Development of Remote Visual Inspection System for BAC Program of RPV-head Penetration in KOREA-NPP
C-K. Kim, H-T. Lim, J-G. Choi, H-H. Kim, Advanced NDE Service Corporation, Republic of Korea

Abstract
RPV-upper/lower head penetration (RPV-HP) is the guide tube which provides through the way of the control rod and monitors nuclear fission reaction. It is welded as a J-groove form to the pressure retain surface. The each ending of the tube is completely sealed by explosive or hydraulic expansion. Recently BAC (Boric Acid Corrosion) of alloy 600 material for RPV-HP tube is becoming a big issue throughout the world. According to US NRC Order EA 03-009, performance volumetric and visual examinations are recommended.

For KOREA-NPP, it is required that the visual inspection equipments are compact size, since the spacing of the RPV-upper head and thermal insulation is smaller than 64mm. This also requires autonomy driving between penetration tubes, allowing inspection without the removal of the thermal insulations. Also, because RPV-lower HP visual inspection is performed on thermal insulation materials, it is necessary that the visual inspection devices should be slide proof and should be able to ride over the uneven thermal insulation seams.

Considering related standards requirements and necessary inspection conditions, ANSCO Inc. developed inspection crawlers which are 82 (W) X 155 (L) X 43mm (H) in dimension with a magnetic wheel drive for the upper device, and 132 (W) X 165 (L) X 90mm (H) in dimension with rubber caterpillar wheels for the lower device. The image acquisition camera features 180 deg. Pan/tilt, zoom in/out and auto/manual focusing with resolution of near vision test chart VT-1. This minimizes the limitation area of the examination.

RPV-HP mock-up and NPP site field test of the new remote visual inspection system provided the following results:

1. Shortened inspection time: Due to the significant improvements of the crawler’s turning angle in 173 mm space between RPV-HP tubes, inspection can be performed with 180 deg. X 2 directions, rather than existing equipment’s 90 deg. X 4 directions.

2. Pan-near approach mechanisms of the new equipment made it possible to perform a visual inspection without the removal of the thermal insulation materials in small spaces, such as the 22mm- between RPV-upper HP higher number row and thermal insulation.

Consequently, it is believed that the new inspection system can bring much more efficient monitoring to the RPV-HP BAC program.

INTRODUCTION
The reactor vessel head penetration of PWR is made out of Alloy 600 material, which could crack on CRDM, causing leaking. The structural safety of the PWR RPV (Reactor Pressure Vessel) head penetration has been questioned due to the discovery of the boric acid leak of RPV lower head’s ICI nozzle penetration from South Texas Plant #1 in April 2003(Figure 1). The cause of the cracks is PWSCC (Primary Water Stress Corrosion Crack) and the hoop stress. Cracks of the PWSCC were started from inside of the upper/lower part of the J-groove and thermal effect zone and cracks of the hoop stress were started from the outside. The main defective direction is found to be the axial direction.
EPRI Boric Acid Corrosion Guidebook (Rev. 1, 2001) shows the boric acid corrosion rates for each material that is used in NPP shows in Graph 1. According to this guide book, it shows almost the same boric acid corrosion rate, regardless of operating conditions. Performance of periodic inspections and confirmations has been requested.

As a result, Korea-NPP adopted the BAC program to evaluate the leakage inspection of the equipment within the reactor coolant pressure boundary and the soundness of the equipment that is exposed to borated water. The BAC program is applied to the safety class1 equipment, such as pressure vessel in the reactor coolant pressure boundary, pumps, valves and pipes. The reactor vessel upper/lower head’s inspection was very limited due to the array of the head penetration and insulation. It could only been inspected by remote visual tests. We developed a small device that is controlled remotely with a high resolution camera to perform the inspection with more accuracy and efficiency.

**INSPECTION TECHNOLOGY FOR RPV HEAD BAC PROGRAM**

**RPV HEAD CONFIGURATION**

The lower head of KSNP (Korea Standard Nuclear Power Plant) RPV has enough space between the insulation and the bare metal for inspection, but the upper head has only 50 mm of clearance with insulation structure as reflective stepped type. The insulation structure is attached to the lift lug to lift the upper head and surrounded by the steel skirt. This structure made higher number row penetration.
tubes very limited to be inspected. As it shows in the Figure 2. (c), it has only 52, 22, 14mm space between the tube and the insulation structure. This means upper insulation structures need to be taken apart to inspect. Since it is a stepped type it takes too long to be taken apart. Not only does it take too long, it was also exposing the workers to high radiation working conditions. A bigger problem of this procedure is the repeated re-assembling that could cause a difference of the original design and it is damaged. That makes the inspection even more difficult and may increase the limited area of the inspection, or a loss of the function of the thermal barrier.

![Figure 2](a) Section view, (b) Plan view, (c) Outside Penetration

For lower head, the inspection is performed on the insulation structures, which were made out of zinc iron sheet. It is very important to be slip-proof and be able to go over the uneven seams of the insulation structures.

![Figure 3](c) RPV Bottom Head

NEW-CONCEPT OF MINIATURE VT EQUIPMENT

US NRC Order EA 03-009 indicates the inspection scope of the reactor vessel head’s boric acid
leakage visual tests. It is requested to perform visual inspection 100% of the RPV head surface (including 360 degree around each RPV head penetration nozzle). Korean BAC program requires 0.044 inch reading of near-distance vision test chart for visual test resolution check. In order to meet that requirement, the camera needs to have wide range of FOV (Field of View) and high resolutions. Actual FOV needs to be measured at the sight for accuracy and scanned about 3/4 of the FOV. For lower head, as shown in Figure 3, the inspection is performed on the insulation surface toward the bare metal. Zoom and focus features are required and pan and tilt features are required to scan around the penetration tube. Considering the previously mentioned requirements, we used upper 63.6mm (L) X 18mm (ø) camera with resolution of 450TVL, 330,000 effective pixels and lower 39.3mm (W) X 44.8mm (H) X 65mm (D) camera with 1/4 -type HAD CCD, 380,000 effective pixels and 10x optical, 4x digital.

Since the clearance of the upper head’s insulation structure is 50mm, the height of the remote visual inspection device is very important. The width and depth need to be considered as well to access the limited areas since the spacing between outer layer penetration tubes and insulation structures is 14mm and the pitch among the tubes is 173mm. For lower head, the device performs the inspection on the zinc iron sheet material and run over the uneven insulation seams. Not like magnetic wheels for upper head, we made the lower head device with rubber caterpillar. To meet those requirements, we developed a crawler with upper device, 82mm (W) X 155mm (L) X 43mm (H), with magnetic wheels and lower device, 132mm (W) X 165mm (L) X 90mm (H), with rubber caterpillar, Figure 5. The visual inspection without the disassemble of the insulation structures of the outer layer penetration tubes that are located in 14mm space (Figure 2 c) is considered limitation area. However our crawler’s 90 degree (left and right) rotating feature made it possible to reach to the outer layer tubes. This Pan-near approach mechanism has a main servo motor, a pan servo motor, LED light modules and a heat sink plate.
In order to produce a small device like above, the drivers and controllers need to be very small. It must be designed for easy repair and parts replacement. Our crawler is designed and produced with a quick change, one-pass type 4-layer board as shown figure 6.

When there is a power failure, we can find another remarkable thing about this crawler. We used to pull the power cable to get the device out. Doing that caused a trouble for the device controller or the device gets tangled by other cables or gets stuck in the penetration tubes, which cause even bigger problems. So often the clutches are used to get the device out but this requires much bigger equipments to take care of the problem. Our crawler is designed to solve this problem emergency wheel idling mechanism, easily by pulling an attached cable to make the wheel axle idle. The video images that are captured by the high resolution camera get transmitted and saved by the recorder to get inspected. Figure 7 shows the system structures.

Figure 5 - Developed Upper Crawler (Left) and Bottom Crawler (Right)

Figure 6 - 4-layer board (a)
Remote Visual Inspection System Diagram-(b) Upper Block, (c) Lower Block
TEST OF MOCK-UP

KSNP reactor vessel upper/lower head is made out of SA 508 CL-3. The nozzle is made out of SB166UNS N06690 (Alloy 690). J-weld welding rod of the head is made out of ENi-Cr-Fe-3(Alloy 182) or ERNi-Cr-3(Alloy 82). Upper head has 83 CEDM nozzles and 1 Vent nozzle in total 84 nozzles. Lower head has 45 ICI nozzles. Since the reactor vessel penetration tube array is symmetrical as shown in figure 2. (b), this mock-up test produced 1/4 of the area as mock-up from 90-180 degrees. The scale was 1:1.

The prior scan path is prepared before the actual inspection in order to inspect so many tubes efficiently. With the existing devices, it was divided into 4 scans (90 degrees each) to perform the inspection of the upper penetration tubes (shown in figure 8). Because the size of the existing devices is hard to go through the 173mm space between the tubes, it was impossible to reach the outer layer’s limited area. However our crawler is only 82mm width. It is small enough to turn 180 degrees around. We could finish the inspection only with 2 scans, which means a half of the time it usually takes.

Our crawler’s pan-near approach mechanism, as shown in figure 2. (c), made the visual inspection possible of the limited area of the 14mm space between the tube and the insulation structures. Figure 9 shows the comparison results.
CONCLUSION

RPV-HP mock-up test of the new remote visual inspection system provided the following results:
(1) Shortened inspection time: Due to the significant improvements of the crawler’s turning angle in 173 mm space between RPV-HP tubes, inspection can be performed with 180 deg. X 2 directions, rather than existing equipment’s 90 deg. X 4 directions.
(2) Pan-near approach mechanisms of the new equipment made it possible to perform a visual inspection without the removal of the thermal insulation materials in small spaces, such as the 22mm-between RPV-upper HP higher number row and thermal insulation.

Consequently, it is believed that the new inspection system can bring much more efficient monitoring to the RPV-HP BAC program.

REFERENCES

1) US, 10CFR50 Appendix A
4) US NRC Bulletin 2001-01, "Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles"
5) US NRC Bulletin 2002-01, "Reactor Pressure Vessel Head Degradation and Reactor Coolant Pressure Boundary Integrity"
6) US NRC Bulletin 2002-02, "Reactor Pressure Vessel Head and Vessel Head Penetration Nozzle Inspection Programs"
8) EPRI Boric Acid Corrosion Guidebook(Rev.1, 2001)
9) Wcap-15988-NP(2003.3) – Generic guidance for an effective Boric Acid inspection program for PWR Reactor