ALLOY 600 – REACTOR VESSEL HEAD PENETRATION ISSUES

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ABSTRACT

Recent discoveries of cracked and leaking penetration nozzles in the top of reactor vessels (RPVs) have been observed in several pressurized water reactors (PWR). These discoveries have raised concerns about the structural integrity of reactor vessel penetration nozzles in the top of reactor vessels at PWRs throughout the industry. Control rod drive shafts pass through penetration nozzles which sit at the top of a reactor vessel head. Control rod drive mechanisms (CRDMs) are used to guide the movement of control rods in and out of a reactor core. Axial cracking of these nozzles has previously been observed but has not been considered a safety concern requiring immediate attention. However since early 2001 circumferential cracking was discovered at several reactors. In addition one younger discovery showed very serious degradations where structural margins of the reactor vessel head were significantly reduced and a potential for a loss of coolant accident was obviously given. One function of the nozzles is to maintain the reactor coolant system pressure boundary. Cracking of the control rod drive mechanism nozzles represent a degradation of the primary reactor coolant system boundary, and hence, is potentially safety significant.

Cracking was first found in a French nuclear power plant (NPP) in 1991. Leakage was thereby detected by an acoustic leak monitoring system during hydrostatic tests. Since that time over 6000 penetrations have been inspected. Only a small amount of indications was found in the worldwide average. Inspection were at this time performed on the surface of the inner penetration diameter only.

This paper discusses potentials for initiation and propagation of cracking as well as new capabilities of inspection techniques. In addition several repair options will be presented reflecting also the field experiences made up to day.

Keywords: reactor vessel, alloy 600, inspection techniques.

I. INTRODUCTION

Control rod drive shafts pass through penetration nozzles, which sit at the top of a reactor pressure vessel (RPV) head. Control rod drive mechanisms (CRDMs) are used to guide the movement of control rods in and out of a reactor core. In Fig. 1 a typical configuration is shown as used in most of the Pressurized Water Reactors (PWRs) worldwide. The penetration of alloy 600 is fitted into the vessel head consisting of ferritic steel. The joint between reactor vessel head and penetration for mechanical fixture and the sealing against the pressure boundary is reached by the so called J-Groove weld with the alloy 600 equivalent filler material alloy 82 or alloy 182.

During plant design phase Alloy 600 was believed to be beneficial for use at transitions between carbon steel because of its thermal expansion behavior which is bridging the difference between carbon and stainless steel resulting in less stresses induced during operation, its good experience for corrosion resistance resulting from numerous installations in conventional plants and because of its good weld ability on stainless, nickel based and carbon steels. With the industry experiences on the alloy 600 it was found that there is a certain susceptibility for primary water stress corrosion cracking (PWSCC).

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techniques to evaluate the penetration itself. Therefore new eddy current tools (DERI 700 / Gap scanner) were developed to access the inner surface of the penetration from the small gap between thermal sleeve and tube inner diameter. Beside this technique visual inspections and dye penetrant testing were used to evaluate the inner and outer surface of the vessel heads.

In early 2001 four new leaks have been identified in the U.S. plants Oconee 1, 2, 3 and ANO 1 as a result of cracking in the J-groove weld and the reactor vessel head penetration tube. Thereby, the circumferential cracking for the first time found at Oconee 3 led to safety concerns by the U.S. Nuclear Regulatory Commission (NRC). These findings resulted in an additional request by NRC for inspections during the coming outages [1]. The youngest, most severed event has been seen on the NPP Davis-Besse in March 2002 with a head wastage leading to a very serious degradation where the structural margins were significantly reduced and the potential for a Loss of Reactor Coolant Accident (LOCA) has been obvious [2]. The root cause analysis for Davis-Besse is still ongoing, but the applicability of established examination programs and the assessment of findings have to be newly determined in the light above.

II. SAFETY ASSESSMENT

The recent identification of cracking indicate that circumferential cracks outside of the J-groove weld can occur, in contrast to an earlier conclusion that the cracks would be predominantly axial in orientation and that cracking of the of the J-groove weld metal can precede cracking of the base metal. Therefore a revised susceptibility model taking into account the above mentioned items had to be established.

In addition, the presence of circumferential cracking where only a small amount of boric acid residue indicated a problem, raised questions on the adequacy of current visual examinations. For boric acid deposits from CRDM nozzle cracks to be detectable at the outer surface of the RPV head, sufficient reactor coolant has to leak through the primary pressure boundary into the annulus between the CRDM nozzle and the RPV head base metal, propagate up the annulus and finally emerge onto the outer surface of the RPV head. Since PWSCC cracks in Alloy 600 and Alloy 182 welds are very tight, leakage from is expected to be small.

The EPRI Materials Reliability Program (MRP) offered an approach by using an assessment of the relative susceptibility of each PWR to OD-initiated or weld PWSCC based on the operating time and temperature of the penetrations [3]. Based on this simplified model, each plant was ranked by the MRP according to the operating time in Effective Full Power Years (EFPY) required for the plant to reach an effective time-at-temperature equivalent to Oconee 3 at the time the above-weld circumferential cracks were identified in early 2001. Based on the experiences at Oconee it was recommended that plants ranked within 10 EFPY should perform a visual inspection of the RPV top head capable of detecting small amounts of leakage.

Although the industry susceptibility ranking model has limitations, such as large uncertainties and no predictive capability, the model does according to NRC provide a starting point for assessing the potential for vessel head penetration nozzle cracking in PWR plants.
III. INSPECTION TECHNIQUES

As a result of the degradation described several NDE techniques has been developed to react on the different requirements.

Boric acid deposits on the top of the reactor vessel head may be indicative of primary coolant leakage through the penetration wall or the J-groove weld from the underside of the reactor vessel. Fig. 2 shows a typical example for boric acid deposits. Westinghouse and partners have available remote tooling and inspection technology to perform “under the insulation” visual inspections to identify evidence of leakage in the form of boric acid deposits. The system consists of a remotely controlled delivery vehicle, high resolution cameras, video monitors and screen writing capability to perform and document these visual inspections. Fig. 3 shows the BTRIS manipulator on a reactor vessel head mock-up.

Figure 2. Boron Accumulation on Vessel Head.

Due to reactor vessel head insulation configurations, some utilities are forced to remove the reactor vessel head insulation.

Westinghouse resources from Germany, Sweden and the United States have cooperatively developed equipment and nondestructive technology for providing “under the head” eddy current and ultrasonic inspection techniques for identification and characterization of degradation that might exist in the penetration tube OD and ID surfaces and the J-Groove welds [4]. Some of these developments represent significant advancements to technologies and equipment developed originally ten years ago.

Recent operating experience has resulted in the need for additional inspection capabilities and to expand the inspection coverage beyond that of only the penetration tube inside diameter surfaces. Advanced ultrasonic and eddy current equipment and techniques have been developed and applied to inspect the J-groove welds, penetration inside diameter surfaces and penetration outside diameter surfaces in plants with open penetrations as well as those containing thermal sleeves. Each of these inspections poses challenges in terms of inspection technology and mechanical systems for probe delivery.

The DERI 700 is the delivery system for all inspection and repair equipment. The DERI 700 manipulator is a multi-axis, remotely operated robot that can access all nozzles without repositioning. The robot is shown in Fig. 4.

Figure 3. BTRIS Delivery Vehicle on a Reactor Vessel Head.

Figure 4. DERI 700 System Testing in Mockup.

For plants having penetrations with thermal sleeves, ultrasonic and eddy current examinations are performed from the annulus between the thermal sleeve and the penetration tube using the Gap scanner end effector. The Gap scanner end effector is specifically designed to deliver eddy current and ultrasonic inspection probes, referred to as blade probes, into the annulus. This annulus is typically on the order of 0.125 inches. The Gap scanner end effector is shown in Fig. 5. Eddy current examinations are typically performed using a differential eddy current probe with two pancake coils. In the event degradation is identified during
eddy current inspection, ultrasonic techniques are used for sizing. The ultrasonic probes for crack sizing consist of undamped, broad band time-of-flight-diffraction (TOFD) probes. By using TOFD probe pairs with different probe spacings, accurate sizing can be accomplished throughout the penetration thickness range. The eddy probes are able to detect cracks with depths as small as 0.01 inches and a length of 0.10 inches. The sensitivity of the TOFD probes is comparable. TOFD sizing can provide depth sizing accuracies of 0.04 inches or less.

For plants where no thermal sleeves are present, the Open Housing Scanner is applied conducting multiple examinations. Typically, these include eddy current examinations of the penetration inside surface as well as ultrasonic examinations for detection of degradation on the outside diameter surfaces of the penetration tubes as well as degradation near the weld to tube interface. Detection and sizing capabilities are on the same order as those described for the blade probes.

When there is a need to perform eddy current examination of the J-Groove welds and/or penetration OD surfaces the Groove man end effector is available for all pressurized water plant designs. The purpose for performing this inspection is to determine if surface flaws exist in the J-Groove welds or nozzle OD and to characterize the indications as axial or circumferential. The end effector is designed to conform to the geometry of the J-Groove welds to allow eddy current probe to follow the contour of the assembly. The Groove man end effector is shown in Fig. 6. An eddy current method is now applied for inspections of the J-Groove welds that were used for pipe weld examination. The quasi surface flaws were detected and confirmed by destructive testing. The method was designed as a volumetric examination to extend approximately 0.050” subsurface, similar to the techniques commonly used for volumetric inspections of steam generator tubes.

Figure 5. Gap Scanner for Inspections of Penetrations With Thermal Sleeves.

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Figure 6. Groove Man End Effector.

In addition, dye-penetrant testing techniques are available for the inner surface of the penetration and for the J-weld.

IV. REPAIR CONCEPT

If an indication is found there is either the option to assess the evidences of non through wall cracks by an evaluation for continued operation until a planned repair or a repair directly following the NDE.

Westinghouse has available repair methods to address the known or anticipated cracking scenarios. Remote repair capability is available for electron discharge machining, welding and dye-penetrant testing. This tooling is delivered using the same manipulators as that for the under the head nondestructive examinations.

In the general Westinghouse repair concept the exposure of cracks in the alloy 600 (82/182) metal to reactor coolant system environment will be eliminated by a welding overlay using the alloy 690 corresponding filler metal alloy 52 or alloy 152. There is either the option of excavating the existing indication and performing a weld overlay using an ambient temperbead weld repair process or directly performing a weld overlay as so called embedded flaw repair. The benefits of using the embedded flaw technique is, beside the elimination of exposure of active flaws to the environment and therefore a stop in crack growth, the limited extend of repair which minimizes the change in residual stresses. The method is applicable also to through wall cracks. In addition, the plant operation time is to be expected longer than or equal to the anticipated operation time prior to repair, a removal of thermal sleeves is not required and it simplifies post-repair non-destructive examination.

Five scenarios have been determined to address different repair methods to different repair positions and
crack orientations. Examples for the different scenarios are shown in the Figs. 7 a 9.

**Crack in the penetration tube wall.** The crack can be oriented either circumferential or axial. A window will be machined into the thermal sleeve by EDM technique, if a thermal sleeve is present. The indication will be excavated and a weld overlay using Alloy 52 will be performed. NDE inspection will be the final step.

![Figure 7. Repair Scenario Crack in Penetration Tube Wall.](image)

**Axial crack in the J-groove weld towards the penetration.** The J-groove weld surface will be prepared by remote flapping. The crack will be embedded by a weld overlay on the J-groove weld surface and the penetration tube OD with a single layer of alloy 52.

![Figure 8. Repair Scenario Crack in J-Groove Wall towards Penetration.](image)

**Mitigative method.** The mitigative method is foreseen as a preventive measure to isolate alloy 600 material from the reactor coolant environment. Therefore first the penetration nozzle tube ID will be machined to allow a weld overlay. Then a weld overlay will be made on the penetration tube ID. In addition the surface preparation will be made on J-groove weld and penetration tube OD, followed by a complete overlay over J-groove weld and penetration tube OD.

![Figure 9. Large Circumferential Crack in Penetration Tube.](image)

**Axial crack on the penetration tube OD below the J-groove weld.** The same method will be used as described one paragraph above.

**Large circumferential crack in the penetration tube (flaw removal method).** The indication in the J-groove weld excavated followed by a verification step with dye-penetrant. If the indication was within 1/8 inch of the reactor vessel head base metal a ambient temperbead weld process will be used. A reweld and a final weld overlay will be performed. Last step is the NDE inspection.

Westinghouse has developed a series of remotely operated end effectors which are used in combination with the DERI 700 manipulator system. To assist the DERI 700 robot in lifting the heavier repair tooling a heavy arms lift system HALS has been built. Figs. 10 and 11 are showing the DERI 700 / HALS system and various end effectors foreseen for different repair tasks. Westinghouse experiences during recent repair field activities have proven and supported the design as well as the reliability of the tools.

![Figure 10. DERI 700 System with HALS System.](image)
REFERENCES


