DEVELOPMENT OF ULTRASONIC AND EDDY CURRENT TESTING SYSTEMS FOR NI-BASED ALLOY WELDSAT THE BWR REACTOR BOTTOM HEAD

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ABSTRACT
Ni-based alloy welds of bottom head penetrations at BWR reactors, such as control rod drive (CRD) stub tubes and in-core monitor (ICM) housings, are pressure boundary joints. Therefore nondestructive evaluation (NDE) of the profile and through-wall-depth of stress corrosion cracks (SCCs) plays important roles in keeping integrity of components and planning of repair or replacement work. Inspection systems including remote access tools and NDE devices utilizing flexible eddy current array probes and ultrasonic phased array probes have been developed in consideration of accessibility to weld lines of BWR bottom head penetrations. This paper describes features and performance confirmation of the NDE techniques and performance confirmation of the inspection systems by applications to mock-ups of BWR bottom head penetrations.

INTRODUCTION
Ni-based alloys have been used in boiling water reactor (BWR) components, especially joints between reactor pressure vessels (made of low alloy steels) and pressure vessel nozzles (made of Ni-based alloys or stainless steels). The Ni-based nozzles are mainly found in the control rod drive (CRD) stub tubes and in-core monitor (ICM) housings in the reactor bottom region. Ni-based alloy welds have stress corrosion cracking susceptibility [1]; therefore, preventive maintenance techniques are particularly important for keeping integrity of such pressure boundary components [2-5].

Getting access to the bottom head region and inspecting weld lines between the reactor pressure vessel (RPV) and nozzles are challenging tasks because of the complex geometries. For example, the number of nozzles per one reactor is about 200 and gaps between nozzles are very narrow (~100mm). As well, the surfaces of the weld line have three-dimensional (3D) curvature like a saddle.

Hitachi-GE Nuclear Energy, Ltd. and The Japan Atomic Power Company have developed inspection systems composed of remote access tools and nondestructive evaluation (NDE) devices, for the weld joints at the BWR bottom head region, e.g. CRD stub tubes, ICM housing tubes and the nozzle of the differential pressure & standby liquid control systems (DP-SLC). Two types of multiple-jointed manipulators have been prepared for inspecting from the inner and outer sides of the RPV. The first type of manipulators is for getting in-vessel access and for scanning for eddy current testing (ECT) and ultrasonic testing (UT); they are installed from the top of the RPV. The second type of manipulators is for getting ex-vessel access and scanning for UT accessing from the outer side of the RPV bottom head region.

NDE techniques utilizing array sensors have been applied to the Ni-based weld inspection. In ECT accessed from the inner side of the RPV (ID-ECT) techniques, flexible multi-coil array probes have been developed for fitting to curvature (radius: ~20mm) of weld surfaces. In UT accessed from the inner side of the RPV (ID-UT) techniques, contact-type phased array UT probes and immersion-type phased array UT probes with an acoustic lens have been developed for examining the curved weld surfaces. In UT accessed from the outer side of the RPV (OD-UT) techniques, the contact-type phased array probes with point focusing have been prepared for examining the thick-walled RPV (thickness: ~200mm).

Main advantages of the flexible multi-coil ECT techniques are their ability to provide highly accurate length sizing and position identification of stress corrosion cracks (SCCs). The phased array UT techniques provide high accurate through-wall depth sizing. Integrity of the RPV can be estimated by
OD-UT techniques sizing.

Performance of the NDE techniques, including inspection procedures and range of applications has been independently verified by members of the Japan Power Engineering and Inspection Corporation (JAPEIC) and an expert committee organized in JAPEIC. Additionally performance of inspection systems was confirmed by applying them to mock-up test pieces of BWR bottom head penetrations with SCCs.

FEATURES OF NDE TECHNIQUES

NDE procedures and targets

Generally, visual testing (VT) is applied to in-vessel inspection with the aim of detection of cracks, as shown in Fig.1. In the case of a crack detected by VT, the ID-ECT techniques are adopted for crack length sizing and estimation of 3D positions of cracks edges on a weld surface. As an optional extra, ID-ECT techniques can be used as an alternative crack detection method. The ID-UT and OD-UT techniques are applied to crack depth sizing by identification of crack tips. In particular, the OD-UT techniques can judge whether crack tips propagate into a RPV or not.

Inspection targets of the NDE techniques are Ni-based weld lines at the bottom head region of BWRs, for example, weld lines of CRD stub tubes, CRD housings, ICM housings and DP/PLC nozzles as shown in Fig.2.

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![Figure 1: Inspection procedures for in-vessel components](image-url)

*1: ID-ECT: ECT accessed from the inner side of the RPV
*2: ID-UT: UT accessed from the inner side of the RPV
*3: OD-UT: UT accessed from the outer side of the RPV
Flexible multi-coil techniques for ID-ECT

In a flexible ECT array probe, coils are arrayed in two lines as indicated in Fig.3. The base of the probe is flexible to allow scanning on a 3D curved weld surface. Coil couples (pairs of a detector coil and an exciting coil) are selected with two mutually perpendicular directions, and they are electrically switched in rapid succession [3].

Figure 3 Structure of the flexible multi-coil array probe for the ID-ECT

C-scan image (raw data)

Flaw identified data (signal processing)

Figure 4 Examples of crack identification for various SCCs
The flexible multi-coil ECT technique allows high-speed inspection through a few line scans on a weld line. Signals obtained by two-direction scanning are highly responsive to the edges of SCCs and independent of crack propagation directions on a weld surface. Curvature radius and shape of a weld have no influence on detectability. Length-sizing accuracy of SCCs is done with the assistance of crack identification software utilizing the phase difference of ECT signals. The software is in accordance with the Japan Electrical Association Guide (JEAG) 4217-2010 that describes regulations in regard to ECT instruments. Examples of SCC identification are shown in Fig.4.

![Array probe and Acoustic lens](image1)

(a) Photo of an ID-UT array probe  
(b) Crack depth sizing by an ID-UT probe

![Tip of SCC](image2)

(c) Image of ID-UT results for SCC

Figure 5 Example of contact-type ID-UT phased array probe and results of SCC

**Phased array technique for ID-UT**

In a contact-type ID-UT phased array probe, piezoelectric elements are arrayed in two lines as shown in Fig.5 (a). One is a transmitter array and the other is a receiver array. An acoustic lens is attached on the probe. The acoustic lens improves mechanical scanning over the curved weld surface and forming focal points for a long distance in the weld. And as for an immersion-type ID-UT phased array probe, piezoelectric elements are arrayed in a single line. Distance between an immersion-type ID-UT array probe and the weld surface is approximately 30mm.

Delay laws of piezoelectric elements are numerically calculated in consideration of refraction on curved boundary surfaces such as the weld metal and the acoustic lens. Delay laws are calculated by a 3D ray-tracing method assisted by 3D CAD models.

In the ID-UT techniques for sizing SCCs, ultrasonic waves are reflected around the crack opening area, rough crack surfaces and crack tips. ID-UT techniques results are obtained as synthesized images acquired at each scanning position as a cross section image. Through-wall depth sizing is quantitatively estimated by measurement of time-of-flight difference between crack opening area and the deepest point.
of the crack tip. A schematic configuration of a contact-type ID-UT array probe and ID-UT results for a SCC are shown in Figs. 5 (b) and (c).

Figure 6 Example of OD-UT phased array probe and results of SCC

Phased array technique for OD-UT

In an OD-UT phased array probe, piezoelectric elements are arrayed in a single line, which plays as both a transmitter and a receiver. The aperture of the probe (a product of the element pitch and the element number) is optimized for a thick-walled RPV [6-7]. Ultrasonic focus beams are formed around the boundary between the base metal of the RPV and the inner clad by phasing based on delay laws. An example of the contact-type OD-UT array probe is shown in Fig.6 (a).

In the OD-UT techniques for SCCs, ultrasonic waves are reflected around rough crack surfaces, crack tips and interfaces between the inner clad and the RPV and between the inner clad and the weld metal. Results of the OD-UT techniques are also obtained as synthesized images acquired at each scanning position as a cross section image. Through-wall depth and crack propagation into the RPV are quantitatively estimated as propagation length (distance) between the outer surface of the RPV and crack tips. A schematic configuration of an OD-UT array probe and OD-UT techniques results for a SCC are shown in Figs. 6 (b) and (c).

In the case of crack propagation to the RPV, the repair strategy may be different from that for small cracks within weld metal. Confirmation of the RPV integrity by the OD-UT can be performed in parallel to the ID-ECT, ID-UT procedures.
PERFORMANCE VERIFICATION

NDE techniques verification test

In the performance verification tests, test pieces simulated curvature of weld joints in the reactor bottom head region were prepared for the ID-ECT, ID-UT and the OD-UT techniques. SCCs were fabricated in test pieces of flat plates, saddle-shape welded blocks, CRD stub tubes, ICM housings and DP-SLC nozzles.

For the ID-ECT techniques, measurement accuracy of SCC length sizing was confirmed to have a standard deviation of 2.0mm and mean error of +0.3mm. Actual lengths of SCCs and ECT measurement values are compared in Fig.7. The following items on length were also confirmed: measurable curvature radius, not less than 5mm; acceptable lift-off, not more than 1mm; measurable minimum size limit of SCCs, 0.5mm deep and 3.3mm long.

For the ID-UT techniques, measurement accuracy of SCC depth sizing was confirmed to have a standard deviation of 2.4-3.4 mm and mean error of −0.9 to +0.3mm. The obtained accuracy depended on ID-UT conditions such as shapes of the acoustic lens and ID-UT probe specifications. Actual depth of SCCs and UT measurement values are compared in Fig.8 (a). The following items on depth sizing were also confirmed: measurable curvature radius, not less than 5mm; measurable maximum depth of SCCs, from 26 to 61mm (the maximum values depend on curvature radius).

For the OD-UT techniques, measurement accuracy of distance sizing from the boundary between the inner clad and the weld metal to crack tips was confirmed to have a standard deviation of 1.3-3.4 mm and mean error of +0.1 to +1.9mm. The obtained accuracy depended on OD-UT probe specifications. Actual distance to crack tips and UT measurement values are compared in Fig.8 (b). Additionally, measurable distance limit was confirmed to be not more than 45mm from the outer surface of the RPV.

![Figure 7 Length sizing accuracy of ID-ECT techniques](image-url)
(a) Depth sizing accuracy of ID-UT OD-UT

Figure 8 measurement accuracy of ID-UT and OD-UT techniques

(b) Measurement accuracy of ID-UT and OD-UT techniques

Figure 9 Length sizing accuracy of ID-ECT techniques
Mock-up tests for inspection systems

Mock-up tests have been performed using actual inspection systems (remote access tools and NDE devices) in an underwater environment. Accessibility and workability around the bottom head region of the BWR have been confirmed as well as sizing performance of the NDE devices. Photos of the inspection systems in the mock-up tests are shown in Fig.9. Inspection targets at the bottom head region was almost completely covered by combination of the ID-ECT inspection systems.

Inspections results were displayed as fusion images between NDE data and 3D CAD data. ECT results were viewed on the scanning weld surface. As an example of the ID-ECT techniques, results for a DP-SLC nozzle are shown in Fig.10(a). Two dimensional position data (switching and scanning direction in Fig.3) were converted to 3D position data on the weld surface.

The ID-UT and OD-UT results were also shown as cross sections in 3D CAD models of inspection target components. Examples are shown in Figs. 10(b) and 10(c). Inspection targets at the bottom head region was almost completely covered by the ID-UT and OD-UT inspection systems, respectively.

CONCLUSIONS

Inspection systems composed of remote access tools and NDE devices have been developed for Ni-based alloy weld components at the bottom head region of BWRs. The ID-ECT, the ID-UT and the OD-UT probes were fabricated to implement NDE techniques for complex shaped welds. Performances of the NDE techniques have been confirmed by JAPEIC. The main results are the following: (a) The ID-ECT
techniques: length sizing accuracy for SCCs was within 2.0mm, and acceptable lift-off was not more than 1mm. (b) The ID-UT techniques: depth sizing accuracy for SCCs was within 3.4mm, and measurable maximum depth is 61mm. (c) The OD-UT techniques: distance measurement accuracy from the outer surface of the RPV and crack tips was within 3.4mm, measurable distance limit was 45mm from outside of the RPV. Performances of the inspection systems have been verified by mock-up using test pieces simulating CRD stub tubes, ICM housings and DP-SLC nozzles. Inspection targets at the bottom head region was almost completely covered by the ID-ECT, ID-UT and OD-UT inspection systems, respectively.

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