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ASSESSING PRIMARY WATER STRESS CORROSION CRACK MORPHOLOGY AND NONDESTRUCTIVE EVALUATION RELIABILITY

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ABSTRACT

A research program on primary water stress corrosion cracking (PWSCC) is being conducted by Pacific Northwest National Laboratory (PNNL). In this program, the material degradation problem in Alloys 600, 182 and 82 is being investigated, with objectives that include compiling a knowledge base on all cracking in nickel-base materials at all degradation sites in nuclear power plants, assessing nondestructive evaluation methods using mockups to quantify the detection, sizing, and characterization of tight cracks, determining the role of material parameters, such as welding processes, in the degradation.

This work is being conducted as a part of an international cooperative research project that has been set up to leverage efforts in several countries to address a significant and common problem. The U.S. Nuclear Regulatory Commission is leading this cooperative project to address this generic problem in a systematic manner over the next four years.

In this paper, published information on the failure history of Alloys 600, 182, and 82 is compiled and presented. The configurations of the welded assemblies that contain these alloys are shown to be important considerations for NDE reliability measurements. The product forms and the welding processes represented in the degraded components are described. The relevant data on crack morphology parameters such as shape and orientation are presented, and their impact on nondestructive evaluation (NDE) reliability is discussed.

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Keywords: PWSCC, Inconel, nickel based alloys

1. INTRODUCTION

Recent events at operating nuclear power plants have underscored the need to reexamine the susceptibility of safety-related components to primary water stress corrosion cracking (PWSCC). This service degradation, in control rod drive mechanism (CRDM) penetration assemblies and dissimilar metal weldments (DMW), motivates the need to better understand PWSCC morphology in nickel-base alloys and to assess the effectiveness of nondestructive examination (NDE) practices.

An international cooperative research program, called the Program for the Inspection of Nickel

Components (PINC), is underway to document the morphology and quantify the features of PWSCC. In this program, we plan to evaluate NDE techniques that are or may be applied in the field to detect and characterize cracks with PWSCC morphology, and to determine whether NDE methods can reliably detect PWSCC in all of the important locations within the welded assembles of interest in a timely manner that allows for necessary corrective actions to be taken before the structural integrity of the component is challenged. Figure 1 shows the supporting organizations for an international cooperative - the Program for the Inspection of Nickel Components. PNNL has conducted a review of available literature addressing this topic. The information has been placed in a framework of product forms – the shapes and alloys joined or deposited by welding.

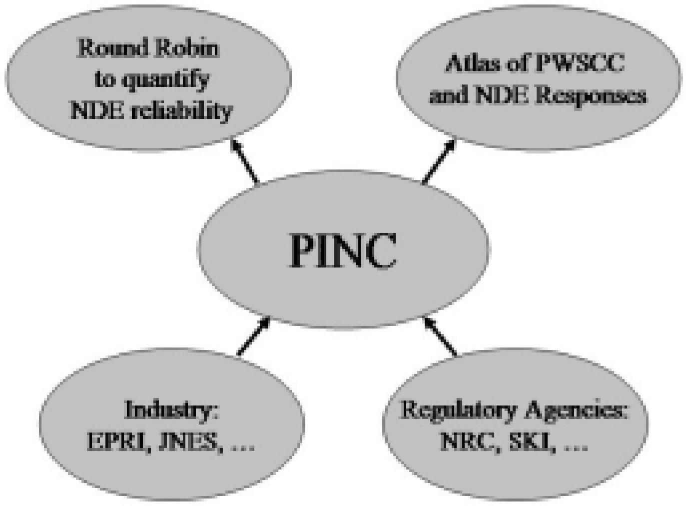

Fig. 1. Support for the program for the Inspection of Nickel Components and outcomes from it.

There are a number of difficulties associated with a quantitative study of the NDE of degradation morphology in reactor components. First, the grain structure is important to the propagation of ultrasound and the grain size can vary from component to component as well as from plant to plant. Second, the product forms have independent degradation mechanisms and fabrication conditions. Third, publicly available literature on destructive validation of degradation morphology is very limited.

This paper describes the product forms and welding process zones for the classification of degradation in welded assemblies that contain nickel-base alloys.
The information in the open literature, while not extensive or complete, was sufficient to provide a framework for needed and useful information on NDE and degradation morphology in CRDM penetration assemblies and dissimilar metal weldments. Section 2 shows a schematic for the welded assemblies and describes the product forms and fabrication zones in them.

The study of NDE responses in these weldments, using eddy current and ultrasound is discussed. NDE techniques, for the inspection of CRDM penetration assemblies and mapping of degradation are described in Section 3. Components removed from service are shown and the planned work on mapping degradation and validating PWSCC morphology is described in Section 4.

2. DEGRADATION IN PRODUCT FORMS

Significant degradation has recently been found in welded assemblies that contain nickel-base alloys [3,4,6,7,11]. 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 information provided in this paper serves as a template and concept that can be easily extended to other assemblies such as pressurizer heater penetrations or bottom mounted instrumentation penetrations. This paper focuses on alloys 600/182/82 because this is the most common nickel-base material being used in operating reactors. Upgrades and changes have been made so that repair and replacement are using new alloys

690/152/52.   No failures have been reported to date with these new alloys.

Figure 2 shows the five product forms in the DMW in the 'A' hot leg nozzle to primary coolant pipe weld in the V.C. Summer Nuclear Station reactor coolant system (RCS).   The nozzle is made of alloy 508, has a typical wall thickness of 5 cm, and is clad with 308 or 309 stainless steel that is typically 6 mm thick.   The nozzle is buttered with alloy 182 to a thickness of approximately 1.5 cm on the weld preparation surface.   Alloy 182 is used for the weld metal that joins the alloy 304 stainless steel pipe to the buttering. These product forms can vary; for example, the cold legs used at the V.C. Summer Nuclear Station have statically cast stainless steel elbows instead of alloy 304 safe-ends.

Figure 3 illustrates the product forms for the CRDM Nozzle.   Five (5) product forms are show in the figure.   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.   The top head is a welded assembly with 308 or 309 stainless steel cladding that is typically 6mm thick.   Before the tube is inserted, the top head is buttered with alloy 182, to a thickness of approximately 1.2 cm, on the seal weld preparation surface of the top head.   The seal weld (J-groove weld) joins the alloy 600 tube to the buttering with alloy 182 weld metal.

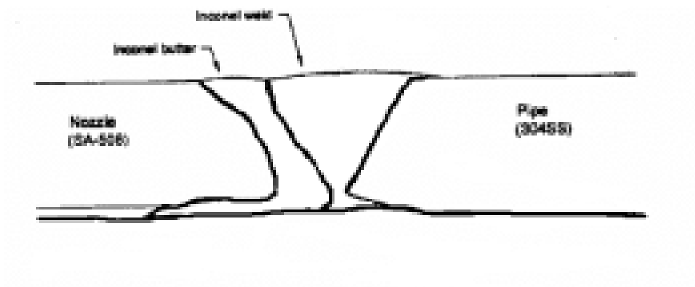

Fig. 2. Product forms in dissimilar metal.

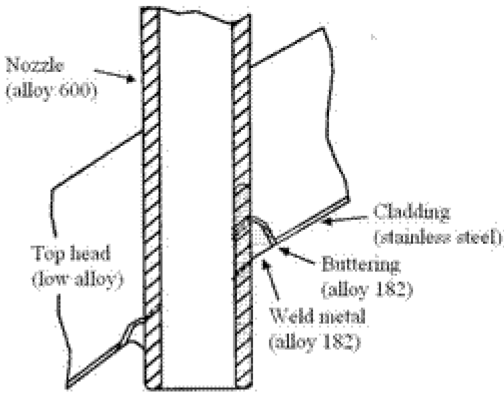

Fig. 3. Product forms in CRDM penetration assembly.

Within the product forms of the CRDM penetration assembly are important fabrication zones. Heat affected zones and re-heat zones are volumes of base metal or buttering that are changed by the heat of welding. Fusion zones are volumes of weld metal adjacent to the base metal or buttering.

2.1 Grain morphology

Grain structure is important to the propagation of ultrasound in that it limits frequency and resolution. The alloy 600 tube is one of the five product forms in a CRDM penetration assembly. One fabrication process zone exists within the product form — the heat affected zone of the tube created by the seal weld. The alloy 182 weld metal and buttering have a coarse structure of columnar weld grains. Because these columnar grains are oriented according to the heat flow during cooling of the molten weld pass, the buttering grains have an orientation that makes them distinct from the alloy 182 weld joint passes. The fine grained low alloy steel of the RPV top head supports the propagation of high frequency ultrasound – frequencies greater than 10 MHz. The alloy 308 and 309 stainless steel cladding has a coarse microstructure similar to other forms of stainless steel weld metal.

The open literature reports the grain morphology for the alloy 600 tube in CRDM penetration assemblies. Micrographs show clear and complete grain boundaries [8]. The grain morphology for the heat affected zone of the tube is also given in [8]. Some useful data exist on the orientation and size distribution of columnar grains in alloy 182 buttering and weld metal. These data show that the columnar grain boundaries do not stain well but the degradation from PWSCC can reveal them [8].

2.2 Morphology of welding flaws

Welding flaws can occur in the alloy 182 buttering and weld passes of the CRDM penetration assemblies and in dissimilar metal welds. Two important types of these flaws were found in the open literature – lack of fusion and hot cracking. Accurate characterization is needed to distinguish these fabrication discontinuities from PWSCC.

For the CRDM penetration assemblies, lack of fusion can occur between the buttering and the low alloy carbon steel, between the buttering and weld, and between the weld and the alloy 600 tube. For dissimilar metal welds, lack of fusion can occur between the buttering and the low alloy carbon steel, between the buttering and weld, and between the weld and the austenitic steel pipe, elbow, or safe-end. Lack of fusion can also occur between buttering passes or between the weld passes.

Hot cracking is a type of welding flaw that can occur during solidification of the buttering or weld passes. Hot cracking and PWSCC both form on the weld grain boundaries so they will be difficult to characterize correctly. A fracto-graphic criteria was presented for classification based on the exposed precipitates and chemical species present on the fracture surfaces in [2]. In the case of hot cracking, significant enrichment in niobium, manganese, and silicon were observed while no significance difference could be seen for SCC when compared to un-cracked surfaces.

2.3 Inter-granular attack

PWSCC begins as inter-granular attack at the wetted surface of the CRDM penetration assemblies and dissimilar metal welds. Three nickel-base product forms are exposed to primary water in a CRDM penetration assembly – the alloy 600 tube, the alloy 182 buttering, and the alloy 182 weld metal. Open literature was found that discussed inter-granular attack for the alloy 600 in laboratory specimens and no references were found for alloy 182. The inter-granular attack results where for alloy 600 from the laboratory testing of a steam generator tube mockup.

2.4 PWSCC

Primary water stress corrosion cracking is an important degradation mechanism for the nickel-base alloys of the CRDM penetration assemblies and dissimilar metal weldments. Limited information was published in the open literature. Tables 1 and 2 give the number of references that describe the PWSCC morphology in the alloy 182 buttering and weld metal of the DMWs. Tables 3, 4, and 5 show the number of references, if any, that were available in the open literature for the nickel-base product forms and weld process zones in CRDM penetration assemblies. Most of the entries are empty- no information was found.

Table 1. PWSCC morphology in the alloy 182 buttering of DMWs and BWR buttering.

Alloy 182 Buttering	Buttering Pass	Fusion Zone	Reheat Zone

		with Nozzle	from Weld
Number of references for PWR DMW	(none)	(none)	(none)
Number of references for BWR feedwater and recirulation nozzle welds	**2**	(none)	(none)

Table 2. PWSCC morphology in the alloy 182 weld metal of DMWs.

Alloy 182 Weld	Weld Pass	Fusion Zone with Buttering	Fusion Zone with Pipe
Number of references for PWR 182 weld	(none)	(none)	(none)
Number of references for BWR 182 weld	**1**	(none)	(none)

Table 3. PWSCC morphology in the alloy 600 tube of CRDM penetration assemblies and laboratory specimens.

Alloy 600	Base metal	Heat affected zone
Number of references for CRDM reactor specimens	**4**	**2**

Table 4. PWSCC morphology in the alloy 182 buttering of CRDM penetration assemblies.

182 buttering	Buttering pass	Fusion zone with top head	Reheat zone from seal weld
Number of references for CRDM reactor specimens	(none)	(none)	(none)

Table 5. PWSCC morphology in the alloy 182 weld metal of CRDM penetration assemblies and laboratory specimens.

182 weld	weld pass	Fusion zone with buttering	Fusion zone with alloy 600 tube
Number of references for CRDM reactor specimens	(none)	(none)	**1**

3. NDE RESPONSES

The objective for the study of NDE responses is to demonstrate and explain the performance of inspection for detecting degradation and preventing breaching of the reactor primary circuit at the welded assemblies that contain nickel-base alloys. It may not be possible to detect all degradation because of the inter-granular nature of the corrosive attack. Not all product forms and process zones are easy to inspect. NDE response information, gathered in this study, will be used to advance and quantify the characterization of welded assemblies that contain nickel-base alloys. Figure 4 shows the new PNNL scanner for inspecting the inside of the CRDM penetration assembly. Figure 5 show the focused ultrasonic probes, eddy current probe, and TODF probe for use with the new scanner.

3.1 Eddy current testing

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.

3.2 Ultrasonic testing from the inside using focused immersion probes

Normal incidence was also employed in scanning from the inside 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 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 tube. Figure 6 is a side view SAFT-UT image using a 10MHz ultrasonic, spherically focused probe from the inside of the CRDM penetration tube.

3.3 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 [1,5,9,11]. 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.

Fig. 4. Laboratory scanner for NDE inspection from the inside of CRDM penetration tube.

Fig. 5. Ultrasonic focused probes, Eddy Current probe, and TOFD probe for use in inspections from the inside of CRDM penetration tube.

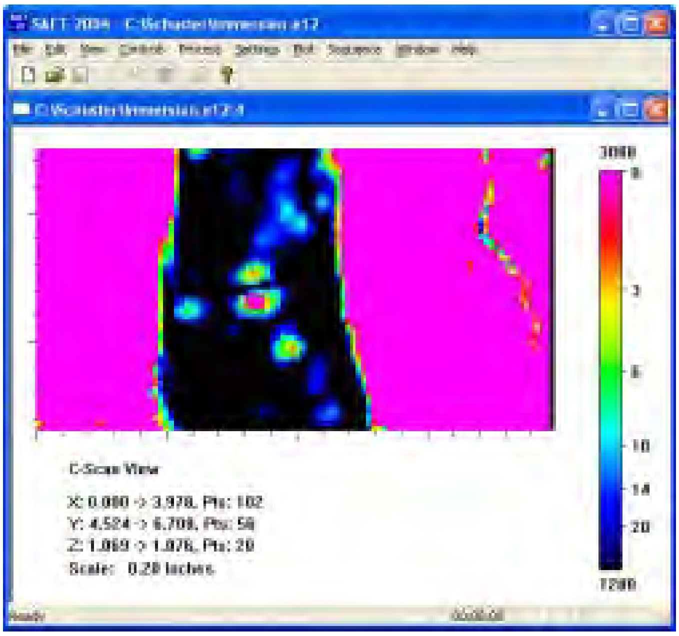

Fig. 6. Side view SAFT-UT image using 5 MHz ultrasound from the inside surface of CRDM penetration alloy 600 tube.

Test material in alloy 600 has been acquired in thickness representative of the CRDM penetration assembly's tube. Table 6 shows the EDM notches that were machined into an alloy 600 tube. Notches were placed on the inside and outside of the tube in axial and circumferential orientations. The through-wall dimensions of the notches are given in the table with the TOFD depth sizing results. Figure 7 shows TOFD data from the circumferentially oriented EDM notch connected to the inside of the tube with a through wall dimension of 2 mm.

Table 6. Ultrasonic reflectors (EMD notches) in alloy 600 tube.

	Inside axial notches				Inside circumferential notches		
	A	B	C		D	E	F
True (mm)	2	4	8		2	4	8
TOFD (mm)	*	5.2	9.1		2.8	4.4	8.2
	Outside axial notches				Outside circumferential notches		
	G	H	I		J	K	L
True (mm)	2	4	8		2	4	8
TOFD (mm)	1.7	3.7	8		1.8	3.9	8.1

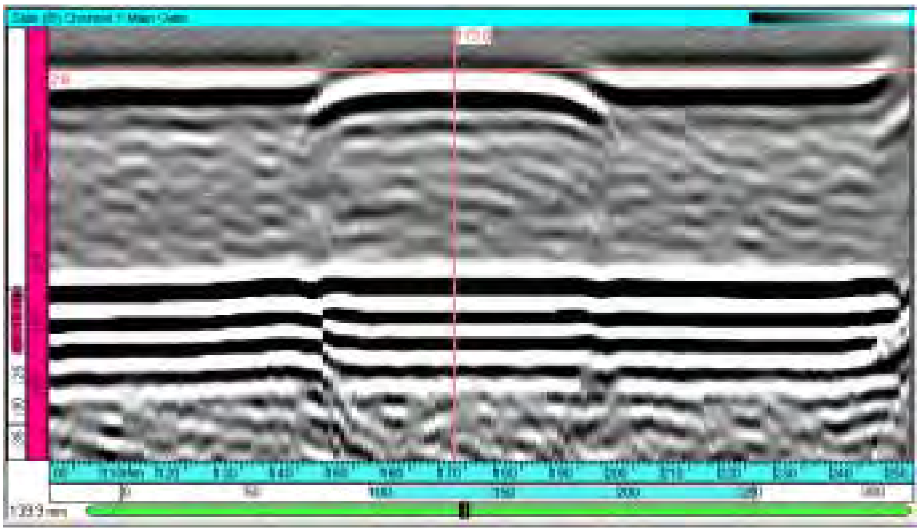

Fig. 7. TOFD data inside an alloy 600 tube from a circumferentially oriented EDM notch connected to the inside of the tube with a through wall dimension of 2 mm.

4. COMPONENTS REMOVED FROM SERVICE

The objective for the examination of CRDM penetration assemblies that have been removed from service is to characterize cracking in the nickel-base alloys and document boric acid corrosion of the low alloy steel. Components were cut from the RPV top heads of North Anna II and Davis-Besse nuclear power stations and sent to PNNL. Research is underway to generate NDE response information from the PWSCC in these components, characterize the degradation using the NDE information, and destructively validate the NDE of the PWSCC by sectioning and metallographic analysis.

The components have been photographed, decontamination techniques have been established and evaluated, and progress on the decontamination has been made. The initial review of the components showed the splatter from the cutting of component from the RPV top head was prevent and would require removal as part of the decontamination process. Figure 8 shows one of the CRDM components after treatment of the flame cut surface with paint. After this treatment, a cutter was used to reduce the length of the penetration tube extending above the reactor vessel head.

A decontamination camber was designed and a lift fixture for gripping the CRDM tubes was put in place. It was decided that the areas of the wetted surface of the nickel-base alloys would be protected by the application of replica material and carbon dioxide ice crystal blasting would be used on the areas where replica material was not applied in order to remove surface contamination there. Once the carbon dioxide ice crystal basting was completed, removal and repeated reapplication/removal of the replica material was used for decontamination of the surface of the nickel-base alloys.

The dose rate decrease was not as anticipated. The overall dose rate was only slightly less than the original rate of approximately 1000 mR/hr. Additional decontamination activities are under way employing gels that etch the surface oxide layer.

Fig. 8. CRDM penetration assembly being prepared for testing.

5. SUMMARY

Research on primary water stress corrosion cracking is being conducted by the Pacific Northwest National Laboratory. The material degradation problem in Alloys 600, 182 and 82 is being investigated with objectives that include compiling a knowledge base on all cracking in nickel-base materials at all degradation sites in nuclear power plants, assessing nondestructive evaluation methods using mockups to quantify the characterization of tight cracks, determining the role of welding processes in degradation, and mapping the degradation in components removed from service.

Product forms and welding process zones are proposed for the classification of degradation in welded assemblies that contain nickel-base alloys. The study of nondestructive evaluation responses in these weldments, using eddy current and ultrasound is discussed. The objective for the study of NDE responses is to demonstrate and explain the performance of inspection for the timely detection of degradation from welded assemblies that contain nickel-base alloys. NDE response information, gathered in this study, will be used to advance and quantify the characterization of welded assemblies that contain nickel-base alloys.

Components removed from service are shown and the planned work on mapping degradation and validating primary water stress corrosion cracking morphology was described. Components were cut from the RPV top heads of North Anna II and Davis Besse nuclear power stations and sent to PNNL. Research is underway to generate NDE response information from the PWSCC in components, characterize the degradation using the NDE information, and destructively validate the NDE of the PWSCC by sectioning and metallographic analysis.

6. GLOSSARY

Benign condition – an unintended discontinuity or flaw that was created during fabrication and does not connect or contribute to degradation of the component during service.
Buttering – nickel-base alloy weld passes that are applied to the weld preparation surface of a low alloy component before it is joined by welding to another, dissimilar metal component.
Crack morphology – the form and structure of a crack as distinguished from its substance or cause.
Degradation – a metallurgical change in a component or assembly that can progress to failure or leak.
Degradation morphosis – the manner in which degradation changes form during its development from onset to component failure or leak.
Dendrite – weld grain (equiaxed, columnar, or tree-like).
Fabrication process zone – the heat affected, re-heat, or fusion zone of a product form.
Fusion zone – a volume of weld metal separate from and adjacent to the heat affected zone of base metal or the re-heat zone of weld metal.
Grain morphology – the shape, orientation, and distribution of metal crystals.

Heat affected zone – a volume of base metal, adjacent to the fusion zone, changed by the heat of welding.
Hot crack – a crack that forms in a casting or in weld metal during solidification.
Lack of fusion – missing metallic bond either between the side-wall of a weld with the base metal or between weld passes (inter-run).
Product form – a distinct shape and alloy jointed or deposited by welding.
Primary water stress corrosion crack – the inter-granular or inter-dendritic cracking of nickel-base alloys that occur in-service and originate from the surfaces of a component that are wetted by the primary water of a PWR.
Re-heat zone – a volume of the buttering that is re-heated during the joining by welding of an assembly (seal weld or dissimilar metal weld).

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