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Nondestructive Evaluation: Program Description for Performance Demonstration of Pressurized Water Reactor Upper Head Penetration Examinations

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ABSTRACT

Service experience with the control rod drive mechanism (CRDM)/control element drive mechanism (CEDM) penetrations in pressurized water reactors (PWRs) worldwide has confirmed primary water stress corrosion cracking (PWSCC) in Alloy 600 at several plants. Since the first reported PWSCC in 1991 at Bugey 3, eddy current, liquid penetrant, and ultrasonic examination methods have been used to examine reactor vessel upper head penetrations. More recently, several leaks originating from the inside diameter and the outside diameter initiated axial cracking of Alloy 600 penetrations as well as a few leaks from other locations with PWSCC have been discovered. In 2001 and 2002, the U.S. Nuclear Regulatory Commission (NRC) released bulletins that contain requests that utilities provide information relating to structural integrity of the penetration nozzles, including the extent of leakage and cracking that has been found thus far and inspections and repairs undertaken. In addition, the bulletins contain requests that utilities demonstrate that their future plans meet the regulatory requirements. The NRC's response to the responding utilities has been to impose further requirements for inspection.

In early 2003, the NRC issued Order EA-03-009, *Order Establishing Interim Inspection Requirements for Reactor Pressure Vessel Heads at Pressurized Water Reactors,* which requires utilities to inspect the reactor pressure vessel (RPV) head penetrations. Many upper heads currently contain Alloy 600 tubing and its weld filler metal alloys, but some PWR owners are choosing to replace the old RPV heads with new heads that contain Alloy 690 tubing and weld filler metals. However, Alloy 600 is likely to remain in the PWR vessel head penetrations for many years.

Most recently, the ASME Section XI Subcommittee published Code Case N-729-1, "Alternative Examination Requirements for PWR Reactor Vessel Upper Heads with Nozzles Having Pressure-Retaining Partial-Penetration Welds Section XI, Division I," which defines the requirements for the examination of the upper head penetrations. This code case and the NRC order have increased the need to upgrade the CRDM performance demonstration program.

Since the issuance of the ASME code case, the Materials Reliability Program (MRP) has directed the MRP Inspection Issue Task Group to develop a performance demonstration program that qualifies the nondestructive evaluation procedures and inspection techniques. This program will also include personnel performance as part of the qualification process. The program description defines the specific requirements for addressing both the previous and future performance demonstrations for upper head penetrations.

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1 INTRODUCTION

1.1 Background

Examination of penetration nozzles in pressurized water reactor (PWR) reactor vessel closure heads (RVCHs) has shown that these Alloy 600 components are susceptible to aging degradation because of primary water stress corrosion cracking (PWSCC). Several PWR plants in the United States have experienced cracking in the control rod drive mechanism (CRDM)/control elements drive mechanism (CEDM) nozzles and associated J-groove welds. Some of these plants have experienced primary coolant leaks from through-wall cracks in the nozzles and/or welds. The stresses that make the nickel-chromium-iron Alloy 600 nozzles and their Alloy 182/82 J-groove attachment welds susceptible to cracking are induced by shrinkage as the J-groove attachment weld that joins the penetration nozzle to the inside surface of the RVCH cools during vessel fabrication.

In the mid-1990s, the Nuclear Utility Management and Resource Committee (NUMARC) formed an Ad Hoc Advisory Committee (AHAC) to organize a cooperative program to develop an upper head penetration inspection vendor's Inspection Capability Demonstration Program. Under the committee's direction, the Electric Power Research Institute (EPRI) developed a program to quantify the capability of the vendor's nondestructive evaluation (NDE) procedures in order to provide utilities with the necessary data about the performance of NDE. This demonstration program did not include the qualification of NDE personnel performing acquisition or interpretation of the data. The key features of the demonstration program were: 1) the development of realistic mockups that contain a wide range of flaws in order to support adequate measurement of NDE procedure capabilities and 2) the development of a protocol that clearly describes the methods to be used for the assessment of NDE procedure capabilities, described in the EPRI report *Demonstration of Inspection Technology for Alloy 600 CRDM Head Penetrations* (TR-106260) [1].

During this early implementation of the demonstration program, the U.S. utilities inspected many upper head penetrations with demonstrated ultrasonic (UT) and eddy current (ET) inspection techniques. Flaws observed during these nozzle inspections revealed the most significant was 27-in. (6.8-mm) deep (43% through-wall) at D.C. Cook. Other plant inspections performed during this same period revealed prevalent inside diameter (ID) shallow surface cracking clustered above and below the J-groove weld that did not extend beyond 0.1 in. (2.5 mm) in depth.

In 2001, the CRDM/CEDM demonstration program evolved to address outside diameter (OD) cracks found during vessel head inspections. These findings changed the inspection volume requirements. New rounds of demonstrations were performed to address degradation in not only the penetration tubing but also the J-groove weld wetted surface. The demonstrations included interrogation of cracks on the ID and OD surfaces of the penetration tubing as well as the attachment weld. New full-scale mockups were fabricated with simulated flaws in the ID and OD of the penetration tube and in the J-groove weld volume. These demonstrations remained focused on quantifying—rather than applying pass/fail criteria—the capabilities of the NDE procedures and techniques without applying personnel qualifications.

In response to in-service inspection findings, the U.S. Nuclear Regulatory Commission (NRC) issued the following three bulletins and one order that has since been revised:

- NRC Bulletin 2001-01: *Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles* [2]
- NRC Bulletin 2002-01: *Reactor Pressure Vessel Head Degradation and Reactor Coolant Pressure Boundary Integrity* [3]
- NRC Bulletin 2002-02: *Reactor Pressure Vessel Head and Vessel Head Penetration Nozzles Inspection Programs* [4]
- NRC Order EA-03-009: *Order Establishing Interim Inspection Requirements for Reactor Pressure Vessel Heads at Pressurized Water Reactors* [5]

Since the issuance of Code Case N-729-1 *Alternative Examination Requirements for PWR Reactor Vessel Upper Heads with Nozzles Having Pressure-Retaining Partial-Penetration Welds Section XI, Division I* [6] by ASME Section XI, the Materials Reliability Program (MRP) has directed the EPRI NDE Center to develop a performance demonstration program that qualifies the NDE techniques, procedures, and personnel required to support future upper head penetration examinations. Furthermore, the MRP Integration and Implementation Group requested that the program comply with the EPRI Quality Assurance (QA) program. Code Case N-729-1—which implements the use of ASME Section V, Article 14, for qualifying NDE procedures—provides requirements for the examination of RVCH penetrations. The upper head penetration qualification program will use intermediate rigor in lieu of the low (statistical) rigor requirement of Code Case N-729-1.

1.2 Objective

This report provides the technical basis for the use of various NDE techniques for the reliable detection of degradations in upper head penetration nozzles and their associated J-groove weld surface (wet side of weld crown). This report addresses the elements necessary for reliable examinations of upper head penetrations, which include technique, procedural, and personnel qualifications. This program will meet the requirements of 10CFR50 Appendix B and the EPRI QA program.

1.3 Scope

The MRP Issues Integration Group directed the MRP Inspection Issue Task Group (ITG) to establish an industry program that is more robust than the current CRDM/CEDM demonstration program. This new qualification program must ensure that the upper head penetration examinations for the fleet are demonstrated to be consistent and reliable. It will be similar to those qualified through Nuclear Energy Institute (NEI) 97-06, Steam Generator Program Guidelines [7], and ASME Section XI, Appendix VIII, “Performance Demonstration Requirements for Ultrasonic Examination Systems.” [8]. The Inspection ITG will develop an

NDE qualification program that addresses the relevant inspection attributes and ensures the reliability of upper head penetration examinations. This program is designed to ensure homogeneous examination results across the industry, which will be accomplished by defining acceptance criteria for personnel and procedure qualifications under a QA program. The qualification program will use the flaw tolerance, inspection volume, and area information from the MRP's upper head safety assessment work to determine acceptance criteria for the upper head penetration examinations and qualifications. The existing MRP demonstration program will be critically examined to maximize the use of existing resources and results.

The upper head penetration NDE qualification program will include centralized procedure, equipment, and personnel demonstrations that comply with the relevant requirements of 10CFR50 Appendix B *Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants; Section IX: Special Processes and Programs* [9] and use acceptance criteria provided by the MRP Assessment ITG. The project is planned so that the qualification program will be in operation by fall 2007, although the NRC is not scheduled to publish the applicable 10CFR50 rule revision until March 2008. Examinations conducted after that date will be qualified accordingly. In summary, the following changes to the current demonstration program are expected in the future:

- Implementation of procedural qualifications
- Implementation of personnel qualifications
- Establishment of qualification acceptance criteria
- Implementation of appropriate QA procedures to ensure compliance with applicable sections of 10CFR50 Appendix B

2 DESCRIPTION OF COMPONENT

2.1 Component Design (Westinghouse, Combustion Engineering, and B&W)

The RVCHs in PWR plants have several upper head penetrations that are used for various purposes including:

- CRDM—or CEDM in Combustion Engineering (CE) plants
- Instrumentation
- Head venting pipe
- Thermocouple nozzles

Babcock and Wilcox (B&W), CE, and Westinghouse plants all have similar head designs with varying numbers of penetrations and tubing sizes. The EPRI report *Materials Reliability Program: Reactor Vessel Closure Head Penetration Safety Assessment for U.S. Pressurized Water Reactor (PWR) Plants (MRP-110): Evaluations Supporting the MRP Inspection Plan* (1009807) contains a full description of plant-specific designs in Appendix A [10].

2.2 Review of Service Experience and Historical Inspection Results

The review of domestic and international service experience was intensive and necessary to ensure that the NDE demonstration program addressed realistic representations of the following:

- Component geometry
- Accessibility
- Flaw types and locations
- NDE methods
- Flaw responses

The review revealed unexpected challenges to inspection, such as the following anomalies that affected flaw detection and characterization:

- Component ovality
- Surface irregularities
- Tight clearances (sometimes filled with debris to the point of blocking access)
- Magnetic deposits
- Tightly clustered flaws
- Scratches

All of this information was used to design and construct realistic demonstration mockups and a demonstration protocol to accommodate NDE techniques and manipulators being used for the various RVHP configurations. Service experience is continually monitored to ensure that the demonstration mockups and demonstration process remain valid and incorporate new information pertaining to flaw types, locations, and flaw responses as it becomes available.

The main degradation of these penetrations is suspected to be PWSCC for the material surface exposed to the primary water (wetted surface). The degradation that has been reported has been orientated in both the axial and circumferential directions. These reported indications have been located on both the inside and outside surfaces of the tubes exposed to primary water. Cracks on the normally wetted surfaces can allow primary coolant to reach the outside surface of the tube in the annulus area and result in reactor coolant system leakage.

Section 4 of the EPRI report 1009807 includes service experiences through December 2003 [10]. Approximately 21 plants have not yet—as of December 2005—completed a volumetric examination of upper head penetrations in accordance with the NRC order [5]. The balance of the fleet has inspected the upper head penetrations to some extent or replaced the RVCH head with a new head that contains PWSCC-resistant Alloy 690 tubes and weld materials. Baseline pre-service inspections using both volumetric and surface examinations are being performed on the replacement reactor pressure vessel (RPV) head penetrations.

2.3 Inspection Challenges

The immediate inspection challenge is accessing the upper head penetration inspection volume from the underside of the closure head. Because of the high radiation level under the RVCH, examination of the penetrations' ID and OD surfaces must be performed remotely with robotic positioning devices. Vendors have developed robotic devices that automatically position the required tooling to access the penetration tubing. The typical NDE methods used for examining the ID surface and the volume of the upper head penetration tubes are ET and UT techniques. The design of some of the CRDMs/CEDMs includes a thermal sleeve that limits the access to the ID surface of the penetration. Inspection vendors have developed tooling that accesses this difficult-to-reach region that has a narrow gap between the thermal sleeve and the penetration. Thin-blade probes containing ET probes and/or UT probes are used to inspect this annulus region.

Inspection can be made difficult by several other conditions. A stress that is induced during the welding process causes the penetration to become oval rather than circular and also distorts the ID surface. The inspection devices must be capable of scanning these surfaces and maintaining contact to provide adequate flaw detection and sizing capabilities. Additional conditions that influence inspections include magnetic deposits, debris that restricts the passage of the probes, and scratches that affect the ET interpretation. In some severe cases, the penetration must be cleaned before any inspection can be performed.

3 INSPECTION OBJECTIVES

3.1 Flaws to Be Detected

PWSCC can occur at various locations in the upper head penetration tubing and J-groove weld wetted surfaces, including the surfaces associated with the buttering material of the J-groove weld wetted surfaces and adjacent cladding weld material. Other plausible aging degradation mechanisms include environmental fatigue, stress corrosion cracking in a nonprimary water environment, low-temperature crack propagation, and boric acid corrosion wastage. The requirements for the detection of flaws are addressed in the ASME Boiler and Pressure Vessel Code Case N-729-1, *Alternative Examination Requirements for PWR Reactor Vessel Upper Heads with Nozzles Having Pressure-Retaining Partial-Penetration Welds Section XI, Division I* [6] and the NRC Order EA-03-009, *Order Establishing Interim Inspection Requirements for Reactor Pressure Vessel Heads at Pressurized Water Reactors* [5].

3.2 Location and Orientation

The actual locations and types of degradation mechanisms as well as their orientations (axial or circumferential) are described in Section 2 of the EPRI report 1009807 [10]. The nine locations of interest for inspection of the upper head penetrations are described as follows:

- Locations 1 and 2: Axial cracks located on both the ID and OD wetted surfaces of the tubing. The primary area of interest for Location 1 is the tube ID surface from the tube end to 2 in. (50.8 mm) above the highest section of the J-groove weld. Location 2 is the tube OD from the bottom of the J-groove weld to the tube end (see Figure 3-1). Location (Type) 1 flaws located at the inside surface adjacent to the weld do not pose an immediate safety concern because they do not lead to rupture, as described in the DEI letter report "Required Flaw Detection Size and Examination Reliability for Reactor Vessel Nozzle Examinations" [11]. They do not lead to rupture because they would be detected by leakage long before growing to a critical (unstable) crack length. These should be detected if they exceed 15% through-wall in depth to avoid initiating OD circumferential cracks in the tube and wastage of the low alloy steel reactor vessel head.
- Location 3: Radial cracks on the entire wetted surface of the J-groove weld as shown in Figure 3-1.
- Location 4: Circumferential cracks on the entire wetted surface of the J-groove weld as shown in Figure 3-1.

- Locations 5 and 6: Circumferential cracks emitting from either the ID or OD surface of the tubing. The area of interest is the volume of the tube from the tube end below the J-groove weld to 2 in. (50.8 mm) above the highest point of the J-groove weld (see Figure 3-1). Location 5 flaws, which are located above or near the top of the weld, present a risk of rupture of the tube and ejection of the nozzle if a through-wall crack exceeds 300° in length as analyzed in EPRI report 1009807 [10]. According to "Required Flaw Detection Size and Examination Reliability for Reactor Vessel Nozzle Examinations" [11], these flaws pose a significant risk of causing rupture and should be qualified to an intermediate rigor as defined in ASME Section V, Article 14.
- Location 7: Lack of fusion indications (welding imperfections) at the interface of the J-groove weld and tubing outside surface (see Figure 3-2).
- Location 8: Craze cracking on the ID surfaces of the tubing (see Figure 3-2).
- Location 9: Circumferential cracking initiating from the J-groove weld wetted surface penetrating into the tubing (see Figure 3-2).

"Required Flaw Detection Size and Examination Reliability for Reactor Vessel Nozzle Examinations" [11] provides a deterministic and probabilistic analysis of the severity of these flaws and determines that only flaw locations 1 and 5 pose a safety concern and should be considered critical and detected at an 80% probability.

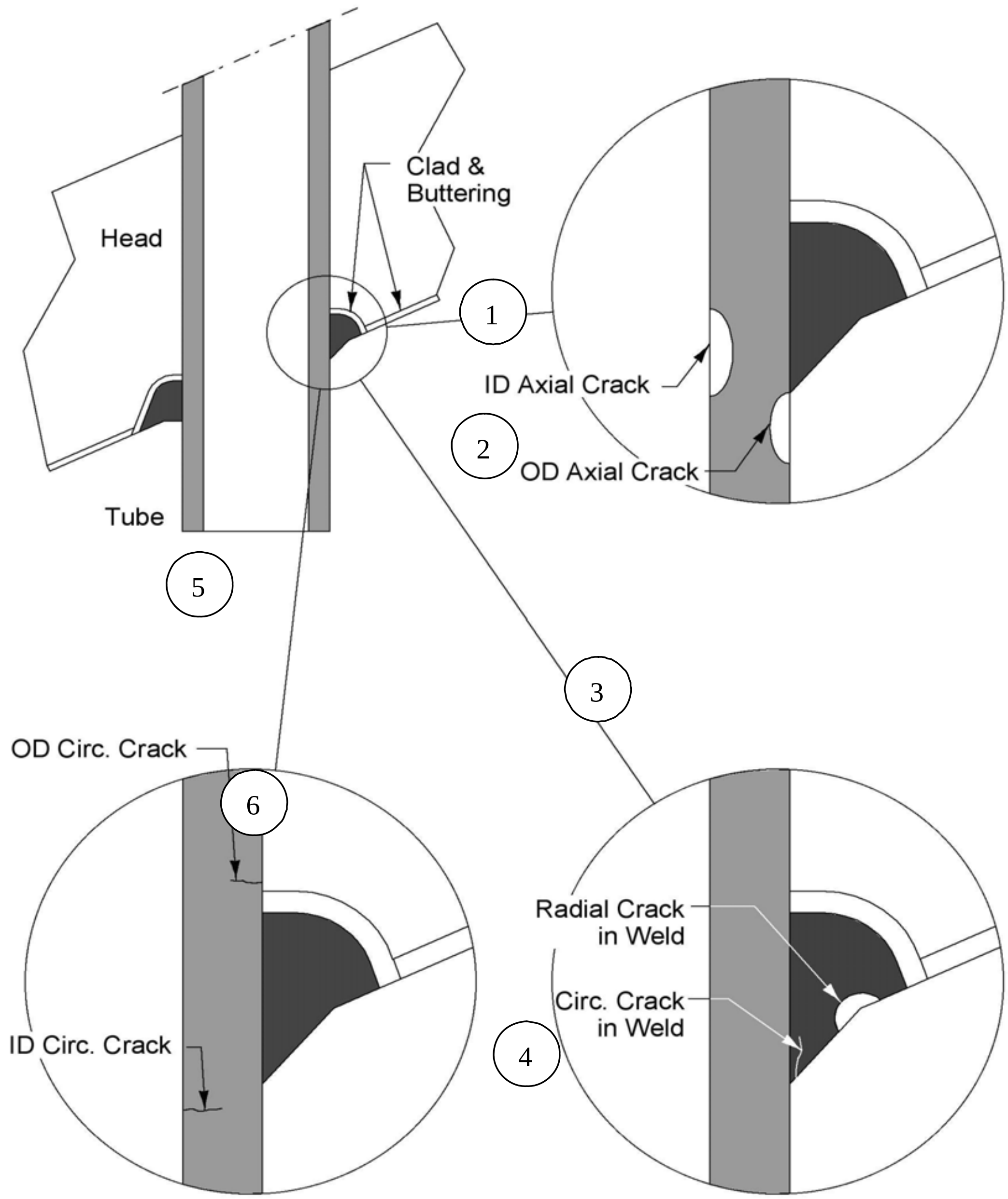


Figure 3-1
Flaw Locations 1 Through 6

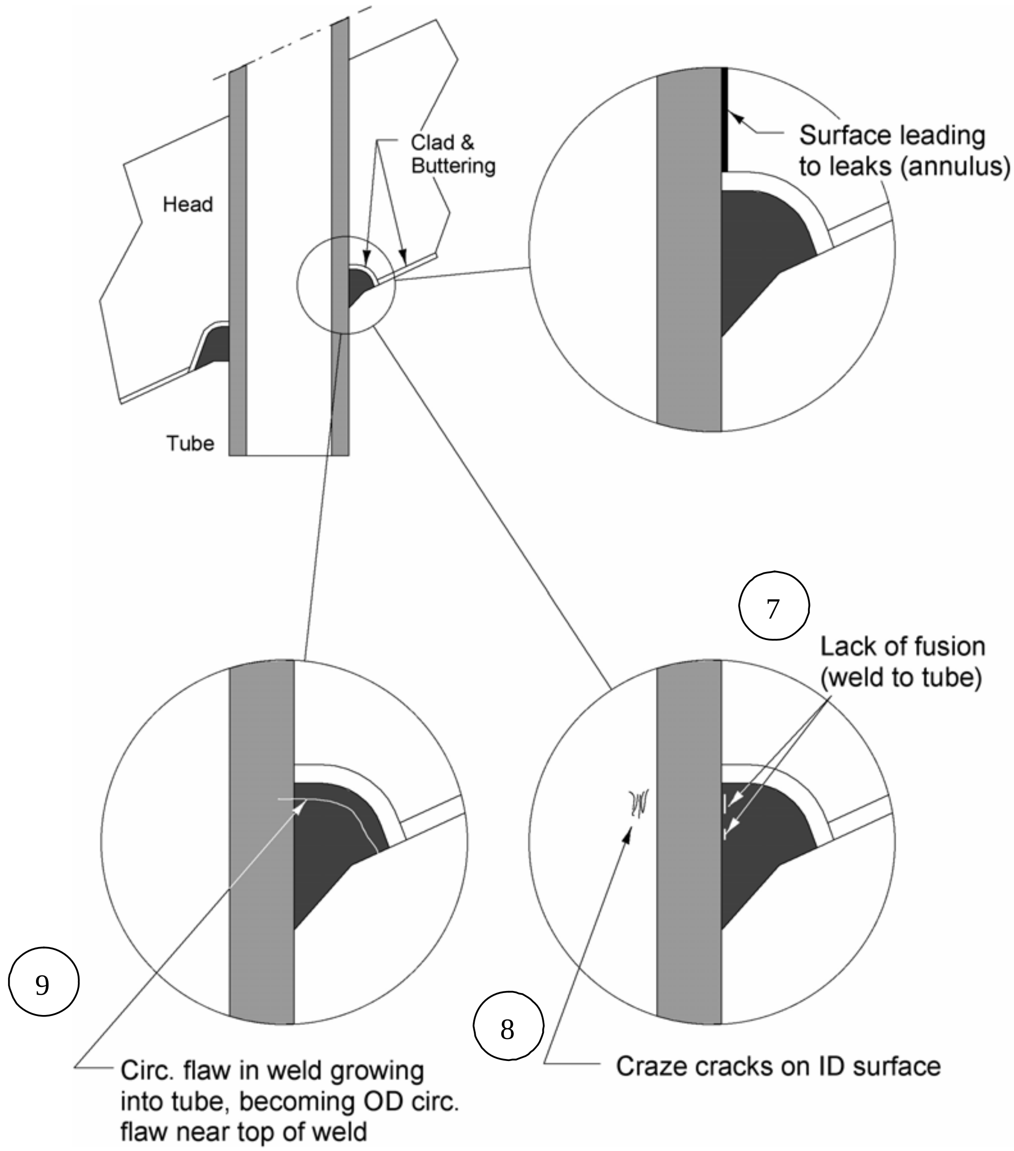


Figure 3-2
Flaw Locations 7 Through 9

3.3 Detection

Detection and reporting of degradation are essential for the engineering evaluation of the conditions for continued service of the penetration or its repair. Flaw location and orientation are identified in the previous paragraph; but, in general, the actual minimum flaw size and depth to report for the various locations are difficult to address. Flaw location with respect to the weld is an important objective of the examinations because each plant and individual penetration has its specific attributes for the determination of actual critical flaw size.

The MRP Assessment ITG has established flaw detection limits based on the following:

- A missed flaw left in service
- Inspection frequency and its effect on the core damage frequency (CDF)
- Public safety
- Leakage management

See Section 7 for the established detection requirements.

3.4 Length and Depth of Critical Flaws

Critical flaw sizes that pose a risk of resulting in rupture or wastage were analyzed. The basic approach used to develop acceptable flaw sizes and required detection probability is determined by keeping the increase in predicted CDF caused by flaws in the nozzles to 1E-6 per year or less. Flaws for which detection is necessary are calculated by determining the critical flaw size. Based on crack growth rates, the time necessary for the cracks to grow to a critical flaw size is calculated considering the following:

- End-of-inspection crack sizes
- Frequency of rupture
- Effect on CDF

Criteria for addressing the length and depths of detected flaws are addressed in Section 7.

3.5 Sizing of Indications

Each indication reported in the demonstration shall be sized based on the qualified inspection technique. For volumetric inspection by UT methods, the indication shall have both length and depth reported. Surface inspection by ET shall report only the length of the indication. Acceptance requirements for the qualified NDE inspection method or technique are addressed in Section 7.

4
REVIEW OF CURRENT DEMONSTRATIONS

4.1 Basis

The upper head penetration demonstration process has evolved to include addressing the inspection findings and the resulting changes to inspection requirements. A CRDM/CEDM NDE demonstration program to address cracking on the ID surface of the penetration has been in place since 1994. This early phase of demonstrations is documented in the EPRI report *Demonstration of Inspection Technology for Alloy 600 CRDM Head Penetrations* (TR-106260) [1].

The CRDM/CEDM demonstration process was expanded after the discovery of cracking of the OD surface and attachment weld. This second phase of demonstrations for OD-initiated flaws began in August 2002. The mockups contained manufactured flaws to simulate PWSCC in both the penetration tube and the attachment weld. The second phase of demonstrations contained enough tube flaws to demonstrate UT detection and depth-sizing capabilities. Flaws in the wetted surface of the attachment weld were also included to demonstrate ET detection and length-sizing capabilities.

A description of the demonstration activities can be found in the EPRI report *Materials Reliability Program: Demonstrations of Vendor Equipment and Procedures for the Inspection of Control Rod Drive Mechanism Head Penetrations (MRP-89)* (1007831) [12].

4.2 Objectives and Results

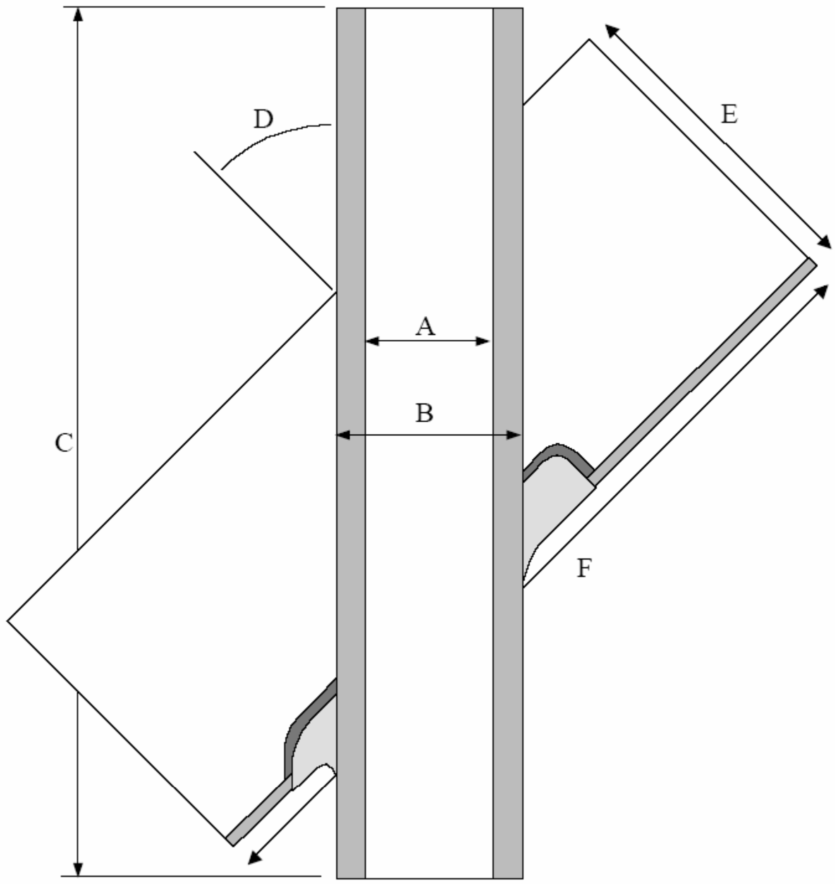
The objective of the CRDM/CEDM demonstrations was to determine the adequacy of the vendor equipment and procedures for the detection of flaws on both surfaces of the penetration tube wall, the volume of the tube, and the interface of the J-groove weld to the penetration. This determination also included designing and constructing a mockup for demonstrating crack detection on the wetted surfaces of the J-groove weld. The original focus was to demonstrate the capabilities of the examination procedures but not those of the personnel. The results of these demonstrations are presented in EPRI report 1007831 [12].

5 MOCKUP DESCRIPTION

5.1 Initial Demonstration Mockup Design Considerations (1992)

The design of the performance demonstration process for CRDM/CEDM examinations began in late 1992 by EPRI staff and members of the AHAC inspection subgroup. The objective was to provide a comprehensive set of blind demonstration mockups with ID-connected base-metal flaws that would allow participating utilities and their inspection vendors to quantify the capabilities of head penetration inspection procedures and techniques through a demonstration process. Only the inside surface was considered to be a credible location for crack initiation; and, therefore, no mockups were made with OD-initiating flaws.

It was not possible to meet the objective of having many flaws with well-controlled and well-known sizes and locations by using field-removed flaws because not enough field-removed flaws were available. Furthermore, accurate dimensioning of field-removed flaws would require destructive analysis of the mockups at the completion of the demonstration activities and remove them from future demonstrations. In addition, the AHAC inspection subgroup determined that all mockups were to remain nonradioactive, which precluded the use of field-removed components. Realistic mockups were recognized as essential to the effective and credible demonstrations of inspection capability. Accordingly, full-scale mockups were designed, constructed, and used for the inspection capability demonstrations, as shown in Figure 5-1.



Mockup ID	Type	Flaw Location	Flaw Type	Vendor Use	A (inch)	B (inch)	C (inch)	D (deg)	E (inch)	F (inch)	Width (inch)	Weight
A	B&W	Alloy 600/Tube ID	EDM CIP	Demo	2.77	4.02	17.0	38.5	6.9	18.0	18.0	~640 lbs
B	CE	Alloy 600/Tube ID	EDM CIP	Demo	2.73	4.05	24.0	52.0	6.8	30.3	12.8	~750 lbs
C	W	Alloy 600/Tube ID	EDM CIP	Demo	2.75	4.02	19.0	47.0	7.0	21.5	18.0	~770 lbs
D	CE/ICI	Alloy 600/Tube ID	EDM CIP	Practice	4.75	5.56	24.0	58.0	6.5	31.0	12.0	~685 lbs
E	Generic	Alloy 600/182/82/Tube ID & Weld	EDM	Practice	2.75	4.00	22.5	43.0	7.0	21.5	18.0	~770 lbs
F	B&W	Alloy 182/82/Weld	MF & LOF	Demo	2.75	4.00	24.0	20.0	6.0	26.0	26.0	~1150 lbs
G	Generic	Alloy 600/Tube OD	EDM	Practice	2.75	4.00	18.0	43.0	6.6	17.5	16.8	~550 lbs
H	Generic	Alloy 600//182/82/Tube OD & Weld	EDM CIP & LOF	Practice	2.75	4.0 to 4.8	15.0	43.0	n/a	n/a	n/a	~45 lbs
I	Generic	Alloy 182/82/Weld	SCC	Practice	2.75	4.00	6.0	43.0	n/a	n/a	n/a	~30 lbs
K	Generic	Alloy 600/182/82/Tube OD & Weld	EDM CIP	Practice	2.75	4.00	12.0	43.0	2.0	18.0	18.0	~200 lbs
L	Generic	Alloy 182/82/Weld coupons	SCC	Demo	2.75	4.00	12.0	43.0	n/a	18.0	18.0	~100 lbs
N	Generic	Alloy 600/182/82/Tube OD & Weld	Axial SCC	Practice	2.75	4.0 to 4.5	9.0	n/a	n/a	n/a	n/a	~25 lbs
P	Generic	Alloy 600/182/82/Tube ID, OD, & Weld	EDM CIP	Demo	2.75	4.00	18.0	43.0	6.6	18.0	18.5	~630 lbs
Q	Generic	Alloy 182/82/Weld	EDM HIP	Demo	2.75	4.00	18.0	43.0	6.6	18.0	18.5	~630 lbs
R	Generic	Alloy 600/Tube ID & OD	EDM CIP	Demo	2.75	4.0 to 4.4	13.0	n/a	n/a	n/a	n/a	~30 lbs
S	Generic	Alloy 600/Tube ID & OD	TF	Practice	2.75	4.00	12.0	n/a	n/a	n/a	n/a	~25 lbs
T	W	Alloy 690/Tube ID Thread & OD	EDM HIP	Demo	2.75	4.00	11.0	n/a	n/a	n/a	n/a	~25 lbs
U	W	Alloy 690/Tube ID & OD Thread	EDM HIP	Demo	2.75	4.00	6.0	n/a	n/a	n/a	n/a	~15 lbs
600C	n/a	Alloy 600/182/82/Tube ID, OD, & Weld	EDM CIP, FBH, & SDH	Trans	2.75	4.0 to 4.7	12.0	n/a	n/a	n/a	n/a	~35 lbs
690C	n/a	Alloy 690/152/52/Tube ID, OD, & Weld	EDM CIP, FBH, & SDH	Trans	2.75	4.0 to 4.7	12.0	n/a	n/a	n/a	n/a	~35 lbs

Abbreviations:
ID-Inside Diameter, OD-Outside Diameter, EDM-Electical Discharge Machining notch, CIP-Squeezed w/Cold Isostatic Processing, MF-Mechanical Fatigue Crack, LOF-Welding Lack of Fusion, SCC-Stress Corrosion Crack, Circ-Circumferentially oriented, HIP-Squeezed w/Hot Isostatic Processing, TF-Thermal Fatigue Crack, Demo-Blind Demonstration Mockup, Practice-Open Practics Mockup, FBH-Flat Bottom Hole, SDH-Side Drilled Hole, Trans-Transfer mockups used to compare Alloy 600 and Alloy 690

Figure 5-1
Mockup Dimensions

Specific dimensions, configurations, and assembly procedures for each penetration design were provided by respective owners group members. The mockups were designed to be used as a set because of similarities in head penetration configurations, physical dimensions, and penetration angles. Mockups A, B, C, D, and E as seen in Figure 5-1 were fabricated during this phase of the manufacturing process. A representative full-scale mockup of the head penetration configurations from each of the original equipment manufacturers (OEMs)—including B&W, CE, and Westinghouse—was fabricated. The mockups were constructed using ferritic material to simulate the vessel head, Alloy 600 tube material, and Alloy 82/182 for the weld material as used by the OEM. Original dimensions and production fabrication methods, including welding processes, were used to ensure that realistic conditions, such as surface distortion and ovality of the tube, were replicated. The review of service experience, described in Section 2, revealed a range of component configurations and challenges to inspection. It is neither practical nor necessary to replicate the full range of geometric conditions that can be found in installed components. Therefore, the mockups used in performance demonstrations contain conditions and features representative of the most challenging situations, such as surface irregularities, slope of penetration weld, clearances, and ovality.

The flaw matrix included a variety of flaw depths, lengths, and orientations. This flaw matrix was distributed throughout the mockups to economize fabrication costs. Each mockup scheme was developed from a combination of flaw acceptance standards developed by the AHAC and from information obtained during European inspection reviews. The flaws placed in these head penetration mockups included the following types of ID-connected flaws:

- Axially oriented flaws
- Circumferentially oriented flaws
- Clustered flaws
  - Parallel orientation
  - End-to-end orientation (linear)
- Skewed flaws (off-axial)
- Branched flaws

Examples of these various flaw types can be seen in Figure 5-2, although the intentional scratches and magnetic deposits are not shown. This phase of the mockup construction for CRDM demonstrations has been in place since 1994. For a complete description of the initial mockup fabrication process, refer to the EPRI report *Demonstration of Inspection Technology for Alloy 600 CRDM Head Penetrations* (TR-106260) [1].

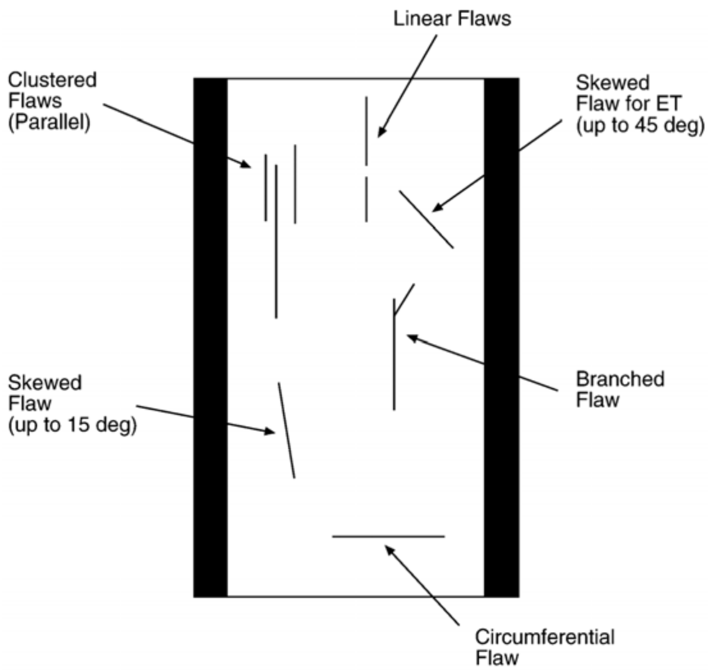


Figure 5-2
Illustration of Various Inside Diameter Flaw Types

5.2 Demonstration Mockup Design Considerations After Inspection Input (2001–2002)

During the spring outage season of 2001, OD tube flaws and J-groove weld cracking were identified in the PWR fleet, and the industry determined that the CRDM/CEDM NDE demonstration program should be expanded to include these findings. Additional mockups were designed and built to accommodate this requirement. The MRP inspection demonstrations were done in the following two phases:

- Phase 1 demonstrations were conducted in the fall of 2001 to support fall 2001 and spring 2002 inspection activities. The mockups addressed flaw detection with UT and ET in only the RPVH tube material with:
  - Field-removed penetrations containing PWSCC axial and circumferential cracking on the ID and the OD of the tubes. The penetrations tube samples were obtained from the reactor head of Oconee Unit 3 and were used in an open demonstration (see Figure 5-3).
  - One full-scale mockup with a minimum number of synthetic flaws connected to the OD surface in the axial and circumferential orientations. This mockup was used in a blind fashion (see Figure 5-4).

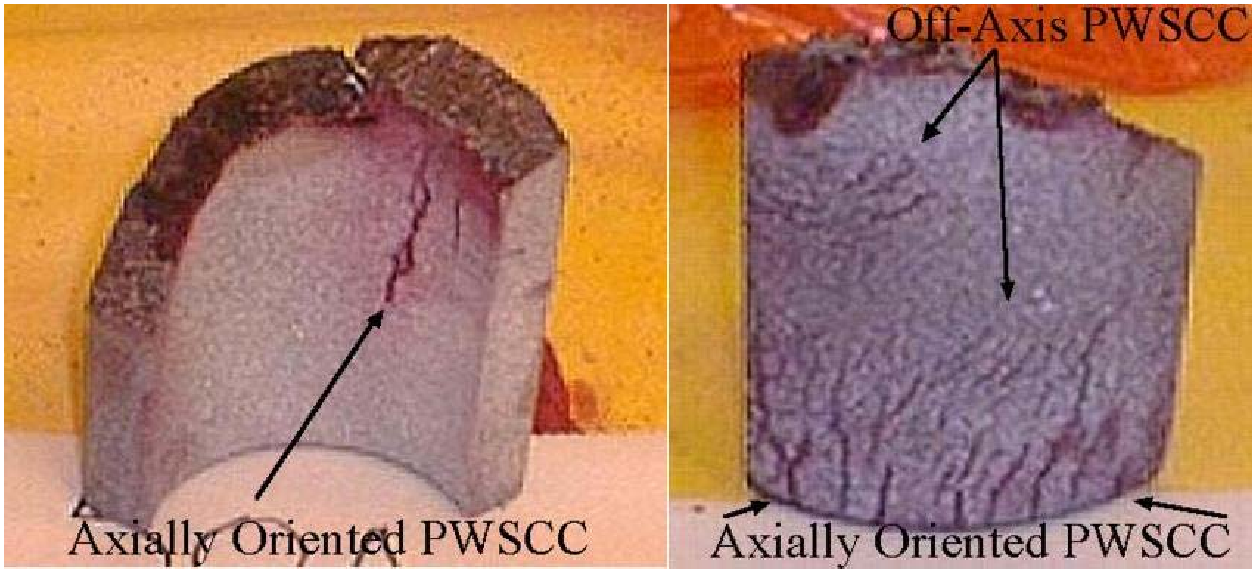


Figure 5-3
Field-Removed Primary Water Stress Corrosion Cracking

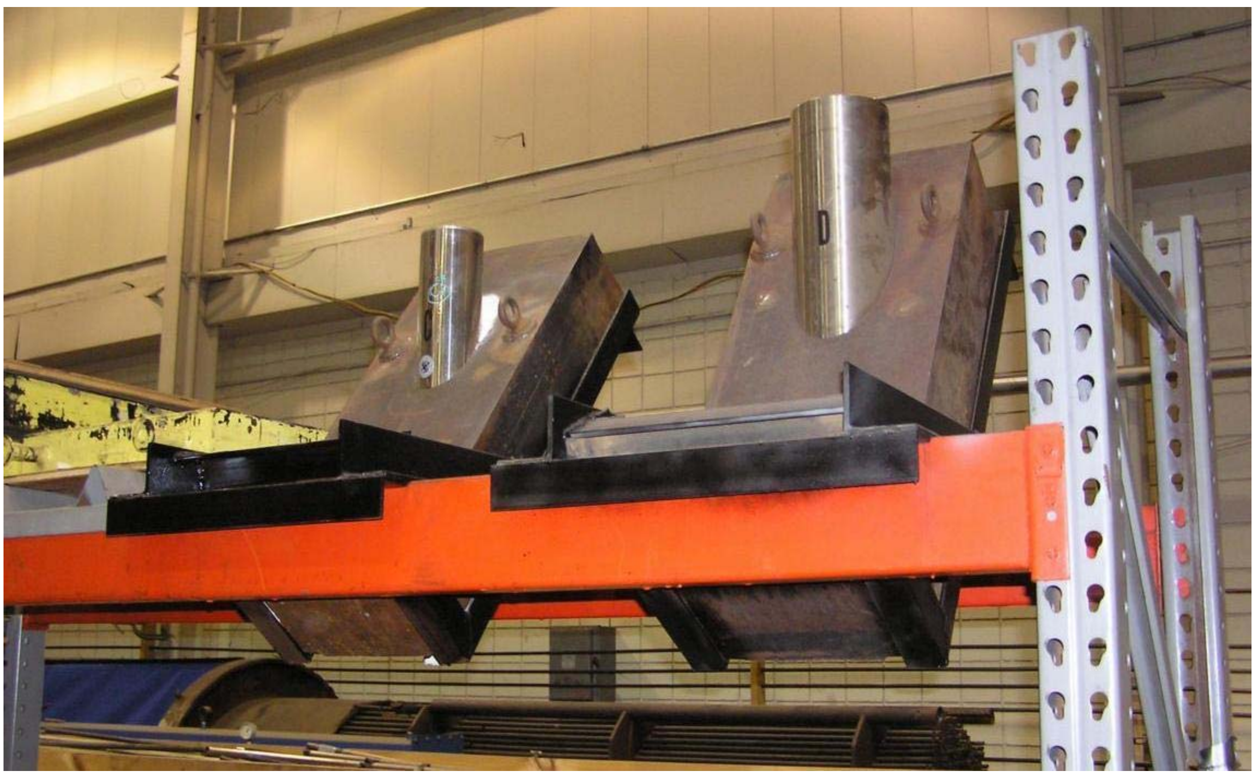


Figure 5-4
Full-Scale Control Rod Drive Mechanism Tubing Mockups

- Phase 2 demonstrations started in August 2002 to support fall 2002 inspections and beyond. The mockups addressed flaw detection with UT and ET in the tube material and in the J-groove weld as follows:
  – One full-scale and one partial-scale mockup with a large number of synthetic flaws connected to the OD surface in the axial and circumferential orientations. These mockups were used in a blind fashion.
  – One of the full-scale mockups with ID connected flaws from the 1994–1998 round of demonstrations was used because the vendors had changed their equipment. This mockup was used in a blind fashion.
  – One full-scale mockup with synthetic flaws in the J-groove weld was used to evaluate the inspection methods with relationship to the complete geometry of the component. This mockup was used in a blind fashion.
  – One full-scale plastic mockup with pockets was used to evaluate surface methods proposed for the wetted surface of the attachment weld. The flaws in this sample were laboratory-grown SCC coupons. The interchangeable SCC flaw inserts contain a range of crack orientations and crack widths on the wetted surface of the attachment weld mockup. Crack width is an important variable for surface inspection methods (for example, ET). The coupons can be rotated to change the configuration. This mockup was used in a blind fashion (see Figure 5-5).

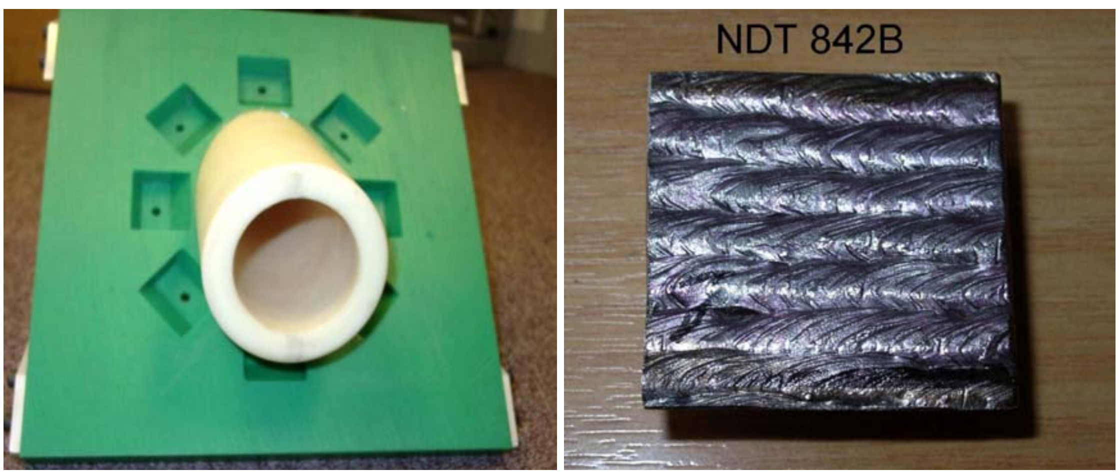


Figure 5-5
Full-Scale CRDM/CEDM J-Groove Weld Mockup

The 2001–2002 demonstrations used full-scale mockups consisting of Alloy 600 tubing welded into a simulated section of RPV head. These mockups contain the following flaw types:

- Axial/radial and circumferential/radial flaws in the tube
- Flaws located above, below, and adjacent to the attachment weld area
- Circumferential flaws following the weld
- Groups of axial/radial and circumferential/radial flaws

Some circumferential flaws are located with a closely associated axial flaw. In addition, axial/radial and circumferential/radial cracks were included on the wetted surface of the attachment weld. Typical mockup dimensions are shown in Figure 5-1.

5.3 Flaw-Making Techniques

Realistic and appropriate mockups are important for technique development and acceptance of NDE inspection technique and procedure demonstration activities. In order to build a realistic mockup, realistic flaw-making techniques must be used. The majority of the tube flaws have been manufactured for the demonstration process using the electrical discharge machine (EDM) squeezed cold isostatic processing (CIP)/hot isostatic processing (HIP) technique as can be seen in Figure 5-1. This manufacturing technique has been used to better demonstrate the depth-sizing capabilities of the inspection techniques. Where detection only or length sizing is of concern, other manufacturing techniques have been used in which the synthetic flaw can be verified visually. The EPRI report *Development of Flaw Making Techniques for Use in NDE Mockups of Austenitic Materials* (1011620) contains a more complete description of all of the flaw-making processes [13].

The flaw-manufacturing focus has been to develop flaws that can be used in the demonstration process for the upper head penetrations and their attachment welds. Many of these flaw-making techniques can be applied to other austenitic mockup configurations throughout the PWR plant. Because the CRDM penetrations have been inspected exclusively with ET and UT NDE inspection techniques, the flaw-making techniques have focused on the development of flaws appropriate for these inspections. The appropriateness and realistic NDE response from the synthetic flaw is important. The EPRI report *Comparison of Field and Manufactured Flaw Data in Austenitic Materials* (1011613) compares actual field-removed flaws with those of manufactured synthetic flaws [14]. In this report, the NDE responses from manufactured flaws are compared to field-removed flaws and are shown to be comparable.

6
EXAMINATION METHODS

6.1 Procedure Requirements

Procedure requirements shall address all essential variables that affect system performance, and they are evaluated through the demonstration process described in Section 7. These influential parameters are addressed in ASME, Section V, Article 14, "Examination System Qualification" [15] and required by ASME Boiler and Pressure Vessel Code Case N-729-1 [6].

The examination procedure shall contain a statement of inspection scope that specifically defines the limits of procedure applicability (that is, materials, thickness, diameter, coverage, flaw orientation, and product form). The acquisition procedure or the analysis procedure—or both, as applicable—shall address the requirements for system calibration. Calibration requirements include those actions required to ensure that the sensitivity and accuracy of the signal amplitude and time outputs of the examination system—whether displayed, recorded, or automatically processed—are repeatable and correct. Any process of calibrating the system is acceptable, and a description of the calibration process shall be included in the procedure. The procedure shall address the surface and cleanliness condition for an acceptable inspection. The procedure shall describe the method for distinguishing between relevant and nonrelevant indications and the following:

- The justification for sensitivity settings
- The criteria for accepting the quality of the data
- The criteria for characterizing flaws

UT procedures shall include techniques that describe depth- and length-sizing of flaws. ET procedures shall include techniques for measuring the length of flaws.

6.2 Essential Variables

An essential variable describes parameters that directly affect the capability of the system to detect and size flaws. The procedures will include clearly identified essential variables. Unless otherwise stated in this document, the examination procedure shall identify parameters for the essential variables listed in the following paragraphs.

6.2.1 Ultrasonic Essential Variables

The examination procedure shall specify a single value or a range of values for all of the identified essential variables and as a minimum shall specify the following essential variables:

- Equipment:
  - System configuration (instrument or system, including manufacturer, model, and series of pulser, receiver, and amplifier)
  - Acquisition software (version or revision)
  - Search units (SUs) information including:
    - Center frequency and bandwidth or waveform duration
    - Mode of propagation and nominal inspection angles
    - Number, size, shape, and configuration of active elements and wedges or shoes
    - Probe center separation for time-of-flight diffraction SUs
    - Additional information for phased array search units:
      - Number, size, shape, and arrangement of array elements
      - Definition of the acceptable number and arrangement of inactive array elements or beamforming channels
      - Definition of electronic scan patterns, including beam angles, focal distances or depths, array elements used in beamforming for each A-scan, and software version or revision number used to calculate the parameters controlling the electronic scan (For each A-scan, this includes the transmission delay, reception delay, gain, and pulse voltage for each array element as well as the beam index position.)
      - Calibration techniques
  - Search unit cable, including:
    - Type
    - Maximum length
    - Maximum number of connectors
  - Recording equipment and media (such as DVD, hard disk, or optical disk when used)

- Acquisition setup:
  - Analog-to-digital digitization rate (frequency of sampling)
  - Scan pattern (for example, helical pitch and direction, rectilinear rotation, length, and scan index or overlap)
  - Sampling rate (for example, data acquisition sample per inch)
  - Scan rate (for example, probe speed [inches per second])
  - Extent of scanning and action to be taken for access restrictions
  - Couplant
- Calibration:
  - Methods of calibration for detection and sizing (that is, the actions required to ensure that the sensitivity and accuracy of the signal amplitude and time outputs of the examination system—whether displayed, recorded, or automatically processed—are repeated from examination to examination).
- Analysis:
  - Analysis software (version or revision)
  - Manufacturer and model of UT data analysis equipment
  - Method and criteria for the discrimination of relevant indications (that is, geometric versus flaw indication, fabrication flaws versus cracking, and for length- and depth-sizing of flaws)
  - Detection and sizing techniques

6.2.2 Eddy Current Essential Variables

The examination procedure shall specifically define the following essential variables as a single value, range of values, or formula; and as a minimum, shall specify the essential variables. The data acquisition procedure shall specify the following:

- Hardware:
  - Instrument or system, including manufacturer’s name and model
  - Recording equipment and media (such as DVD, hard disk, or optical disk when used)
  - Size and type of probe, including orientation of coil(s), manufacturer’s name and part number (magnetic bias probe)
  - Probe cable type and length
  - Extension cable type and length

- Acquisition:
  - Examination frequencies, or minimum and maximum range, as applicable
  - Coil excitation mode (for example, absolute or differential)
  - Extent or area of the component to be examined
  - Minimum data to be recorded
  - Analog-to-digital digitization rate (frequency of sampling)
  - Scan pattern (for example, helical pitch and direction, rectilinear rotation, length, and scan index or overlap):
    - Sampling rate (for example, data acquisition sample per inch)
    - Scan rate (for example, probe speed [inches per second])
    - Extent of scanning and action to be taken for access restrictions
- Calibration:
  - Method and criteria for the discrimination of indications (that is, geometric versus flaw indication, fabrication flaws versus cracking, and for length sizing of flaws)
- Analysis:
  - Method of calibration (for example, phase angle or amplitude adjustments)
  - Channel and frequencies used for analysis
  - Extent or area of the component evaluated
  - Data review requirements (for example, secondary data review and computer data screening)
  - Reporting requirements (that is, signal-to-noise threshold, voltage threshold, and flaw-depth threshold)
  - Methods of identifying relevant indications and distinguishing them from nonrelevant indications (such as indications from probe liftoff or conductivity and permeability changes)
  - Manufacturer and model of ET data analysis equipment
  - Manufacturer, title, and version of data analysis software (as applicable)

7
QUALIFICATION PROGRAM

7.1 Demonstration Process

The demonstration program will meet the intent of ASME Section V, Article 14, "Examination System Qualification," [15] by using intermediate rigor. The sample sets for these qualifications will be sufficient to ensure that qualified procedures and personnel will have acceptable detection and false call rates and sizing accuracy for flaws defined by the MRP Assessment ITG. These performance demonstrations will achieve this through the use of blind mockup testing.

7.2 Protocol

The demonstration process addresses the capability of UT procedures applied from the ID or OD of the tube and surface ET methods on the wetted surfaces of the tubing and J-groove weld.

The objectives of this qualification program are:

- To ensure that adequate inspection capabilities are available
- To provide information on the performance of NDE procedures to characterize flaws that can be present in the penetration base material and the attachment weld wetted surfaces
- To provide a means to evaluate flaw detection, location, and sizing capabilities

The inspection techniques shall address the following:

- Ultrasonic examination:
  - Detection of axial and circumferential degradation within the penetration tube volume
  - Detection of isolated flaws
  - Discrimination of axial and circumferential flaws in close proximity
  - Detection of ID- and OD-connected flaws
  - Detection of lack of fusion and other flaws at the tube to weld interface
  - Discrimination of flaws from sources of nonrelevant indications (false calls)
  - Measurement of flaw location relative to component geometry
  - Measurement of flaw length and depth sizing (only for flaws emulating service-induced conditions)

- Eddy current examination:
  - Detection and length sizing of radial and circumferential degradation of both the wetted surface of the tube and the wetted surfaces of the J-groove attachment weld
  - Discrimination of flaws from sources of nonrelevant indications (false calls)
  - Measurement of flaw location relative to component geometry

The protocol used during previous demonstrations is documented in Section 8 of the EPRI MRP report *Materials Reliability Program: Demonstrations of Vendor Equipment and Procedures for the Inspection of Control Rod Dive Mechanism Head Penetrations (MRP-89)* (1007831) [12] and is the foundation of the qualification program addressed under the MRP Performance Demonstration Project Quality Plan.

7.3 Review of Procedures

The procedure review is outlined in the MRP NDE Performance Demonstration Project Quality Plan and Quality Plan Instructions. These instructions provide the means to review and control the procedural documents that are intended to meet the requirements of this program. It shall ensure, as a minimum, that the procedure has addressed all techniques, essential variables, and procedural requirements necessary to conduct a qualification demonstration.

7.4 Demonstration Flaws

Demonstration flaws shall be planar defects connected to a wetted or potentially wetted surface. Flaws may be oriented in either the axial or the circumferential direction. Circumferential flaws should follow the direction of the J-weld rather than follow the circumference of the nozzle.

Demonstration target flaw sizes of interest are based on an analysis performed by the MRP Assessment ITG. Target flaw sizes are those with dimensions that must be detected to ensure that the structural integrity of the penetrations between inspection cycles is maintained. The values and basis are found in the letter report “Required Flaw Detection Size and Examination Reliability for Reactor Vessel Head Nozzle Examinations” [11]. The sizes are bounding, but the information in the letter report may be used to develop plant-specific target flaw size criteria, which might be useful in qualifying techniques more quickly.

The depth of all flaws shall be at least 10% of the nozzle thickness. The target size of interest for axial flaws is a depth of 15% of the nozzle thickness and a length of 90% of the nozzle thickness. The target size of interest for circumferential flaws is a depth of 100% of the nozzle thickness and a length of 10°, or flaws of equivalent area (for example, 25% through-wall and 40° long).

In each demonstration specimen set, at least 30% of the flaws shall be in the depth range 10–30% through-wall, and at least 30% of the flaws shall be in the depth range 31–50% through-wall. At least 30% of the nozzle flaws shall be connected to the nozzle inside surface, and at least 30% shall be connected to the nozzle outside surface. Axial flaws shall represent 30–60% of the total number of flaws.

The demonstration specimen set must contain at least a minimum amount of unflawed area. For the purpose of determining detection, each demonstration flaw shall have a location tolerance of 0.5 in. (12.7 mm) in the axial direction and 10° in the circumferential direction. An unflawed area is considered to be the entire surface area within the examination volume that is susceptible to crack initiation, minus the combined area of all the demonstration flaws and their associated location tolerances. (For example, an axial flaw 0.75-in. [19.05-mm] long has a location tolerance area of 1.75 in. [44.45 mm] in the axial direction multiplied by 20° in the circumferential direction. A circumferential flaw 30° long has a location tolerance area of 1 in. [25.4 mm] in the axial direction multiplied by 50° in the circumferential direction.) In an acceptable demonstration specimen set, the unflawed area must be at least three times the combined area of the demonstration flaws' location tolerances.

7.5 Acceptance Criteria

The objective of this performance demonstration program is to meet the intent of ASME Boiler and Pressure Code Case N-729-1 [6]. The demonstrations shall meet the requirements for intermediate rigor as defined in ASME Section V, Article 14 [15].

7.5.1 Detection and False Calls

If any part of a reported flaw indication falls within the location tolerance of a demonstration flaw, the demonstration flaw shall be considered to have been detected. If a reported flaw indication intersects none of the demonstration flaws' location tolerances, the reported flaw indication shall be considered to be a false call.

7.5.1.1 Procedure Demonstration

Procedure demonstration specimen sets shall include a sufficient number of flaws to comprise at least three separate personnel demonstrations. All flaws equal to or greater than the target flaw size of interest must be detected. The number of false calls must be ≤20% of the number of flaws in the specimen set.

7.5.1.2 Personnel Demonstration

Personnel demonstration specimen sets shall include at least 10 flaws that are as large as, or larger than the target flaw size of interest. In an acceptable demonstration, at least 80% of all flaws larger than the target size of interest must be detected, and the number of false calls must be ≤20% of the number of flaws in the specimen set.

7.5.2 Length Sizing

In an acceptable demonstration, the RMS value of length-sizing errors shall be ≤0.375 in. (≤9.525 mm).

7.5.3 Depth Sizing

In an acceptable demonstration, the RMS value of depth-sizing errors shall be ≤0.125 in. (≤3.175 mm).

7.6 Reporting Criteria

The procedures for each inspection method shall have criteria for reporting and resolutions of indications detected. There shall be clear instructions for the resolution and final assessment of each indication reported. The procedures shall define the responsibilities for resolutions and disposition of all indications reported.

7.7 Security Program

The MRP NDE Performance Demonstration Project Quality Plan will use the PDI Quality Instructions for security plan requirements. The security plan will encompass the demonstration specimens, answer keys, and the acquired data and records (both paper and digital) to the level of security necessary to ensure the security of the program.

7.8 Retest

Retesting for procedure qualification may be done as many times as necessary to qualify the procedure. Before any retesting, the procedure shall be reviewed to determine changes needed to improve the procedure performance. Retesting shall require that at least 50% of the flaws in the new test set were not included in the previous test set.

For personnel retesting for the first time, the candidate shall have been given feedback from the performance demonstration administrator before retesting. If the candidate fails a second time, the individual shall receive the necessary retraining of the specific technique application from the employer. There shall be at least a seven-day waiting period before retesting, and the employer shall provide appropriate documentation of the training administered. Retesting shall require that at least 50% of the flaws in the new test set were not included in the previous test set.

7.9 Use of Existing Mockups

The existing mockups will be submitted for Nuclear Commercial Grade Dedication (CGD) according to the EPRI Quality Assurance Procedure (QAP) 7.2, Revision 7. The CGD will include the materials, product form, induced artificial flaws as well as the verification of flaw response to the NDE method being used to detect and size these flaws. In addition, the nonrelevant responses and nonflawed areas shall be mapped to facilitate grading. After the CGD is complete and the mockup flaws are acceptable to the requirements of this program description, the acceptable mockup flaws used in previous procedure demonstrations will be incorporated into this program.

7.10 Use of Previous Demonstration Results

Demonstrations performed before the publication of this program description may be evaluated for acceptance based on the requirements set forth herein. Such evaluations shall include procedure review to ensure compliance to the essential variables, detection, sizing, and false call requirements of this program description. Demonstrations will be reviewed to determine whether the personnel that performed the procedure demonstration (analysis) meet the personnel qualification requirements for detection and sizing. All procedures and personnel that passed these qualification program requirements shall be considered to be qualified.

7.11 Record Retention

Records of demonstrations and their results will be maintained according to the MRP Performance Demonstration Project Quality Plan and Quality Plan Instructions. The qualified procedures and personnel will be posted on the EPRIQ web server under MRP NDE Performance Demonstrations.

8
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