NUREG/CR-3894
ANL-84-1

NUREG/CR-3894
ANL-84-1

ULTRASONIC AND METALLURGICAL EXAMINATION OF A CRACKED TYPE 304 STAINLESS STEEL BWR PIPE WELDMENT

by

J. Y. Park and D. Kupperman

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS
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Prepared for the Office of Nuclear Regulatory Research
U. S. NUCLEAR REGULATORY COMMISSION
under Interagency Agreement DOE 40-550-75

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NUREG/CR-3894
ANL-84-1

Distribution
Code: R5

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Argonne, Illinois 60439

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Materials Science and Technology Division

January 1984

Prepared for the Division of Engineering Technology
Office of Nuclear Regulatory Research
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555
Under Interagency Agreement DOE 40-550-75

NRC FIN No. A2212

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ABSTRACT

An ultrasonic in-service inspection (ISI) indicated that a crack had developed in a 22-inch-diameter Type 304 stainless steel pipe manifold end-cap weldment of the Hatch-2 boiling water reactor. A section of the weldment was sent to Argonne National Laboratory (ANL) for further examination. The ANL effort included ultrasonic examinations, destructive crack-depth measurements, metallography, degree of sensitization (DOS) measurements, and chemical analyses of material. The results showed that the extent of the cracking was significantly less than indicated by the ISI.

NRC FIN No.	FIN Title
A2212	Environmentally Assisted Cracking in Light Water Reactors

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EXECUTIVE SUMMARY

An ultrasonic in-service inspection (ISI) indicated that a crack had developed in a 22-inch-diameter Type 304 stainless steel (SS) pipe manifold end-cap weldment (Weld No. 2B31-1RC-22BM-4) of the Hatch-2 boiling water reactor operated by the Georgia Power Company. Examination of a section of the weldment at Argonne National Laboratory revealed the following:

1. Intergranular cracks with a maximum depth of 0.265 in. were observed in the HAZ of the end cap side of the weldment. The cracks are similar to the IGSCCs observed in the sensitized Type 304 SS components of other BWRs. The cracks were located close to the WFL, but did not propagate more than a half-grain diameter through the weld metal.

2. There was no cracking on the pipe side of the weldment. The reason for cracking only in the end cap side is not clear. However, it is noted that the end cap is constructed of a different heat of material than that of the pipe, and that the end cap has a higher DOS and a smaller grain size.

3. The ISI resulted in a significant overcall of the extent of the cracking. This difficulty was probably related to the nature of the geometric reflectors at the weld root. Ultrasonic indications suggest the presence of cracks in the HAZ less than 13 mm from the fusion line.

4. There was poor correlation between the measured IGSCC depth and that estimated by commonly used probe motion techniques.

5. Crack-tip echoes were not detectable, and thus time-of-flight (satellite pulse) techniques for sizing of cracks could not be used.

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[a]RSR FIN Budget No. A2212; RSR Contact: J. Strosnider.

ULTRASONIC AND METALLURGICAL EXAMINATION OF A CRACKED TYPE 304 STAINLESS STEEL PIPE WELDMENT

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I. INTRODUCTION

An ultrasonic in-service inspection (ISI) indicated that a crack had developed in a 22-inch-diameter Type 304 stainless steel (SS) pipe manifold end-cap weldment (Weld No. 2B31-1RC-22BM-4) of the Hatch-2 boiling water reactor (BWR) operated by the Georgia Power Company. Figure 1 shows a schematic of the BWR and the location of the manifold. At the request of the U.S. Nuclear Regulatory Commission (NRC), a section of the weldment (Fig. 2) was sent to Argonne National Laboratory (ANL) for further examination. The ANL effort included ultrasonic examinations, destructive crack-depth measurements, metallography, degree of sensitization (DOS) measurements, and chemical analyses of material.

II. IN-SERVICE INSPECTION

The results of the ultrasonic ISI, which was performed according to NRC I&E Bulletin 83-02, were provided to ANL by the Georgia Power Company and are reproduced in Fig. 3. The results of the ISI indicated that circumferential cracks had developed on both sides of the weldment to a depth of 30% of the pipe wall thickness. The location of the ultrasonic test (UT) indications, however, does not agree with the location of the actual crack, as discussed in the next section. The crack depth estimated from the UT indications is in general agreement with the actual value. However, data will be presented in the following sections to show that this agreement is probably a coincidence.

III. DESTRUCTIVE EXAMINATION

The pipe manifold end-cap weldment was decontaminated with inhibited solutions of potassium permanganate/potassium hydroxide and phosphoric acid (Turco Decon 4502 and Turco WO No. 2) in order to remove corrosion film and reduce radioactivity. Magnaflux dye penetrant was then applied to the inner surface of the weldment. Extensive penetration of the dye was observed at the weld fusion line (WFL) on both sides of the weldment (dark lines in Fig. 2). However, destructive examination of the weldment section (discussed below) showed that the dye penetrated mostly through geometric discontinuities and undercuts at the WFL.

Postweld grinding marks were visible on the inner surface of the weld crown and at the heat-affected zone (HAZ), as shown in Fig. 4. Postweld grinding of the HAZ is known to increase susceptibility to cracking, since it introduces heavy cold work and unfavorable residual stresses.[1]

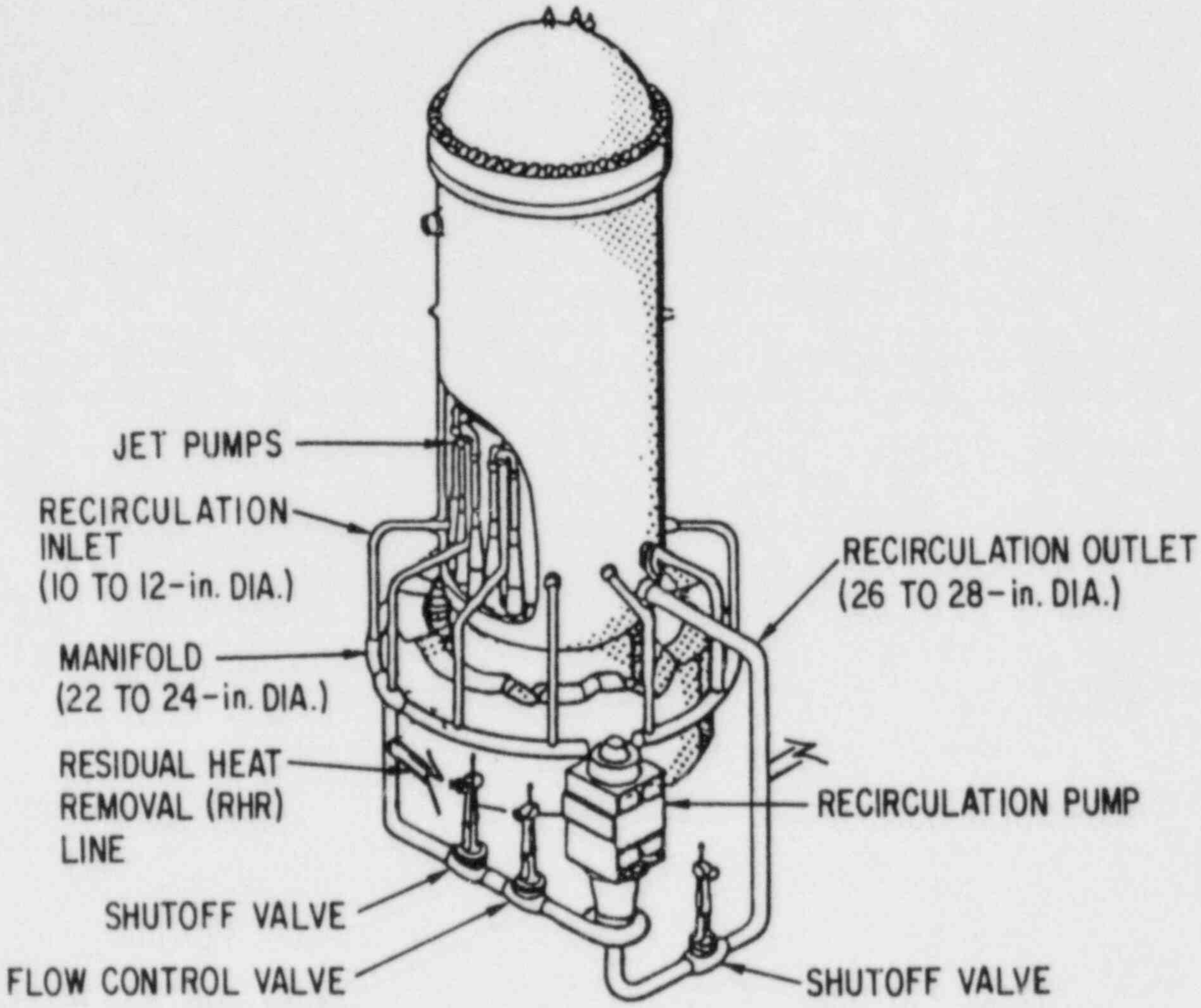

Fig. 1. Schematic of a BWR.

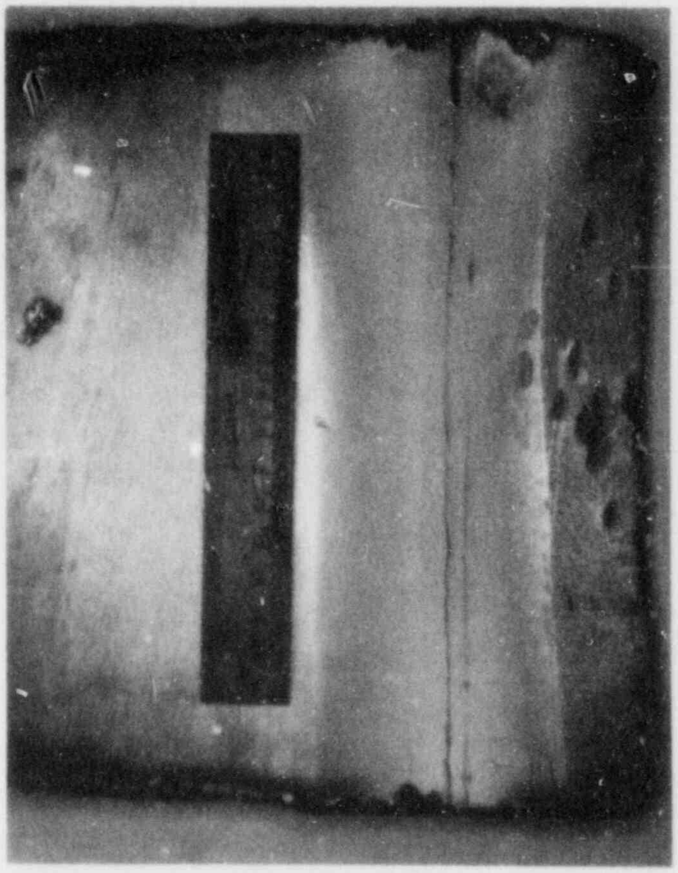

Fig. 2. Manifold End Cap of Hatch-2 after Dye Penetration Check of Inner Surface.

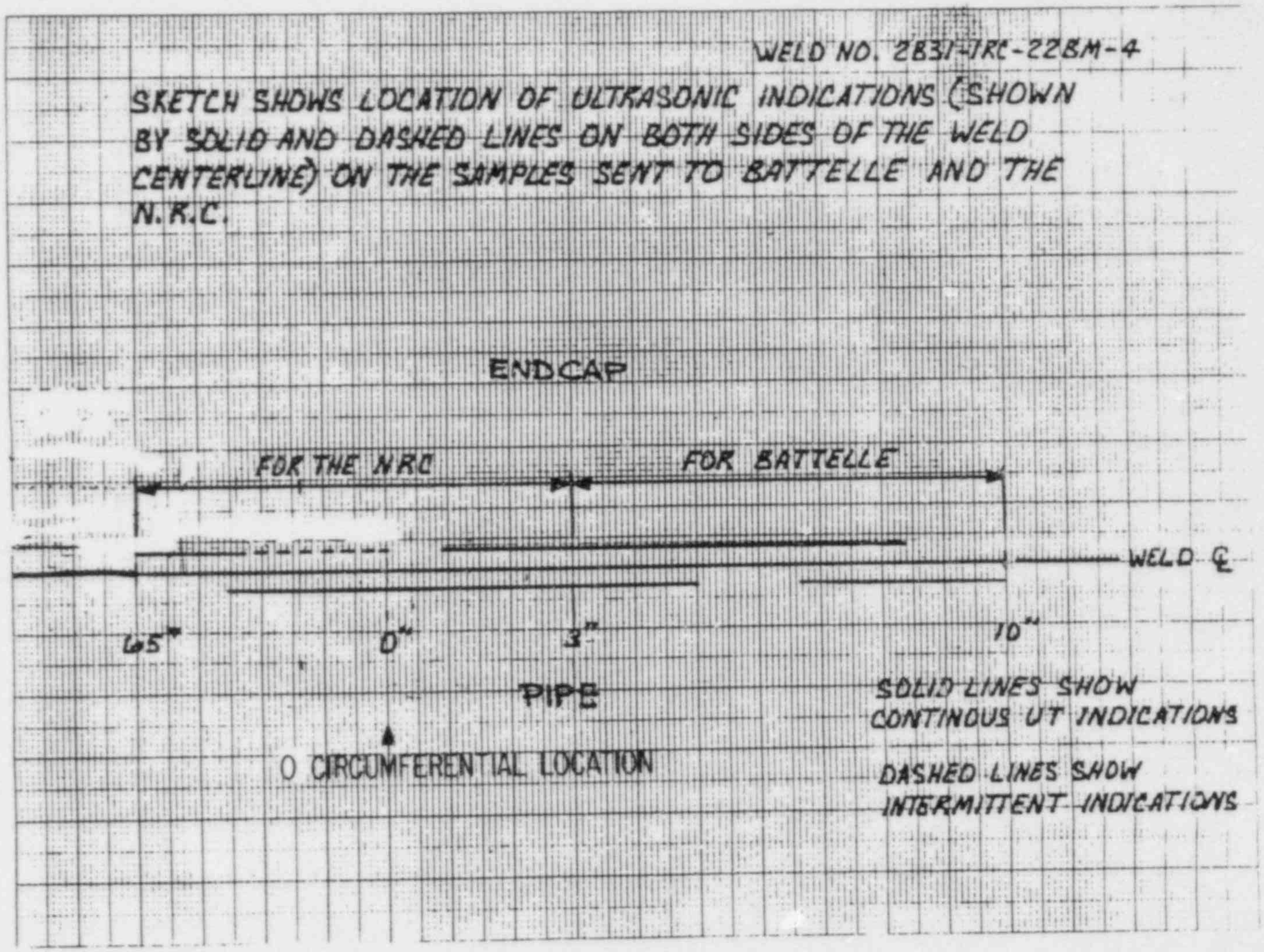

Fig. 3. Results of Ultrasonic In-Service Inspection of Hatch-2 End Cap.

Fig. 4. Inner Surface of End Cap Weld Crown and HAZ Showing Postweld Grinding Marks.

The weldment was sliced into 12 pieces (0.25 to 1 in. in width) by sawcutting in the axial direction (Fig. 5). Cross sections of the weldment were examined for cracking at metallographically polished faces of the slices. Cracks were observed in the end-cap side of the weldment sections between circumferential locations 4 to 7 inches from the reference mark 0* (Sections 1 through 4 in Fig. 5). There was no cracking on the pipe side of the weldment. The cracks initiated at the inner surface close to the WFL in the HAZ. The cracks are intergranular but they have not propagated into the weld metal more than a quarter of a grain diameter. They appear to be typical of intergranular stress corrosion cracks (IGSCCs) which have been observed frequently in sensitized Type 304 SS under stress in BWR or oxygenated-water environments (see Fig. 6). The depth of the crack in each slice of the weldment was optically measured at 50X magnification and plotted in Fig. 7. The maximum depth was 0.265 in. (23% of the nominal pipe wall thickness of 1.125 in.) at the circumferential location -4.7 in. (Fig. 7). This value is consistent with the ISI estimate that the maximum crack depth was 30% of the wall thickness, but the results discussed in the next section of this report suggest that the agreement is fortuitous. Undercuts at the WFL of the weld on the end cap side were observed at the inner surface, as shown in Fig. 8.

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*A "0" mark was permanently scribed on the outside diameter of the pipe as delivered. The location of the 0 mark is indicated in Fig. 3, which shows the ultrasonic ISI results provided by Hatch-2 personnel. Circumferential locations on the pipe are expressed with reference to this 0 mark throughout the manuscript, unless otherwise specified. A positive number indicates the right side and a negative number indicates the left side of the 0 mark in Fig. 3.

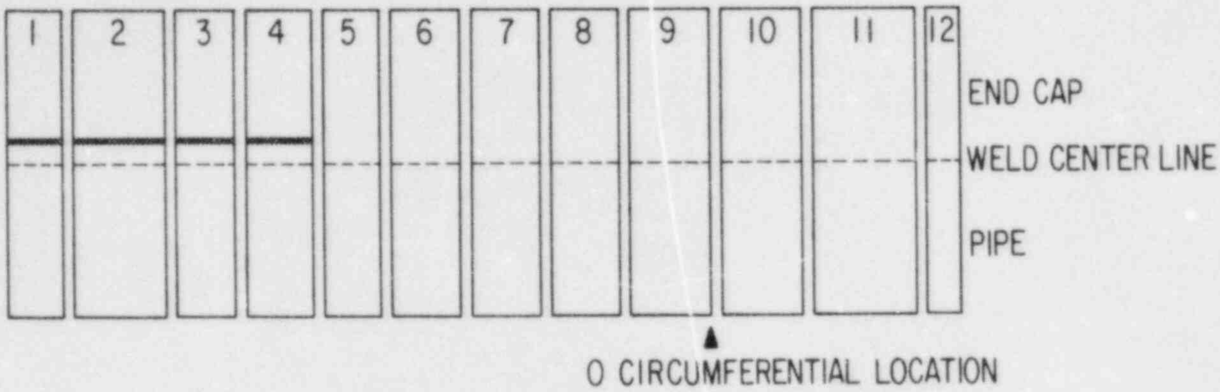


Fig. 5. Hatch-2 End Cap Weldment (No. 2B31-1RC-22BM-4) Sectioned to Examine Cracking (Viewed from the OD). The sections containing cracks (sections 1 to 4) are marked with xxxx.

Fig. 6

Intergranular Crack in HAZ of End Cap at -6.25 in. from the Reference 0.

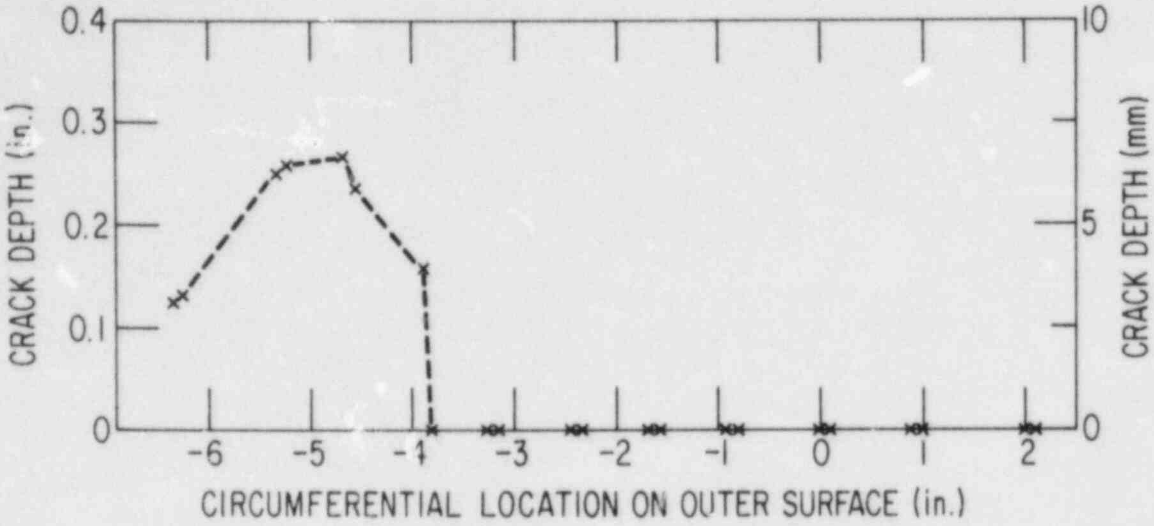


Fig. 7. Crack Depth vs Circumferential Location.

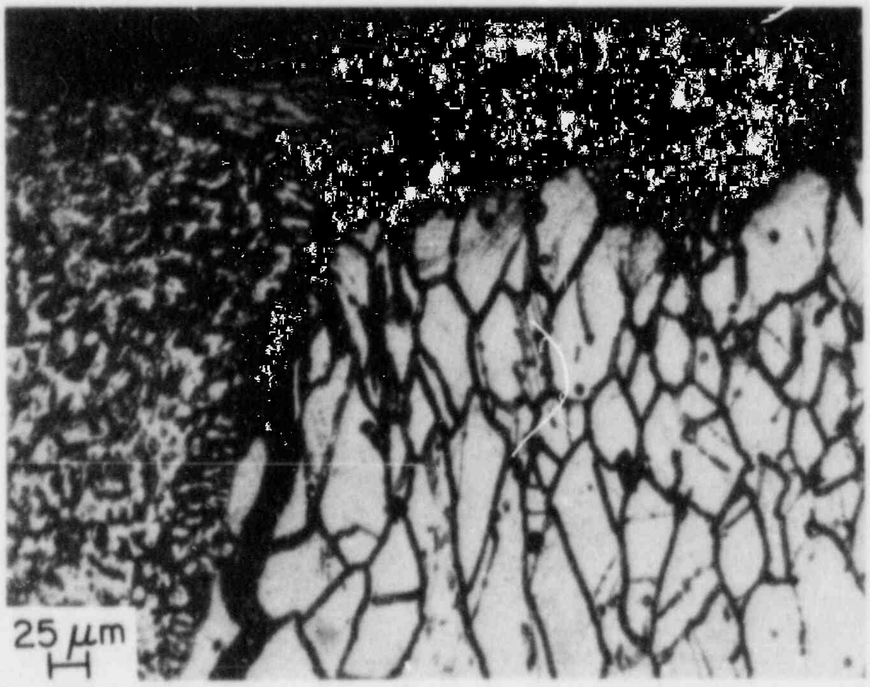


Fig. 8. Undercut at Weld Fusion Line of the End Cap.

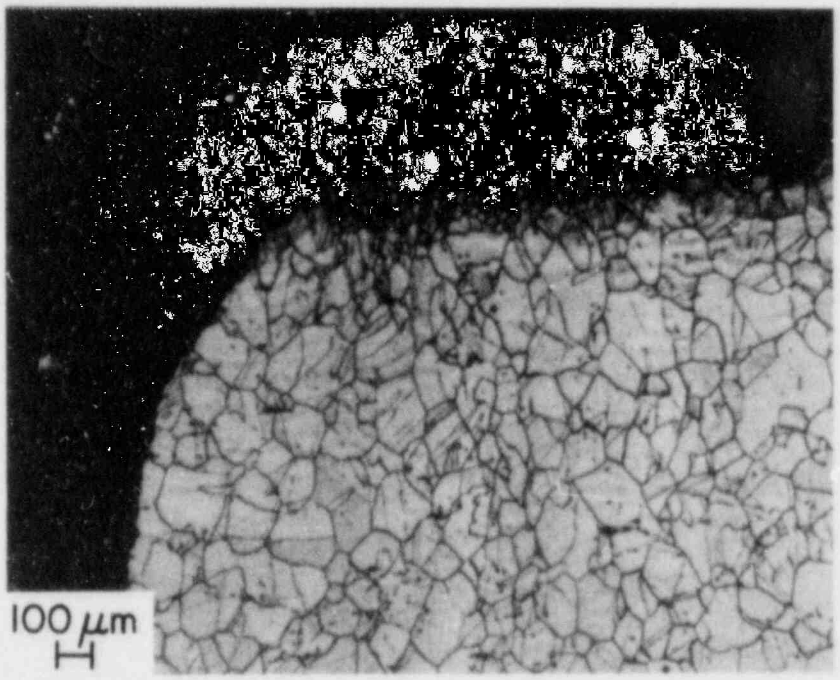
Crevice conditions may have occurred in the undercuts; however, it was not possible to determine accurately from metallographic examination whether the crevice formation would have been severe enough to initiate cracking.

The degree of sensitization (DOS) in the HAZ of the weldment was measured by the ASTM A262-A and -E and the electrochemical potentiokinetic reactivation (EPR) methods.[2] The ASTM A262-A test showed that the DOS is higher on the end cap side of the weldment (ditch structure) than on the pipe side (dual structure), as shown in Figs. 9a and 9b. The ASTM A262-E test also showed that the end cap side is significantly sensitized: intergranular attack was observed at the end cap side about 2.5 mm from WFL to a maximum depth of 0.5 mm (Fig. 10), while no intergranular attack was visible at the pipe side. The EPR measurements were performed at different locations (0.3-2 mm from the WFL) in the HAZ, and the EPR values ranged from 22 to 29 C/cm^2 for the end-cap side and from 37 to 50 C/cm^2 for the pipe side. However, the correlation of the measured EPR values with grain boundary sensitization or intergranular corrosion susceptibility is less satisfactory for this weldment than in many other cases because of the presence of many intragranular precipitates in the base material and the large grain size of the pipe material (ASTM No. 0.3). The electrochemical potentiokinetic activation ratio (EPAR) was also measured.[3] The EPAR value was 5% for the end cap and 1.5% for the pipe. It has been reported that materials with EPAR values of less than 1% possess excellent resistance to intergranular stress corrosion cracking.[3]

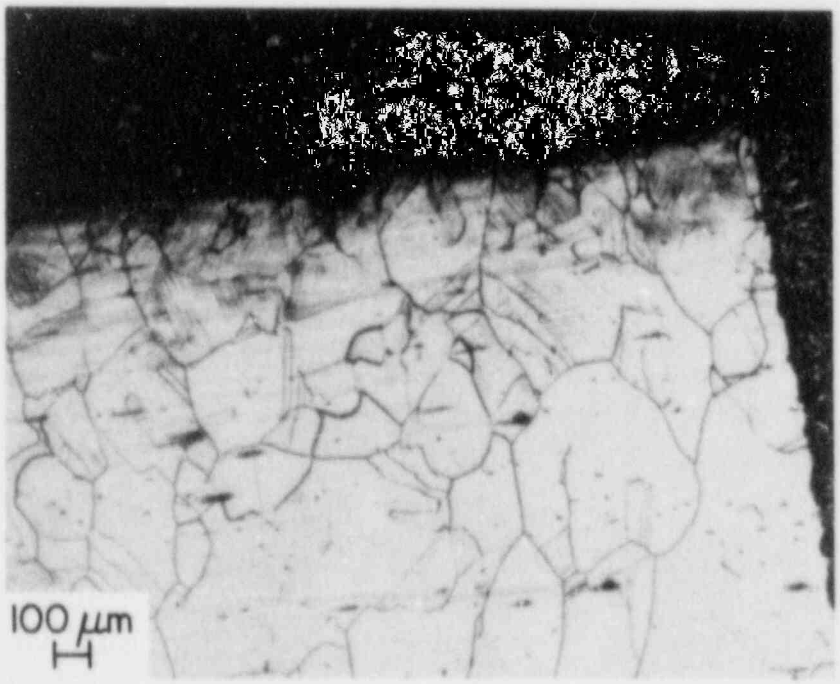
IV. LABORATORY ULTRASONIC EXAMINATION

A laboratory ultrasonic examination was performed before the destructive examination described in the previous section. ANL personnel examined the specimen with a Sonic Mark I pulser-receiver, a KB-Aerotech dual 1.5-MHz, 45° shear-wave probe, and Ultragel couplant. A 32-mm-diam side-drilled hole was used as a reference reflector. Figure 11 shows the ultrasonic echo amplitude data as a function of the circumferential position of the transducer; the indications reported by Hatch are also shown in this figure. The amplitudes of echo signals obtained from both sides of the weld were generally greater than 10% of DAC values, and showed a variation of ~10 dB. The echoes from the cap side had greater amplitudes than those from the pipe side. The ISI suggested that cracks were present on both sides of the weld, but subsequent destructive analysis revealed a crack on the cap side only. The largest echo signal observed at ANL was from this region but it was only a few dB larger than the cap-side signals that were produced by geometrical reflectors. At each of two cap-side probe positions, two separate signals with different transit times were detected. In such a case, the two signals could be interpreted as arising from a crack and from the weld root, respectively. However, destructive analysis revealed that no cracks were present at one of those positions. Both signals at that position were attributable to geometrical reflectors.

Considerable overcalling of cracks is evident in this example. The overcalling appears to be due to the presence of the undercuts on the cap side of the weld and a weld root oriented in such a way that relatively strong signals reflected from the root were detected with the transducer on the pipe side.



(a)



(b)

Fig. 9. Results of ASTM A262-A Etch Test. (a) End cap side; (b) pipe side.

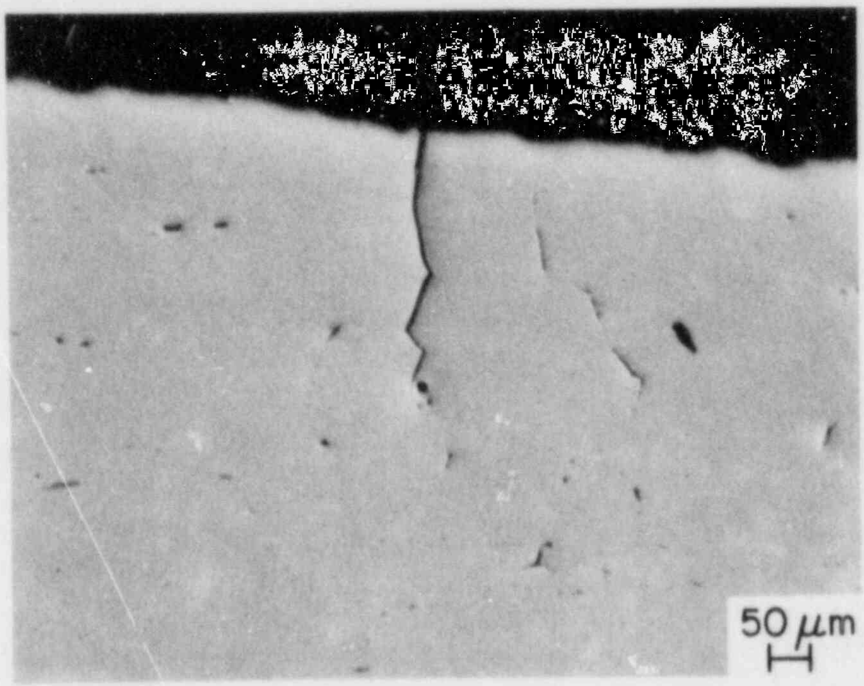


Fig. 10. Intergranular Fissure in HAZ of End Cap Weldment after ASTM A262-E Test.

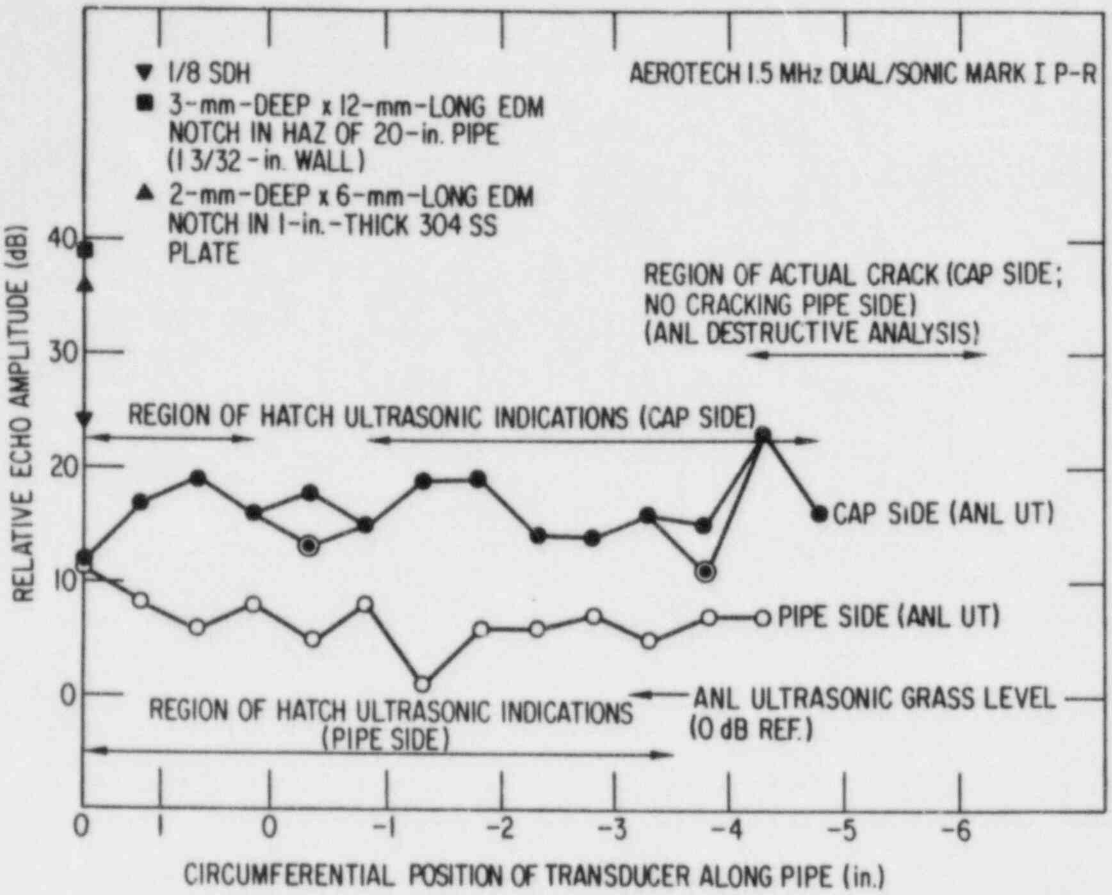


Fig. 11. Ultrasonic Echo Amplitude Data as a Function of Circumferential Position of Transducer. In the two locations indicated by dotted circles, two distinct but very closely spaced echoes were observed simultaneously from the cap side.

It is generally believed that IGSCC depths cannot be accurately estimated from the amplitude of the ultrasonic echo signal. This is because the emplitude is affected by the extreme tightness of the crack, the presence of corrosion products between crack surfaces, branching of the crack, and the irregular crack faces. Figure 12 shows the echo signal amplitude as a function of circumferential position and the crack depths obtained from destructive examination. As expected, there is no correlation between crack depth and echo amplitude. (The irregular cutting of the as-received specimen prevented ultrasonic data from being acquired near the end of the crack.)

Another commonly used method for crack depth sizing is the probe motion (also called dynamic echo or amplitude drop) technique. In this technique, the transducer is moved across the defect and the echo amplitude is obtained as a function of transducer position. The size (depth) of the reflector is related to the distance the transducer moves between the two "drop points" at which the signal is 20 dB (or 6 dB) below its maximum value.

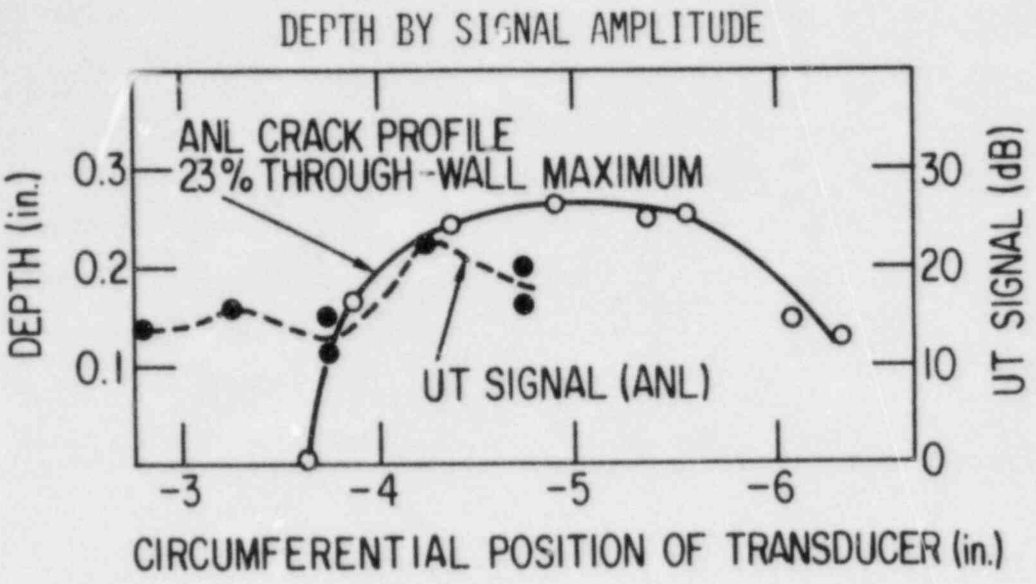


Fig. 12. Comparison of Actual Crack Profile with Echo Signal Amplitude as a Function of Circumferential Position of Transducer.

This technique can provide useful data for reflectors with surfaces normal to the ultrasonic beam, with very rough surfaces, or with irregular geometry. However, in situations where the pipe inner surface was inaccessible or where angle beam waves were used, attempts to measure IGSCC depths have been unsuccessful; shallow crack depths were overestimated and deep ones were underestimated.[4] The ANL data presented in Fig. 13 are consistent with previous experience. Flaw sizes estimated from the 20-dB drop points, obtained with a 0.25-in., 2.25-MHz, 45° shear-wave probe, were independent of actual depth. Furthermore, the same level of response was obtained when a geometrical reflector or the end of the pipe was examined. Similar results were obtained with 6-dB drop points; that is, no correlation was found between the results of the probe motion technique and the actual crack depth in the IGSCC specimen. From the 6-dB drop ultrasonic measurement, the crack depth is estimated to be 28% throughwall. This is close to the Hatch result (30% throughwall). which suggests that they used the 6-dB drop method.

Two other ultrasonic techniques, the time-of-flight and satellite pulse methods, were considered for estimating the crack depth. These methods rely on the assumption that signals from the crack tip will arrive at the transducer sooner than signals from the more distant base (corner) of the crack. With proper calibration procedures, this difference in signal arrival times can be related to crack depth. However, no crack-tip echo signals could be detected from the end-cap weldment, and thus, these techniques could not be applied.

The conclusions from the ultrasonic examination are as follows: (1) Although one region of the end cap contained IGSCCs (as indicated by UT), field inspection teams misidentified geometrical reflectors as cracks where

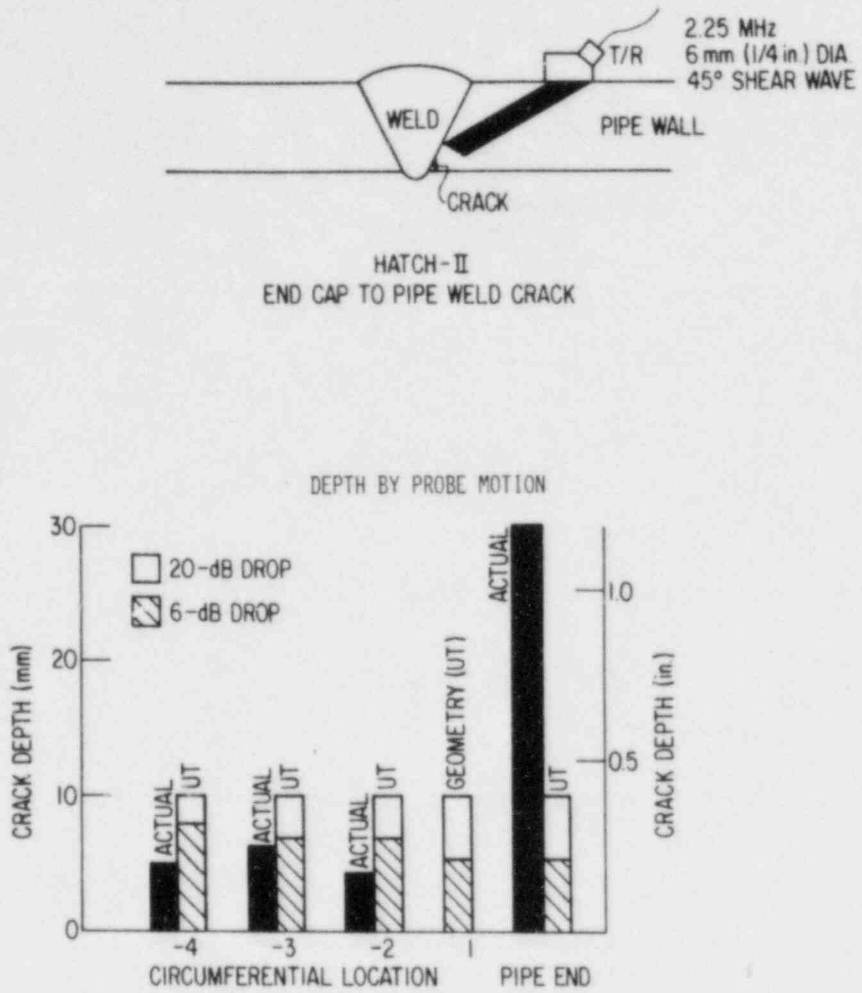


Fig. 13. Application of Probe Motion Method to Sizing of Cracks in Hatch-2 End Cap Specimen. (Top) Schematic showing relative positions of transducer and crack; (bottom) results obtained with 20- and 6-dB drop points, compared with actual crack depth determined by destructive examination.

cracks were not present (overcalling); (2) It was not possible to size the IGSCCs with commonly used probe motion techniques; (3) Crack-tip echoes were not detectable and thus the time-of-flight and satellite pulse techniques could not be used for sizing.

V. MATERIALS ANALYSIS

The chemical composition of the pipe and end cap was analyzed. The bulk composition of the material conforms to the ASTM Standard Specification A312 as shown in Table I. The ASTM grain sizes of the pipe material range from 0.2 to 3 (0.2 to 0.3 for the sections near the inner and outer surfaces, and 3 for the interior of the pipe wall); the end cap contains size 3

Table I. Chemical Composition of Pipe and End Cap Material

	Si	Mn	C	P	S	Ni	Cr	Mo	Cu	B	N	O
Pipe	0.44	1.25	0.05	0.027	0.014	9.44	18.47	0.18	0.10	<0.0005	0.0371	0.0026
End Cap	0.60	1.47	0.05	0.016	0.030	8.35	18.37	0.16	0.22	<0.0005	0.0732	0.0023
ASTM A312	1.00[a]	2.00[a]	0.08[a]	0.045[a]	0.030[a]	8.00 to 12.00	18.00 to 20.00	-	-	-	-	-

[a]Maximum concentration.

grains. The larger grain sizes observed near the WFL are presumably due to grain growth caused by welding heat, whereas the fine grain sizes observed at the inner surface in the HAZ are due to recrystallization.

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1. REPORT NUMBER (Assigned by TIDC, add Vol. No., if any)
NUREG/CR-3894
ANL-84-1

2. TITLE AND SUBTITLE
Ultrasonic and Metallurgical Examination of a Cracked Type 304 Stainless Steel BWR Pipe Weldment

3. LEAVE BLANK

4. DATE REPORT COMPLETED

MONTH	YEAR
January	1984

5. AUTHOR(S)
J. Y. Park and D. Kupperman

6. DATE REPORT ISSUED

MONTH	YEAR
July	1984

7. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

8. PROJECT/TASK/WORK UNIT NUMBER

9. FIN OR GRANT NUMBER
A2212

10. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)
Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D. C. 20555

11a. TYPE OF REPORT
Technical

b. PERIOD COVERED (Inclusive dates)

12. SUPPLEMENTARY NOTES

13. ABSTRACT (200 words or less)

An ultrasonic in-service inspection (ISI) indicated that a crack had developed in a 22-inch-diameter Type 304 stainless steel pipe manifold end-cap weldment of the Hatch-2 boiling water reactor. A section of the weldment was sent to Argonne National Laboratory (ANL) for further examination. The ANL effort included ultrasonic examinations, destructive crack-depth measurements, metallography, degree of sensitization (DOS) measurements, and chemical analyses of material. The results showed that the extent of the cracking was significantly less than indicated by the ISI.

14. DOCUMENT ANALYSIS – a. KEYWORDS/DESCRIPTORS
nondestructive evaluation
pipe cracking

b. IDENTIFIERS/OPEN-ENDED TERMS

15. AVAILABILITY STATEMENT
unlimited

16. SECURITY CLASSIFICATION
(This page)
unclassified
(This report)
unclassified

17. NUMBER OF PAGES

18. PRICE