Steam Generator Tube Inspection I

Development of Smart Array Probe and Introduction of New Inspection System
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ABSTRACT

NEL has developed X-probe in collaboration with major overseas manufacturers. X- Probe is an Eddy Current Testing (ECT) probe to inspect steam generator (SG) tubes at pressurized water reactor (PWR) plants. After that, NEL has developed on its own the higher-performance ECT probe, Smart Array Probe. Concurrently, two kinds of easy-to-handle, high performance inspection systems have been introduced from Westinghouse to replace the existing testing set (consisting of a tester, pusher and robot): OMNI-200 pusher-incorporated tester and Pegasys tube-walking robot. New inspection system (Fig. 1) incorporating NEL3DView analysis software, which was developed by NEL, has been created in collaboration with Westinghouse technologies. This paper reports the verification of the benefits of the new system.

INTRODUCTION

SGs, where heat is exchanged between the primary and secondary coolant, work as a primary coolant boundary and is regarded as one of the most crucial pieces of equipment at PWR plants. For this reason, in-service inspection (ISI) utilizes ECT techniques, which allow highly accurate and high-speed inspection, to examine SG tubes where the primary coolant is flowing. Bobbin probes are most commonly used, although there has been criticism that bobbin technology lacks accuracy in detecting circumferential flaws.

NEL, in collaboration with overseas manufacturers, has developed the array-type X-Probe in 1998 to offer better flaw detectability and resolution [1]-[6]. It is equipped with a total of 48 pancake coils (16 on the circumferential and 3 rows of coils on the axial orientation); Some ICs incorporated in the probe head selects coils in sequence to detect tight circumferential and axial flaws on the inner and the outer surfaces of SG tubes. Fig. 2 shows the schema of detecting flaws. X-probe simultaneously obtains data from the axial and circumferential detection modes. X-probe, which is EPRI SG Guideline Appendix H qualified, has been widely applied to detailed inspections of SG tubes at PWR plants mainly in the US, Canada, and Europe [7], [8]. In Japan, qualification tests have been conducted by the Japan Power Engineering Inspection Corporation (JAPEIC) as well as PWR plants with positive results.

![Figure 1- New Inspection System](image-url)
Although X-probe has excellent resolution (both axial and circumferential modes use 32 channels to fully inspect tubes), there is inconsistency between the data obtained from 16 channels on Rows B and C for the circumferential mode. This complicates data analysis, and therefore the circumferential mode is often treated as a 16-channel mode. Therefore, detectability deteriorates at some regions, depending on the relative positioning between flaws and coils, and this could reduce flaw sizing and positioning capabilities.

In order to overcome this difficulty, NEL has developed on its own Smart Array Probe with better detectability and resolution by utilizing the numerical simulation code based on the reduced magnetic vector potential (Ar) method [9]-[11]. Concurrently, two kinds of easy-to-handle, high performance inspection systems have been introduced from Westinghouse: OMNI-200 pusher-incorporated tester and Pegasys tube-walking robot.

NEL3DView analysis software, which was developed by NEL and suitable to analyze data from array probes, was adopted for the new inspection system.

This paper reports the features of the new inspection unit consisting of the probe, tester, robot and software (Fig. 1), and verification tests to prove the performance of the new system.

DESCRIPTION OF NEW INSPECTION SYSTEM

Smart Array Probe

The coil positioning of Smart Array Probe is almost the same as that of X-probe. It has, however, improved circumferential detectability and resolution as a result of better combination of transmitter and receiver coils: 32 channels for circumferential mode are aligned on the same circumference. Fig. 3 illustrates the flaw detection schema. Generally, when transmitter and receiver coil pairs do not match the orientation of a flaw, detectability declines [12], but Smart Array Probe has improved the detectability to a small degree by choosing the coil pairs as shown in Fig. 3 to provide shorter distance between coils. No data correction is necessary for axial positioning as the 32 channels are positioned on the same circumference. There is no significant improvement in the axial mode, though detectability has improved due to the shorter distance between coils.

The other features and benefits of Smart Array Probe are:

![Figure 2 - 3x16 X-probe](image1)

![Figure 3 - Smart Array Probe](image2)
Table 1 - Performance Comparison of X-probe and Smart Array Probe

<table>
<thead>
<tr>
<th></th>
<th>Detectability</th>
<th>Resolution</th>
<th>Axial positioning data correction</th>
<th>Inspection speed</th>
<th>Manufacturability</th>
<th>Calibration</th>
<th>Analysis</th>
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<tbody>
<tr>
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<td>3</td>
<td>Circum.</td>
<td>Axial</td>
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<td>Necessary</td>
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<td>6</td>
<td>Positioning</td>
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<td>7</td>
<td>Inspection</td>
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<td>8</td>
<td>Calibration</td>
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<tr>
<td>9</td>
<td>Analysis</td>
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</table>

- Faster inspection speed: at maximum 1.5 times faster than X-probe. In obtaining circumferential data from 32 channels, it needs only 8 time slots (12 time slots for X-probe).
- No complicated coil switching needed. Better manufacturability from relatively simple circuit design without transmitter-cum-receiver coils.
- Full-length and U-bend designs available as with X-probe. The full-length design can be applied to the full length of Rows 4 to 46 as well as the straight segment of Rows 1 to 3, whereas the U-bend design can be applied to the small radius U-bend segment of Rows 1 to 3. Smart Array Probe has the same applicability as X-probe, as the configuration of the probes is almost the same and the applicable surface is the same.
- The same signal format as that of X-probe means that existing methods and knowledge can be applied to calibration and analysis.

Table 1 compares the performance of 3x16 X-probe and Smart Array Probe.

**OMNI-200 (pusher-incorporated tester)**

OMNI-200 is a pusher-incorporated tester developed by Westinghouse. It is capable of both time-sharing and simultaneous multifrequency testing. The tester is...
housed in the pusher reel and rotates with the reel. Therefore, analogue signals from probes are converted to digital signals without passing the rotating part, which results in better noise-resistance and lighter workload for cable installation and setup. This unit can carry, in addition to conventional bobbin probes, and X-probe. Regarding Smart Array Probe, a new interface module has newly developed by Westinghouse. Figs. 4 and 5 illustrate the concept and the photo of OMNI-200, respectively. Table 2 shows the specifications of OMNI-200.

**Pegasys (tube-walking robot)**

Pegasys is a tube-walking robot developed by Westinghouse. With improved positioning accuracy and less decentering at tube ends compared with existing arm-type robots, Pegasys provides higher quality data with no dead zone. Pegasys is much lighter (approx. 13 kg) than conventional arm-type robots (over 90 kg); it can reduce heavy workload of workers as well as radiation exposure when setting up and removing. Fig. 6 shows the photo of Pegasys.

**ANSER (inspection software)**

OMNI-200 and Pegasys are coordinated and controlled by EWS acquisition software called ANSER, which was developed by Westinghouse. One click can automatically insert, withdraw or move probes to the next address. The software can simultaneously control multiple OMNI-200 and Pegasys units.

<table>
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<tr>
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<th><strong>OMNI-200 Specifications</strong></th>
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<tr>
<td>1.</td>
<td>Inspection frequency</td>
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<tr>
<td>2.</td>
<td>Max. multifrequency</td>
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<td>3.</td>
<td>Max. number of coils connected</td>
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<tr>
<td>4.</td>
<td>Max. number of channels</td>
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<td>5.</td>
<td>Signal output mode</td>
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<td>6.</td>
<td>Max. sampling rate</td>
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<td>7.</td>
<td>CPU</td>
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Table 2 - OMNI-200 Specifications
NEL3DView (analysis software)

Inspection using array probes with fast and high accuracy performance including X-probe and Smart Array Probe instantaneously produces a large amount of data, which requires efficient and accurate data analysis and evaluation capability. NEL3DView incorporates, in addition to conventional manual analysis functions, three automated capabilities to satisfy this requirement: calibration, signal screening and depth sizing. It can also analyze data from conventional bobbin-type probes. Fig. 7 presents an example of images plotted by NEL3DView.

VERIFICATION OF CAPABILITIES OF NEW INSPECTION SYSTEM

Detectability and resolution of Smart Array Probe

Inner axially oriented (IA) EDM notches and outer circumferentially oriented (OC) EDM notches were used to validate the detection and resolution capability of Smart Array Probe. The above-mentioned new inspection system was used in combination with this new probe.

![Figure 8 - Comparison of Detectability and Resolution using EDM Notches (300 kHz)](image-url)
Fig. 8 presents examples of detection data together with data from X-probe in combination with TC7700, a conventional tester. These images indicate that the detectability is 1.2 times higher for the axial mode and 1.1 times higher for the circumferential mode than those of X-probe. The noise level is almost the same; the S/N ratio has also improved. This suggests that Smart Array Probe is more capable of detecting tight flaws.

The comparison of the minimum detectability ratio (min./max. detectability) for the axis mode reveals very little difference: 86% for X-probe and 87% for Smart Array Probe. It, however, shows great improvement for the circumferential mode: 68% for X-probe and 86% for Smart Array Probe. This improvement was achieved by the fact that Smart Array Probe has 32 channels whereas X-probe has 16 channels. The minimum detectability ratio depends on the resolution of flaws. X-probe can improve the minimum detectability ratio by using 32 channels for the circumferential mode, but it needs axial positioning correction. For this reason, the evaluation of signals could be complicated when the inspection speed changes. It can be inferred that Smart Array Probe has higher reliability as the variation of detectability is smaller and axial positioning correction is not required at all.

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**Figure 9 - Artificial SCC Signals with Smart Array Probe and Destructive Test Results**

(a) IA SCC on straight section

(b) IA SCC on expansion transition

(c) IA SCC on expansion section with TS

(d) OC SCC on expansion transition

Artificial SCC signals

Destructive test results

Max. depth 36%TW
Length 3.9mm

Max. depth 29%TW
Length 7.6mm

Max. depth 34%TW
Length 3.8mm

Max. depth 66%TW
Length 5.9mm

Axial mode 300 kHz

TS

Axial mode 300 kHz

TS

Axial mode 300 kHz

TS

Circum. mode 100 kHz

TS
It was also confirmed that the new testing unit is capable of generating the same quality of data as conventional techniques and detection and analysis software performs without any problems.

Smart Array Probe detectability of artificial SCC

The second validation test was conducted using test sections with artificially induced stress corrosion cracks (SCC), which simulated SCC observed at PWR plants. The test pieces were made of Inconel-600 SG tubes and exposed to a corrosive solution while stress was applied to the orientation of crack growth. Another test pieces simulating SCC on the expanded tube and expansion transition was manufactured. The test pieces were expanded before stress was applied. A mock-up tube sheet of carbon steel was applied to the expanded tube in flaw detection.

Test pieces were destroyed after tests to identify the configuration of flaws. Fig. 9 indicates detection and destructive test results. The tests confirmed that the new inspection system is capable of detecting SCC on the expanded tube and expansion transition, which are difficult to detect with bobbin probes, including the shallowest flaw (IA crack on the expansion transition with the maximum depth of 29% TW (approx. 0.37 mm)).

Verification of automated screening and depth sizing capabilities of NEL3DView

The third evaluation was carried out using test sections simulating flaws in SG tubes in order to verify the automated screening and depth sizing capabilities of NEL3DView. Fig. 10 presents an example of images generated by NEL3DView. An EDM notch simulating an outer axially oriented (OA) flaw on the surface of SG tube supported by BEC type tube support plate (TSP) was used to verify automated screening capability. The result indicates that the software recognized signals from the flaw, although signals were very small.

![Automated screening (OA EDM (20%TW) with BEC type TSP)](image)

(a) Automated screening (OA EDM (20%TW) with BEC type TSP)

![Automated depth sizing (Wear (19%TW))] (image)

(b) Automated depth sizing (Wear (19%TW))

Figure 10 - Verification Results of Automated Screening and Depth Sizing Capabilities
Wear on the surface of SG tube was simulated to evaluate automated depth sizing capability. It was evaluated that the depth was 22% TW, whereas measurement confirmed 19% TW: the difference was 3% (less than 0.1 mm). This result indicates that the software is capable of evaluating flaw depth accurately.

CONCLUSIONS

1) Smart Array Probe with high detection and resolution capabilities for axial and circumferential flaws was developed and manufactured.
2) It was confirmed that the performance of Smart Array Probe exceeded that of X-probe in a number of aspects and the new design has a good flaw detection capability.
3) It was verified that the new inspection system is capable of generating equally high quality data as existing designs.
4) It was demonstrated that there are no glitches in the NEL3DView detection and sizing software functions and it has accurate automated screening and depth sizing capabilities.

REFERENCES

8) G. Lafontaine, et al. “X-probe Steam Generator Inspection Device”, 3rd Int. Conf. on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components, 2001