6th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components
October 2007, Budapest, Hungary

RPV and Primary Circuit Inspection II

Core Shroud Inspection Coverage and Inspection Time Improvements through Phased Array Technique and Manipulator Improvements

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ABSTRACT

In December 2006, the Boiling Water Reactor Vessel and Internals Project (BWRVIP) issued a letter mandating two-sided coverage for the volumetric examination of BWR core shroud welds. In this letter, they noted that:

> "Ultrasonic flaw detection and sizing performance is degraded by stainless steel or nickel allow weld metal. The base metal examination volumes on both sides of the weld should be examined using sound beams that have not passed through the weld metal. Whenever possible, stainless steel or nickel-alloy weld joints should be examined by scanning on both of the two components that are jointed by the weld. When one side of the weld is examined using only beams that have passed through the weld metal, that side of the weld should be considered to have received a "best effort" examination."

This long awaited letter and the associated new requirements coupled with continued customer interest in improved coverage and reduced outages have supported AREVA's comprehensive program to modify their core shroud inspection tools and techniques. The basic approach was to address all welds from the annulus between the vessel and the shroud so as to minimize interference with refueling, to examine horizontal, vertical, and ring segment welds with maximum coverage, and to complete the task in the shortest possible time. This paper will discuss: the UT techniques adopted to achieve two-sided phased array coverage of the welds; the tool modifications particularly regarding the reduction in tool height to maximize coverage; software features to enhance the tool ergonomics and minimize the possibility of operator errors; and auxiliary tool features to facilitate completion of the inspection in the shortest possible time and with minimal dependence on site resources including the polar crane. The tool has been deployed to two sites following the improvements discussed herein and those field performances are also discussed.

INTRODUCTION

The BWR core shroud is a cylindrical shell that separates the reactor core from the jet-pump annulus. The cylinder is about 1 meter smaller in radius than the vessel ID and is typically fabricated with 7 to 10 welds depending on the specific design (figure 1). The cylinder material is normally 30-50 mm 304 or 304L stainless steel with stainless steel welds, or alloy 182 welds. This configuration is known to be susceptible to inter-granular stress corrosion cracking (IGSCC) and cracks have been known to occur since their initial observation at several plants in 1993. Core shroud inspection has been a key focus of the Boiling Water Reactor Vessel & Internals Project (BWRVIP) since the group's inception in 1994. The BWRVIP has recommended a periodic inspection program consisting of ultrasonic (UT) and visual (VT) examinations, and most plants have implemented the recommended BWRVIP inspection program. Although significant cracking can be tolerated without safety or operational significance, some plants have also implemented tie-rod repairs to reinforce the structure.

Core shroud inspection challenges are significant. The geometry of the shroud and obstructions from the jet-pumps and other structures in the annulus between the shroud and the vessel create occlusion areas where no transducers can reach. Many other areas are only accessible by very narrow low-profile transducers and delivery manipulators. Being mostly in the core region, the radiation levels are high in many areas. This inspection also is conducted in close proximity to refueling and in-vessel maintenance activities.

In December 2006, an EPRI report (reference 1) was issued via EPRI letter 2006-511 recommending two-sided coverage of the core shroud welds because the welds tended to mask sound reflections from flaws on the opposite side from the transducer. A technical basis for implementing two-sided examinations of BWR shroud welds was presented. This report also observed the advantages of phased array UT technology to improve coverage with fewer transducers. AREVA along with other inspection vendors followed these recommendations and undertook new demonstrations with phased array technology.

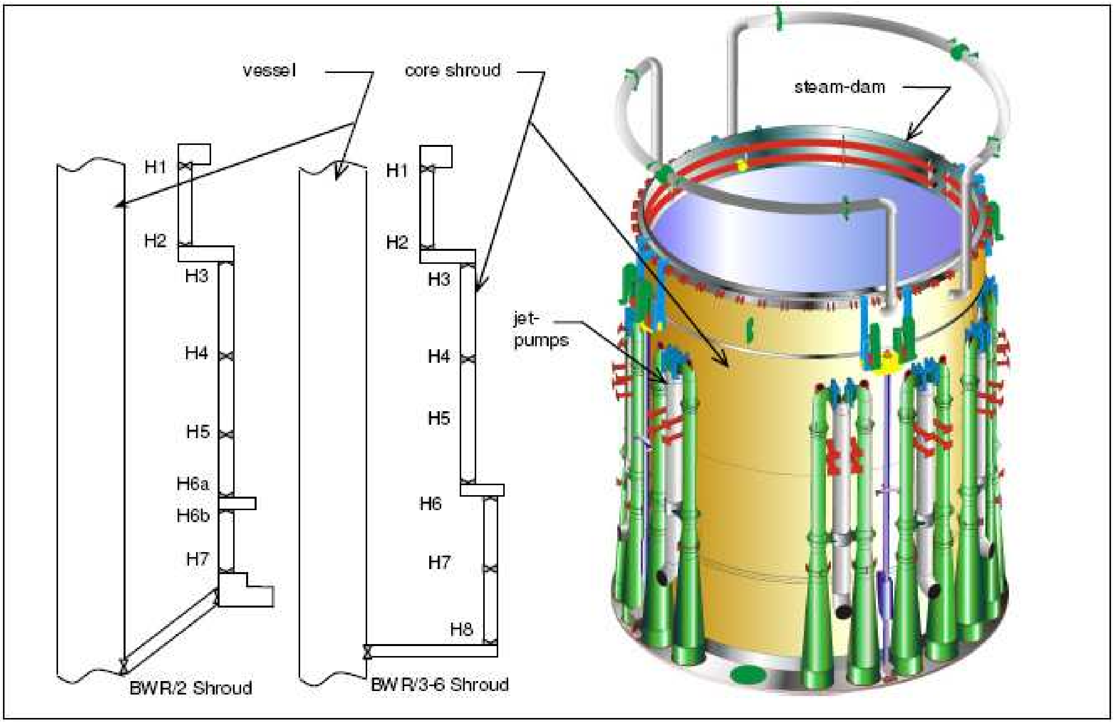

Figure 1 - Typical BWR shroud arrangement and weld configuration

AREVA has evolved their core-shroud inspection tool over many years to improve reliability, increase coverage, minimize cost and schedule, and reduce interaction and conflict with refueling activities. In 2006, AREVA completed their two-sided phased array technique demonstration in accordance with the BWRVIP-03 guidelines. The phased array technology however was only one aspect of the overall investment to improve the BWR shroud inspection capability.

TOOL EVOLUTION

The AREVA Core Shroud Inspection Tool (CSIT) began in the mid-90's as a stepper-motor mast system that was manually lowered from the refueling platform into the annulus between each set of jet-pumps. The end of the mast supported a scanning arm that folded parallel to the mast during raising and lowering. A scissors jack driven by a linear slide was used to position the X-axis against the shroud for scanning. The scanning arms themselves were engaged with the shroud using a pneumatic cylinder designed to apply a relatively controlled force on the transducers.

The mast was positioned and locked in place circumferentially and axially by a trolley that rode the steam-damn. Circumferential positioning was based on tracking wheels with encoders and axial position was based on a video camera view of a tape measure attached to the mast.

Since 2003, numerous tool improvements have been implemented to reduce the inspection time, improve the coverage, and generally increase the reliability of the system. All stepper motors were replaced with brushless DC motors. This essentially eliminated any induced noise on the UT signals and improved the strength and/or lowered the profile of the joints since the brushless motors offer improved strength-to-volume attributes over stepper motor technology. The straight X-arm was replaced with a belt-driven curved arm to lower the tool profile and improve access behind obstacles close to the shroud wall (figure 2). The array of six conventional transducers facing in two (2) directions was replaced with a low-profile set of four (4) phased-array transducers facing in four (4) directions to allow a single scan to cover the weld without flipping or rotating the array.

The trolley was improved to replace manual manipulation of the mast with a fully encoded remote manipulator control. Use of the steam-dam was also eliminated by changing the trolley anchor point to a ring clamped just above the steam-dam. This eliminated concern over a damaged steam-dam lip. In addition, a small radiation tolerant camera with a pneumatic "dual-position" actuator was added to verify proper installation and operation of the tool.

Two additional simple masts were developed to scan the H1/H2/H3 welds above the jet-pumps. The simpler tools are feasible because the transducers are not required to pass behind jet-pumps or other obstacles. Another special tool was developed to improve H7 access near the sensing lines in a BWR/4 (Fermi) (Figure 4). These tools can be easily changed out with the primary mast used for the lower welds, or can be installed on a second trolley also attached to the guide rings.

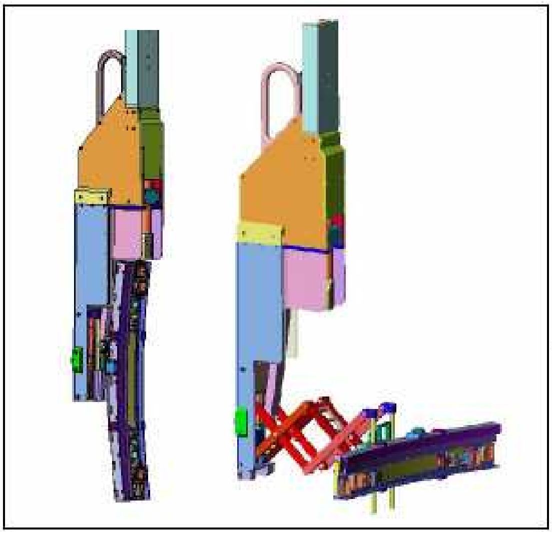

Figure 2 - CSIT folded for installation (left) and operating configuration (right)

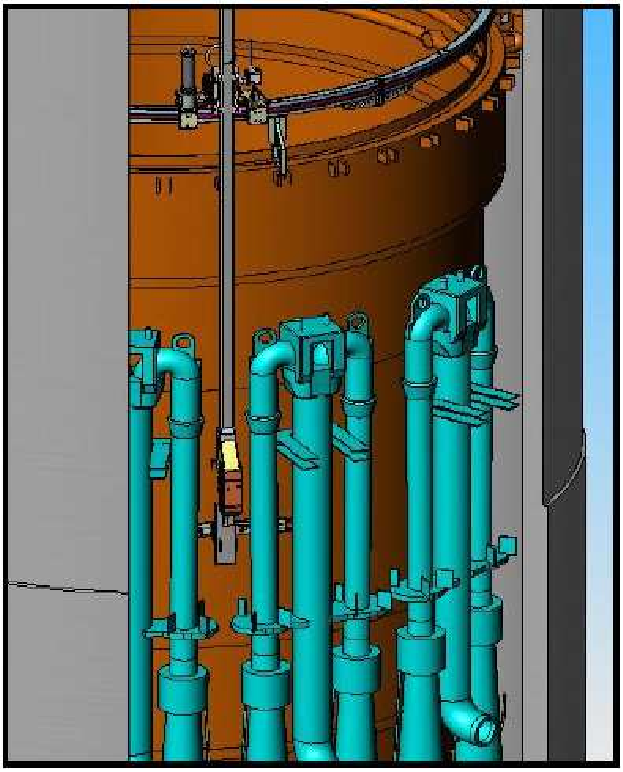

Figure 3 - Ring and cart with mast extending between jet-pumps

NDE TECHNIQUE

Implementation of the phased array UT technology for the core shroud examination focused on two sided coverage as recommended in the EPRI guideline, achieving improved examination coverage, and minimizing the scan time. Data acquisition uses Zetec's Z-Scan phased array instrument with Ultravision software for data analysis. The phased array technique relies on a (16) element, dual array transducer, specially commissioned for low-profile access behind the jet-pumps and other obstructions near the core shroud. The transducer is capable of producing 30° to 85° longitudinal waves, and 30° to 45° shear waves. The 30° to 45° shear waves are used for detection and length sizing for ID/OD flaws, and depth sizing of shallow (≤0.25") ID/OD flaws. The 30° to 85° longitudinal waves are used for detection and length sizing for ID/OD flaws, and depth sizing of ID/OD flaws. The 70° to 85° longitudinal waves are used for detection and length sizing for OD flaws, and depth sizing of shallow

(≤0.25”) ID/OD flaws. Four (4) identical transducers are mounted on the delivery tool to eliminate the need for multiple scans of the same region. The transducers are suitable for detection and sizing so the tool need not be pulled to change transducers as with some previous head configurations. Scanning is normally performed along the weld axis. Because of the PA technique, the scan increment is fairly wide and only a few line scans are required to achieve complete coverage. Although flaws may be detected and characterized either parallel to or perpendicular to the welds, only flaws orientated predominantly parallel to the weld axis are considered relevant.

The H3 shroud weld presents a special case for the two-sided UT technique (figure 5). The first part of the ring/ledge examination consists of scanning from the plate side of the weld. The second part of the examination is performed with the probe on the shroud-ring side of the weld. The ultrasonic beam propagates through the shroud ring material in order to achieve two-sided coverage. A sector scan is performed with the transducer scanning in the circumferential direction and indexing in the radial direction.(Reference 2)

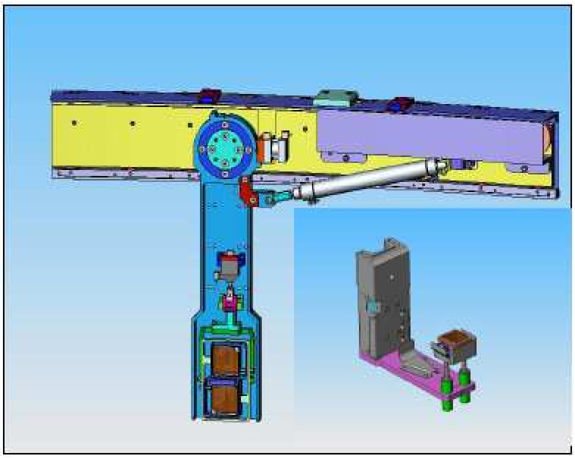

Figure 4 - Adaptations for H7 (left) and H3 (right).

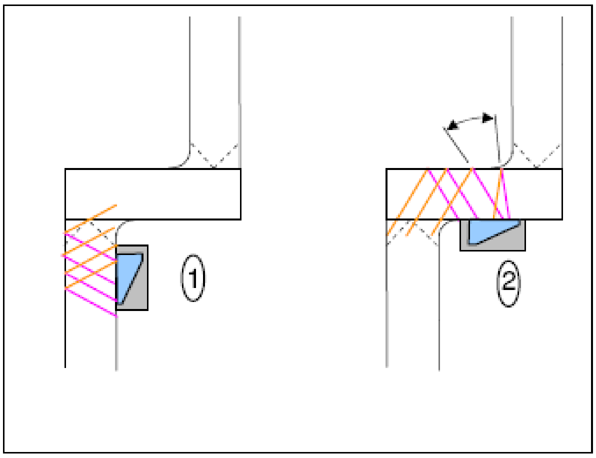

Figure 5 - PA inspection of H3 ring segment weld

CONTROL SOFTWARE

AREVA has invested heavily in 3-D graphic interfaces for the operators using gaming technology graphic software tools. Multiple views of the tool including theoretical CAD representations of what the video cameras should be viewing as well as live video views are available to the operator. The fully encoded manipulator position is fed to the control computer so the model represents the real position and configuration of the tool shown in its operating environment. This improves the operator’s perception and confidence of the tool position and thereby facilitates more rapid setup of each scan.

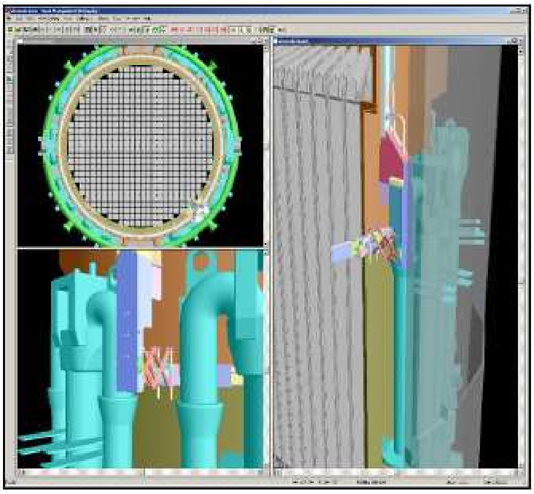

Figure 6 - Operator control window with ergonomically engineered multiple tool views

CHOREOGRAPHY SOFTWARE

An additional software feature to improve the core shroud inspection task coordination with refuel and other critical path refuel floor activities is the choreography software. The plant refuel schedule and associated fuel cells that are involved are prepared well in advance of the outage. This schedule is provided to the refuel choreography software so the operator can visualize where the CSIT activity is relative to refuel activity. The current and near-term planned activities are updated with periodic calls to the control room or via a computer link to the refuel coordinator. Based on this feedback, the operator can drive the CSIT to a position that is least likely to interfere with the refuel work or any other work shown on the refuel floor and in-vessel map.

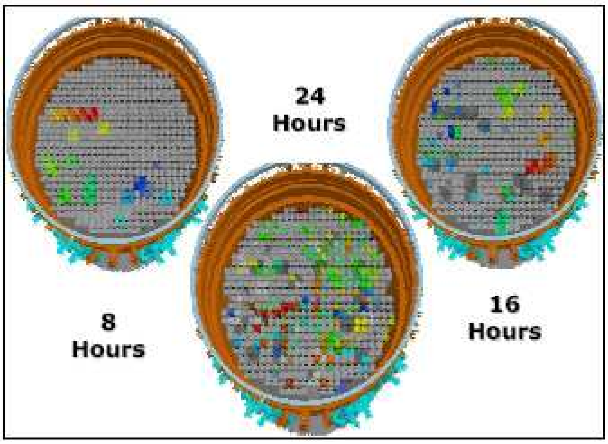

Figure 7 - Choreography software allows operator to avoid refuel activities and possible interference with critical path work.

WORK-PLATFORM

Although certainly not required to perform core shroud inspection work, AREVA has developed a BWR Work-Platform that can substantially aid the refuel floor activity by allowing personnel access to most of the periphery of the vessel at the top of the refuel pool without interfering with the refuel activity. The Work-Platform is a “C-shaped” bridge with legs that extend over the periphery of the vessel to rest on the refuel pool deck. IVVI and other pole controlled activities may be conducted completely independently of the refuel work. Although the CSIT is independent once installed and does not need any pole support, if a problem occurs requiring the tool to be raised, this can normally be done from the work platform without interfering with the refuel team. Without the work-platform, servicing the CSIT requires interruption of the refuel task.

FIELD PERFORMANCE

Browns Ferry committed to performing UT examinations of the core shroud welds in accordance with BWRVIP-76 ("BWR Core Shroud Inspection and Flaw Evaluation Guidelines"). All seven (7) horizontal welds were at the end of their 10-year re-inspection cycle and were re-examined during the U2C14 RFO. In addition, a baseline examination was performed for two (2) vertical welds.

The results of the examination are as follows:

- Weld H1: 77.08 % examined (Lower), 1.73% of examined length containing indications
- Weld H2: 62.40 % examined (Upper), 82.72 % examined (Lower), 0.80% of examined length containing indications
- Weld H3: 80.78 % examined (Upper), 82.07 % examined (Lower), 15.03% of examined length containing indications
- Weld H4: 98.60 % examined (Upper), 98.60 % examined (Lower), 0.00% of examined length containing indications
- Weld H5: 89.60 % examined (Upper), 98.60 % examined (Lower), 1.61% of examined length containing indications
- Weld H6: 98.60 % examined (Upper), 91.70 % examined (Lower), 9.30% of examined length containing indications
- Weld H7: 63.30 % examined (Upper), 53.80 % examined (Lower), 11.50% of examined length containing indications
- Weld V7: 100.00 % examined (Upper), 100.00 % examined (Lower), 0.00% of examined length containing indications
- Weld V8: 100.00 % examined (Upper), 100.00 % examined (Lower), 0.00% of examined length containing indications

Weld coverage were obtained during this examination that were superior to any previous core shroud examinations conducted at Browns Ferry. The overall schedule was 6 days - vs. a planned schedule of 9 days. This did not include a one week delay while the crew waited for completion of a repair task before the last weld could be inspected. (Reference 3)

Cooper Station also committed to do reinspections of H5, H6A, H6B, and H7 core shroud welds during their RE23 refuel outage in fall 2006. Because of the configuration of the Cooper H6A and H6B plate to ring welds, the welds were examined using AREVA's phased array plate to plate weld technique that was demonstrated in mid 2006. The results of the examination are as follows:

- Weld H5: 72.44% examined, 1.46% of examined length containing indications
- Weld H6A 72.44 % examined, 0.54% of examined length containing indications
- Weld H6: 72.44% examined , 0.46% of examined length containing indications
- Weld H7: 53.78 % examined, 1.60% of examined length containing indications

Weld coverage for Cooper Station also exceeded previous efforts and the examination was completed well ahead of schedule.

CONCLUSION

Evolutionary improvements of AREVA's CSIT include mechanical modifications, advancements in the UT technique, software enhancements to improve the operator's awareness of the tool position thereby facilitating more rapid setup and operation, and auxiliary functions like improved on-board video and the work-platform to assure the CSIT support tasks are independent of other refuel tasks. Two-sided coverage with low-profile PA transducers has enhanced the overall coverage performance of the tool as well as reduced the overall amount of scanning. Field results have been exceptional with outstanding coverage and on or under-schedule performances since these changes have been implemented.

REFERENCES

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3. INPO OE24623 - Successful Core Shroud Weld Examinations during Unit 2 Cycle 14 Refueling Outage (Browns Ferry 2), 04-20-2007, Vic Schiavone - TVA