld, were examined by UT.

In the lower scroll weld, several indications were detected (using ACCUSONEX) in an area bounded by a rectangle with a length of 4.1 inches and a through-wall dimension of 1.8 inches at a depth of 0.9 inches below the outer weld surface in a region where the weld is 4.75 inches thick. These indications were considered to be slag inclusions located approximately 0.5 inches to 0.75 inches from the weld centerline. The upper scroll weld could not be examined with ACCUSONEX due to insufficient access for the robot; however, a manual scan was performed which identified three indications. The composite size was conservatively determined to be no larger than a 4.5 inch long by 1.25 inch through-wall dimension rectangle at a depth of 1.35 inches from the outside surface. The weld is also 4.75 inches thick in this region. This indication is located approximately on the weld centerline to 0.6 inches from the centerline. It is also considered to consist of slag inclusions resulting from the original construction welding process and not a service induced condition.

Table IWB-3518-2 shows that the maximum allowable dimensions for an indication found by UT are 1.8 inches for the length and 0.30 inches for one-half through-wall dimension. Figures 4-1 through 4-6 show the locations of the lower and upper scroll weld flaw indications found by the UT examinations. The "B" RCP factory radiographs for these areas and the low density radiographs of these areas taken during this outage were computer enhanced. The analysis of these enhanced radiographs showed no rejectable indications in the welds. It was thus concluded that these indications are small preservice slag indications.

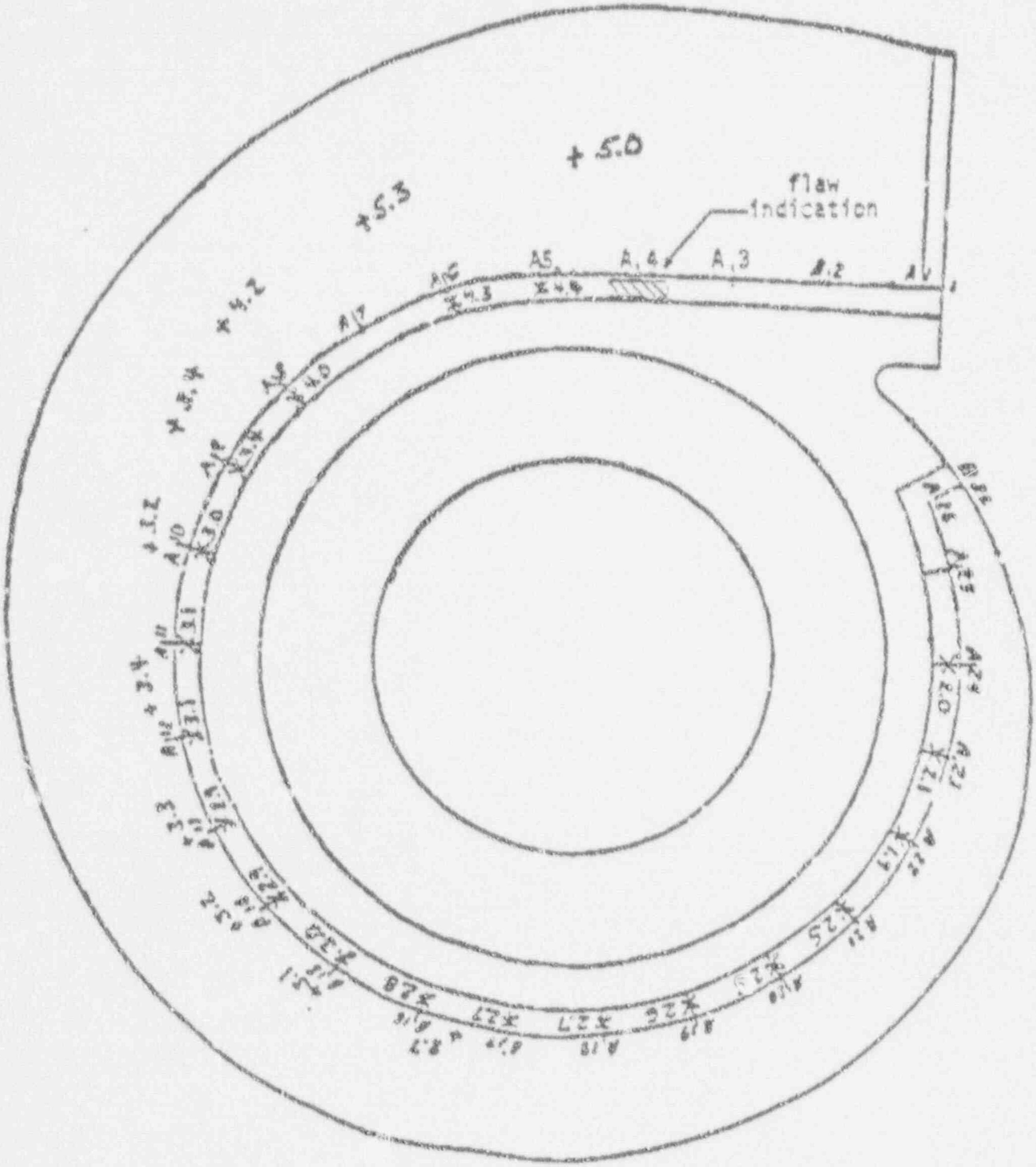
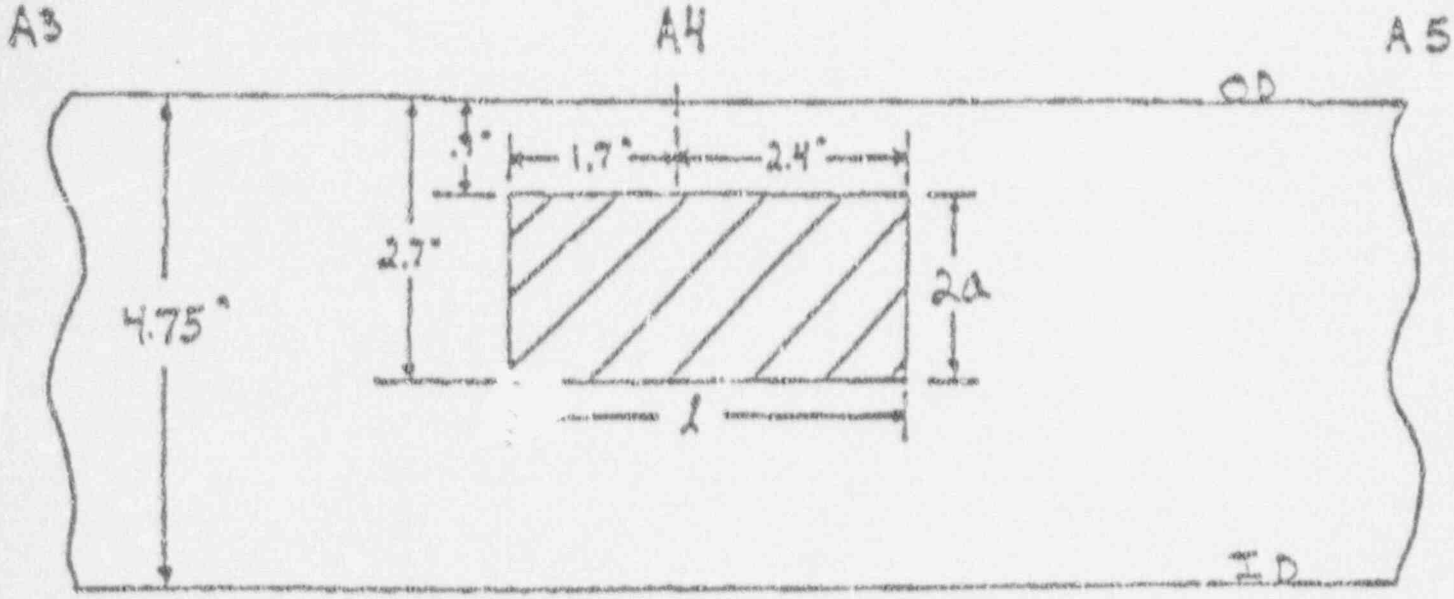


Figure 4-1. Byron-Jackson Reactor Coolant Pump Weld and Base Material Thickness Lower Scroll Weld Flaw Indications ANO-1 "B" RCP 1988 UT Exam



l = 4.1"
2a = 1.8" (a = 0.90")
s = 0.90"

Figure 4-2. ANO-1 1988 UT Exam of "B" RCP Lower Scroll Weld Indication Section View

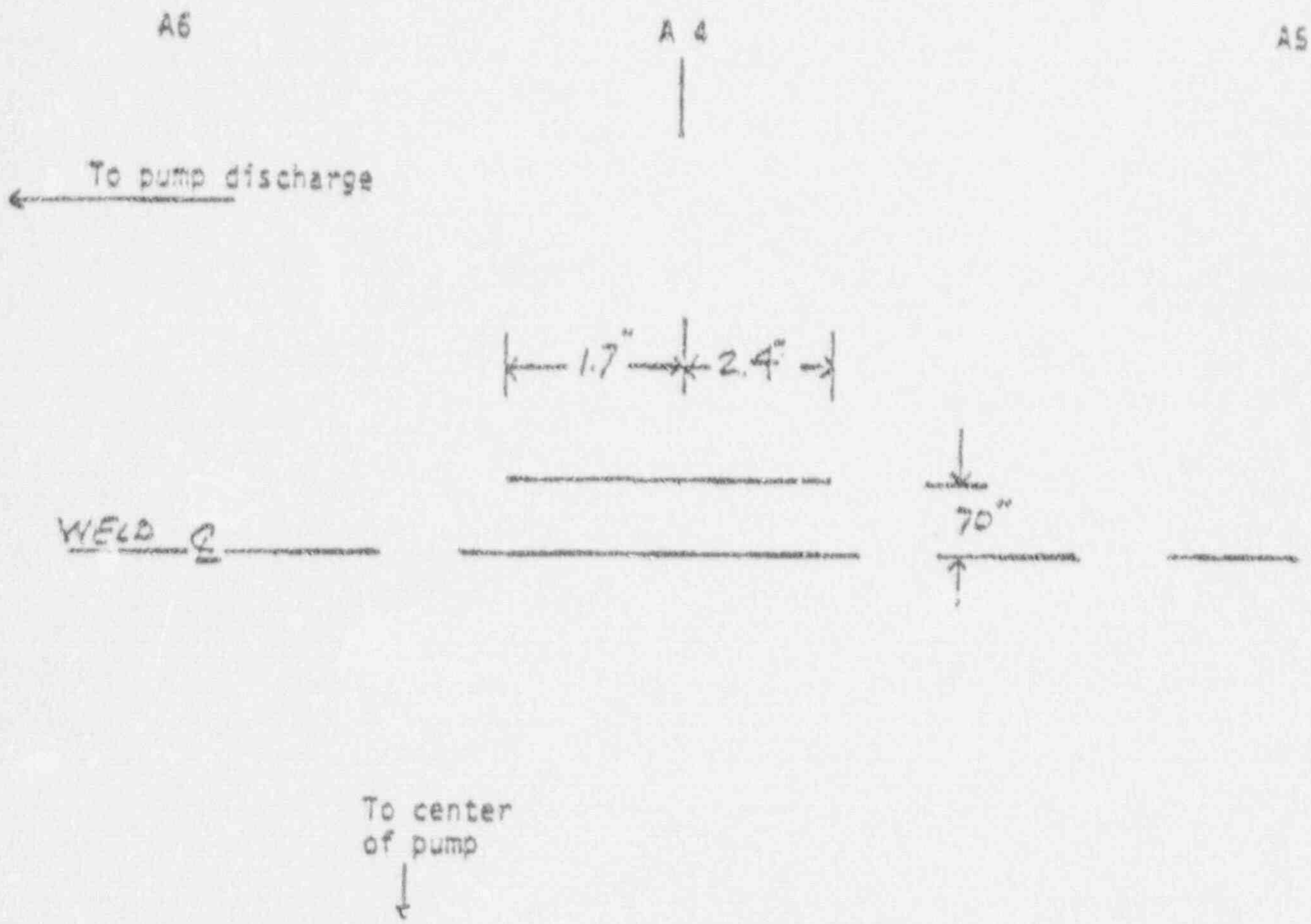


Figure 4-3. ANO-1 1988 UT Exam of "B" RCP Lower Scroll Weld Indication Plan View

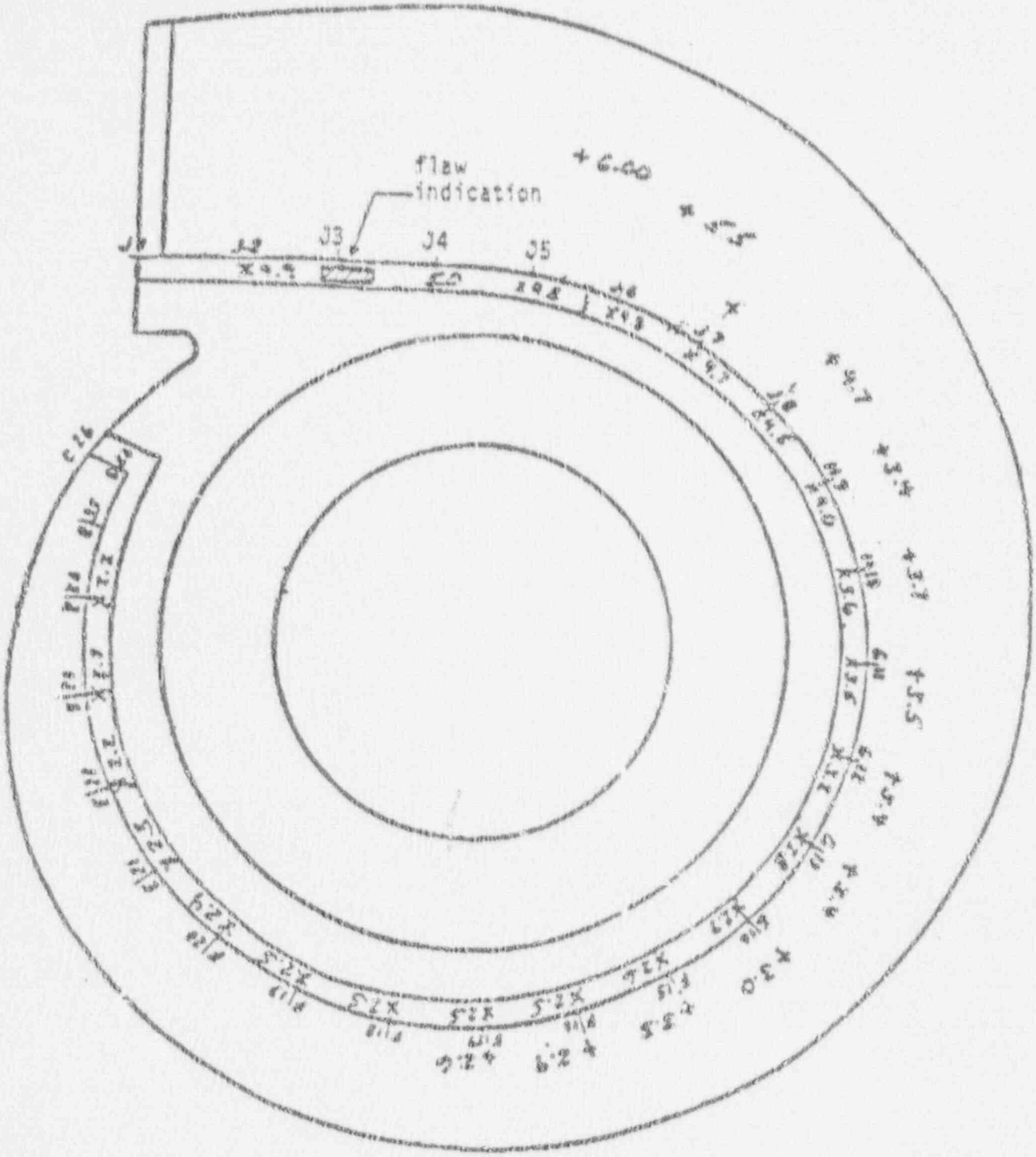
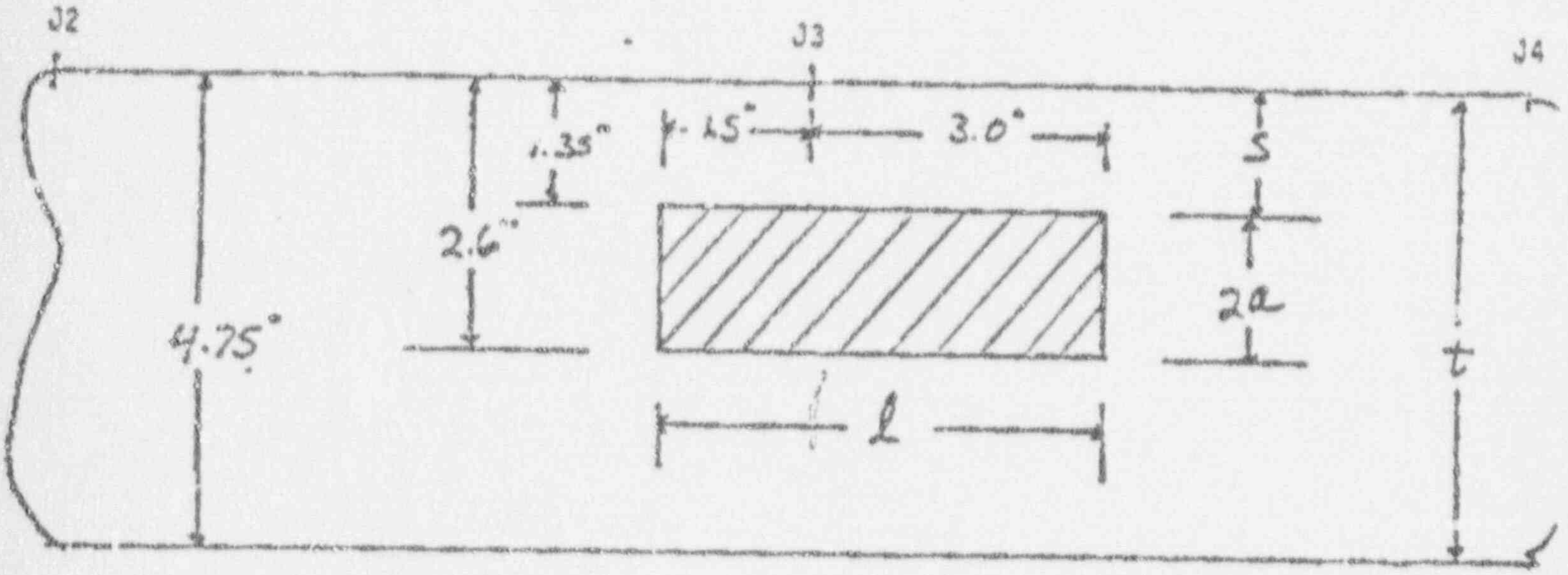


Figure 4-4 Byron-Jackson Reactor Coolant Pump Weld and Base Material Thickness Upper Scroll Weld Flaw Indication ANO-1 "B" RCP 1988 UT Exam



l = 4.5"
2a = 1.25" (a = 0.62")
s = 1.35"

Figure 4-5. ANO-1 1988 UT Exam of "B" RCP Upper Scroll Weld Indication Section View

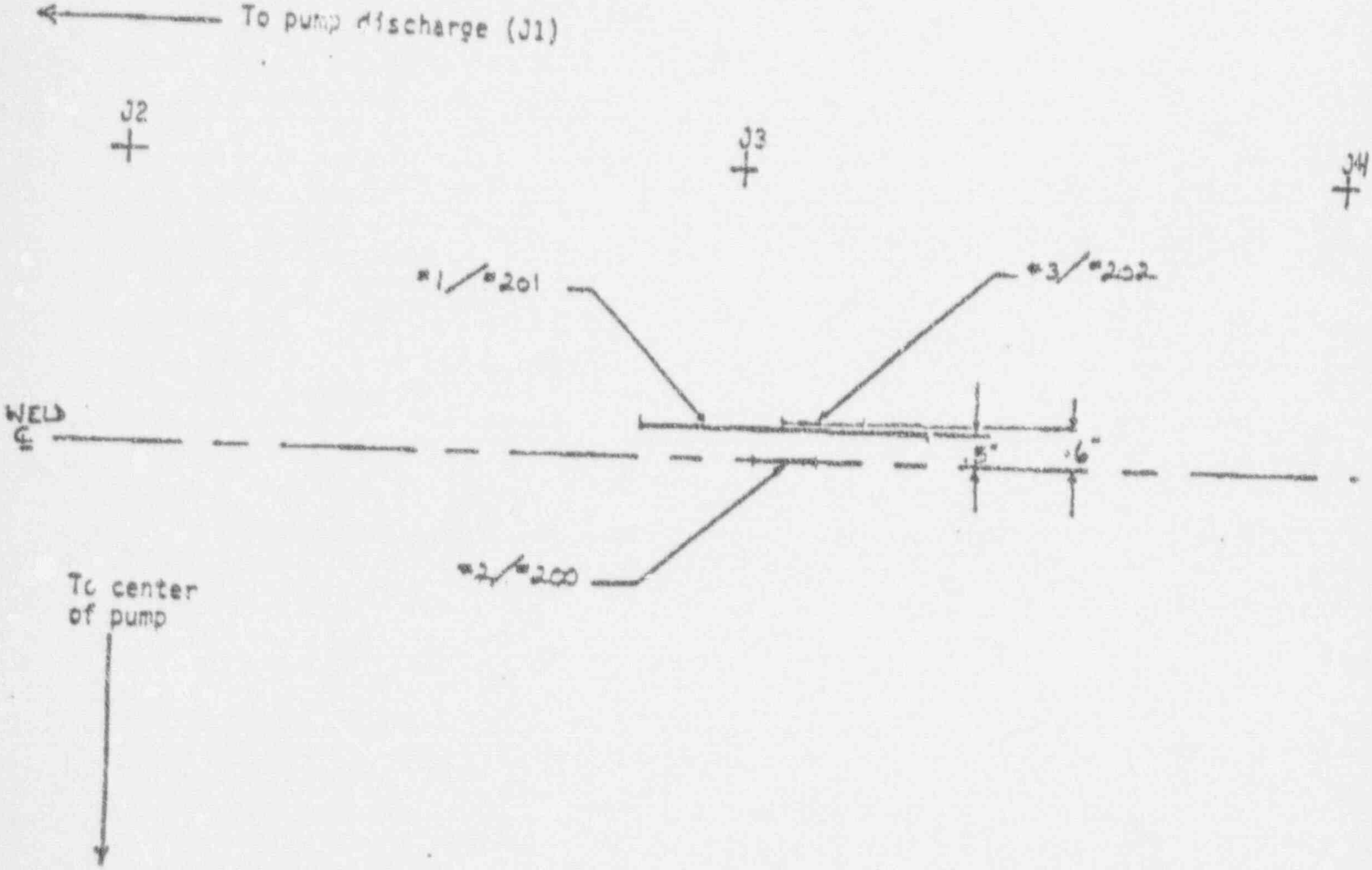


Figure 4-6. ANO-1 1988 UT Exam of "B" RCP Upper Scroll Weld Indication Plan View

5.0 1988 FRACTURE MECHANICS EVALUATIONS

The fracture mechanics analysis of the flaws identified during the 1988 outage was very similar to that performed in 1986. The linear elastic fracture mechanics approach outlined in ASME Code Section XI, Appendix A was used. The flaws in the upper and lower scroll welds of the "B" pump casing were treated as subsurface flaws using conservative dimensions shown in Figures 4-2 and 4-5. A toughness value of J_{IC} = 1171 in-lb/in^2, the same as used in 1986, was utilized in the evaluation. Stresses used in the evaluation were also obtained from the same source as the 1986 evaluation, with consideration given to both normal operating and emergency/faulted conditions. Because these flaws are subsurface, the effect of welding residual stresses on crack growth was judged to be minimal.

The safety factors obtained from these evaluations are 4.3 for normal operating and 3.2 for emergency/faulted conditions. These factors exceed those required by ASME Section XI, which are, 3.16 and 1.41 for normal operating and emergency/faulted conditions, respectively. Crack growth was also found to be less than 10% of the original crack size, considering the 40-year plant life.

6.0 ASME CODE CASE N-481 EVALUATION

A seven-step evaluation procedure is outlined in Code Case N-481 in order to demonstrate the safety and serviceability of the pump casing. In reviewing this procedure, it is recognized that except for a few salient points, most of the requirements have been addressed in the 1936 and 1988 fracture mechanics evaluations discussed in the previous sections. The seven items in this Code Case, as they relate to the ANO-1 pumps, are briefly discussed below.

(1) Evaluate Material Properties, Including Fracture Toughness

The material property that is of significance in this evaluation is the fracture toughness of the castings. In the previous fracture mechanics evaluation, a value of J_{IC} = 1171 in-lb/in^2 was used. This value was derived from the Grade CF8A weldment which was considered to be equivalent to CF8M weldment. In the 1989 NRR safety evaluation report, it was suggested that a value of J_{IC} of 650 in-lb/in^2 for submerged arc welding and shielded metal arc welding contained in EPRI report NP-4690-SR [1] should be used, unless technical justification is provided for a higher value. Since the publication of this EPRI work, several additional studies have been performed by EPRI[2] and Argonne National Laboratories [3], among others, to determine lower bound toughness values for cast austenitic stainless weldments. Data from these more recent studies suggest that J_{IC} values (following thermal aging) are dependent on the chemical composition of the casting. Hence, in this study, the certified material test reports of the pump casings will be reviewed to determine if higher values of J_{IC} can be justified. Even if a J_{IC} value of 650 in-lb/in^2 is used in the 1986 and 1988 fracture mechanics evaluations, safety margins greater than the ASME Code allowables, would still be demonstrated.

The use of linear elastic fracture mechanics (LEFM), with K_{IC}, for cast austenitic stainless steel castings is conservative for the applied stresses in this study. More recent studies [2,3] have shown that because of the ductile nature of these materials, the toughness can be described in terms of the J-R resistance curve. The use of this curve to describe the toughness, coupled with an elastic-plastic fracture mechanics (EPFM) analysis using the J-Integral/Tearing Modulus analysis, would show even more substantial safety margins.

(2) Perform a Stress Analysis of the Pump Casing

A stress report of the ANO-1 pump casings was performed in 1973 by Byron Jackson. However, in the 1986 and 1988 evaluations, a more current stress report for the Consumers Power Company's Midland plant, which has pump casings identical to the ANO-1 pump casings, was used. This stress report contains more detailed stress distributions for fracture mechanics evaluations. This same stress report will be used in the Code Case evaluation.

In addition to the applied stresses, weld residual stresses will be considered in this evaluation. A generic fracture mechanics evaluation [3] performed on a cast stainless steel pump with consideration of weld residual stresses indicated that the conclusions of the 1986 and 1988 fracture mechanics evaluations would not have changed.

(3) Review Operating History of the Pump

The inspections performed in 1986 and 1988 indicated that none of the flaws identified were service induced and that none of the indications had shown any crack growth due to plant operations. None of the pumps have been out of operation due to service-induced flaws. The pumps have also not undergone any unusual transients through their operating history. No other unexpected events due to operation, other than those considered in the 1986 and 1988 evaluations, need to be addressed.

(4) Selection of Locations for Postulating Flaws

Areas where indications have previously been found are natural locations for postulating flaws. These locations have previously been evaluated in 1986 and 1988 and found acceptable with large safety margins. These locations will be selected again and evaluated using revised toughness values based on actual properties of the pump casings. In addition, other high stress locations where flaws have not been identified will be selected for evaluation.

(5) Postulating One-Quarter Thickness Flaw With Length Six Times Its Depth

This flaw will be postulated at each of the selected locations. In the 1986 evaluation of the "B" pump casing, a flaw with a depth three times the depth of this postulated flaw was considered and found to be acceptable with a large safety factor. Even considering a lower bound toughness of 650 in-lb/in^2, this very conservative flaw would still be acceptable by the Code.

(6) Establish the Stability of the Selected Flaw Under Governing Stress Condition

The only potential crack growth mechanism is fatigue crack growth due to operating conditions. In previous evaluations, fatigue crack growth was considered assuming transients for the 40-year plant life. Crack growth was found to be insignificantly small, even with the three-quarter-thickness flaw. It is, therefore, expected that crack growth of the one-quarter-thickness flaw will also be insignificant.

(7) **Consider Thermal Aging Embrittlement and Any Other Processes that May Degrade the Properties of the Pump Casing During Service**

The effect of long-term aging (thermal embrittlement) is to reduce the toughness of cast austenitic stainless steel castings. The toughness reaches a saturation value after exposure to long-term thermal aging. The value of 650 in-lb/in^2 suggested by the NRR represents a lower bound toughness, considering long-term aging. Actual material properties and exposure time of the ANO-1 pump casing will be used, if necessary, to determine a more appropriate toughness value. Consideration will also be given to performing the evaluation using J-R resistance curves , accounting for thermal aging, and utilizing the EPFM methodology.

7.0 CONCLUSION

This scoping evaluation has shown that based on previous successful fracture mechanics evaluations performed on the ANO-1 "A" and "B" pump casings, there is sufficient basis to believe that the pump casings will meet the safety and serviceability requirements of ASME Code Cas N-481. These previous evaluations were based on conservative linear elastic fracture mechanics principles. The use of specific material toughness properties, based on the latest data, combined with the most appropriate fracture mechanics methods, is expected to verify acceptable safety margins. This conclusion is supported by other generic evaluations performed on similar pumps elsewhere.

8.0 REFERENCES

1. EPRI Report NP-4690-SR, "Evaluation of Flaws in Austenitic Steel Piping", July 1986.

2. EPRI Report TR-100034, "Cast Austenitic Stainless Steel Sourcebook", prepared by EPRI and Structural Integrity Associates, October 1991.

3. NUREG/CR-4513, ANL-90/42, "Estimation of Fracture Toughness of Cast Stainless Steels During Thermal Aging in LWR Systems", prepared by O. K. Chopra, June 1991.

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