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NDE STUDIES ON CRDMS REMOVED FROM SERVICE

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ABSTRACT

Studies being conducted at the Pacific Northwest National Laboratory (PNNL) in Richland, Washington are focused on assessing the effectiveness of Non-Destructive Evaluation (NDE) inspections of control rod drive mechanism (CRDM) nozzles and J-groove weldments. The primary objective of this work is to provide information to the United States Nuclear Regulatory Commission (US NRC) on the effectiveness of ultrasonic testing (UT) and eddy current testing (ET) as related to the in-service inspection of CRDM nozzles and J-groove weldments, and to enhance the knowledge base of primary water stress corrosion cracking (PWSCC) through destructive characterization of the CRDM assemblies. In describing two CRDM assemblies removed from service, decontaminated, and then used in a series of NDE measurements, this paper will address the following questions: 1) What did each technique detect?, 2) What did each technique miss?, and 3) How accurately did each technique characterize the detected flaws? Two CRDM assemblies including the CRDM nozzle, the J-groove weld, buttering, and a portion of the ferritic head material were selected for this study. One contained suspected PWSCC, based on in-service inspection data; the other contained evidence suggesting through-wall leakage, but this was unconfirmed by boric acid deposits.

The selected NDE measurements will follow standard industry techniques for conducting in-service inspections of CRDM nozzles and the crown of the J-groove welds and buttering. In addition, laboratory based NDE methods will be employed to conduct inspections of the CRDM assemblies, with particular emphasis on inspecting the J-groove weld and buttering. This paper will also describe the NDE methods to be used and discuss the NDE results. Future work will involve using the results from these NDE studies to guide the development of a destructive characterization plan to reveal the crack morphology, to be compared with NDE responses.

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1. INTRODUCTION

Control rod drive mechanism (CRDM) nozzle assemblies with Primary Water Stress Corrosion Cracking (PWSCC) have been identified and removed from service in light water reactors. Some of these CRDM nozzle assemblies are being studied at the Pacific Northwest National Laboratory (PNNL) in Richland, Washington. The purpose of the research is to quantify the effectiveness of NDE inspections in the product forms and fabrication zones of the degraded control rod drive mechanism (CRDM) nozzle assemblies removed from service.

The primary objective of this work is to provide information to the United States Nuclear Regulatory Commission (US NRC) on the effectiveness of NDE as related to the in-service inspection of CRDM nozzles and J-groove welds. The selected NDE measurements follow standard industry techniques for conducting in-service inspections of CRDM nozzles and the crown of the J-groove welds and buttering. In addition, laboratory based NDE methods will be employed to conduct inspections of the CRDM assemblies, with particular emphasis on inspecting the J-groove weld and buttering. Two CRDM assemblies, including the CRDM nozzle, the J-groove weld, buttering, and a portion of the ferritic head material, were selected for this study. One contained suspected PWSCC, based on in-service inspection data; the other contained evidence suggesting through-wall leakage, but this was unconfirmed.

A secondary objective is to enhance the knowledge base of PWSCC through destructive characterization of the CRDM assemblies. Project efforts will include using the results from NDE studies to guide the development of a destructive characterization plan. The follow-on destructive analysis is to reveal the crack morphology, to be compared with NDE responses and address the following questions: 1) What did each technique detect?, 2) What did each technique miss?, 3) How accurately did each technique characterize the detected flaws?

Figure 1 shows the program concept - NDE studies of CRDM nozzle assemblies removed from service. Nondestructive evaluation will be made of the surfaces and volumes for the various product forms in the CRDM nozzle assemblies. A description of these product forms can be found in [11]. It is the nickel base alloy product forms that contain PWSCC. Three nondestructive testing modalities are planned at PNNL for use on two CRDM nozzle assemblies removed from service – eddy current, ultrasonic, and visual testing.

Once the NDE inspections are completed, the data from all of the inspections will be combined or fused into an assessment of degradation. This assessment will be used to guide the development of a destructive evaluation plan. Then, the research will involve sectioning and metallurgical study of the two CRDM nozzle assemblies using that plan. Small cubes, 25-50 mm on a side, containing NDE degradation indications will be the result of the gross sectioning.

Metallographic techniques, including micro-polishing and etching, will be used on the small cubes removed from the two CRDM nozzle assemblies. Photographs and micrographs from an optical microscope will be combined with electron images of exposed degradation from a scanning electron microscope (SEM). Atomic elemental composition at the site of PWSCC will be determined using the X-ray spectrographic analysis. This work will be performed for the purpose of contributing to the knowledge base of PWSCC, especially its morphology and location.

During the destructive evaluation, the location of degradation will be recorded in the coordinate system used by the NDE inspections. When the destructive evaluation portion of the research is completed, the electron and optical images of the degradation will be combined or fused with the images of the nondestructive indications. The purpose of this portion of the project is to quantify the sensitivity of the NDE to the shape and form of the degradation.

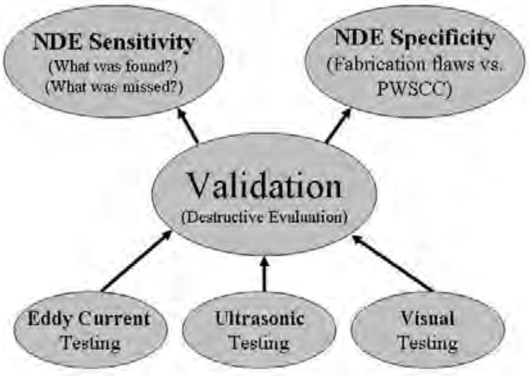

Fig. 1. NDE Studies of CRDM Nozzle Assemblies removed from service.

Figure 2 shows a CRDM penetration-nozzle assembly as received at PNNL from the North Anna 2 reactor. This work is being conducted as a collaborative effort between the U.S. NRC and the Electric Power Research Institute (EPRI). The North Anna 2 CRDMs were provided by EPRI for these studies. In the figure, a CRDM nozzle assembly is shown wrapped, bolted, and strapped to the bottom of a shipping container. The outer wrapper for the assembly is taped to help prevent the spreading of radioactive contamination. The portion of the CRDM nozzle assembly that would be above the vessel's top head is shown at the left and resting on the lumber (wooden) portion of the attachment fixture. In the figure on the right and beneath the wrapper is a portion of the vessel's top head, flame cut from its location and surrounding a degraded CRDM nozzle seal weld.

In Figure 3, a CRDM nozzle assembly is shown being lifted from the container in which it was sent to PNNL. The assembly is surrounded by wrapping additional to that shown in Figure 2 to prevent escape of radioactive contamination that may have spread during transport. The staff member shown is assisting by guiding the lift by an overhead crane (not shown).

This paper presents work, to date and planned, on NDE of CRDMs removed from service. Section 2 of the paper describes the decontamination activities at PNNL and shows a CRDM penetration-nozzle assembly prepared for removal of its radioactive oxide layer. NDE probes and measurements, for the inspection of CRDM penetration assemblies and mapping of degradation are described in Section 3. The analysis that will quantify NDE sensitivity on PWSCC and the ability to discriminate it from fabrication flaws is described in Section 4. Finally, a summary is provided.

Fig. 2. A CRDM penetration-nozzle assembly as received by PNNL.

Fig. 3. CRDM muzzle assembly being removed from shipping container.

2. DECONTAMINATION OF CRDM NOZZLE ASSEMBLIES

Significant degradation has recently been found in welded assemblies that contain nickel-base alloys [2,3,6,7,10]. The CRDM penetration assembly includes the alloy 600 tube where it penetrates the RPV top head and the seal weld at the wetted surface. The alloy 600 tube (nozzle) has a typical outside diameter of 10 cm and a wall thickness of 1.5 cm. The tube is inserted into the carbon steel (low alloy) top head of the RPV, with an interference fit. The top head is a welded assembly with 308 or 309 stainless steel cladding that is typically 6mm thick. Before the tube is inserted, weld passes with alloy 182 are applied (buttering), to a thickness of approximately 1.2 cm, on the J-groove weld preparation surface of the top head. The J-groove weld then joins the alloy 600 tube to the buttering with alloy 182 weld metal. A description of this weldment can be found in [11].

Figure 4 shows a CRDM penetration-nozzle assembly, which was removed from service, in a glove box. Before the CRDM penetration-nozzle assemblies can be inspected by the NDE techniques, the assemblies must be decontaminated in order to minimize the radiation exposure for PNNL personnel. In the figure, the flame cut surface of the vessel top head is shown after being painted to trap small amounts of contamination there. On the left in the figure is the CRDM penetration tube that extends above the vessel's top head. This portion of the assembly is not wetted by the reactors coolant water and so is largely free of radioactive contamination. The wetted surfaces of both the top head and the penetration tube are coated with a highly radioactive, hard oxide layer. PNNL conducted decontamination of the CRDM using a CO_2 pellet blasting process and repeated application of replica material. These worked well for removing the loose contamination but did not reduce the dose level. Thus, it was concluded that the oxide layer must be removed in order to reduce the dose. The removal of this hard oxide layer is accomplished by repeated application of a commercially available etchant-gel. The gel dries after application in about 2 hours, and then the etched portion of the dissolved reactive oxide layer can be wiped away with a cloth.

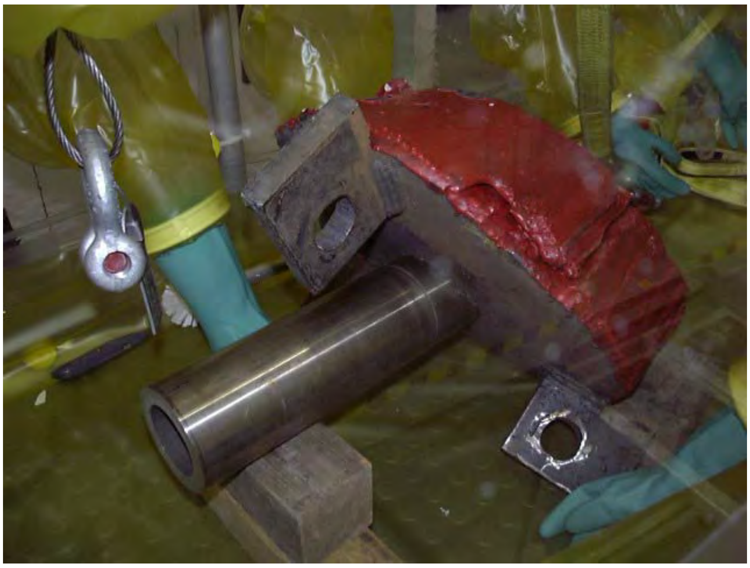

Fig. 4. CRDM penetration-nozzle assembly in glove box.

3. NDE PROBE AND MEASUREMENTS

The primary objective of this work is to provide information to the United States Nuclear Regulatory Commission (US NRC) on the effectiveness of NDE as related to the in-service inspection of CRDM nozzles and J-groove welds. Table 1 lists the NDE techniques to be used for study of CRDM penetration nozzle assemblies removed from service. Five techniques are listed in the rows of the table. Eddy current testing is planned for the surface of the inside of the alloy 600 tube and surface of the J-groove weld. The eddy current technique will examine the near surface region with a depth of penetration that varies between 1 and 3 mm depending on the frequency of coil excitation and size of the coil. Ultrasonic testing with spherically focused probes will be used from the inside the alloy 600 nozzle to inspect the fusion zone of the J-groove weld with the nozzle and beyond into the weld metal. Time of flight diffraction (TOFD) is an ultrasonic technique that will be applied to the volume of the alloy 600 nozzle from the inside surface of the tube. Visual testing will be performed on the surface of the J-groove weld using a high resolution camera. Penetrant testing will be used to confirm the visual testing results.

Table 1. NDE techniques for study of CRDM nozzle assemblies removed from service.

NDE Technique	**Product Form**	**Volumetric of Surface**
Eddy Current Testing	J-groove weld Alloy 600 nozzle	Near surface examination (1-3 mm depth of penetration)
Focused Probe Ultrasound	J-groove weld and buttering	Volumetric examination
Time of Flight Diffraction	Alloy 600 nozzle	Volumetric examination
Visual Testing	J-groove weld crown	Surface examination
Penetrant Testing	J-groove weld crown	Surface examination

3.1 Eddy Current testing from the inside of the CRDM nozzle

Eddy current testing is important for the in-service inspection of welded assemblies that contain nickel base alloys [1]. PWSCC originates at the wetted surface of a nickel-base alloy, and eddy current techniques can detect and characterize such surface degradation. PNNL is developing eddy current procedures for use in mapping degradation in CRDM penetration assemblies removed from service.

A two-axis scanner is shown in Figure 5 for use in the NDE inspections performed from the inside surface of the CRDM nozzle. The first axis of motion is into and out of the nozzle; the motor shown at the top of the figure accomplishes this motion. This motor turns a lead-screw to translate the fixture shown on the lead-screw, which is centered on the axis of the penetration-nozzle. The second axis is defined as rotation of the first axis, to inspect the (inside) circumference of the nozzle.

Table 2 lists the eddy current testing parameters for the nozzle inside surface. Six inspections are planned at three frequencies and two gain settings. The eddy current coil is designed to operate at 250 KHz, so the frequency range is centered on that value. Two coil orientations are required for sensitivity to all crack orientations in the nozzle. The gain setting of 0 dB is established in the calibration tests on EDM notches. At this setting the 2, 4, and 8 mm through wall notches are unsaturated in the image data. The gain setting of 40 dB (factor of 100) is used to image small, shallow, scratch-sized discontinuities.

Fig. 5. Laboratory scanner for inspection from inside the nozzle.

Table 2. Eddy Current testing parameters for inside surface of nozzle.

Inspection #	Frequency (KHz)	Coil Orientations (Degrees)	Gain (dB)
1	150	0 and 45	0
2	250	0 and 45	0
3	350	0 and 45	0
4	150	0 and 45	40
5	250	0 and 45	40
6	350	0 and 45	40

Figure 6 shows an example of eddy current data from the inside of a calibration standard. The figure shows the eddy current signals from the portion of the calibration standard that contains a 1 mm hole that is 1 mm below the surface of the alloy 600 tube. The signal from the hole is 6 dB above the peak noise level. In this test, the eddy current coil was driven at 150 KHz and the step sizes were 1 mm in both directions.

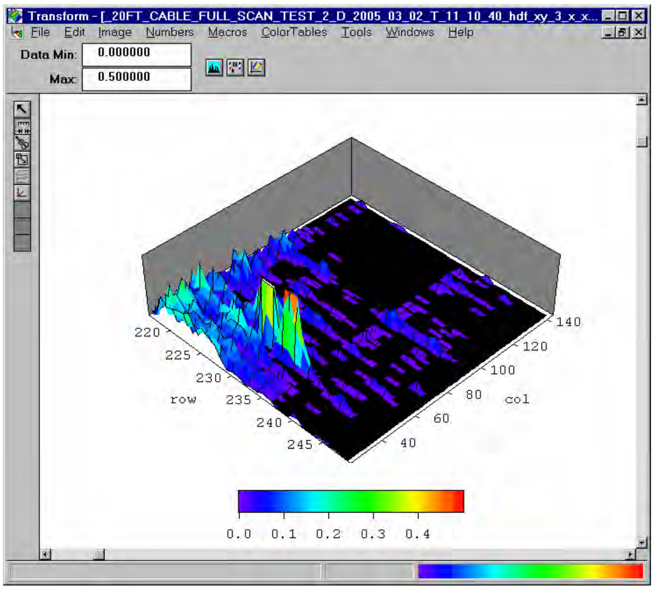

Fig. 6. Eddy Current data from the inside of the calibration standard.

3.2 Eddy Current testing on the surface of the J-groove weld

Figure 7 shows a laboratory scanner for inspection from surface of the J-groove weld. The first axis of this two-axis scanner provides motion that is radically toward and away from the nozzle; this motion is accomplished by the motor shown at the right in the figure. This motor turns a lead-screw to translate the fixture on the lead-screw, which is shown holding an eddy current pancake coil probe. The second axis turns the first axis about the circumference of the penetration-nozzle.

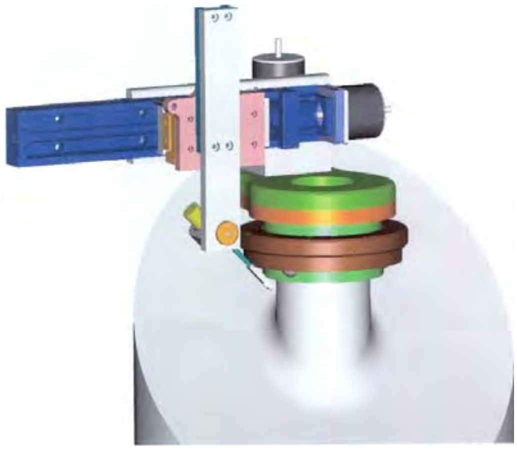

Fig. 7. Laboratory scanner for inspection from surface of the J-groove weld.

3.3 Ultrasonic testing from the inside using focused immersion probes

Normal incidence ultrasound is being employed in scanning from the inside of the alloy 600 nozzle using an acoustic mirror to change the sound beam by 90°. Multiple reflections are observed except where the J-groove weld bonds the alloy 600 tube to the top head. In the region of this bond, ultrasound can be made to pass beyond the alloy 600 nozzle and into the alloy 182 weld metal. Small fabrication flaws have been found in the fusion zone of the alloy 182 weld with the alloy 600 nozzle.

Table 3 lists the ultrasonic focused probe testing parameters for three transducer apertures. Spherically focused ultrasonic transducers are selected for inspection of the J-groove weld from the inside surface of the alloy 600 nozzle. Three transducer apertures will be used to provide increasing focus for resolving small acoustic discontinuities in the J-groove weld. For spherical transducers, the lateral resolution ΔX_t is given by

$$\Delta X_t = \frac{1.22\lambda_c F_L}{A_t}$$

where λ_c is the wavelength in the coupling material (water in this case), F_L is the focal length of the transducer, A_t is the transducer aperture, and the factor of 1.22 comes from the first zero crossing of a Bessel function [9].

Table 3. Ultrasonic focused probe testing parameters for three transducer apertures.

Inspection	Frequency	λ_c	F_L	A_t	ΔX_t
#	(MHz)	(mm)	(mm)	(mm)	(mm)
1	10.0	0.15	102	12.7	1.4
2	10.0	0.15	102	19.0	1.0
3	10.0	0.15	102	25.4	0.7

Table 4 lists the ultrasonic focused probe testing parameters for three frequencies. The alloy 600 nozzle and the J-groove weld scatter ultrasonic waves increasingly according to their frequency. Three ultrasonic frequencies are chosen to improve coverage of the acoustic discontinuities in the J-groove weld when inspected from the inside surface of the alloy 600 nozzle.

Figure 8 shows an example of ultrasonic data from the inside surface of a calibration CRDM penetration nozzle. The figure shows the ultrasonic reflections from fabrication flaws at the fusion zone of the J-groove weld with the alloy 600 nozzle. These reflections are inside the dark band that is centered left to right and runs from top to bottom in the image. The bright reflections on the left in the figure are from the non-welded interference fit region of the nozzle with the vessel's top head. The bright reflections on the right in the figure are from the outside of the alloy 600 nozzle below the cladding of the vessel's top head.

Table 4. Ultrasonic focused probe testing parameters for three frequencies.

Inspection #	Frequency (MHz)	λ_c (mm)	F_L (mm)	A_t (mm)	ΔX_t (mm)
1	7.5	0.20	102	12.7	1.9
2	5.0	0.30	102	12.7	2.9
3	3.5	0.42	flat	6.2	3.1

3.4 Time of flight diffraction technique for the alloy 600 tube

The time of flight diffraction technique is used for the in-service inspection of the alloy 600 tube for PWSCC as reported in [1,5,8,10]. TOFD is a pitch catch technique that requires two transducers – a transmitter and a receiver. Coupling of the transducers to the inside wall of the alloy 600 tube is accomplished by separate loading mechanisms (springs) for the two transducers and by wetting the surface of the alloy 600 tube with flowing water from above the probe.

Table 5 lists the TOFD Testing Parameters. Five inspections of the volume of the alloy 600 nozzle are planned using TOFD. These inspections will deploy three ultrasonic frequencies and three pitch-catch angles. A description of the TOFD technique can be found in [4].

Figure 9 shows an example of TOFD data from the inside surface of a calibration standard. The figure shows the diffracted signal from an electro-discharge machine (EDM) notch introduced on the outside surface of the calibration standard. The EDM notch was circumferentially oriented and 4 mm through wall.

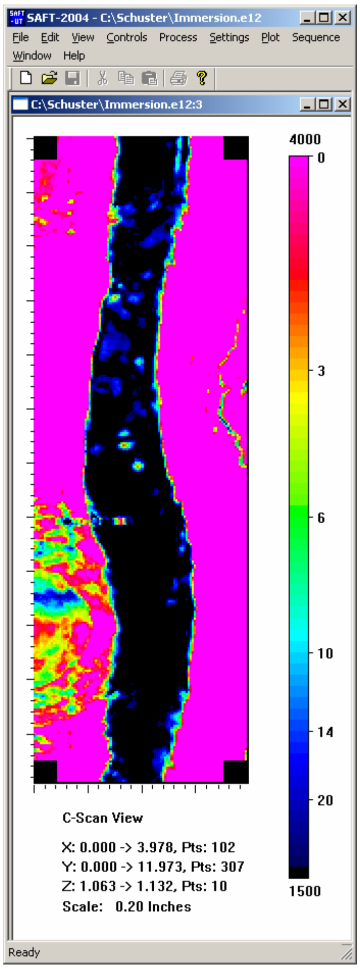

Fig. 8. Ultrasonic data from inside of a calibration CRDM penetration-nozzle.

Table 5. Time of Flight Diffraction Testing Parameters.

Inspection (#)	Angle (degrees)	Frequency (MHz)
1	60º	7.5 MHz
2	60º	5.0 MHz
3	60º	3.5 MHz
4	55º	7.5 MHz
5	65º	7.5 MHz

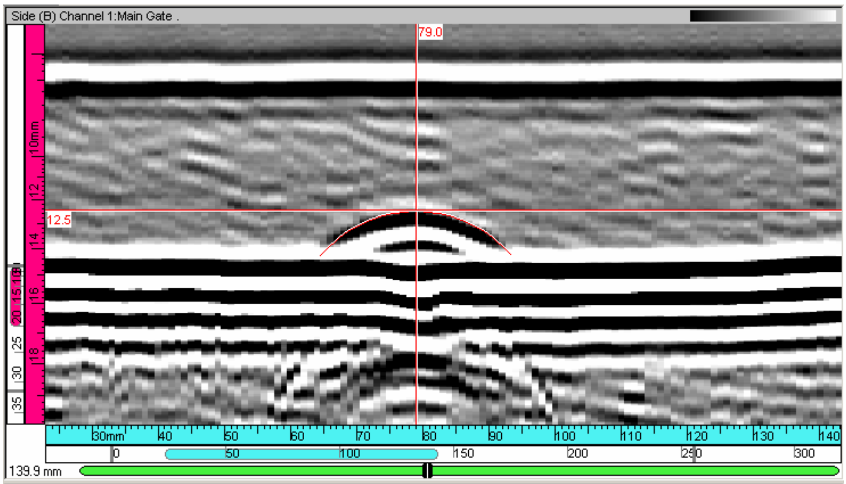

Fig. 9. TOFD data from the inside of the calibration standard.

3.5 Visual testing of the surface of the J-groove weld using a remote video camera

Automated visual testing, when applied properly, can be a useful tool in detecting and identifying surface-breaking features. When compared to a technique such as eddy current testing, visual testing is able to provide a much higher level of detail on the detected features, as the resolution of a camera system can far exceed the resolving power of other surface techniques.

To achieve this high level of resolution with the visual testing system, one needs a high pixel-count camera system, a high quality lens, and a proper lighting arrangement. To achieve a strong contrast between the surface features and the surface material, one needs careful lighting. A low resolution camera or incorrect lighting can strongly reduce the reliability of a visual system. For the proposed visual tests, PNNL will use a Lightwise LW-1.3-S-1394 camera body with a Navitar 12x zoom lens. The system uses a diffuse LED ring light to provide flat, uniform illumination. The system will be indexed over the CRDM surface with an imaged area of 35 mm by 24 mm. If the camera operator detects a surface feature of interest, the magnification will then be increased to image an area of 3 mm by 2 mm to identify, characterize, and measure the feature. The resolving power of the camera in the two modes is given in Table 6.

Table 6. Visual testing parameters.

Magnification	Imaged Area	Pixel Size	Resolution
Low	35 mm x 24 mm	27 μm	11.31 lines/mm
High	3 mm x 2 mm	2.3 μm	90.5 lines/mm

This range of magnifications is very useful for detecting and identifying cracks. Stress corrosion cracks in stainless steel typically have surface widths of 5-310 microns with median widths of 30-40 microns (Ekström and Wåle 1995, MacDonald 1985). A camera system with diffuse lighting and a pixel size of 27 m would be able to detect a crack as narrow as 5 mm, and definitively identify it as a crack at the higher magnification. Most cracks would be identifiable even at the lower magnification. A 23 m-wide crack imaged with this system is shown in Figure 10.

Low Magnification High Magnification

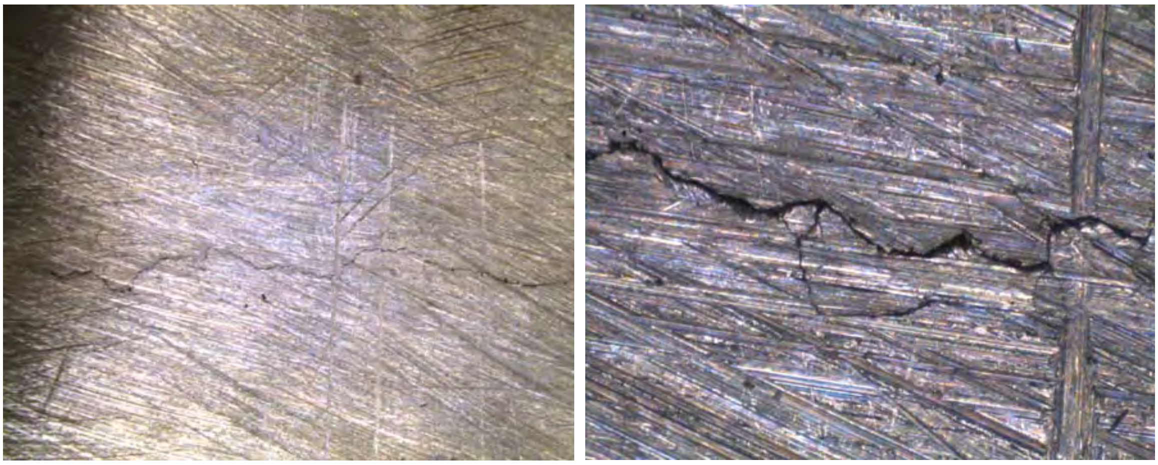

Fig. 10. A 23 μm-wide crack imaged using a Lightwise LW-1.3-S-1394 camera and a diffuse ring light.

4. LEVELS OF NDE EFFECTIVENESS, SENSITIVTY, AND SPECIFICITY

During the destructive evaluation, the location of degradation will be recorded in the coordinate system used by the NDE inspections. When the destructive evaluation portion of the research is completed, the electron and optical images of the degradation will be combined or fused with the images of the nondestructive indications. The purpose of this portion of the project is to quantify the sensitivity of the NDE to the shape and form of the degradation. The expected results will show the portions of the cracking that could be imaged with various NDE techniques and what sensitivity was achieved. Also of interest is a quantification of what was missed with recommendation for improving NDE sensitivity to PWSCC.

It is to be expected that the J-groove weld will contain fabrication flaws - lack of fusion and porosity, and possibly hot cracks. One role of NDE is to distinguish or separately characterize these fabrication flaws from indications of active degradation, PWSCC in this case. The evaluation produced by the NDE specificity task will be to show to what extent the NDE images distinguish PWSCC from fabrication flaws.

5. SUMMARY

Studies being conducted at the Pacific Northwest National Laboratory are focused on assessing the effectiveness of NDE inspections of control rod drive mechanism nozzles and J-groove weldments. The primary objective of this work is to provide information to the United States Nuclear Regulatory Commission (US NRC) on the effectiveness of ultrasonic testing and eddy current testing as related to the in-service inspection of CRDM nozzles and J-groove weldments, and to enhance the knowledge base of primary water stress corrosion cracking through destructive characterization of the

CRDM assemblies.

Before the CRDM penetration nozzle assemblies can be inspected by the NDE techniques, the assemblies are being decontaminated in order to minimize the radiation exposure for personnel. The wetted surfaces of the top head and penetration tube are coated with a highly radioactive, hard oxide layer. Decontamination procedures are being applied to remove this hard oxide layer by repeated application of an etchant-gel.

Five NDE techniques are being applied to CRDM nozzles and J-groove weldments,

- Eddy current testing is planned for the surface of the inside of the alloy 600 tube and surface of the J-groove weld.
- Ultrasonic testing with spherically focused probes will be used from the inside of alloy 600 nozzle to inspect the fusion zone of the J-groove weld with the nozzle and beyond into the weld metal.
- Time of flight diffraction is an ultrasonic technique that will be applied to the volume of the alloy 600 nozzle from the inside surface of the tube.
- Visual testing will be performed on the surface of the J-groove weld using a high resolution camera.
- Penetrant testing will be used to confirm the visual testing results.

The NDE measurements are to be completed by the summer of 2005, and the destructive testing/validation will begin during that time.

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