Pressurised Water Reactor Bottom Mounted Instrumentation (BMI)
Repair and Inspection at Gravelines 1

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Abstract
In December 2011, an indication was detected in a Bottom Mounted Instrumentation (BMI) penetration in the reactor vessel (RV) at EDF Gravelines Unit 1 in France\cite{1}. WesDyne & Westinghouse were awarded a contract in March 2013 to develop, qualify and implement a first of a kind inspection & repair of the BMI. This repair involved removing the BMI and installing a plug from the inside of the reactor vessel\cite{2}. WesDyne & Westinghouse assembled a team with expertise in reactor vessel design, welding, machining, non-destructive testing, 3D scanning and sealing. The repair took place over a 50 day period and was completed at the end of October 2016. The removal of the BMI, the machining and welding activities for installing the permanent plug, as well as volumetric and surface examinations, were performed remotely from the refueling floor using a 20m deep coffer dam, inserted into the flooded reactor cavity. The team addressed multiple technical challenges such as design, welding and remotely operated tooling, in a very constrained environment. Twenty different tools were developed including ones for automated Penetrant Testing (PT), Ultrasonic Testing (UT) and dimensional measurements.

0. Introduction
Because this was a first of a kind repair, it involved the mobilization of a strong engineering team over a three year period. This project was a great challenge in terms of safety, nuclear safety, technical requirements, project management, interfacing an international team and on site implementation. The team was composed of various competencies in different technical areas; for the design of the repair process, the tooling design for each part of the process, the performance justifications for each application (including NDE), and qualification of each application. After successful qualification of the processes including; welding, machining, and non-destructive testing, the complete repair and inspection operation, following a flowchart with more than one hundred items and activities, was performed under representative site conditions at the Westinghouse Vasteras facility (Sweden).

This repair scenario and demonstration was successfully completed three times:
1. For Westinghouse and WesDyne internal purposes as a dry run,
2. For EDF as qualification of the operation.

The site intervention was performed during September and October 2016.
1. Component
The Bottom Mounted Instrumentation is a tube welded into the reactor vessel and it allows the introduction of nuclear instrumentation into the core of the reactor. Fifty BMI nozzles are typically welded at the bottom of the vessel for a 900MWe plant.

![Figure 1: BMI nozzle description](image1)

Defects in the J-weld area of the BMI may create leaks which constitute a breach of the primary coolant system. The solution is to remove the BMI nozzle (Figure 3) and replace it with a welded plug (Figure 4):

![Figure 2: BMI nozzle defect location](image2)

![Figure 3: BMI nozzle top view](image3)
2. Description of the repair

2.1 Global process of repair

The process of the repair was a sequence of different steps which were performed remotely, 20 metres below the operating platform, at the bottom of a 0.5m diameter coffer dam.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>✔️</td>
<td>Isolation equipment setup</td>
</tr>
<tr>
<td>✔️</td>
<td>Prepare and inspection of the RV cladding around BMI 4</td>
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<tr>
<td>✔️</td>
<td>Removal of BMI 4</td>
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<tr>
<td>✔️</td>
<td>Welding of the buffer layer</td>
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<tr>
<td>✔️</td>
<td>Check for removal of initial defect and buffer layer inspection</td>
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<tr>
<td>✔️</td>
<td>Welding of the 52M buffer layer</td>
</tr>
<tr>
<td>✔️</td>
<td>Check for removal of defect in 52M buffer layer</td>
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<tr>
<td>✔️</td>
<td>Machining of the plug at repair dimensions and setup</td>
</tr>
<tr>
<td>✔️</td>
<td>Welding of the plug</td>
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<tr>
<td>✔️</td>
<td>Control of the repair</td>
</tr>
<tr>
<td>✔️</td>
<td>Demobilization</td>
</tr>
</tbody>
</table>

*Figure 4: BMI repair design and final plug*
To ensure the reactor vessel (RV) integrity after removing the BMI by permanent plugging, 20 different remote and automated tools were developed and qualified including:

- PT tooling
- UT tooling
- Dimensional Scanning
- Welding Head
- Precision Milling
- EDM tools

The first step was to prepare the operating conditions, and more particularly, to ensure a perfect sealing of the dam on the bottom of the vessel around the BMI to be inspected. This was made possible thanks to a special adaptor between the bottom of the vessel and the coffer dam.

The work area was high pressure cleaned and visually inspected before applying the RV adaptor (RVA) onto the vessel; the RVA was clamped to the adjacent BMI. The coffer dam
was then fixed onto the RVA and the water drained out. The tools were lowered down through the coffer dam to the BMI area. The RVA was also designed to provide a reference point for the tools when they were operating on the BMI.

2.2 NDE prior the cutting out of the BMI
Four remote controlled inspections were needed to check if the BMI tube could be extracted.

2.2.1 UT inspection of the triple point elevation
Prior to the removal of the BMI it was required to locate the triple point. The triple point of the BMI is the interface between the nozzle OD, the weld buttering and the J Weld. A UT inspection was used to measure the triple point elevation of the J-weld to define the BMI cutting parameters (Classic BMI inspection with Vessel Bottom Tool). This position was used as a reference point to determine the exact configuration of the excavation tooling and therefore the amount of material which was to be removed.

A special probe was designed to work inside the BMI taking into account the BMI geometry and material type. Although this is not considered an inspection in accordance with a code, certain aspects of the positioning technique were in accordance with RCC M III and RCC M IV. The triple point was positioned within a tolerance of ±10° (angular axis) and ±2.5mm (vertical axis). The UT inspection measuring the triple point elevation was qualified under EDF supervision.
2.2.2 UT inspection of the cladding

The cladding was first machined in the relevant area around the BMI. The Westinghouse UTT ECJ tool was used to inspect the integrity and the thickness of the vessel cladding. The condition of the cladding for the welding of the 308L buffer layer was determined by the NDE results. This UT inspection consists of an ultrasonic exam with application of RCC-M S7710 criteria applied to buttering according to RCC M III and RCC M IV. In order to deposit the buffer layer on the cladding, without stress relieving heat treatment and technical justification, the cladding thickness must be at least 5 mm to satisfy the requirements of appendix 1.4 RSEM.

For UT cladding inspection, the standard probe SEB4KF8, allowed the compliance with RCC-M specifications to be demonstrated and the DAC to be constructed from 3.2 mm diameter FBHs. For UT cladding thickness measurement, a special TRL probe was used to identify and measure the interface between cladding and ferritic base material. The UT cladding inspection and thickness measurement were qualified under EDF supervision.

<table>
<thead>
<tr>
<th>Examination</th>
<th>Items</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cladding inspection</td>
<td>Sensitivity</td>
<td>The flaws are correctly detected with amplitude greater than the threshold</td>
</tr>
<tr>
<td></td>
<td>Depth positioning</td>
<td>± 1 mm</td>
</tr>
<tr>
<td></td>
<td>Sizing</td>
<td>± 3 mm</td>
</tr>
<tr>
<td></td>
<td>Positioning</td>
<td>± 3 mm</td>
</tr>
</tbody>
</table>
2.2.3 ET J-Weld interface location
An eddy current (ET) inspection was performed to define the weld boundary on the vessel and then the future buttering area on the vessel bottom with the UTT ECJ tool on the surface of the cladding. During the replacement process a “buffer layer” was welded to the existing RV cladding. When the preparation machining for the “buffer layer” was complete, the positioning of the J-Weld boundary was performed.

The goal of the inspection was to identify and quantify the interface between the Inconel 182 Weld and Stainless Steel Cladding. An ET probe designed for material recognition was used. The difference in the material characteristic/electromagnetic changes in conductivity was used to determine the interface between the two materials. The radius of the J weld interface was positioned within a tolerance of ±2.5mm.

Figure 12: ET J-weld interface between cladding and J weld

The ET inspection was qualified under EDF supervision.

2.2.4 PT Examination
During the various stages of the BMI repair penetrant testing with the PTT tool was carried out:

1. Penetrant testing on the vessel bottom head buttering after machining the area receiving the buffer zone
2. Penetrant testing after completing the SS 308L buffer layer
3. Penetrant testing of the machining of the 52M buttering for receiving the plug and of the excavation made at the BMI in order to check the defect removal.
4. Final penetrant testing of the 52M buttering, the weld and the plug pocket partial machining.

If indications were detected through NDE and a repair be initiated, a PT of the repair cavity and, if applicable, of the buildup would have needed to be performed.

The different phases of the PT examination were:

- Degreasing
- Drying
- Application of the penetrant liquid
- Penetration duration
- Elimination of the excess penetrant
- Verification that the excess penetrant has been eliminated
- Drying
- Application of the developer
- Drying of the developer
- Development and examination of the indications
- Defect sizing
- Final cleaning

*Figure 13: PT tool and process*

The type of defect sought was one detectable by a level 2 sensitivity PT system. The PT system sensitivity level was determined in accordance with the standard RCC-M. For the defect sizing, a video probe allowed a 3D measurement of the indications. The device included:

- A video probe with a pneumatic linkage and a 30m long wire.
- A high-resolution LCD VGA monitor.
- A transportation, storage and control case.
- A control joystick.

The video probe implements an optical metrology measurement process through phase shifting, consisting in projecting several line patterns onto the surface. The camera captures
and processes the projected patterns so as to generate a 3D map of the inspected surface. In this case, the video probe projects sinusoidal-phase shadow patterns onto the surface through 3 LEDs located on either side of the optics (Figure 14). The component distance is calculated for each point, through shadow triangulation. These patterns are analyzed through specific algorithms and a scatter diagram representing said surface is generated.

![Figure 14: Video probe and 3D phase measurement](image)

The 3D measurement technology displays several advantages, such as using one and the same lens during the inspection and measurement phase, which means an increased productivity. But it also displays very good performances in terms of indication measurements. A vertical-pointing laser is located on the developer and sizing heads so as to point the indication and thus position it thanks to the head coordinates. The in-house tests highlighted a maximum positioning inaccuracy of 1.5mm and a maximum positioning repeatability of 0.5mm. The EDF surveillance tests, during tool acceptance, over 12 measurements highlighted the following:

- Maximum positioning deviation: 1.5 mm
- Average positioning deviation: 0.67 mm
- Positioning repeatability: 0.5 mm

A positioning test was also performed during the PT process qualification so as to validate the claimed positioning tolerance. For 8 measurements, the results were as follows:

- Maximum positioning deviation: 1.1 mm
- Average positioning deviation: 0.85 mm

The PT inspection for the four surfaces was qualified according to RCC-M rules under EDF supervision.

When all inspection conditions were met following the first four examinations; UT triple point elevation, UT cladding examination, ET J-Weld extend and PT of the cladding, the BMI tube was cut out using EDM and removed.
2.3 NDE after each step of welding

2.3.1 UT inspection of the Buffer layer

The buffer layer 308L (item 3 Figure 15) was welded on the cladding. The cladding and its buffer layer was inspected using UT to check the quality of the buttering with the UTT-ECJ tool. The defect detection was assured by using a Pulse Echo technique with receiver/transmitter separated 0° standard probes such as SEB10KF3 and SEB4KF8. The reference reflector was a FBH Ø3.2 mm according RCC-M. DAC compensation was also applied. The UT buffer layer examination was qualified according to RCC-M rules under EDF supervision.

2.3.2 PT inspection of the Buffer layer

The buffer layer was machined to obtain the right thickness and then flapped and inspected using PT with the same conditions detailed in section 2.2.4.

2.3.3 UT inspection of the 52M Buttering

The 52M buttering (item 2 see figure 15) was overlaid on the buffer layer, and the cladding, to prepare the plug pocket. The 52 M build up was flapped and inspected using UT with the UTT-ECJ tool. The defect detection was assured by using a pulse echo technique with receiver/transmitter separated 0° standard probes such as SEB10KF3 and SEB4KF8. The reference reflector was a FBH Ø3.2 mm according to RCC-M. The DAC compensation is applied. The UT 52M buttering examination was qualified according to RCC-M rules under EDF supervision.

2.3.4 PT inspection of the 52 M Buttering
The plug pocket was created in the buttering by EDM, milling and flapping, and then inspected using PT with the same conditions detailed in the section 2.2.4.

2.3.5 3D scan of the plug pocket
The 3D scanning was performed to acquire a three-dimensional model of the actual geometry during the repair process. The dimensions of the plug pocket were measured by a 3D laser scan. The plug (item 1, Figure 15) was also checked with a 3D scan.

![Figure 17: The 3D Laser Measurement of excavation](image)

The volumetric accuracy obtained during the 3D scanning was:
- ± 0,040 mm on the ball diameters (spherical references).
- ± 0,040 mm for the distances between the balls.

2.3.6 UT and PT of the final weld
When the plug and the pocket were matched, the plug was welded in the pocket as shown in figure 18:

![Figure 18: Final weld](image)

After EDM of the weld profile, UT and PT final inspections were performed on the plug weld. The final weld was machined then flapped and inspected using PT with the conditions detailed in section 2.2.4. The UT examination met the requirements of RCC-M section MC 2610 for the detection of defects like lack of fusion in stainless steel welds. When the RCC-M code could not be applied directly, because of technical difficulties in austenitic welds, we justified the criteria developed. The potential flaws were lack of fusion / bonding type, oriented along the chamfer and between weld beads. The target defect had the following characteristics; circumferential orientated, 2.5 mm high and 10 mm long. The technique used dual element ultrasonic longitudinal probes at: 0° (2 transducers, 10 MHz and 4 MHz), 35° and 50° (2 MHz). One set of three probes was used in the direction towards the plug and the other set was facing away from the plug. DAC compensation was also applied.
For the qualification, a representative mockup was built with 13 lack of fusion defects in different locations. All 2.5x10mm lack of fusion flaws were detected with amplitude measurements and measured greater than the required detection criteria. All flaws detected above the nominal threshold $\geq 50\%$ and $\geq 5\text{ mm}$ length were considered unacceptable and would lead to a repair. The UT final weld inspection was qualified to RCC-M rules under EDF supervision.

Figure 19: Final Weld volume coverage

Figure 20: Polar view of the qualification mockup UT examination with TRL 0°

Figure 21: Final weld UT examination with one set of the three probes
3. Summary of NDE tools
More than 20 manipulators were developed for entire project and all the NDE applications were developed, and qualified by EDF according to RCC-M French codes, for the different steps of the BMI 4 repair process. The different NDE applications developed and associated tools are summarized below:

BoroMir UTT-ECJ

Figure 22: UT and ET Tools

1. UT of cladding and thickness measurement
2. UT of the buffer layer
3. UT of 52M buttering
4. UT of final weld
5. ET Location of J-weld to cladding interface

BoroMir UTT-VBP

1. Existing J-weld triple point positioning with UT

BoroMir SCN

Figure 22: 3D-Scan and PT Tools

1. Measurement of excavation before final machining of plug
2. Measurement of final plug installation

PTT Manipulator

1. PT of Cladding
2. PT of 308 Buffer Layer
3. PT of 52M Buffer layer
4. PT of final weld
5. PT of local defects
4. Conclusions

In this paper we have shown the capability of the WesDyne / Westinghouse team when it comes to challenging inspection and repair campaigns in hazardous environments using the example of the work performed in Gravelines 1. We have focused on presenting the non-destructive inspection aspects of the work and only briefly mentioned the engineering, welding and cutting scope when discussing the consecutive steps of the repair of the BMI#4 from the design to the site implementation.

For the NDE scope each inspection was qualified separately according to RCC-M rules, using purpose built remote automated tools, at the WesDyne facility in Täby, Sweden. To ensure the work was performed right the first time, full scale demonstrations of the complete repair scenario under representative site conditions with the whole team was repeated three times at the Westinghouse facility in Västerås, Sweden:

1. For Westinghouse and WesDyne internal purposes as a dry run,
2. In front of EDF as qualification of the repair and inspections.

This first of a kind repair of the BMI was completed by a Westinghouse and WesDyne International team at the end of October 2016. It was performed over a fifty day period working three eight hour shifts, seven days per week, with zero accidents.

The repair solution was implemented at site flawlessly, on time and with, no rework or additional actions required by the customer – a significant achievement. The unit is now re-connected to the grid.

5. Acknowledgements

EDF BMI#4 team for their strong support during the development, qualification and on site operation of this project.

6. References and footnotes