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FLAW DENSITY EXAMINATIONS OF A CLAD BOILING WATER REACTOR PRESSURE VESSEL SEGMENT*

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INTRODUCTION

Flaw density is the greatest uncertainty involved in probabilistic analyses of reactor pressure vessel failure. As part of the Heavy-Section Steel Technology (HSST) Program, studies have been conducted to determine flaw density in a section of reactor pressure vessel cut from the Hope Creek Unit 2 vessel [nominally 0.7 by 3 m (2 by 10 ft)]. This section (removed from the scrapped vessel that was never in service) was evaluated nondestructively to determine the as-fabricated status. We had four primary objectives: (1) evaluate longitudinal and girth welds for flaws with manual ultrasonics, (2) evaluate the zone under the nominal 6.3-mm (0.25-in.) clad for cracking (again with manual ultrasonics), (3) evaluate the cladding for cracks with a high-sensitivity fluorescent penetrant method, and (4) determine the source of indications detected.

The seam welds were located by grinding and etching procedures and the boiling water reactor (BWR) vessel cylindrical segment was cut into four samples so that both nondestructive and destructive testing could be performed. The three largest samples were examined nondestructively. Approximately 0.67 m (2 ft) of girth weld and 2.5 m (8 ft) of longitudinal weld were included in the three pieces for a total of approximately 3.2 m (10 ft) of seam weld. The cladding surface in the three samples is 1.8 m^2 (18 ft^2). The one piece containing the girth weld is approximately 1.22 m long (4 ft) and is identified in Fig. 1 as sample 1. The other two samples, containing only longitudinal weldment, were assigned those identification numbers by the same drawing (Fig. 1) and are approximately 0.91 and 0.67 m long (3 and 2 ft), respectively.

Figure 2 shows the three samples, which are supported by multiple 100- by 100-mm (4- by 4-in.) wooden blocks. All three samples are oriented with the cladding (inner radius of the pressure vessel) in the upward position for examination from the inner surface. Part of sample 2 is evident on the left of the photograph. A calibration block, patterned after the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code requirements, is located between block 2 and the large ultrasonic immersion tank shown in the background. Block 3 is in the

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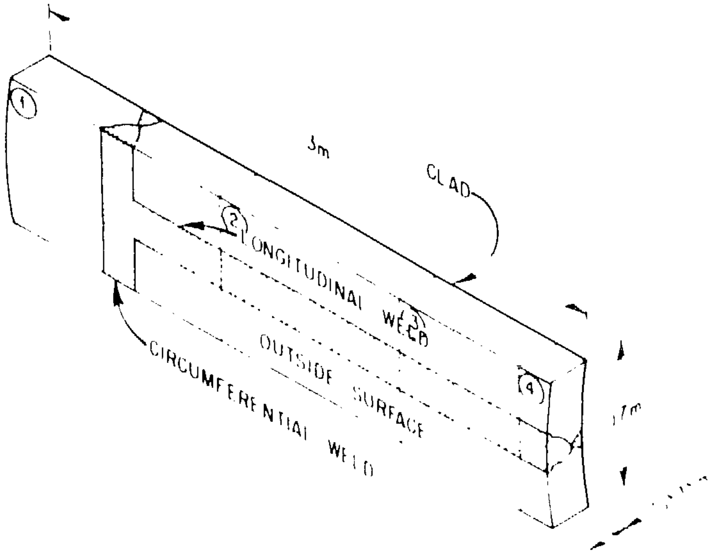

Fig. 1. Hope Creek boiling water reactor vessel cylindrical segment.

Fig. 2. Section of pressure vessel from Hope Creek Unit 2 reactor with ultrasonic equipment.

center of the photograph, and sample 1 (the largest section) is on the right in the photograph. External marking (evident on the surface of each sample in Fig. 2) was used to approximate the weldment location in each of the specimens. The ultrasonic flaw detector, along with three of the search units used for the manual ultrasonic inspections, is shown in Fig. 2. Note the dual longitudinal 2.25-MHz search unit (used for underclad cracking inspection) on the near side of sample 3, above the side-drilled holes machined at three different depths (at the quarter-, half-, and three-quarter thickness from either surface and commonly referred to in the ASME Code as 1/4T, 1/2T, and 3/4T hole reflectors for calibration).

The other two search units located in front of the ultrasonic flaw detector (on the left and right in Fig. 2) were used for normal-beam (2-MHz) ultrasonic manual inspections and 45° angle-beam (2.25-MHz) shear-wave ultrasonic manual inspections.

In addition to the three side-drilled holes evident in sample 3 (Fig. 2) that are perpendicular to the longitudinal weldment, three more side-drilled holes that are parallel to the weld were machined on the left end of sample 3 (not evident). All the holes are of ASME Code size for the 17.1-cm (6.8-in.) thickness [~7.9 mm (5/16 in.) in diameter]. Notches were also placed parallel to the holes on both surfaces of the sample in accordance with the ASME Sect. XI (Rules for Inservice Inspection of Nuclear Power Plant Components) Code requirements. We identified the weld position and configuration by polishing the surface of the end of the block and etching with a 10% ammonium persulfate solution to reveal the weld. The weld was apparently made from both surfaces as a double-J-shaped weld with the major portion being from the outer surface (as illustrated in Fig. 1, the two welds join at about the 2/3T position when measured from the outside diameter). A photograph of the weld cross section in sample 2 is shown in Fig. 3.

ULTRASONIC INSPECTIONS PERFORMED

As mentioned earlier, all ultrasonic examinations were performed manually using contact techniques. Different search units were applied, depending on the specific ultrasonic method being employed. The couplant used for all tests was a nuclear grade with a stable gel viscosity and water soluble. This nontoxic, rust-inhibitive couplant performed satisfactorily for the contact methods employed. We also used a commercial flaw detector for all ultrasonic testing.

PRELIMINARY METHODS

One ultrasonic examination using a normal-beam technique was applied, from the unclad outer surface of the samples only, prior to any machining of reflectors. The primary function of the normal-beam, 2-MHz examination was to confirm that no large delaminations were present (and none were located) that might preclude valid angle-beam examination. Calibration of this pulse-echo normal (straight) longitudinal beam examination was

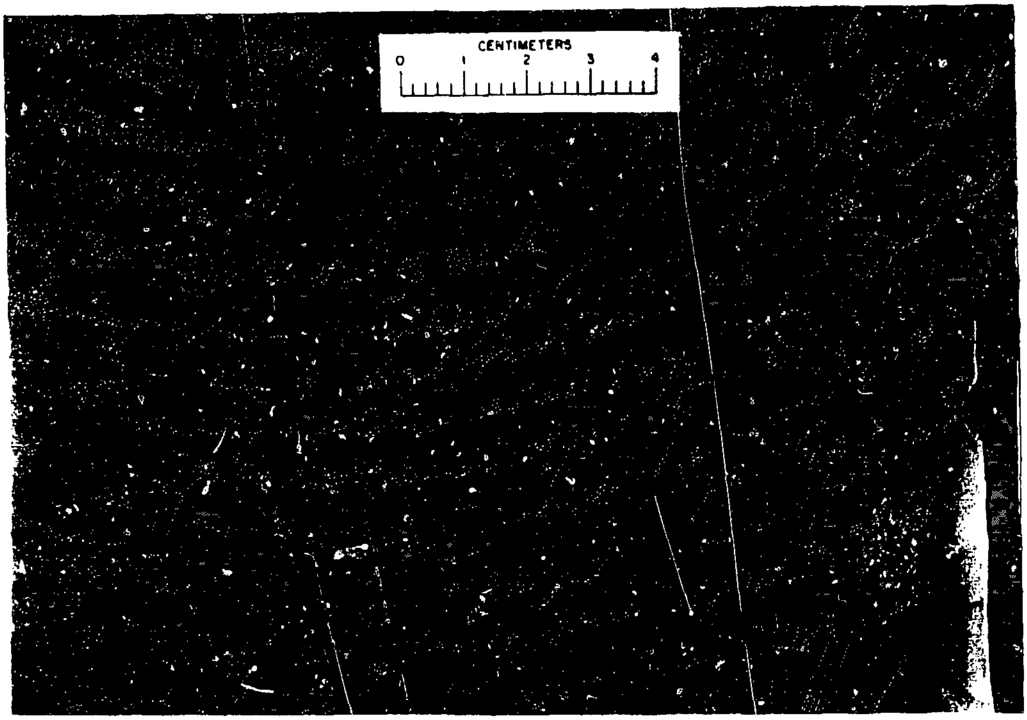

Fig. 3. Weld cross section for Hope Creek Unit 2 vessel.

performed on the flat calibration block previously fabricated,[1] using a 2-MHz search unit with a protective membrane. Figure 4 shows this calibration block, which was designed according to ASME Code requirements.

The calibration block shown in Fig. 4 was also used to establish preliminary calibration of a 45° shear-wave, pulse-echo technique. This examination was performed on sample 3 from the unclad side after the normal-beam examination to assure the validity of using sample 3 as a representative curved calibration block. A prime reason for selecting block 3 was its smaller size (for easier handling). Of course, the emphasis for the preliminary 45° shear-wave examination was placed on the two areas where reflectors were to be machined.

EVALUATION FOR VOLUMETRIC FLAWS

Volumetric ultrasonic, pulse-echo, angle-beam examinations of the 3.2-m (10-ft) length of seam welds in the three samples were performed using ASME Code techniques, as near as possible. The small size of the samples limited the application of 60° shear waves; however, all weld sections were interrogated with 45° shear-wave beams from two orientations (perpendicular and parallel to the weld centerline) and, when possible, from two directions. In addition, these tests were performed from both the outer and inner surfaces of the samples. No recordable indications were detected from the outer surface [i.e., in accordance with ASME Code requirements, no indications with amplitudes >50% of the distance

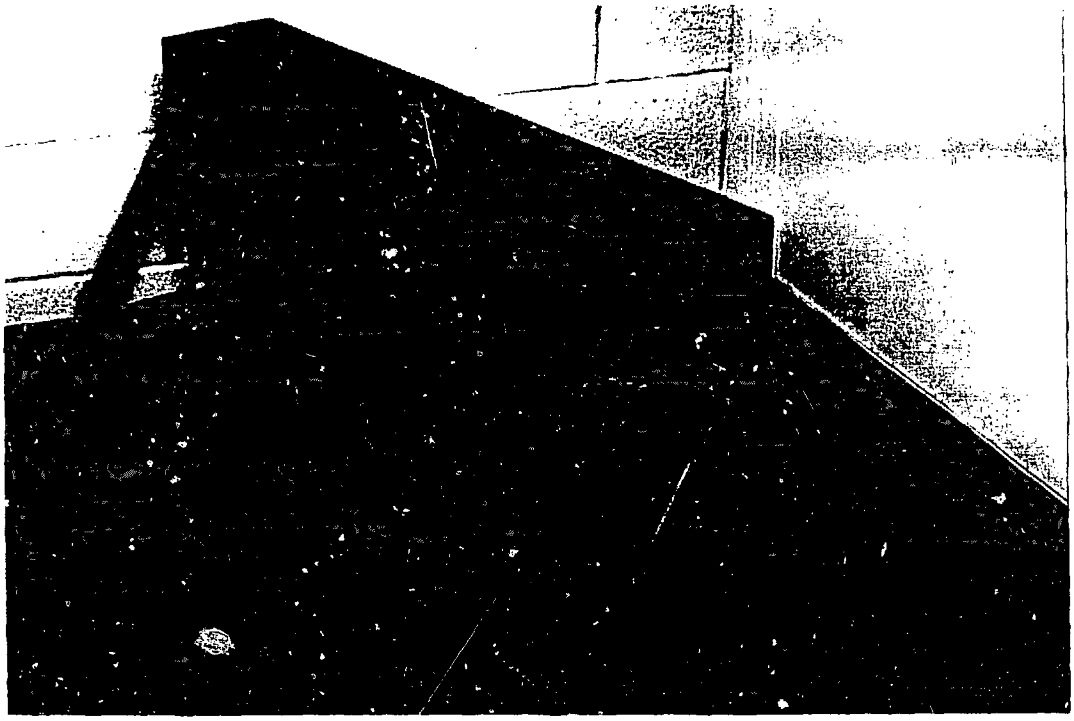

Fig. 4. Calibration block patterned after ASME Code.

amplitude correction (DAC) curve established with the appropriate set of side-drilled holes machined in the reference standard (sample 3)]. In addition, no 20% DAC indications were detected from the outer surface. Five ASME Code-recordable indications were detected from the clad side, and seven others were noted when 20% DAC recording was used for a total of 12 indications. Because of concern that the recordable indications could have been caused by refracted or mode-converted beams reflecting from external clad or block surfaces, we investigated this possibility but found no evidence that this phenomenon was causing the indications. After detection of the Code-recordable indications, these areas were reexamined with high sensitivity from the opposite surface (unclad), but no indications were detected that could be correlated with the clad-side examinations.

Volumetric flaw detection was also performed with tandem-probe angle-beam techniques. Calibration of both the one-side, pitch-catch, or V-path flaw-shadowing technique (using the receiver at the right side of Fig. 5) and the pulse-echo zonal-monitoring technique (using the receiver in the middle of Fig. 5) used the side-drilled holes in section 3 of the Hope Creek vessel. Examinations were made from the clad surface only; however, they were performed in both axial directions. No recordable indications were detected with the tandem evaluations.

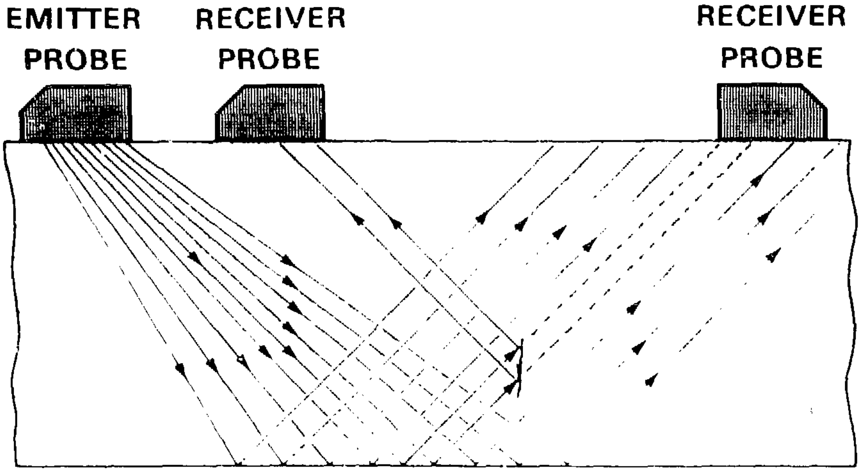

Fig. 5. Ultrasonic flaw detection by tandem techniques.

EVALUATION FOR UNDERCLAD CRACKING

A dual-element search unit that generates nominal 70° longitudinal beams with a second angle to produce a pitch-catch maximum sensitivity to underclad cracking at a depth of about 9.5 mm (0.375 in.) was used to examine the approximate 1.8-m^2 (18-ft^2) clad surface for underclad cracking. A reference reflection signal established on the clad surface notch that is perpendicular to the longitudinal weld in sample 3 was used simply to assure reproducibility of our procedures. Since this notch is approximately 10.8 mm deep by 6.4 mm thick by 50.1 mm long (0.385 × 0.25 × 2 in.), one would expect a large reflected signal. The signal was easily detected; however, for the examinations we increased the gain during scanning so that background signals were evident and observed the readout for discrete signals above background. No significant indications were detected near the clad interface.

In addition to the large reference notch in sample 3, we demonstrated detectability for underclad cracks using the response from reflectors fabricated in a flawed block for studies on underclad cracks. This block (previously identified as a flawed block 2) had been fabricated for a previous U.S. Nuclear Regulatory Commission (NRC) activity; however, we had to complete grinding work on the clad surface in order to use it. Figure 6 shows the location and size of simulated flaws placed in the pressure vessel steel block with stainless steel strip cladding. Simulated flaws S1, S2, 5, and 6 most nearly represent underclad cracks. This is especially true for flaw 6, which was produced by hydrogen-embrittlement cracking of an electron-beam weldment prior to cladding of the block at Combustion Engineering, Inc., in Chattanooga, Tennessee. All four of these simulated flaws produced large indications, as did the side-drilled holes (D and E in Fig. 6) that more nearly represent the

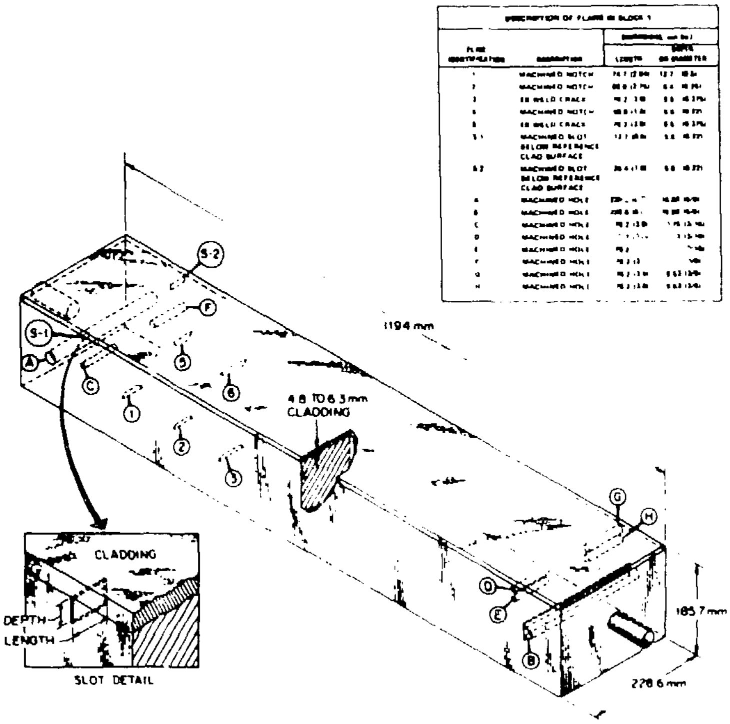

Fig. 6. Flawed block 2.

calibration reflectors used by field inspectors for underclad cracking. All six of the simulated flaws produced large indications very similar to those from the reference notch in sample 3. This block would have been used for flaw sizing if flaws were detected.

As stated earlier, no significant indications of cracking at the clad interface were detected. In fact, the only indication detected by this test was 13 to 20 mm below the clad surface and coincides with an indication detected by a 45° shear-wave inspection from the clad surface (albeit the indication was 30% DAC, non-ASME Code-recordable).

DISCUSSION OF ULTRASONIC INSPECTION RESULTS

ANGLE-BEAM EXAMINATIONS PATTERNED AFTER THE ASME CODE

As previously reported, the preliminary normal-beam inspection performed from the outer surfaces of samples 1, 2, and 3 provided confidence that valid ASME Code-type angle-beam volumetric flaw detection inspection of the seam welds could be performed without interference from laminar flaws. Further, no Code-significant indications of flaws were detected from the outer surface angle-beam inspections. Five Code-recordable indications were detected, however, with the 45° shear-wave inspections performed from the clad side. These five indications were sized using Article 4 of Sect. V of the ASME Code as a guide, even though we were aware of the limitations of the Code procedures.[1] These Code evaluations indicated lengths and through-wall depths of 25 by 25 mm (1 by 1 in.) or less. All were assumed to be subsurface indications until analyzed further.

TANDEM PROBE EXAMINATIONS

Tandem probe, 45° shear-wave evaluations were also performed on the seam welds where possible, with entry from the clad side. Basically, these dual-probe, transmitter-receiver examinations were applied with two techniques. One used a V-path shadow or one-side pitch-catch technique along the longitudinal axis (see Fig. 5). We also applied zonal tandem techniques (again in the axial direction) using the receiver shown in the middle of Fig. 5 to monitor near the 1/4T, 1/2T, and 3/4T through-wall positions for flaws (of course, the receiver was located at different distances from the emitter to coincide with the zone of interest). The three side-drilled holes used to establish the DAC curves were used to calibrate this examination. No significant indications were detected by any of the tandem techniques.

SUPPLEMENTAL NORMAL-BEAM EVALUATIONS

In addition to the planned volumetric evaluation techniques, we also used pulse-echo, normal-beam interrogation from the clad side of the zones where the 12 indications (20% DAC or larger) were detected. Search units with diameters of about 12.5 mm (0.5 in.) and frequencies of 15, 10, 5, and 2.25 MHz were used for these interrogations. Only one zone with two time-separated indications showed discernible reflection signals with this supplemental technique. The original indication with the 45° shear wave was 30% DAC. In addition, the straight-beam data (performed from the outer surface) showed a partial loss of back reflection; the dual 70° longitudinal test detected a small indication below the clad interface. This zone was located about 25 mm (1 in.) from the end of sample 2 in the longitudinal seam weld. The normal-beam tests from the clad surface detected two discrete reflections, one of which was about 19 mm deep and the other about 13 mm deep from the clad surface. The 19-mm-deep reflection could be detected for about 20 mm along the surface, whereas the 13-mm-deep reflection was much shorter. Spectrum analysis of the reflected signals indicated a peak response of about 3 MHz. Apparently the cladding scatters or attenuates the higher frequencies such that a 5-MHz search unit provides as much spectral information as the 10- or 15-MHz unit. When all reflecting signals were gated into the spectrum analyzer, no additional information was obtained; however, the spectral data did suggest an approximate 6-mm (0.24-in.) separation for discrete reflectors, which was also observed directly in the time difference of the pulse-echo readout (supplemental normal-beam evaluation). Further, the radio frequency (rf) waveforms for two discrete reflectors were of the same phase, which indicated two individual reflectors instead of two signals from one large source (see destructive results to follow in evaluation of one indication).

DISCUSSION OF THE STUDY TO DETERMINE THE SOURCE OF INDICATIONS

EFFECT OF CLAD REMOVAL

After reconfirming the reproducibility of the angle-beam indications detected only from the clad side, we removed the stainless cladding to determine the effect on the indications. A simple clad removal was done on sample 3, and reinspection after clad removal detected no indications. Thus, we concluded that indications that appeared to be deep within the section were in fact due to clad anomalies. A partial clad removal was performed on sample 2 with machining on the clad surface performed on a 2.7-mm (9-ft) curvature that approximated that of the vessel segment. A variation in the surface due to warpage of the cut section did not allow a constant surface removal; however, the removal was limited to about 2.5 mm (0.1 in.) with a minimum of 0.75 mm (0.030 in.) removed so that approximately 3.8 mm (0.15 in.) of clad remained in place. Again a reinspection with angle-beam techniques showed that the indications were deleted. Thus, we again concluded that the indications are clad related (particularly the external clad surface). It appears that mode conversion ultrasonic energy propagating within the cladding is detecting (1) the rough surface of the 25-mm-wide weld cladding, (2) the cast structure in the clad, or (3) subsurface flaws in the cladding. A wave guide action in the cladding may be involved since the time of arrival of the signals implies the presence of reflectors near the middle of the section thickness. Surface-damping techniques did not disclose any beam interaction with accessible surfaces. In any event, 11 of the 12 indications (20% DAC) were apparently clad anomalies.

EVALUATION OF ONE INDICATION

One indication located approximately 25 mm (1 in.) from the end of sample 2 in the longitudinal seam weld was detected by multiple ultrasonic examination techniques as described in the previous sections. Prior to removing the cladding, we removed a slice containing this indication (from sample 2) and, after further machining, currently have it in an approximate 51-mm-square (2-in.) specimen as shown in Fig. 7. Radiographs (Fig. 8) of the 51-mm-square specimen indicate the three-dimensional shape of the reflector as projected on the surfaces identified arbitrarily as A, B, and C (Fig. 7). Subsequent ultrasonic evaluation of the specimen confirmed a similar shape for the reflector and reconfirmed the two discrete (i.e., time-separated) indications from the clad side as reported earlier in the section on supplemental normal-beam evaluations (i.e., measurements made prior to machining the specimen from the vessel segment).

The reflector is basically a linear indication along the weld direction with a planar extension of about 6 mm (view A of Fig. 9) in one small zone [~3 mm wide in the shape of the vertical tail section of an airplane (view C of Fig. 9)]. The linear dimension approximates 20-mm. Figure 10 is a three-dimensional drawing showing the assumed flaw shape. Plans are to further analyze the size and source with metallographic techniques.

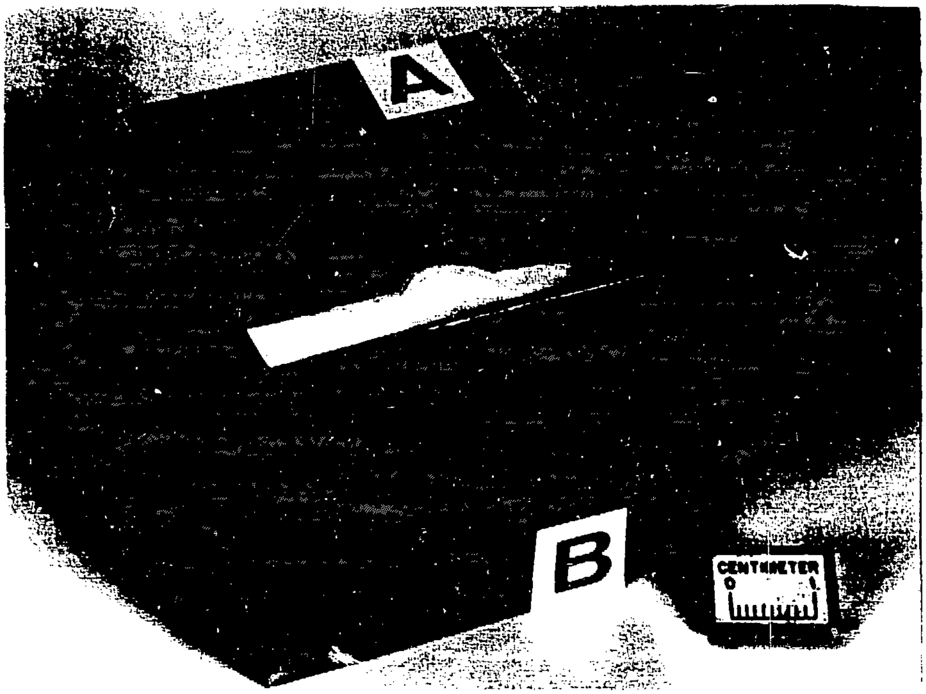

Fig. 7. Cubic sample (51 mm) containing discontinuity.

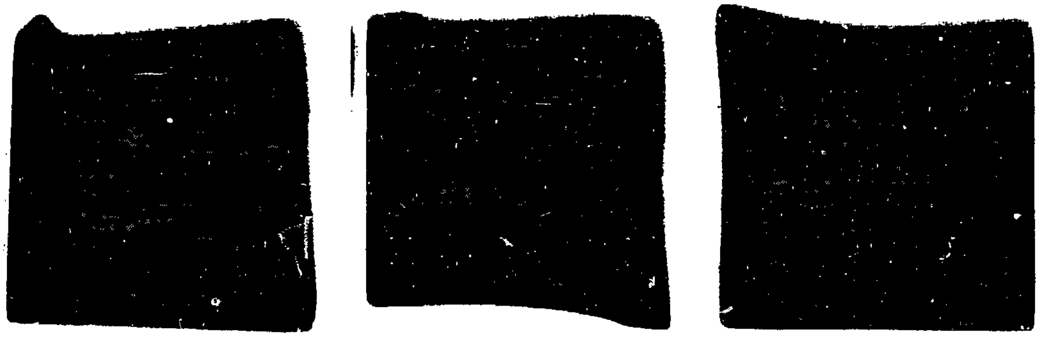

Fig. 8. Radiographs (three views) of specimen from Hope Creek Unit 2 containing a discontinuity detected by ultrasonic tests.

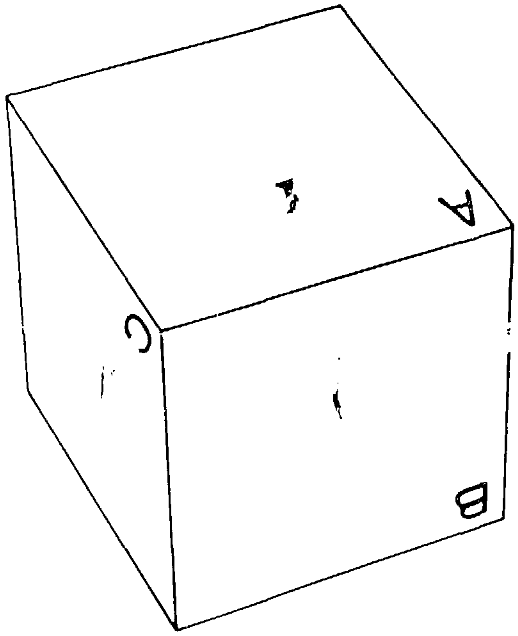

Fig. 9. Approximate shape of discontinuity in Hope Creek Unit 2 specimen (projections from radiography).

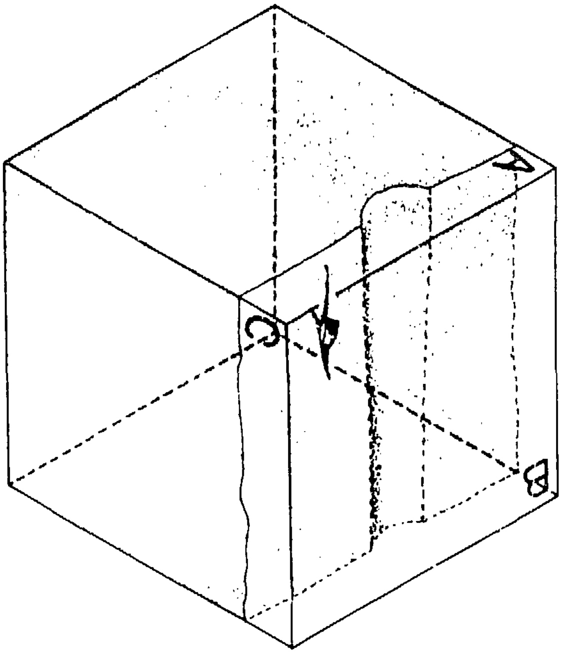

Fig. 10. Isometric drawing showing approximate shape of discontinuity detected in Hope Creek Unit 2 sample by ultrasonics.

LIQUID PENETRANT INSPECTION

SURFACE PREPARATION

Approximately 1.8 m^2 of clad surface was inspected for surface-breaking flaws with a fluorescent penetrant technique. This method is very dependent on the surface cleanliness and on the flaws being open to the surface. For these reasons we planned to have the clad surfaces etched chemically to remove any dirt, grease, or smeared metal that might prevent the penetration of the dye-containing oil-base penetrant. Experiments were performed on a small area of sample 1 with an acid solution normally used for stainless steel etching. Even the small area etched produced excessive fumes and demonstrated that pickling baths or a hooded area for etching would be necessary. Since these were not readily accessible, rather than going to the expensive method of pickling these relatively large samples, we simply cleaned the surfaces and performed the fluorescent dye-penetrant inspection.

A black residue was present on all three samples that required scraping to remove. In addition, we determined that a commercial cleaner for penetrant removal worked much better than acetone and/or alcohol to remove the residue. All three samples were thoroughly cleaned with this cleaner prior to the application of fluorescent dye penetrant

INSPECTION METHOD AND RESULTS

After the dye penetrant had remained on the cladding surfaces for a minimum of 30 min, we used a soft cloth dampened with acetone to remove the penetrant from the surface. If the cloth is too saturated with acetone, penetrant can be flushed from the open flaws, thereby reducing the sensitivity. We have had experience with this type of penetrant removal in the past and feel that results can be comparable to the removal with emulsification and water wash that is done normally (usually on smaller samples). After removing the surface penetrant, a developer was applied and the surfaces inspected with a 100-W fluorescent black light in our darkened laboratory area. Some rather bright green glowing indications were observed and were recorded on tracing paper before being evaluated. The evaluation consisted of repeating the surface penetrant removal and development steps. In all cases, the penetrant was removed by this action. All subsequently removed indications were obviously caused by rough surface areas and, in most instances, were produced by the weld perturbations that exist between weldment strips [at about 25.4-mm (1-in.) widths along the longitudinal axis of the pressure vessel section]. Thus, no significant indications of surface flaws were detected. There were no obvious differences in the small acid-etched area, thereby lending further confidence in the cleaning method employed.

RESULTS AND CONCLUSIONS

Several nondestructive examinations have been performed on approximately 3.2 m (10 ft) of pressure vessel longitudinal and girth seam weld, and 1.8 m^2 (18 ft^2) of cladding contained in three samples taken from the BWR Hope Creek Unit 2 vessel (a scrapped vessel that was never in service). When inspecting to the more stringent requirements of recording 20% DAC indications (ASME Code requires 50% DAC recording), the only indications of significant reflectors appear to be subsurface and were detected by the clad-side, angle-beam examinations. Twelve such indications were recorded, with five being Code-recordable (i.e., 50% DAC or more in amplitude response). Eleven of the 12 indications were deleted by removing clad from our samples and were identified as clad-associated anomalies. We conclude that the surface roughness and/or small surface voids or cast structure in the stainless were the source of these indications, which were detected most probably by mode-converted ultrasonic signals. However, we were not successful in demonstrating the assumed mode conversion detection (i.e., finger damping did not detect beam interactions with any accessible surface) even though we did demonstrate their deletion by clad removal.

The one indication that remains is apparently a real discontinuity located in the longitudinal weld. It appears to be a "pipelike" indication, about 20 mm (0.8 in.) long extending along the length of the longitudinal weld in which it is located, and is about 20 mm below the clad surface. As observed from three-view radiography, the flaw appears to be three-dimensional and has a through-wall dimension (or length) of about 6 mm (~0.24 in.) for an approximate 3-mm (0.1-in.) distance along the 20-mm major length. The maximum through-wall dimension (i.e., the 6-mm length) determined by radiography begins about 14 mm (0.6 in.) below the clad surface and extends to the approximate 20-mm depth of the major (pipelike) flaw that it intersects.

Further investigations of the actual dimensions and sources will be done with metallographic sectioning. This indication is being destructively analyzed, even though it is not of Code size because it was recorded by a 20% DAC recording criteria and was detected by multiple ultrasonic tests.

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