PNNL-33730

Literature Review: NDE of Partial Penetration Welds in Reactor Pressure Vessels

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PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
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Summary

Reactor pressure vessel upper head and bottom mounted penetrations, fabricated from Alloy 600, 82, and 182 materials, have experienced PWSCC-related degradation over the past 25 years. There is currently no accepted or qualified volumetric inspection technique for partial penetration welds. The need to better understand the potential impact and relevance of nondestructive examination (NDE) advancements and novel ultrasonic probe designs on improvements to volumetric examination capabilities for these welds has been identified. PNNL conducted a literature search to identify new techniques and advanced NDE capabilities, including off-the-shelf ultrasonic probes and the latest research aimed at detecting and sizing flaws in these welds. A synopsis of findings from the literature review are provided here.

Overall findings:

- There have been few innovative or nonconventional ultrasonic NDE approaches to inspecting partial penetration welds in nuclear reactor pressure vessels to emerge in the past 20 years.
- Many reports were conference papers that lacked important details of ultrasonic probe construction and inspection methods, so it cannot be discerned if methods were novel.
- References from companies that discuss progress or new probes do not reveal trade secrets or details about methods or equipment.
- There are few research articles on the topic, indicating that little academic attention is paid to this field.
- Much recent work is focused on robotic or remote deployment systems and not NDE.
- Several reports described confirmatory research and round robins to assess inspection capabilities; however, these reports were published by Pacific Northwest National Laboratory (PNNL) and funded by the U.S. Nuclear Regulatory Commission (NRC).
- Most references cited a need for better and more frequent examinations, which was motivated by cracking and leakage found in U.S. plants in the late 1990s and early 2000s. However, as noted in section 3.0 of this report, American Society of Mechanical Engineers (ASME) Code now addresses the requirements for upper and lower head examinations.

Primary needs identified:

- The following primary needs were identified as research drivers:
  - Rapid examinations to reduce examination time, radiation exposure, and outage downtime
  - Non-contact examinations or remote examinations
  - Examinations that do not require removal of pressure vessel head
  - Cost reductions
  - Continuous monitoring or structural health monitoring
  - Earlier detection of smaller cracks
  - Better inspection of complex geometries, such as control rod drive mechanism J-groove weld curvature
  - Inspection techniques that meet regulatory requirements.

Acronyms and Abbreviations

ASME	American Society of Mechanical Engineers
BMI	bottom mounted instrumentation
BMVE	bare metal visual examination
BWR	boiling water reactor
CASS	cast austenitic stainless steel
CISCC	chloride induced stress corrosion cracking
CFR	Code of Federal Regulations
CEDM	control element drive mechanism
CRDM	control rod drive mechanism
DMW	dissimilar metal weld
EPRI	Electric Power Research Institute
ET	eddy current testing
ID	inner diameter
ISI	inservice inspection
LWR	light water reactor
MRP	Materials Reliability Program
NDE	nondestructive examination or evaluation
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
OD	outside diameter
OE	operating experience
PA	phased array
PARENT	Program to Assess the Reliability of Emerging Nondestructive Techniques
PA-UT	phased array ultrasonic testing
PINC	Program for the Inspection of Nickel Alloy Components
PNNL	Pacific Northwest National Laboratory
POD	probability of detection
PT	penetrant testing
PWR	pressurized water reactor
PWSCC	primary water stress corrosion cracking
NDE	nondestructive evaluation
NRC	U.S. Nuclear Regulatory Commission
RES	Office of Nuclear Regulatory Research
RPV	reactor pressure vessel
SCC	stress corrosion cracking

TLR	technical letter report
TOFD	time-of-flight diffraction
UPI	ultrasonic propagation imaging
UT	ultrasonic testing
VT	visual testing

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1.0 Introduction

For many years, the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES), has directed Pacific Northwest National Laboratory (PNNL) to conduct confirmatory nondestructive examination (NDE) research to support its mission. These research studies are generally focused on NDE related technical challenges or issues encountered during inservice inspections (ISI) of commercial U.S. nuclear power plants (NPPs). One such challenge deals with high nickel alloy materials found to be susceptible to a degradation mechanism known as primary water stress corrosion cracking (PWSCC). This issue has been a key area of focus for both industry experts and regulators for nearly 30 years (Cumblidge et al. 2010; IAEA 2011; Meyer and Heasler 2017).

Across the U.S. fleet of light water reactors (LWRs), Alloys 600, 82, and 182—nickel-chromium-iron-based steels—were used for component fabrication in both pressurized water reactors (PWRs) and boiling water reactors (BWRs). In PWRs, these alloys were used to fabricate upper head penetrations and partial penetration welds located within the reactor pressure vessel (RPV). As examples, these include upper head penetrations for thermocouples and control rod drive mechanisms (CRDMs), and bottom mounted instrumentation (BMI) nozzles. For welding purposes, Alloys 82 and 182 are filler metals used when welding to Alloy 600 base materials. There are numerous reasons for using Alloy 600 in this capacity, including its resistance to chloride induced stress corrosion cracking (CISCC) and lower susceptibility to cracking on the wetted surface. However, many years of operating experience (OE) indicate the need for more effective volumetric inspection techniques for these materials as current techniques are not capable of full-volumetric examinations of partial penetration welds (Cumblidge et al. 2010; Gorman et al. 2006; Grimmel 2005; IAEA 2011; Sullivan and Anderson 2014).

For upper head penetration assemblies, qualified volumetric examinations in accordance with American Society of Mechanical Engineers (ASME) Section XI, Appendix VIII, Supplement 15 are currently in use. Examinations for BMI nozzles are required to be demonstrated but not qualified in accordance with Appendix VIII. Most BMI nozzle examinations are performed visually in accordance with ASME Code Case N-722.

In this report, the term “J-groove weld” is associated with both CRDM penetrations and BMI nozzle penetrations and used interchangeably with the term “partial penetration weld” throughout the document. Partial penetration welds have experienced cracking in several past and recent inspections both domestically and internationally (Gorman et al. 2006; Grimmel 2005; IAEA 2011). The only methods currently available for inspecting partial penetration welds are bare metal visual examinations (BMVE) or surface examinations, such as penetrant testing (PT) or eddy current testing (ET) from the wetted surface. Ultrasonic testing (UT) using time-of-flight diffraction (TOFD) along with conventional UT examinations are performed from the inside of the CRDM penetration nozzles to inspect the nozzle base material for flaws. During these routine ultrasonic examinations of the penetration tube wall, UT signal responses can sometimes be acquired from portions of the J-groove weld volume. However, full-volume insonification of the J-groove weld cannot be achieved. These ultrasonic examinations can sometimes detect flaws in the adjacent volume of the partial penetration weld (Cumblidge et al. 2007b; Cumblidge et al. 2007a; Lara 2002; Lara 2003; Pajnić et al. 2010).

PNNL conducted a literature search to identify off-the-shelf ultrasonic probes/techniques, potential new and advanced NDE capabilities, and the latest research aimed at detecting and

sizing flaws in partial penetration welds. This report introduces the examination challenges and provides a discussion of current surface and volumetric NDE techniques performed for ISI of partial penetration welds, as a starting point. More effective volumetric inspection techniques for partial penetration welds would allow for more robust examinations and enhanced detection and characterization of flaws initiating from PWSCC. The report then summarizes new findings and recent NDE advances, including commercially available probes that could be applied for improved flaw detection performance and enhanced volumetric coverage.

1.1 Motivation for the Current Work

The U.S. NRC has identified a need to better understand the potential impact and relevance of NDE advancements and novel ultrasonic probe designs on improvements to volumetric examination capabilities for partial penetration welds. As NDE sensor technologies, detection techniques and signal processing methods continue to advance, flaw detection and characterization capabilities become more effective and reliable. Based upon OE and the history and susceptibility of Alloy 600/82/182 to PWSCC, NRC RES directed PNNL to conduct a literature search to identify and evaluate advanced NDE research, novel probe development, and state-of-the-art UT techniques for applicability to partial penetration weld examinations.

1.2 Scope and Objectives

PWSCC is a significant regulatory concern due to the potential for cracking or boric acid corrosion that could lead to a loss-of-coolant accident. As such, the NRC has been proactive in establishing regulatory requirements aimed at implementing more effective PWSCC inspection and mitigation techniques for partial penetration welds. The NRC has directed PNNL to conduct a literature search to identify and evaluate potential advances to the state-of-the-art in NDE for partial penetration welds. This effort focuses on novel or advanced probe designs and/or UT inspection techniques with the potential to improve volumetric examination capabilities for partial penetration welds.

The objective of the work is to report on these advancements and any relevant work showing promise for addressing the volumetric examination challenges inherent to these PWSCC susceptible materials. This activity targeted available published literature and reported research conducted by industry, ISI vendors, academia, and other NDE laboratories, both domestically and internationally.

1.3 Technical Approach to this Work

The approach taken for this technical letter report (TLR) was to identify and summarize the latest research and any existing commercially available instrumentation, probes, or techniques appropriate for volumetric UT examinations of partial penetration welds in RPVs. Initially it was assumed that ISI vendors and UT probe/instrumentation manufacturers would have published data or citable literature of partial penetration weld examination advancements available for review. However, the body of relevant work and technical details associated with vendor research in this area was very limited. This may be due to the competitive and proprietary nature of intellectual property used for commercial development and product designs/specifications by manufacturers. Information and research results that could be obtained and that provided sufficient technical details were reviewed and discussed here, based on their use for potentially improving volumetric UT examination of these welds. This TLR describes the findings from this literature survey.

1.4 Report Organization

For this effort, the authors assume that the reader is generally familiar with NDE and, in particular, with volumetric UT approaches for ISI, general RPV designs, and materials and relevant component geometries in PWRs. In this literature review, the primary focus was on partial penetration welds associated with upper head penetrations and BMI nozzles.

The report begins with a brief overview of partial penetration welds, including specific components, materials, weld designs and geometries that play a role in defining and impacting volumetric UT examinations. In addition, a brief discussion of the degradation mechanism (PWSCC), flaw characteristics, and resultant examination limitations and access issues are provided. Section 2.0 ends with a summary of NDE challenges and identified gaps that exist in terms of component/weld history and OE. Section 3.0 provides the reader with an understanding of current NDE ISI techniques for examining partial penetration welds, including ASME Code examination guidelines and requirements as well as illustrating the required examination volumes for these welds. Section 4.0 provides details of the literature search review and the pertinent findings, while section 5.0 provides a brief discussion of conclusions, summarizing those findings. Finally, section 6.0 contains the full listing of the references cited in this review.

2.0 Partial Penetration Welds

2.1 Components, Materials, Weld Designs and Geometries

The components of an operating nuclear power plant are subjected to operating conditions that may initiate flaws in susceptible materials. Attention on RPV head penetration examinations has increased in recent years due to their susceptibility to PWSCC. Penetrations in both the top and bottom RPV heads provide access for instrumentation or control mechanisms for various operating parameters and monitoring of the resulting conditions

The top head penetrations in a Westinghouse and Babcock & Wilcox design are known as CRDMs, while the Combustion Engineering design is called a control element drive mechanism (CEDM). The design and function are the same, and both are installed through the top surface of the RPV head and used to guide the movement of control rods in and out of the reactor core. The upper head is bolted to the RPV via a flange and must be removed during reactor refueling. The number of penetrations in the upper head varies, based on reactor design, and can include up to 97 penetrations.

The penetration nozzle, also referred to as a penetration tube, typically ranges from 89 mm (3.5 in.) to 109 mm (4.3 in.) in diameter. Most CRDM nozzles originally placed into service in PWRs were fabricated from the nickel-based alloy referred to as Alloy 600, along with the Alloy 82 and 182 partial penetration welds.

The installation is somewhat unique in that the nozzles are installed through the reactor vessel head (RVH) with a very small tolerance, typically with a maximum interface of 0.1 mm (0.004 in.) and shrink fitted. Once the nozzle has been inserted through the RPV head, it is welded to the inside surface with a partial penetration “J-groove” weld, named for the shape of the weld. The partial penetration weld provides a structural seal at the inside surface of the RPV head in addition to preventing distortion of the nozzle tube during stress relief that would occur from a full structural welding process. Figure 2.1 depicts this configuration (Cumblidge et al. 2007b) and figure 2.3 shows a photograph of the outside surface of an RPV upper head.

In typical Westinghouse PWR designs, a stainless steel thermal sleeve rests inside each CRDM nozzle and extends beyond the CRDM nozzle to just above the upper guide tube, as shown in figure 2.2. The thermal sleeves provide a lead-in for the rod cluster control assembly (RCCA) drive rods into the head penetration tubes during RVH installation and provide shielding of the head penetration tubes from thermal transients produced by varying temperature water that passes through the penetration area during RCCA drive rod stepping movements.

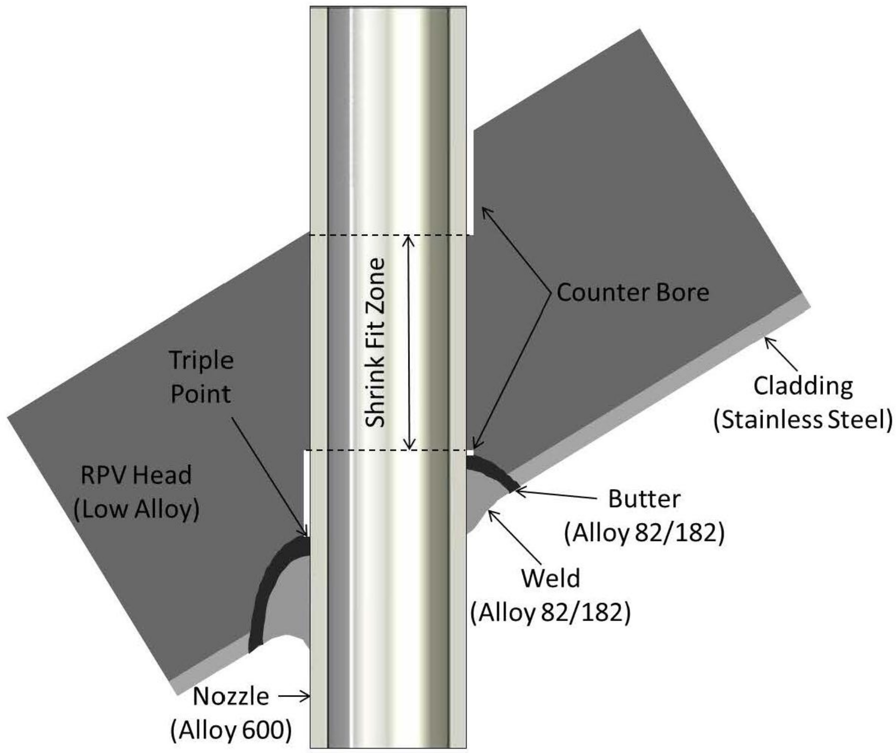


Figure 2.1. Upper Head Penetration with J-Groove Weld

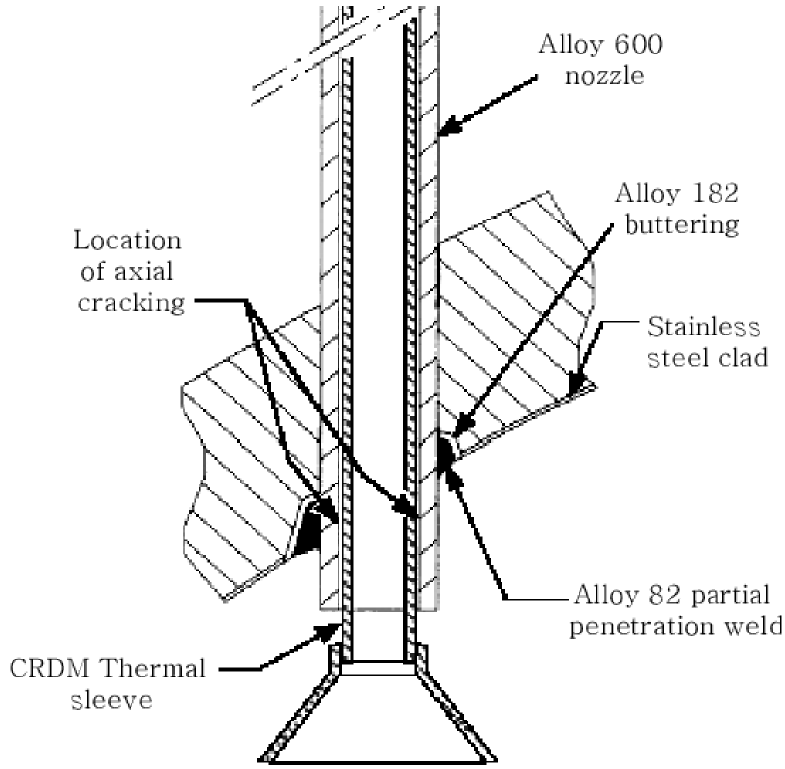


Figure 2.2. CRDM Thermal Sleeve Location

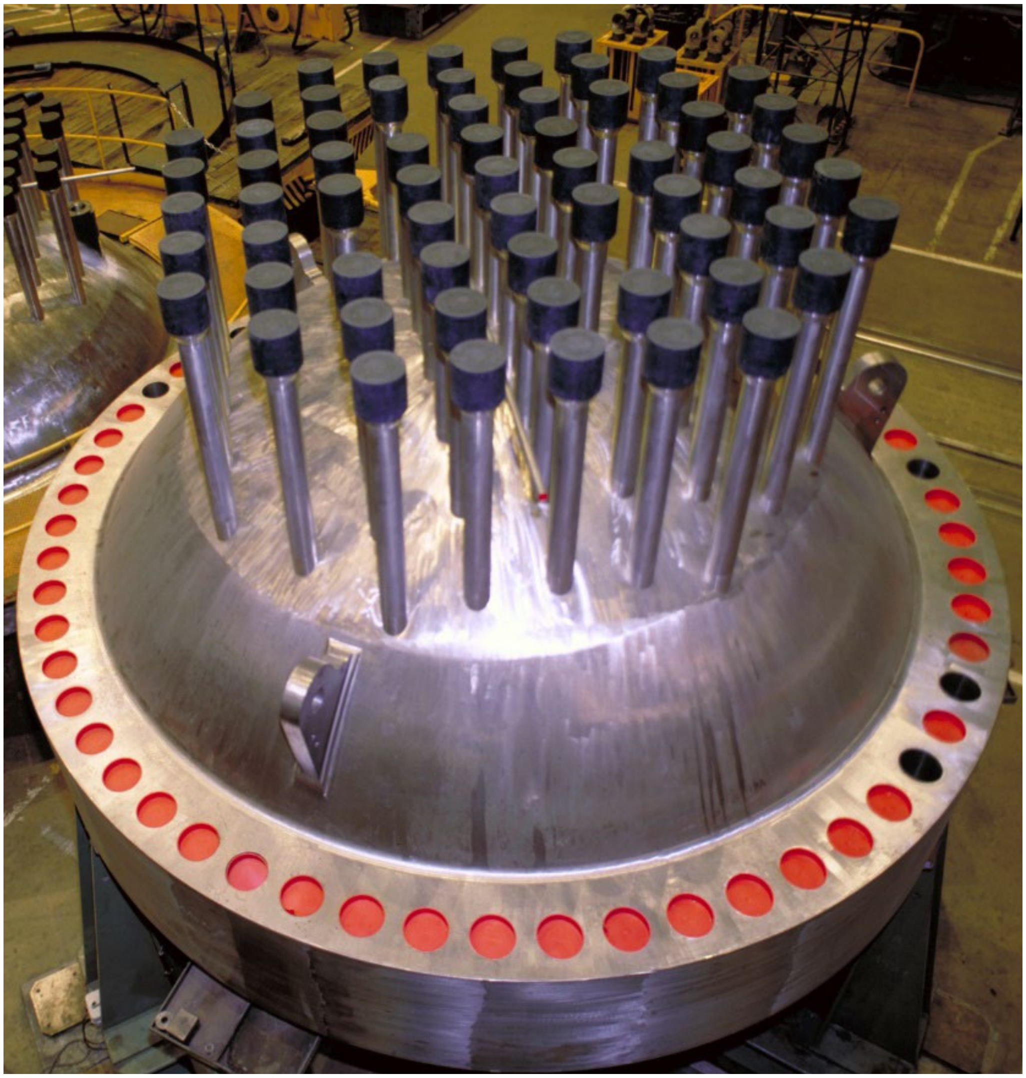


Figure 2.3. Photograph of New Reactor Pressure Vessel Head

During assembly of the RVH, the nozzle tube is dipped in liquid nitrogen, causing the tube to contract slightly. It is then inserted into the head penetration opening; as it returns to an ambient temperature, it expands to complete a shrink fit. This permits the penetration tube to be held in place with an interference fit, represented as the area labeled “shrink fit zone” between the two horizontal dashed lines in the figure 2.1, and seal-welded to the underside of the vessel head with a J-groove weld. Counterbore regions are not designed to be compression-fit zones between the nozzle and RPV head. As noted in PNNL-17763 (Anderson et al. 2008), many reactors had counterbores machined from both bottom and top surfaces of the RPV head for nozzle locations other than the center location to ease the alignment of the tube against the penetration hole during the shrink-fitting installation step. The depth of the counterbore is designed to be flush with the lowest point of the RPV head surface. Most RPV heads with counterbored penetrations are found in French reactor designs, though there are a few reactors in the United States with counterbored penetrations. The counterbore region in figure 2.1. is shown at an exaggerated scale for clarity.

If a thermal sleeve is installed, it is placed in the CRDM housing before the CRDM is welded. The thermal sleeve is supported by an internal chamfer (ledge) in the CRDM housing. This allows the thermal sleeve freedom to move up, move down, and rotate about its axis.

The bottom RPV head is attached via a permanent full structural weld, and it is obviously not removable. The bottom head nozzle penetrations are instrumentation nozzles commonly known as BMI nozzles. These nozzles are smaller than the upper head nozzles, typically ranging in diameter from 38 mm (1.5 in.) to 89 mm (3.5 in.) and are welded to the inside surface of the bottom head via a J-groove weld in similar fashion to the upper head penetrations. Figure 2.4 depicts the construction profile of a BMI nozzle along with a photograph of an RPV bottom head. Because bottom mounted instrumentation nozzles are located at the bottom of the RPV, BMI nozzle inspection, repair, or replacement poses considerable challenges. These challenges include high radiation levels, restricted access to the J-groove weld (i.e., access from inside the vessel), and restricted access to the BMI (i.e., access from outside and beneath the vessel).

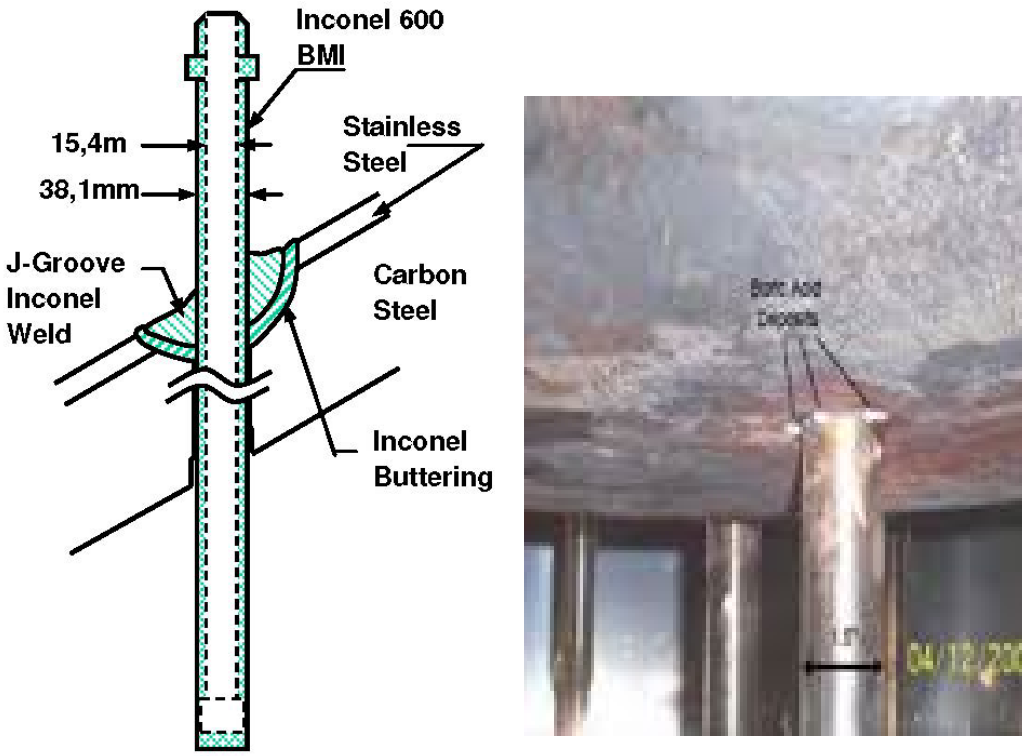


Figure 2.4. Bottom Mounted Head Instrumentation Nozzle

2.2 Degradation Mechanisms and Flaws

The interactions of stress, environment, and material conditions result in stress corrosion cracking that propagates between grain boundaries of a material. PWSCC is the degradation mechanism inherent to Alloy 600 penetration tubes. PWSCC is a basic intergranular stress corrosion mechanism that occurs in a primary water environment, and it has been identified in several plant components, including instrumentation nozzles, steam generator tubes, and RVH penetrations. When Alloy 600 material was selected for use for penetration tubes, its susceptibility to PWSCC was unknown. Plant OE revealed that PWSCC can initiate in the Alloy

600 base metal and propagate into the Alloy 182 weld metal. When this occurs, cracks may then propagate through the J-groove weld surface and into the "triple point" area, allowing borated water into the annulus region between the nozzle outer diameter (OD) and the RPV head. The triple point is shown in figure 2.5, and it is the point at which the RPV head, weld buttering, and Alloy 600 CRDM tube meet. Typical flaws are shown in figure 2.6. Once the boundary formed by an intact J-groove weld is compromised, there is the potential for a leak path through the interference fit, allowing reactor coolant to reach the outer surface of the RPV. The coolant can flash to steam, leaving boric acid deposits on the head and in the interference fit region around the leak path. Additionally, a steam-cut leak path through the interference fit and annulus may also be produced at operating temperature and pressure in a plant when a gap in the low-alloy steel RPV head at the uphill and downhill positions open due to material expansions.

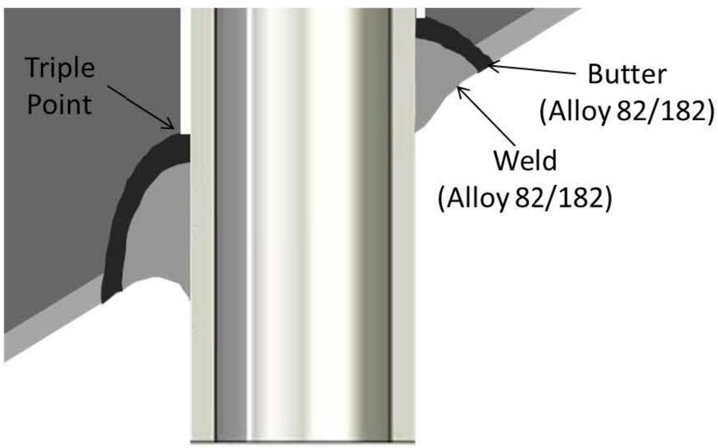


Figure 2.5. Depiction of "Triple Point" Area

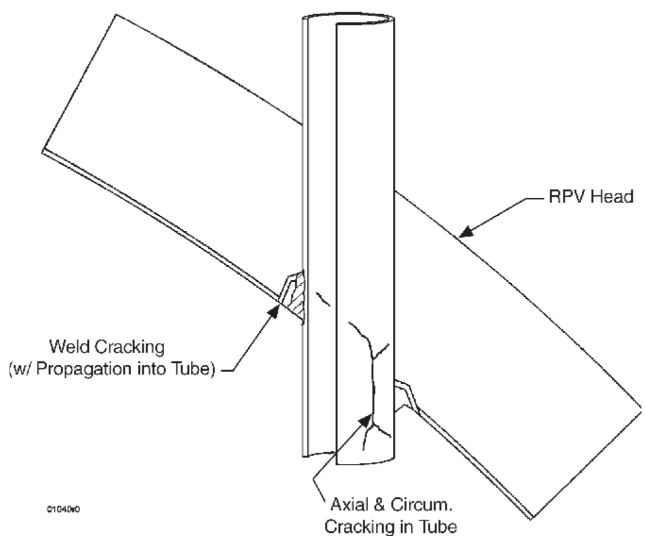


Figure 2.6. Typical Flaws

2.3 NDE Challenges, Gaps, Limitations and Access Issues

The most challenging aspect to performing a successful NDE of RVH penetrations is access. While the upper and bottom head penetrations contain essentially the same weld configuration, access is significantly different.

Bare metal visual examinations are performed by directly viewing the outside surface of the RVH; however, due to close spacing and the large number of penetration tubes, viewing may be restricted. An examiner must maintain a viewing angle with adequate lighting sufficient to identify any boric acid buildup around each penetration.

Volumetric examinations are performed from the inside surface of the penetration tube after the RVH has been removed and placed on the removal stand during a refueling outage. A robotic crawler maneuvers underneath the RVH and remotely inserts an ET and UT probe into the penetration tube. The high levels of radiation do not permit human access underneath the RVH except under extremely time-limited conditions. Access into the penetration tubes in the BMI nozzles can only be performed when the RPV's core barrel is removed and then must be conducted with a special tool from the top of the RPV through water remaining inside the vessel.

Other issues can reduce access even further. 1) Some penetrations include a thermal sleeve that creates a narrow gap between the sleeve and the penetration that reduces access to the inside diameter (ID) surface of the penetration. 2) Depending on the location of the penetration on the RPV head, a very steep intersection can exist. 3) Stresses induced during the welding process can cause the penetration to become oval rather than circular and distort the ID surface.

Examination of RPV head penetrations involves a leak path assessment using a variety of NDE techniques, such as UT, to determine whether a flow path exists through the interference fit that would allow reactor coolant to access the outside of the RPV head. The nominal wall thickness of the upper head penetration tube is approximately 16 mm (0.625 in.). This wall thickness combined with the inner diameter (radius of curvature) of the tube presents complications for most UT techniques. Further, the confined space restricts the size of the probes that may be used. Flaw orientation also complicates a UT examination as axially oriented flaws require specially contoured wedges for the inside surface of the tube. ET examination may provide an advantage over UT as the probes are small and thin and are specifically designed to be used in tubes; however, ET is limited in depth of penetration and may miss non-surface-breaking flaws.

Bare metal visual examination of the outside surface of the RPV head can provide solid evidence that a flaw exists (e.g., boric acid residue); however, unrestricted visual access to all areas of the head may not be possible, as can be seen in the RPV upper head photo of figure 2.3.

2.4 Operating Experience

PWSCC of a CRDM nozzle in a PWR was first identified in the Bugey Unit 3 plant in France during an over pressurization test in 1991 (Economou et al. 1994). The crack initiated in the Alloy 600 base metal and propagated into the Alloy 182 weld metal. In late 2000 and early 2001, reactor coolant leakage to the RPV head from axial through-wall cracks in CRDM nozzles was identified at Arkansas Nuclear One Unit 1 and Oconee Unit 1 (Grimmel 2005). Follow-up inspections at Oconee Units 2 and 3 in 2001 identified axially and circumferentially oriented

cracks. The circumferentially oriented cracks were of particular concern because of the possibility of nozzle ejection (Crawford et al. 2012).

In response to the discovery of the CRDM cracks at Oconee Unit 3, in August 2001, the NRC issued Bulletin 2001-01, “Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles” (NRC 2001). PWR licensees were directed to evaluate the susceptibility of head penetration nozzles to PWSCC and to provide inspection plans to detect potential cracking. Thereafter, CRDM cracking was identified at additional PWRs, including Davis Besse (Bennetch et al. 2002) and North Anna Unit 2 (Crawford et al. 2012). At Davis Besse, reactor coolant leakage led to significant wastage of the low-alloy steel in a portion of the RPV head, leaving only a thin layer of 9.5 mm (0.375 in.) stainless steel cladding at the pressure boundary. In response to the occurrences of RPV head leakage, in 2004 NRC issued First Revised Order EA-03-009 for PWR licensees requiring additional periodic inspections and evaluation of boric acid deposits as they pertain to the reasonable assurance of plant operational safety.

3.0 Current NDE Techniques for Examining Partial Penetration Welds

3.1 Code and Regulatory Requirements for Partial Penetration Weld Exams

Examination requirements for RPV head penetration welds were identified in ASME Boiler and Pressure Vessel Code (Code) Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components, Table IWB-2500-1, Examination Category B-P in the 1980 through 2004 Edition and Examination Category B-E in the 1980 through 1992 Edition. Requirements that might be used for PWR RPV upper heads with nozzles having pressure-retaining partial penetration welds were also listed in IWB-220, IWB-2400, and IWB-3000.

In response to the discovery of CRDM cracking in late 2000, the NRC issued Bulletin 2001-01, "Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles." PWR licensees were directed to evaluate the susceptibility of head penetration nozzles to PWSCC and to provide inspection plans to detect potential cracking. In response to subsequent occurrences of RPV head leakage, on February 11, 2003, the NRC issued Order EA-03-009, "Interim Inspection Requirements for Reactor Pressure Vessel Heads at Pressurized Water Reactors." This order required PWR licensees to modify their licenses to require specific inspections of the RPV upper head and associated penetration nozzles. In response to internal review and stakeholder input, the NRC issued First Revised Order EA-03-009 on February 20, 2004, which refined the inspection requirements of NRC Order EA-03-009 by taking into account lessons learned from inspections performed from February 2003 to January 2004. In February 2006, ASME, Section XI, Code Case N-729-1, "Alternative Examination Requirements for Pressurized-Water Reactor Vessel Upper Heads with Nozzles Having Pressure-Retaining Partial-Penetration Welds," was approved by the ASME for use as an alternative to current ASME Code inspection requirements for RPV upper head penetrations.

The requirements of EA-03-009 were superseded by the adoption of ASME, Section XI Code Case N-729-1 by rulemaking in Title 10 of the Code of Federal Regulations (10 CFR) Part 50.55(a)(g)(6)(ii)(D)(1). Additionally, as a condition in 10 CFR 50.55(a)(g)(6)(ii)(D)(3), licensees are directed to perform a demonstrated surface or volumetric leak path assessment of all J-groove welds in the RPV head.

The Code Case and the NRC 10 CFR 50.55a rule of September 10, 2008, provided requirements to qualify ultrasonic procedures and personnel for upper head penetrations and required demonstrated volumetric leak path assessment procedures. After the issuance of the Code Case, the Materials Reliability Program (MRP) directed the MRP Inspection Technical Advisory Committee to develop a performance demonstration program qualifying the nondestructive evaluation procedures and personnel for upper head penetrations. Since August 29, 2017, as mandated by 10 CFR 50.55a, the reactor vessel upper head inspection and qualification requirements in ASME Boiler and Pressure Vessel Code Case N-729-4 have been implemented.

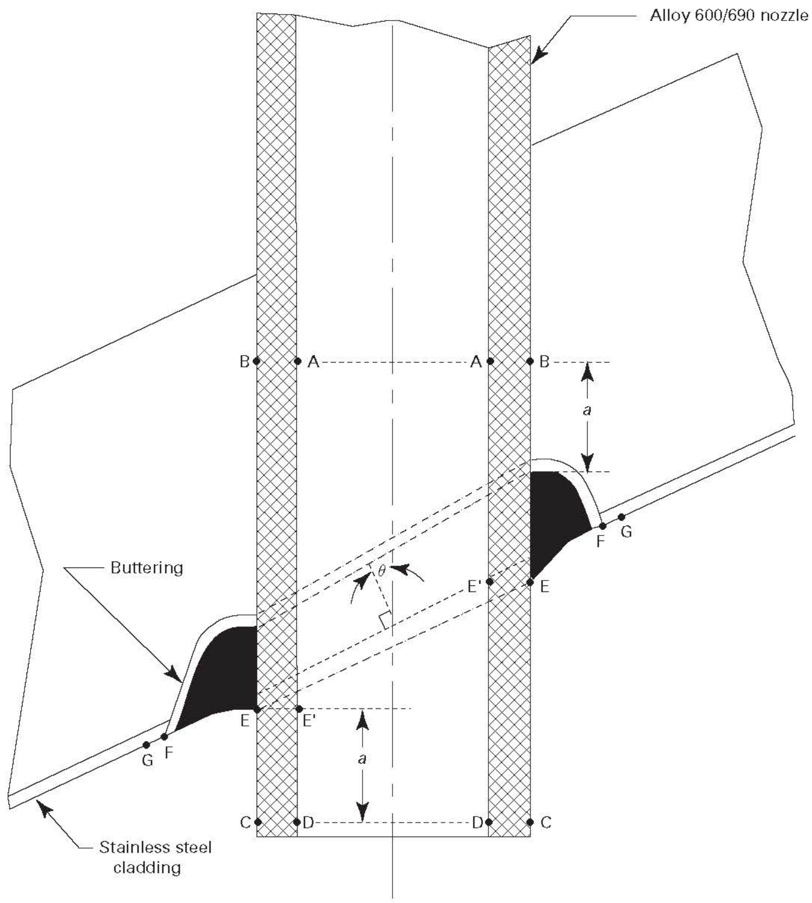
In July 2018, an ASME Code action proposed a new Supplement 15 to ASME Section XI, Appendix VIII, to specifically identify performance demonstration requirements in Section XI. This was approved by the ASME Board on May 28, 2020. As of the publication date of this TLR, ASME is considering a revision to Code Case N-729, currently at Revision 9, to remove the

procedure and qualification requirements and simply apply the requirements of Appendix VIII, Supplement 15 (ASME 2006, 2021; EPRI 2020).

3.1.1 Required Examination Volume

The current examination requirements are identified in ASME Code Case N-729. This includes the examination volume for the nozzle base metal and the examination area for the weld and nozzle base metal as show in figure 3.1 below.

Figure 2
Examination Volume for Nozzle Base Metal and Examination Area for Weld and Nozzle Base Metal



Legend:

a = 1.5 in. (38 mm) for Incidence Angle, θ, ≤ 30 deg and for all nozzles ≥ 4.5 in. (115 mm) OD or 1 in. (25 mm) for Incidence Angle, θ, > 30 deg; or to the end of the tube, whichever is less

A-B-C-D = extent of volumetric examination for the tube (base metal)

A-D = extent of surface examination for the tube inside surface

G-F = $^1/_4$ in. (6 mm) from the theoretical point "F" in accordance with the design drawings, including tolerances, unless the point "F" can be physically determined.

G-F-E-C = extent of surface examination for the J-groove weld (filler metal and buttering) and tube outside surface below the weld

G-F-E = extent of surface examination zone for the J-groove weld (filler metal and buttering)

Figure 3.1. Required Examination Volume from ASME Code Case N-729-8

In situations where the examination area or volume requirements cannot be met, alternative requirements are identified in Mandatory Appendix I of N-729.

3.2 Current NDE Techniques used in ISI

The NDE techniques currently employed for RPV penetrations and partial penetration welds has not advanced much in the past several years, most likely due to no evidence of missed detections using existing techniques. The few examples of reported plant OE have indicated a root cause of human performance rather than an insufficient NDE technique.

3.2.1 Ultrasonic Testing

UT techniques used to examine the penetration tube and partially covering the J-groove weld at the tube interface vary depending on the specific situation. In performance demonstration trials, blade probes have been proven to be effective in accessing the inside surface of the penetration tube and detecting cracks (see figure 3.2). To date these have included:

- Blade probes that contain two TOFD probes and a 0° probe for interrogating the inside surface for flaws. The TOFD probes provide clear lateral wave breaks for ID flaws in the penetration tube and can even detect minor surface scratches. Most of the inspection challenges with this approach relate to outside surface indications located near the J-groove weld toe.
- A Japanese company has conducted experiments with phased array (PA) elements being placed in a blade probe configuration. The objective was to permit larger volumetric coverage of the J-groove weld material volume for flaw detection. To date no results have been published.

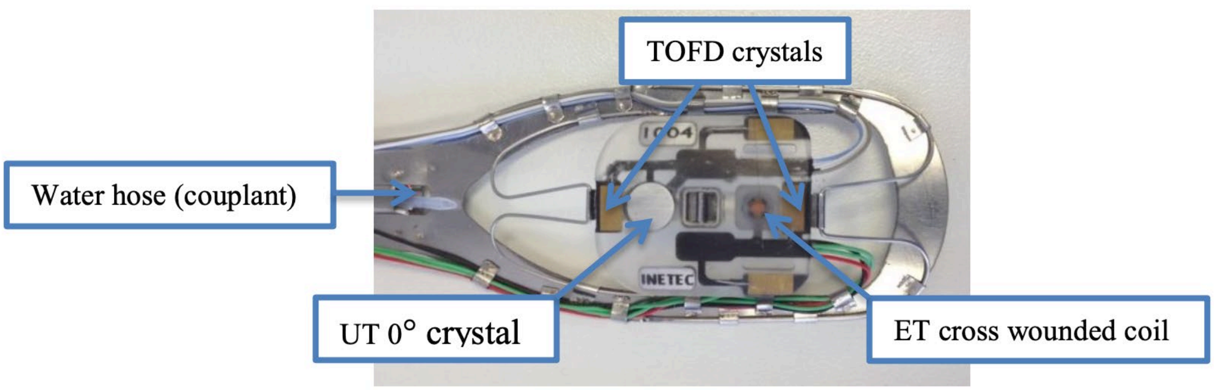


Figure 3.2. Saber probe described by Tomašić et al.

Pitch-catch shear waves have only been used to examine a very small number of penetrations that do not contain thermal sleeves. There hasn’t been a significant change in the typical UT examination technology itself. The Electric Power Research Institute (EPRI) is developing an automated analysis application for TOFD examinations and performed a field trial at an operating plant in 2022 in collaboration with TrueFlaw Ltd. (Espoo, Finland) to develop the analysis protocol.

For this work, a software model was developed and trained to automatically flag regions of interest in reactor vessel upper head penetrations using a time-of-flight tip diffraction UT technique. The model is trained on real stress corrosion crack (SSC) field flaws to flag flaw like signatures, and synthetic flaws are used to train the model for potential conditions. To train the model in what not to call, data containing geometry signals that appear flaw like were also used.

EPRI's automated data analysis development is not envisioned to replace UT examiners, but instead will be used to provide an independent evaluation of the UT data. For example, the system could be used as a secondary review or to aid with utility oversight. It could also be applied to review previous examination data to prioritize inspection order, assess needed resources, or familiarize examiners with expected results from a previous examination.

3.2.2 Eddy Current Testing

ET examinations are sometimes performed on the OD of the penetration tube or face of the J-groove weld. Significant research has been conducted in this area using padded/flexible eddy current arrays that offer increased depth of penetration (up to around ~6 mm [0.25 in.]). One inspection vendor utilizes eddy current arrays. The bulk of the research into this area has utilized EddyFi instruments and arrays (EddyFi Technologies, Quebec, Canada). As a matter of note, an eddy current examination from the ID surface of the penetration tube does not provide information on the condition of the J-groove weld due to its lack of volumetric penetration.

3.2.3 Visual Testing

A direct visual examination of the bare metal surface of the entire outer surface of the head, including essentially 100% of the intersection of each nozzle with the head, is required by Code Case N-729. Personnel performing visual examinations shall be certified to a minimum VT-2 Level II and must have received four hours of specific training in the detection of borated water leakage. The visual examinations have been successful in identifying evidence of reactor coolant leakage indicated by corrosion, boric acid deposits, and discoloration (EPRI 2020).

4.0 Literature Search Review

To keep this report relevant to recent advancements, the literature search was limited primarily to publications after 2000 and focused on publications from about the past 10 years (2012–2022). Search queries included combinations of “J-groove weld,” “partial penetration weld,” “CRDM,” “BMI,” “ultrasonic,” “inspection,” “NDE,” and “NDT.” There were a limited number of search results. For example, a Google Scholar search[1] of “J-groove weld ultrasonic inspection” from 2012–2022 yielded only 141 results. This is a very low number of hits for a literature query (for comparison, a search of “ultrasonic dissimilar metal weld inspection” over the same time period yielded 17,300 results). Furthermore, most results in any literature query are not directly relevant, many are conference abstracts with no associated paper, and some are not in English. Thus, the number of relevant results is typically a fraction (~20% and often *much* less) of those returned.

From the literature search, about 35 references were found to be directly relevant. There were reports from a range of different countries, including Korea, China, Sweden, Switzerland, Spain, Japan, Croatia, and the United States. About 12 of the search results were reports of confirmatory research, round robins, or overviews of industry or regulator findings. About 14 of the results were by authors from industry, including EPRI, WesDyne, Westinghouse, AREVA/Framatome, Toshiba, Tecnatom, and DEKRA Industrial. Note that only four of the 14 industry results were published *after* 2010 and none after 2012, whereas the majority of the academic and confirmatory publications were after 2010. The sparse number of reports from industry may be due to several reasons: it is not common practice for industry to publish in-house findings, especially if they contain trade secrets or products in development; most companies that perform NDE are typically not involved in research in the absence of cost drivers, especially when there is no push by regulators; reports from industry may not be indexed by standard indexing services, especially if they are published on a company’s website or disseminated at industry meetings. The summaries presented herein represent the status of the research at the time the references were published. No further information about the current state of the research or the utilization in ISIs was available.

4.1 Results

Results of the literature search will be broken down into three basic categories: academic research, industrial research, and confirmatory research/round-robin reports.

Overall, the literature search revealed the following primary drivers for research in partial penetration welds:

- Rapid examinations to reduce examination time, radiation exposure, and outage downtime
- Non-contact examinations or remote examinations
- Examinations that do not require removal of pressure vessel head
- Cost reductions
- Continuous monitoring or structural health monitoring
- Earlier detection of smaller cracks
- Better inspection of complex geometries, such as CRDM J-groove weld curvature

[1] Conducted in February 2022.

- Inspection techniques that meet regulatory requirements.

4.1.1 Academic Research

Lee et al. (2011) and Choi et al. (2014) used a laser ultrasonic propagation imaging (UPI) approach to visualize waves in a CRDM assembly. A laser was used to excite ultrasonic waves, and UT transducers with center frequencies of 200 kHz to 350 kHz were used for detection. The transducers were placed on the inner surface of the RVH using a robotic arm. By rastering the laser across region of the assembly while leaving the UT probe stationary, the wave fronts were visualized and interference patterns from flaws were identified. A method called Adjacent Wave Subtraction compared waves received from different excitation pulses to detect anomalies. The method showed that flaws of any orientation could be detected with low background; however, the laser must hit a flaw directly in order for the appropriate signal to be received. Thus, a dense scanning grid must be used (~100 μm spacing). Laser UT approaches have potential shortcomings. First, the wave fronts propagate out in all directions, so the sound energy cannot be directed or focused into an area of interest. Second, the detected interference patterns are complex; interactions of the wave front with geometry, grain structures, and flaws all create interference patterns. Third, analysis of such results in a complicated CRDM J-groove weld geometry are challenging.

In research specific to shrink-fit boundaries, such as CRDM assemblies, Lee et al. (2015) and Lee et al. (2016) tested methods of measuring interference patterns from surface waves propagated axially up the shrink-fit boundary. The idea was to interrogate the weld from the outside of the pressure vessel by sending guided ultrasonic waves to the weld through the unwelded boundary. CRDM mockups with machined defects were used for testing. Results showed the ability to detect the location and size of the defects. For this method to work, it appears that a clean signal and high time-resolution are needed. It is unclear what the effects of corrosion, boric acid, or water in the shrink-fit region would have on detection, so this approach is likely feasible for new construction only to interrogate the integrity of the shrink-fit region.

Abdallah and Nam (2016) and Abdallah and Namgung (2018) developed the concept of a remote inspection system to detect PWSCC in underwater BMI nozzles at PWR plants. The driving need was to inspect BMI nozzles without removing the pressure vessel head or the reactor internals while still providing regular and thorough inspections. The work mostly focused on hardware design for a system to access BMI nozzles while using commercially available UT and ET probe assemblies.

Kauppinen et al. (2013) used UT to check for water between the corrosion protection tube and the nozzle of a control rod. Although this was not strictly an application to a partial penetration weld, the same concept applies. The method was basically an application of a wall thickness measurement—when water or corrosion exists in the gap, then the echo signal from the gap will be dampened. They used a 5 MHz, single-element, hand-held UT probe on the nozzle's outer surface. They noted that certain frequencies can be transmitted through the gap, depending on the gap width, so this effect should be taken into account. It should be noted that failing to detect water in one location does not mean that there is not water elsewhere in the gap or that water was not previously in the gap.

Pajnić et al. (2010) and Tomašić et al. (2013) described a "trinity" probe or "saber" probe with pulse-echo UT, TOFD, and ET capabilities in a slim, "sword-like" geometry that can fit between the thermal sleeve and the inner surface of the penetration nozzle as shown in section 3.2.1. The probe is guided by a "Gap End Effector" tool. A second ET probe fits around the CRDM

penetration and is used for examining the J-groove weld on the inner surface of the RPV head. Although elements of the probe design may be novel, the principles of the exams themselves are straightforward. Tomašić et al. further described a robotic inspection manipulator for remotely positioning and manipulating the probe. Budimir et al. (2013) described a similar probe and showed results of finite element modeling used to predict the performance and empirical tests to evaluate the probe. Park et al. (2004) also described the use of a Remote Operated Head Inspection System (ROHIS) that incorporated a sword probe. They stated that ET is used for flaw detection and pulse-echo UT for flaw sizing. UT is also used to detect flaws in the J-groove weld region and the CRDM tube. TOFD is used for depth sizing of flaws at least 1 mm (0.04 in.) deep as well as for nozzle inspections. ET is also used for the surface of the J-groove weld. Park et al. noted that grain boundaries, lack of fusion, and inclusions present TOFD signals that are similar to those of flaws and tips. A modified 8-axis robotic manipulator was also described. The ROHIS system was used for RPV J-groove weld inspections in Korea, and the system, or variations of the system, will continue to be used.

Overall, innovations from academia focused on partial penetration J-groove welds are limited. Most of the work appears to focus on remote or robotic deployment of commercially available inspection technology and was therefore not described herein.

4.1.2 Industrial Research

Ammirato (2002) listed no clear industrial affiliation in the paper but gave a succinct yet thorough overview of industry issues. Although the paper is 20 years old, the issues still resonate today. Challenges with inspections of CRDM penetrations and J-groove welds have not changed much and include:

- The presence of an austenitic weld. Austenitic welds pose well-documented challenges to ultrasonic inspections, including beam redirection, beam scatter, and increased noise signals.
- Challenging geometries. The changing tapers and curvature around the tube penetration due to the hemispherical shape of the RPV head pose significant challenges. Further, the small ID of the tubes poses probe design limits.
- Access restrictions to the ID surfaces of nozzles. The ID of CRDMs can be accessed only from within the RPV when the head is removed, which limits the frequency of inspections. Thermal sleeves also restrict access and force significant restrictions to probe design. BMIs sit at the bottom of the vessel and must be accessed for volumetric examination from inside the vessel using underwater techniques.
- OD examination limitations. For CRDMs, the wetted surface of the tube and J-groove weld are accessible when the head is removed from the vessel. For the BMI nozzles, the OD inspections are conducted from under the vessel using remote, surface, or visual examination techniques.
- High rad environment. Time and access are severely limited by the radiation environment and force the use of fully-automated inspection equipment.

Ammirato discussed some specific ISI issues, such as PA-UT scans from the ID of CRDM penetrations tending to have poor coupling due to uneven contours along the ID of the tube. He noted that inspection companies work continually to improve the design of search units and remote deployment mechanisms.

Ammirato concluded that the U.S. inspection industry should address the problems of CRDM penetration inspections in several ways:

- Share experiences among utilities and inspectors so that the latest information can be used across the industry
- Develop guidance for uniform inspections
- Create realistic mockups for performance demonstration
- Develop more effective NDE techniques to improve reliability and reduce costs.

Publications by Toshiba (Ochiai 2008) and AREVA/Framatome (Glass and Piriou 2005) discuss nonconventional, laser-based approaches to CRDM inspections. Ochiai (2008) demonstrated a laser UT system for detecting surface-breaking SCC ≥0.1 mm (0.004 in.) deep in the ID of BMI nozzle tubes; the same laser can be used for peening. The system was used in NPP inspections in Japan starting in 2004. It is unclear if the laser UT research of Lee et al. (2011) and Choi et al. (2014) discussed above and also deployed in Japanese plants is related to this work.

Glass et al. described a completely different laser-based approach to CRDM penetration inspection using photothermal NDE with laser excitation. A system with a laser and infrared camera was used for non-contact flaw detection; thus, it has the advantage over standard ET and PT of being unaffected by surface conditions. The paper says that the method "has proven equivalent or superior to PT methods and ET methods" for detection of surface-breaking cracks. The method was demonstrated in laboratory studies and on a CRDM nozzle specimen from EPRI with "generally encouraging" results. However, industry interest was lacking, as the technology did not fit into the existing performance demonstration program.

Other work by Toshiba exploring nonconventional approaches was published by Miura et al. (2013). They described a PA-UT method for curved surfaces, such as a J-groove weld, employing a conformable wedge and synthetic focusing. Essentially, the method detects the surface contour from an initial pulse, the delay laws are then calculated based on the curvature, and then the inspection is completed with the new delay laws. Results on mockups showed a dramatic reduction of spurious echoes and clear flaw signals. They also described a new ET probe design that is more compact to enable measurements over curved areas.

Additional work by AREVA/Framatome (Glass et al. 2012a; Glass and Cole 2004) was primarily focused on remote access, manipulators, and robotics to reduce time and cost of inspections. The approaches use standard three-in-one pulse-echo UT, TOFD, and ET probes. Note that these papers are representative of several others found during this literature review (but not described herein) that focused on robotics and deployment rather than NDE techniques. Wendel and Sjö (2013) of DEKRA Industrial also described work on manipulators and remotely-operated inspection hardware for CRDM ID and OD inspections of J-groove welds. Although robotics and remote access hardware are critical for inspections of CRDM partial penetration welds, the focus of this literature search was on NDE inspection methods and not engineering solutions for deployment.

Lenz et al. (2002) of Westinghouse published an overview of RVH penetration issues, including NDE. Although few details of the work were documented in the paper, they described deployment and inspection systems for J-groove weld inspections. Similar to Pajnić et al., Tomašić et al., and Park et al., they use a GAP scanner end effector with blade UT and ET probes for thermal sleeve access. Probes were equipped with pulse-echo UT, broadband

TOFD, and ET. Accurate sizing was achieved with TOFD probe pairs of different spacing, and depth sizing accuracy was about 1 mm (0.04 in.) or less.

Westinghouse, in cooperation with WesDyne and others (Adamonis et al. 2004), described an Open Housing Scanner with UT and ET for ID inspection of RVH penetrations. The scanner can deploy TOFD, pulse-echo UT, and ET. Some general descriptions of improved probe designs were provided, such as better blade probes for variable sleeve and tube conditions, but no data were shown. Primary advancements appear to not be in NDE but in robotics and deployment methods.

Fernández et al. (2013) described Tecnatom's efforts to develop and qualify an inspection system for a control rod drive housing in a Swiss NPP that meets the ISI requirements of Code Case N-730 and Swiss regulatory requirements. They described testing multiple probes with pulse-echo, TOFD, and ET on CRDM tube mockups and J-groove welds. Details of the final probe designs were not given.

Glass et al. (2012b) presented updates on AREVA's approach to J-groove weld inspection for RPV head and RPV bottom mount nozzles during the 9th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components. The paper addressed work to advance eddy current and UT examinations in applying ASME Code Case N-729-1.

Alley et al. (2002) described the CRDM inspection activities of the U.S. nuclear industry following the discovery of PWSCC in CRDM penetrations. The primary outcomes described were the establishment of an EPRI Material Reliability Program inspection committee and demonstrations of appropriate mockups. Some results of the committee's work are in MRP-296 (EPRI 2010), which describes a "capability study" involving WesDyne and AREVA that was started in 2004. The purpose was to study bottom mounted nozzle head penetration inspections using vendor equipment and procedures. This appears to be a round-robin type of study but with only two participants. The inspection methods used were TOFD and ET. The mockups included Babcock and Wilcox tube designs, Westinghouse 2-Loop designs, and Westinghouse 3&4-Loop designs. Some mockups were open, and others were secure. Tested parameters were flaw detection, orientation, length sizing, false calls, depth sizing. Unfortunately, this report shows no POD curves, no conclusions, and no summary. Based on the results shown, it can be surmised that there were few missed detections, though measuring the correct flaw orientations was challenging. As far as sizing, it appears that flaws were by-and-large undersized, although there did not appear to be consistent trends. It is unclear if or how the results of this study have been used to improve head penetration inspections.

In 2002 and 2003, EPRI (EPRI 2002, 2003) published two reports on J-groove weld condition assessments. They stated that NRC Order EA-03-009 requires UT *or* both ET and PT testing of wetted surfaces. The EPRI protocols require ET scanning followed by TOFD if an indication is found; however, these reports only discuss ET inspection methods.

4.1.3 Confirmatory and Round-Robin Reports

PNNL has been involved in confirmatory research and round-robin studies of CRDM partial penetration welds for many years and has published 11 publicly-available reports on the subject since 2005. Doctor et al. (2005), Doctor et al. (2006), Cumblidge et al. (2007b), Cinson et al. (2011), and Crawford et al. (2012) described NDE studies of three CRDMs removed from service. NDE techniques included ET, VT, UT, and TOFD. Although NDE found weld fabrication flaws and cracklike indications in both nozzles, "there was no convergence of NDE results on

any cracklike indications by the different NDE techniques" (Doctor et al. 2006). Cinson et al. (2011) and Crawford et al. (2012) used an immersion annular PA probe to study one of the removed-from-service CRDM nozzles in addition to an interference fit mockup (no weld). Machined flaws in the mockup interference fit region were detected as well as a relatively uniform UT signal response. In the CRDM nozzle, however, a wide range of UT signal intensities were detected in the interference fit region, indicating the presence of boric acid. Importantly, a potential leak path was detected by laboratory UT and then compared to industry ISI data of the same CRDM; the lab data independently confirmed that the potential leak path was visible using industry standard inspection methods. Further, destructive testing confirmed the findings of both sets of UT scans.

Four of the most relevant PNNL reports concern two international round robins that had a significant focus on detecting flaws in BMI nozzles. The first, Program for the Inspection of Nickel Alloy Components (PINC), was held to address PWSCC in Alloy 600 components, including BMI nozzles (Cumblidge et al. 2010). PINC was designed "to document the crack morphology and NDE responses of PWSCC" and "to study the capability of various NDE methods to detect and size the through-wall extent of PWSCC." Five teams participated in the BMI nozzle portion of the round-robin, which utilized 14 BMI nozzle test blocks. Regarding BMI nozzles, conclusions of the PINC round-robin were:

- ET with a cross-coil probe had a high POD and a low false call rate. However, ET with an array probe performed considerably worse in POD and false calls.
- The closely-coupled potential drop and induced-current potential drop techniques did not perform well and would require further testing and development.
- Adaptive PA-UT was able to detect all of the flaws in the baseline-difficulty test blocks (test blocks with PODs of about 0.8) but none of the flaws in the challenging test blocks. Challenging flaws were "designed to mimic difficult-to-detect indications found in the North Anna 2 Nozzle 31 J-groove weld" (Doctor et al. 2006; Doctor et al. 2005).
- The authors concluded "adaptive phased array ultrasound can be effectively used to find flaws in BMI nozzle welds." Adaptive PA-UT uses surface profile measurements from an initial scan to adapt the PA laws for the inspection.
- Both ET and PA-UT were able to accurately length-size the flaws in J-groove welds.
- Depth sizing with PA-UT was difficult.
- Teams with formal NDE qualifications performed better than teams without formal qualifications.

The second international round-robin, the Program to Assess the Reliability of Emerging Nondestructive Techniques (PARENT), was designed to be a follow-on activity to PINC (Prokofiev et al. 2013). The documentation of the PARENT results was split into open-testing and blind-testing NUREG/CRs so that the more experimental techniques applied to open specimens could be separated from established techniques applied to blind specimens (Meyer and Heasler 2017; Meyer et al. 2017). The open test included four BMI nozzle test blocks, and the blind test included five. A variety of UT and ET techniques were employed. In both NUREG/CRS, there was insufficient data from the BMI nozzle test blocks for the authors to draw conclusions, though recommendations were given for additional BMI nozzle studies. A final report combined the PARENT data with PINC data to increase the BMI nozzle statistical sample size, but only for the ET data (Meyer et al. 2018). Results showed that higher frequency ET (> 250 kHz) had higher POD and lower false call rates than lower frequencies, and that

array ET probes performed worse than non-array probes. Some confounding variables in the analysis complicated the determination of true PWSCC flaw detection performance on BMI nozzles. UT data were not considered in Meyer et al. (2018).

Finally, Diaz et al. (2019) described UT and ET performed on upper head penetration nozzles obtained from a cancelled NPP. The purpose of the project was to evaluate the effectiveness of residual stress relief through peening, which included pre- and post-peening NDE characterization of the J-groove welds. Multiple CRDM penetration nozzle assemblies were identified for full NDE testing prior to any peening activities. For UT, machined reflectors were added into the weld region from the outer surface to demonstrate effective depth of penetration and detection resolution. The reflectors included flat-bottom holes in sets of three (with diameters of 1.59, 3, and 4.76 mm [1/16, 1/8, and 3/16 in.]), where sets of holes were put in at different metal paths from the OD of the pipe (3 mm [1/8 in.] away, 12.7 mm [0.5 in.], and 25.4 mm [1.0 in.] distance). PA-UT was conducted from the tube ID using an annular probe, and ET was performed on the J-groove weld. UT clearly showed the weld and the interference fit region and the 3 mm (1/8 in.) deep holes were clearly detected. The 25.4 mm (1.0 in.) deep holes were detected for the two larger diameter holes (3 mm [1/8 in.] and 4.76 mm [3/16 in.] diameter holes). The 1.59 mm (1/16 in.) hole was not detected. The report noted with interest that the 12.7 mm (0.5 in.) deep holes were not detected at all. Several fabrication flaws were seen in the weld and it was concluded these clusters of other weld fabrication defects or fusion issues in the weld occurring in “front” of where the reflectors were placed caused the missed detection. No surface-breaking cracks were detected (and none were known to be in the samples).

For ET, a set of various resolution standards were designed and fabricated to empirically quantify ET depth of penetration and detection capabilities for various ET probes as a function of remaining ligament and flaw size/diameter. ET Probes from UniWest and WesDyne showed the ability to confirm/validate the PA-UT detection and characterization analyses for any indications that were identified as near-subsurface flaws (< 1 mm [0.04 in.] from the J-groove weld surface). These probes illustrated the capability to detect something comparable to a void or inclusion at subsurface depths of 1.02 mm (0.04 in.), with length extents or diameters of 1.6 mm (1/16”) consistently.

5.0 Summary

Overall, aside from robotics and remote access innovations, there have been very few novel NDE approaches to J-groove weld and partial penetration weld inspection to come out of academia or industry in the past 20 years. After cracking and leakage of CRDM nozzles was found in the late 1990s and early 2000s in the United States, there was a flurry of activity over the next ~10 years to vet what were then current inspection methods and to see if other new, more effective methods could be found. However, with the added attention, no additional significant events have been found. It therefore appears that the primary drivers of cost savings and/or regulatory pressure (i.e., increased safety) needed to motivate research are lacking.

Overall, research shows that CRDMs, BMI nozzles, and J-groove welds can be inspected using conventional UT and ET methods that are able to find cracks, fabrication flaws, and anomalies (such as boric acid corrosion). However, extensive round-robin testing was generally inconclusive on the success of NDE of finding PWSCC in CRDMs. More studies are needed to determine the effectiveness of ultrasonic methods that are outside the envelope of current industry ISI for detection and sizing PWSCC.

Most references cited a need for better and more frequent examinations motivated by cracking and leakage found in U.S. plants in the late 1990s and early 2000s. However, as noted in section 3.0 of this report, ASME Code now addresses the requirements for upper and lower head examinations.

Overall findings of this literature survey:

- There have been few innovative or nonconventional ultrasonic NDE approaches to emerge in the past 20 years.
- Many reports were conference papers that lacked important details of UT probe construction and inspection methods, so it cannot be discerned if methods were novel.
- References from companies that discuss progress or new probes do not reveal trade secrets or details about methods or equipment.
- There are few research articles on the topic, indicating that little academic attention is paid to this field.
- Much recent work is focused on robotic or remote deployment systems and not the NDE.
- Several reports described confirmatory research and round robins to assess inspection capabilities; all such reports for this work were published by PNNL and funded by the NRC.

The following primary needs were identified as research drivers:

- Rapid examinations to reduce examination time, radiation exposure, and outage downtime
- Non-contact examinations or remote examinations
- Examinations that do not require removal of pressure vessel head
- Cost reductions
- Continuous monitoring or structural health monitoring
- Earlier detection of smaller cracks
- Better inspection of complex geometries, such as CRDM J-groove weld curvature

- Inspection techniques that meet regulatory requirements.

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