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Modeling in the Development of Complex NDE Solutions for AECL NRU Reactor

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Abstract
In May of 2009, the NRU (National Research Universal) reactor was forced to shut down after a small heavy water leak. In 2009-2010 repairs were performed in order to restart medical isotope production mid-August 2010. Since the NRU's return to service, a series of periodic inspections is required to ensure the safe operation of the reactor.
Eclipse Scientific was mandated to develop the NDE procedures and robotic manipulator for the In-Service Inspection program of the NRU vessel. This included the development and implementation of phased array ultrasonic inspection techniques and eddy current array technology techniques to be used with unique material characteristics, property and physical state changes. The inspection mandates were required in a short time frame and environmental conditions represented very difficult delivery and inspection circumstances. This paper presents how modeling was used in the development process to achieve the inspection mandates. The modeling software used ranged from advanced ray tracing (ESBeamTool) to full UT/ET simulation (CIVA) and was key in obtaining approval of the procedures, developing good training material and obtaining excellent data from the inspections.

Keywords: complex inspection, phased array, ultrasound, modeling, simulation

1. Introduction

On May 15, 2009 a heavy water leak was discovered in the National Research Universal (NRU) nuclear reactor vessel at the Atomic Energy of Canada Limited's (AECL's) Chalk River Laboratories facility. The leak was attributed to a small hole in the reactor vessel wall caused by corrosion and a thorough non-destructive examination (NDE) of the calandria (reactor vessel) found additional areas of wall thinning and localized pitting. Ten repair sites were identified and the chosen method of repair was to increase the thickness of the wall from the vessel inside diameter (ID) using a variety of techniques involving weld build-up. The repairs were completed and inspected and the NRU reactor was returned to service on August 17, 2010. The facility was restarted with the provision that in-service inspections (ISI) of the reactor vessel be conducted annually to monitor for further corrosion and assess the repair welds[1]. The team contracted to perform these inspections consisted of Eclipse Scientific Inc. (Waterloo, Ontario, Canada), Liburdi Automation (Stoney Creek, Ontario, Canada) and Utex Scientific Ltd. (Mississauga, Ontario, Canada). A unique robotic inspection system was designed and built to perform NDT inspections for signs of corrosion, cracks, and metal loss from inside the reactor vessel while it is fueled and filled with heavy water.
The challenge of performing all the necessary development work in the brief time before the first inspection could not have been met without the use of modeling. The two tools most utilized were ESBeamTool (an ultrasonic ray-tracing, drawing and reporting application) and CIVA (a semi-analytical ultrasonic and eddy current simulation application).

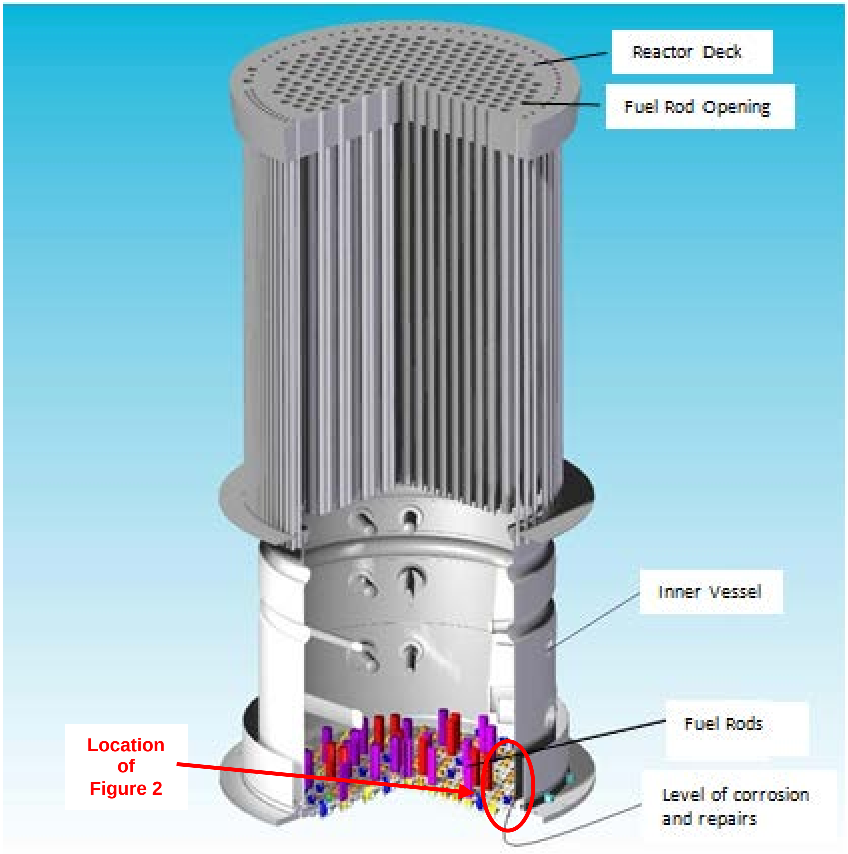

Figure 1. Cutaway view of NRU reactor

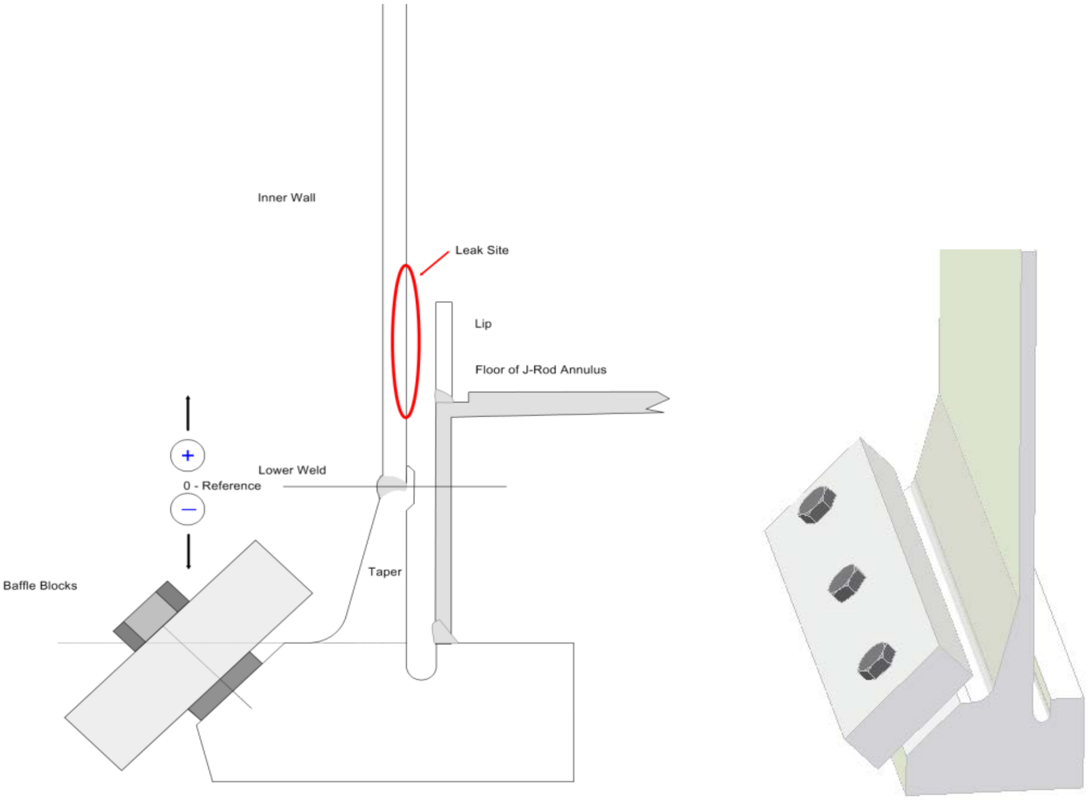

Figure 2. Cross section of reactor wall at the bottom in the region of the corrosion

2. Scope of In Service Inspection (ISI)

The Canadian Nuclear Safety Commission (CNSC) license of the NRU depends on completing the ISI according to the inspection specifications. These inspections are discussed below.

2.1 NRU Calandria and Required Inspections

The NRU calandria is approximately 11 m in circumference and is filled with the fuel rods and heavy water during the ISI (Figure 1). The location of the leak and other corroded areas was at the very bottom of the vessel wall as shown in Figures 1 and 2[2].

The reactor vessel is obviously a very difficult environment containing high radiation fields and radioactive materials which contaminate the inspection equipment. Additionally, access to the calandria is very restricted. The only point of entry for the inspection equipment is through existing 120 mm diameter fuel rod openings in the reactor deck at the top of the 9 m tall reactor structure (Figure 1).

A number of inspections are required. The only inspection required on the bare calandria wall is wall thickness measurement and monitoring with baseline and follow-up inspections at specified intervals in order to monitor for any continuing wall loss. There is a variety of welded repair types: some repair sites consist simply of layers of weld on the calandria ID; some sites include small plates which were tack welded to the calandria ID and then welded over; finally some sites include small structural plates which were fully welded to the calandria ID. The inspections required on or around the repair sites are described in Section 5.

3. Inspection Procedures

A combination of ultrasonic (UT) and eddy current (ET) techniques was used to meet the requirements. This paper describes the UT techniques and modeling tools used to develop them.

3.1 Delivery Tool

The delivery tool consists of a long tube which fits through the fuel rod opening and reaches to the bottom of the calandria (Figure 3). A robotic arm with a specially designed fixture at the end extends from the tube as seen in Figure 3. There are a total of five different inspection heads (also known as end effecters) which fit onto the end of the arm in order to complete all of the required inspections. There are two UT heads and three ET heads which are used with a total of seven different inspection techniques. The UT techniques are discussed in more detail below.

3.2 Ultrasonic Techniques

The first UT inspection head holds two phased array probes and can be tilted at controlled angles to produce shear waves when required. The larger probe is used for all wall thickness inspections and for examining the Heat Affected Zone (HAZ) around the sides and along the top of the repair welds. The smaller probe is used to inspect the welds holding the structural repair plates.

The second UT head holds another larger phased array probe protected by ‘bumpers’ to scan the HAZ along the bottom of repair welds. This requires the probe to move between the baffle block and wall (Figure 2) scanning upward with shear waves. The four UT techniques used were:

- Wall Thickness (WT) over both bare wall and over weld repair build-up.

- HAZ inspection along the sides and top of the weld repairs.
- Lower HAZ (LHAZ) inspection along the bottom of the weld repairs.
- Edge of plate inspection for the welds holding the structural repair plates.

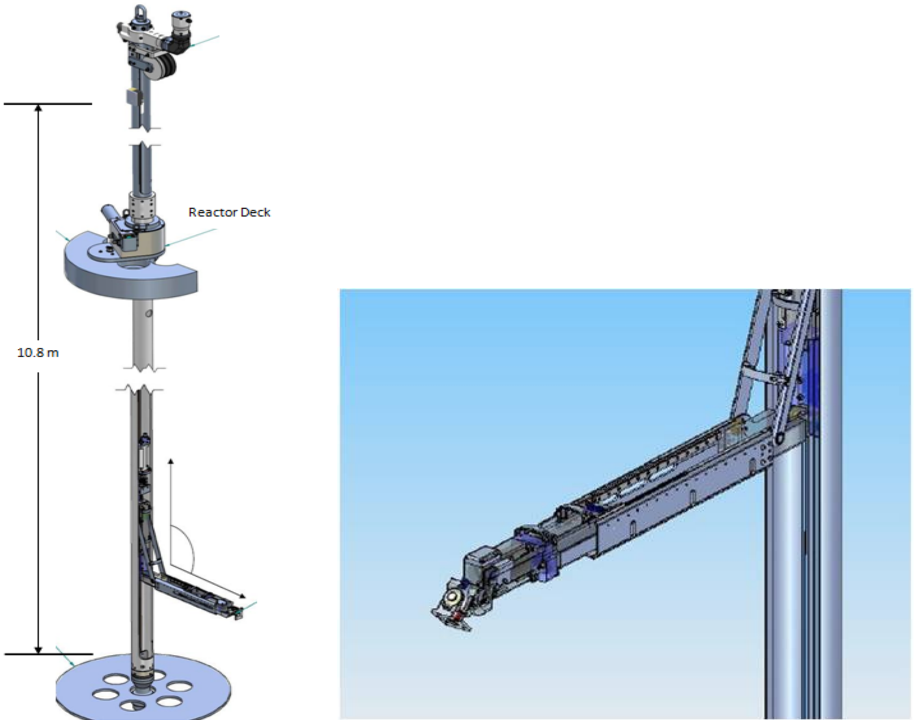

Figure 3. View of Delivery Tool and of Robotic Arm Extended

4. Modeling Tools

In order to optimize the accuracy and coverage of the inspection while minimizing worker exposure to radiation, all development work had to be done using either mock-ups or modeling. It was not possible to practice in the NRU so the first time the probe faced the calandria wall was for the first real inspection during an outage. While the mock-ups were being designed and built, the techniques were being concurrently developed in order to have a starting point for the inspection as soon as a mock-up was available to test the proposed techniques. This was accomplished by using computer generated NDE modeling. Continued development and refinement was accomplished with a combination of modeling and mock-up work.

The procedures must be qualified by the CANDU Inspection Qualification Bureau (CIQB). Part of the qualification process includes a Technical Justification document. Experimental results made up the bulk of this document but modeling played a vital role. It helped prove that techniques provided the required coverage, were sufficiently sensitive to the right kind of defect, while sufficiently insensitive to things like slight skew of the probes, and helped answer several other technical questions.

Extensive training was necessary for tool operators, UT and ET data acquisition teams and UT and ET data analysis teams. The training plan also had to be qualified by the CIQB. Practice time on mock-ups and with real data was essential but modeling provided the best material for introducing personnel to the project and for study when there was no access to equipment.

4.1 ESBeamTool UT Ray Tracing Software

This software package was developed by Eclipse Scientific Ltd. The user defines the piece to be inspected using CAD like drawing tools and then adds and positions ultrasonic probes (conventional UT, phased array or time of flight diffraction (TOFD)) and finally defines the beamset or beamsets which will be used for the inspection. This allows the user to confirm coverage of the area of interest. Defects can be added to ensure that the sound is reflected back to the probe at the desired angle.

This was the tool used most often and at all levels from the first draft of techniques through to the Technical Justification document. Creating a simple workspace can be quite fast. Then, once a workspace is created, either simple or complex, adjusting positions and beamsets is very straightforward and gives an immediate result. This allows the user to develop techniques more rapidly. Any problems which arose while performing acquisition could be modeled and a solution sought immediately.

4.2 CIVA UT and ET Simulation Software

This software package was developed by CEA (France) with EXTENDE acting as distributor, technical support and consultant for users. The user defines the piece to be inspected either in the software, which includes predefined shapes as well as a basic CAD editor, or by importing a CAD file. The ultrasonic probes (conventional UT, tandem, phased array or TOFD) are added by defining probe characteristics (size, frequency, angle etc.). CIVA uses the pencil method to determine the beam shape and strength.

CIVA provides a semi-analytical simulation and can include the effects of attenuation in its 2D or 3D models. The materials may be homogenous or heterogeneous and can be composed of layers with differing acoustical properties. This more complex modeling allows for more accurate prediction of sound beam interaction with defects and how the reflected signal strength will vary with parameters like probe skew or focusing and steering of phased array beams.

This tool was used most often in the later stages of technique development. One example was to show that a given technique would be able to detect defects of the required size and orientation under design conditions, but also when the delivery tool held the probe at an incorrect angle (within certain tolerances). Another example helped to determine the method of calibrating the sensitivity of one of the techniques in order to detect defects of the required size. These models take more time to set up and to run but provide more complete answers than ray tracing software.

5. ESBeamTool Examples

5.1 Wall Thickness Technique

This technique is performed in the same manner over bare wall or over repair weld and meets the requirements for each inspection. It is a phased array rastered scan using a single group configured for a 0 degree compression wave linear scan. It was designed for proper coverage and had to balance sufficient standoff distance (to prevent possible collision with the wall) with being close enough that small errors in angle positioning would not be amplified too much.

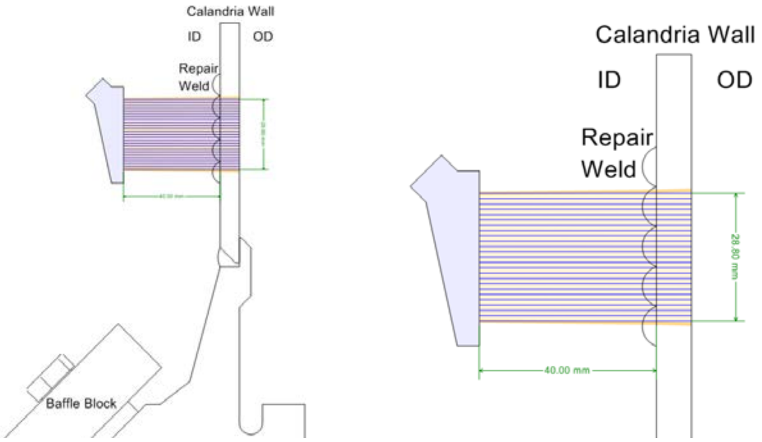

Figure 4. Wall thickness technique: Overview and detail

5.2 Heat Affected Zone Technique

This technique is performed to meet the requirements for inspection of the HAZ and is performed as a single line scan along the top and both sides of repair weld sites. The larger probe is set up with two groups, each a shear wave sectorial scan with one group near to the weld and the other away from the weld. This inspection covers the inside diameter (ID) and outside diameter (OD) HAZ if there is sufficient access around the weld. The only areas with restricted access are below some welds. In these regions the other UT head must be used (Section 5.3).
It was necessary to consider possible errors in translational positioning or angular positioning. The angles used had to be sensitive to surface connected cracking on both the ID and OD.

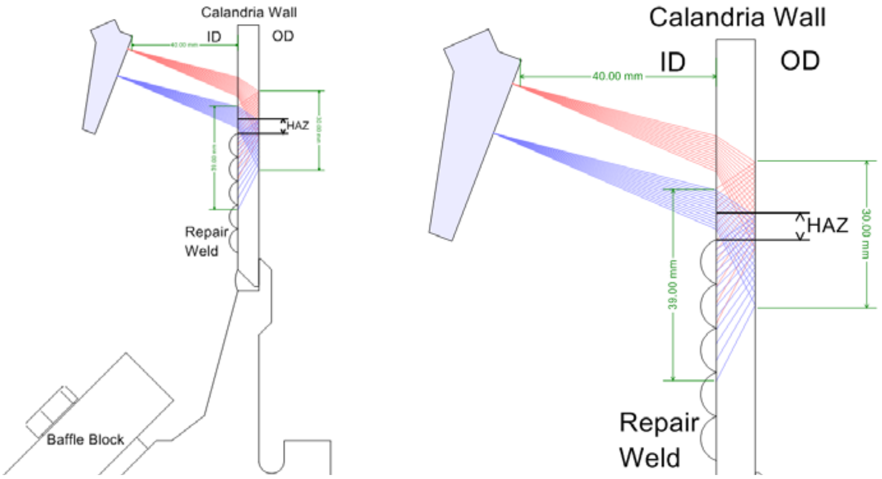

Figure 5. HAZ technique: Overview and detail

5.3 Lower HAZ Technique

This technique is performed to meet the requirements for inspection of the HAZ and is performed as a single line scan along the bottom of repair weld sites. Note that it only covers the OD of the calandria. It is performed with the larger probe with two groups configured as shear wave linear scans. One group is designed to refract from tapered surface below the calandria wall to the area of interest and the other group is designed to refract from the surface of the flat wall (in the sites where a small region of flat wall exists below the weld and above the taper).

Figure 6. Lower HAZ technique: Overview and detail

5.4 Edge of Plate Technique

This technique is performed to meet the requirements for inspection of the structural plate welds and is performed as a single line scan along each edge of a repair plate. The smaller probe is used with a single group configured as a shear wave sectorial scan. This is a volumetric inspection of the welds. The Edge of Plate technique was designed for thin plate (high angles) but required sufficient sensitivity as well as the ability to locate defects within tolerances.

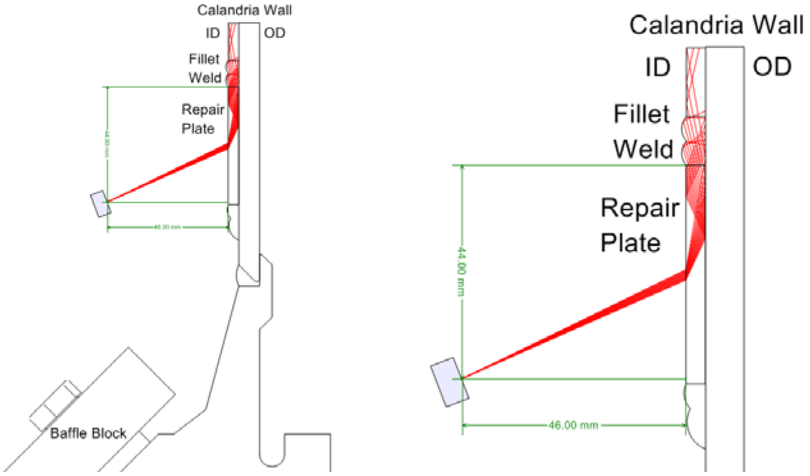

Figure 7. Edge of plate technique: Overview and detail

6. CIVA Examples

6.1 Development of Wall Thickness Technique

The wall thickness technique seems relatively straightforward but the inspection requirements specify a certain accuracy even when the top surface is a series of weld beads in the as-welded condition. Modeling with CIVA allowed the determination of optimum aperture size and focusing method in order to balance the requirements of small defect detection and accurate backwall depth measurement.

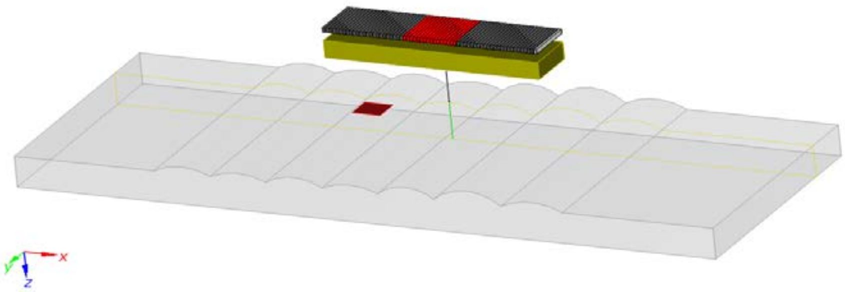

Figure 8. CIVA model of probe and piece with as-welded surface containing a laminar defect

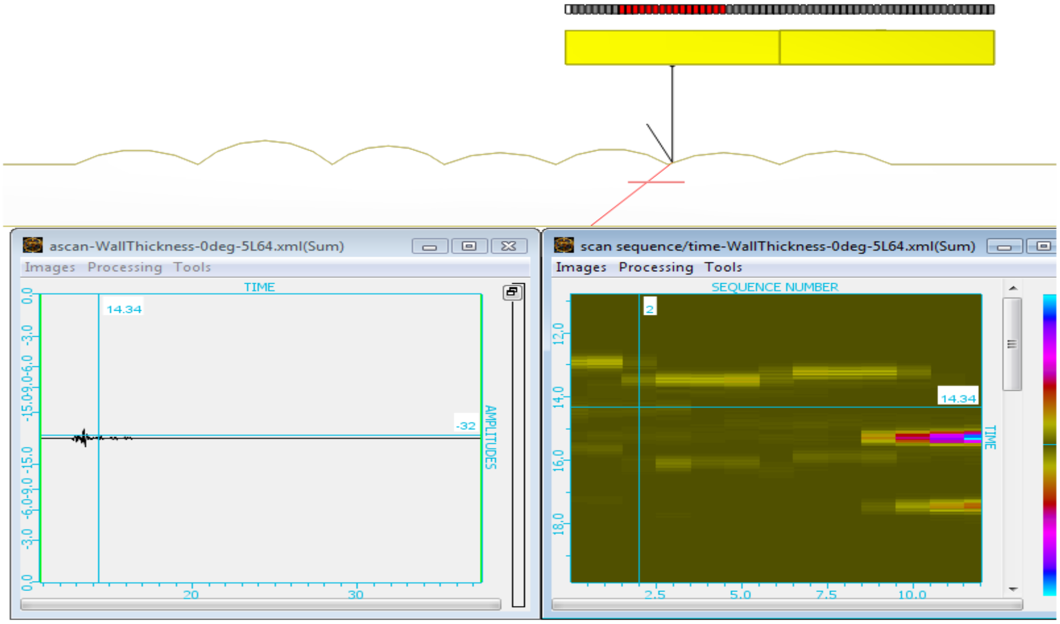

Figure 9. Simulated response from an unfocused focal law.

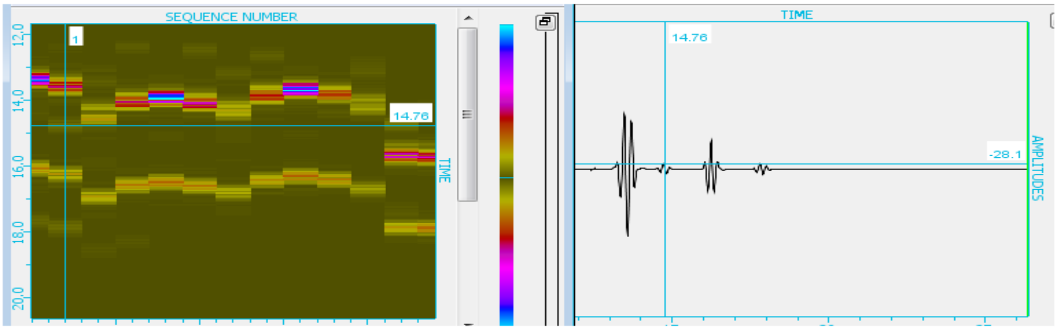

Figure 10. Simulated response (improved) from focal laws using compensated focusing

6.2 Amplitude and POD from different size notches

In preparing the technical justification document, some initial results were obtained using CIVA to determine minimum indication sizes which are reliably detectable. These simulations provided information on appropriate reflector sizes for the production of standards used for calibration and setting of sensitivity.

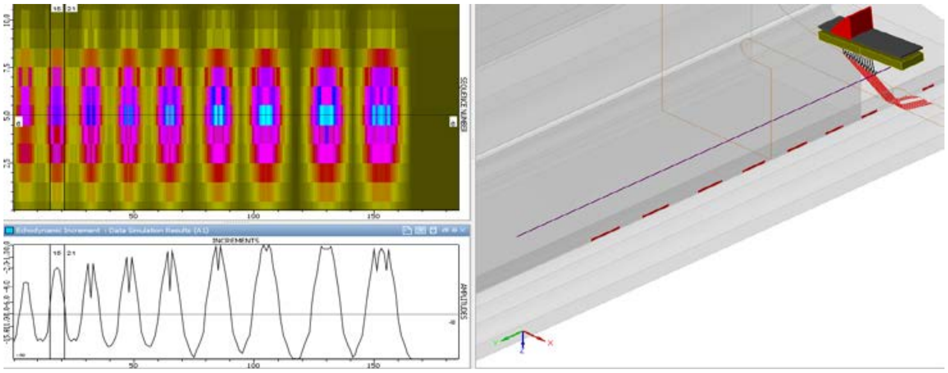

Figure 11. CIVA models of different size OD notches on the lower section of the vessel

6.3 Comparison of Contact With Immersion

In order to speed the development process and to be able to easily compare results, the techniques for the ISI were based on those used for the inspection which had been performed immediately after the calandria repairs. That inspection was performed as a contact inspection with the reactor defueled and drained. The ISI is performed as immersion in heavy water. CIVA simulated the comparison of contact and immersion inspections using the same techniques to confirm their viability.

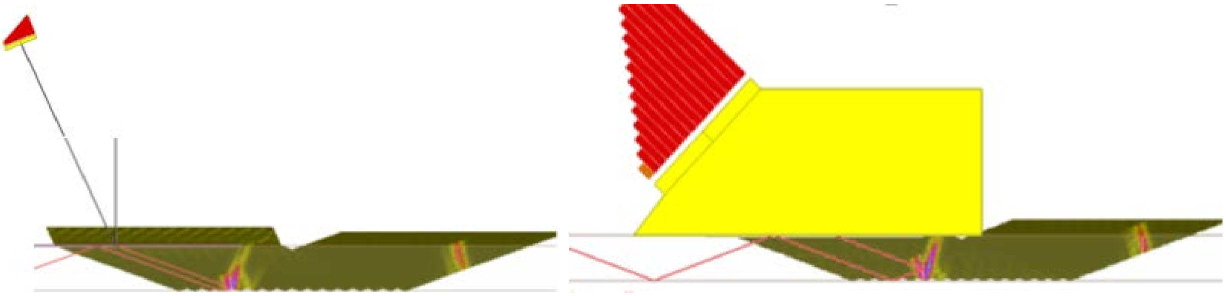

Figure 12. CIVA models of immersion and contact in plate with ID and OD notches

6.4 Comparison of Heavy Water with Light Water as Couplant

An additional concern in the development of the ISI program was that the actual inspection would be conducted with the probes immersed in heavy water while the vast majority of the development work would be done using light water. A study was conducted to determine if the work done in light water was applicable to the techniques which would be performed in heavy water. The result showed virtually no difference between the two couplants. There was a slight increase in sound pressure in the light water due to the slightly greater impedance value.

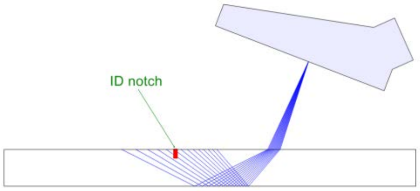

Figure 13. Diagram showing beam being modeled with light and heavy water couplant

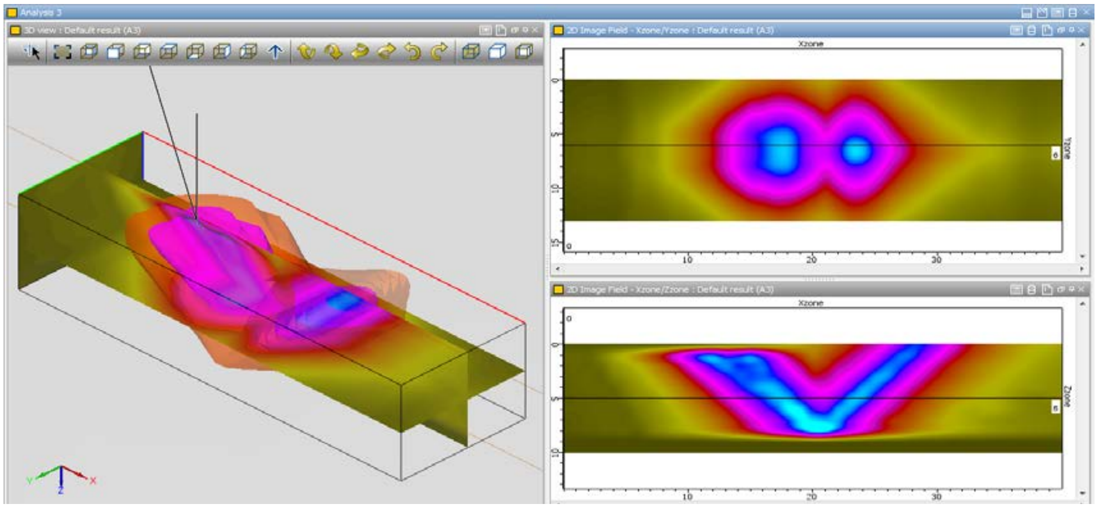

Figure 14. CIVA 3D model of beam with light water as couplant

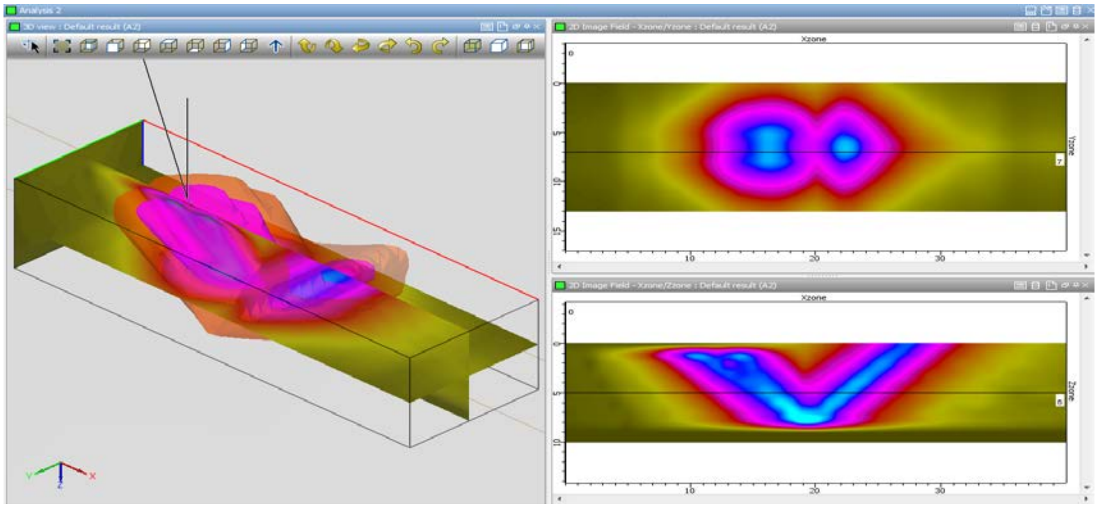

Figure 15. CIVA 3D model of beam with heavy water as couplant

7. Conclusions

Modeling was vital to the development of all of the inspection techniques. It ensured that there was proper coverage and sensitivity to meet the requirements of the inspection specification. It was as valuable as mock-up tests in obtaining approval for the techniques from the CIQB. It was essential as a training tool for both acquisition and analysis personnel. A combination of the ESBeamTool's ease of use and quick results and the detailed and accurate simulation of CIVA was important in obtaining the desired results.

References

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