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Development of Ultrasonic Inspection for Main Coolant Line Welds in EPR Nuclear Power Plant

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ABSTRACT

The main coolant line (MCL) is a part of the primary coolant boundary and it is the key factor for the reactor safety. In order to guarantee the integrity of the primary circuit, full volumetric ultrasonic examination is required for the MCL welds of the European Pressurized Reactor (EPR) according to the RSE-M code 2010 Version. The difficulties for application of the ultrasonic inspection on the MCL welds are mainly caused by limited access space and coarse austenitic grain structure. In this study, inspection system including automated scanner and transmitter/receiver longitudinal wave technique has been developed in consideration of the multiple constraints. The qualification process of the ultrasonic examination on the test mock-ups including flaw sizing results is also presented and commented.

KEYWORDS

EPR; Main coolant line; Ultrasonic inspection; Austenitic stainless steel

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1. Introduction

The European Pressurized Reactor (EPR) is a third generation pressurized water reactor (PWR), developed based on the experience from the French N4 reactor and German Konvoi reactor [1,2]. The main coolant line (MCL) is a part of the reactor coolant pressure boundary, it takes coolant from the reactor pressure vessel to the steam generator, and then provides cold coolant back to the vessel through a reactor coolant pump. Different from the cast austenitic stainless steel main coolant piping of the Chinese existing PWR, the pipes of the EPR plant are forged by austenitic stainless steel, and an automatic narrow gap gas tungsten arc welding (GTAW) has been implemented for the butt welding with ER316L filler metal. The MCL in the EPR plant consists of four loops, each loop has nine homogenous welds and two dissimilar metal welds.

- homogenous welds between primary pipes
- homogenous welds between primary pipe and pump
- dissimilar metal welds between primary pipe and steam generator
- dissimilar metal welds between primary pipe and reactor vessel

Fig. 1 shows the typical locations of MCL welds and a schematic of pipe-to-pipe weld.1

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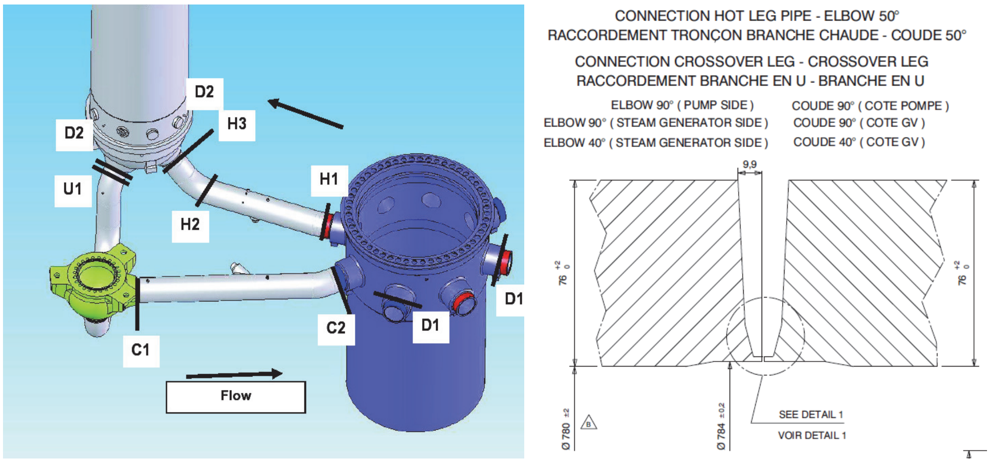


(a) **(b)**

Fig. 1 Typical locations of MCL welds (a) and a schematic of pipe-to-pipe weld (b)

It is very important to evaluate the structural integrity of the main coolant line using highly reliable non-destructive examinations (NDE). Ultrasonic techniques (UT) are extensively used in the inspection of the main primary system because of their capabilities to detect and size potential in-depth flaws. According to the RSE-M code 2010 version, automated ultrasonic examination has been introduced on the MCL welds of the EPR plant as a major NDE method in lieu of radiographic examination (RT). The volume to be inspected for each weld extends through the full thickness of the material and to the fusion faces of the welds. However, there are some constraints which must be regarded for the development of ultrasonic inspection the MCL welds:

- Access limitations. The pipes may be vertical, horizontal or inclined, and some straight pipes are joined to elbow pieces or nozzles (Fig. 2). Due to the space and location limit, many welds have some access restrictions, this makes it difficult to design the inspection scanner.
- Various dimensions of MCL pipes. The outer diameter of the MCL pipes range between 932mm to 974mm and the thickness ranges between 76mm to 97mm (see Table 1). To meet the requirement of the complete weld volume inspection, each weld shall be scanned in accordance with a dedicated scan plan.
- Accuracy of UT characterization. It is difficult to detect and size defects by ultrasonic inspection due to the coarse grained and anisotropic crystal structure of the weld [3-5]. The large grains could scatter the sound energy leading to a high degree of attenuation, and often to beam-distortion.

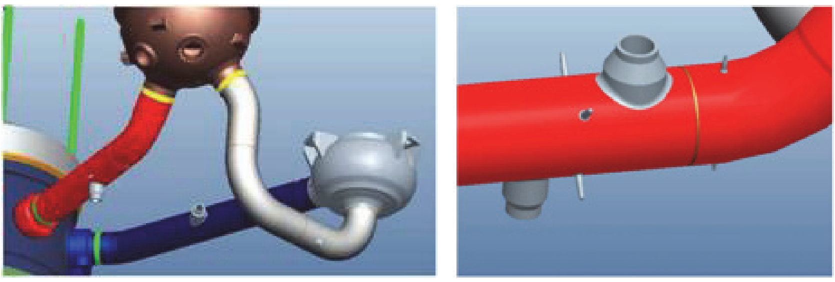


Fig. 2 Examples of the environmental constraints

Table 1 Dimensions of the main coolant line

Weld	Outer Diameter	Thickness
C2	932mm	76mm
C1	935mm	77.5mm
U4	960mm	90mm
U3	938mm	76mm
U2	938mm	76mm
U1	974mm	97mm
H3	974mm	97mm
H2	938mm	76mm
H1	938mm	76mm

To achieve the inspection requirements, it was needed to develop ultrasonic technology with qualified procedure, scanner and personnel. In this study, a specific manipulator taking into consideration the environmental constraints was developed to inspect thick-walled pipes with varing diameters. A demonstration of the capabilities of the ultrasonic techniques has been done on the test mock-ups.

2. Inspection System

2.1. Description of the scanner design

CGN inspection technology company has developed an inspection system for the MCL welds according to the structure characteristic and examination requirements. Schematic representation of the inspection system is shown in Fig. 3. The system consists of scanner, control system, removable guide rail, and couplant recovery system.

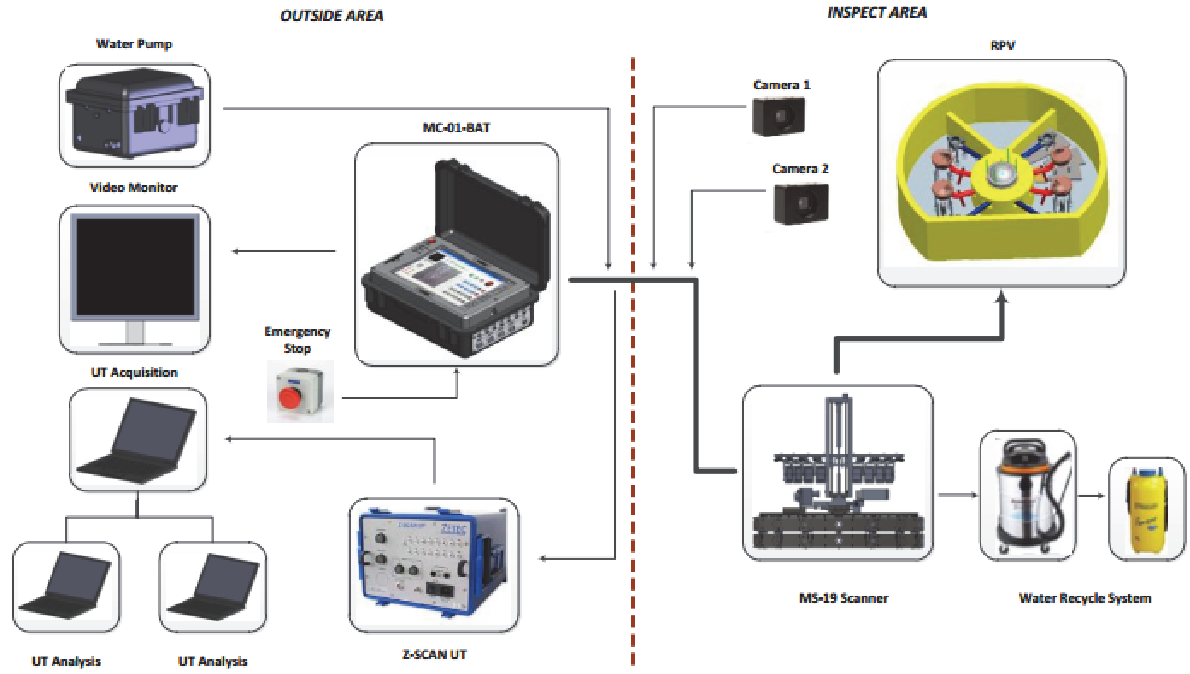


Fig. 3. The inspection system

Fig. 4 shows the structure of the scanner, the scanner is positioned on the pipe to be inspected by using removable guide rails installed on the pipe. An array of probes mounted in the scanner are placed on the pipe and the weld area is inspected as the scanner is moved along the weld. The probes can be moved around and along the external surface of the pipe using either circumferential or axial raster scan pattern. An encoder will record the probe position in relation to the distance traveled.

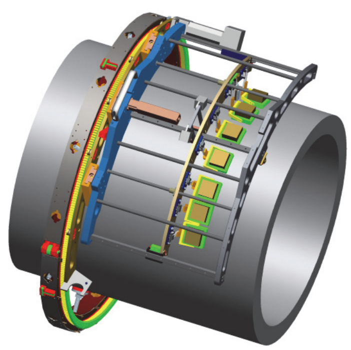


Fig. 4. A sketch of the scanner

In order to overcome the axial movement restrictions such as the elbow sections, three different stroke lengths (220 mm, 380 mm and 460 mm) of the axial movement modules are designed. Removable guide rail is made up of two semicircle arch supports. It can be easily installed on the outer surface of the different diameter pipes with seven adjustable clamping screws to the pipe (Fig. 5). For some special locations which are difficult to fix, the rails also use several auxiliary fixtures to install on the pipe, as shown in Fig. 6.

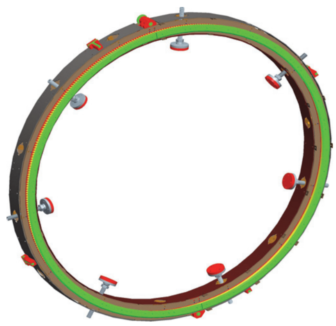
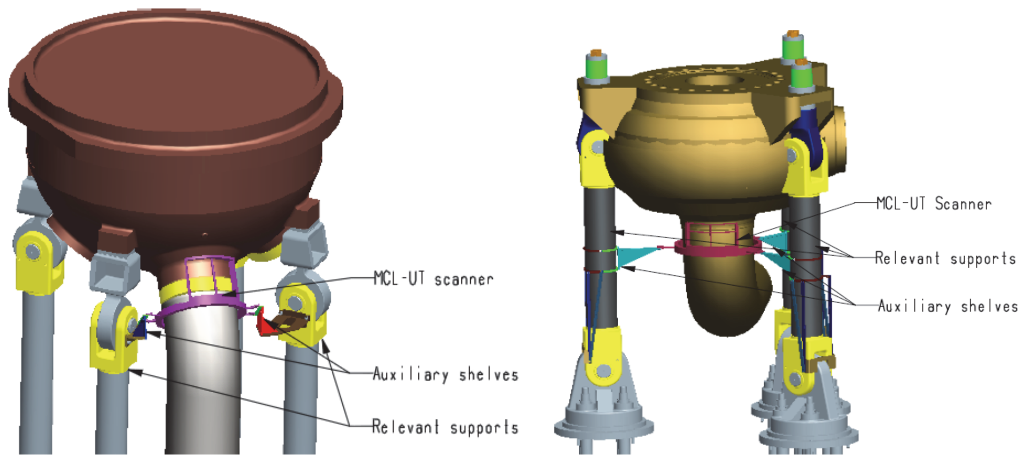


Fig. 5. Guide rail



(a) Steam generator **(b) Reactor coolant pump**

Fig. 6. Auxiliary fixtures used for steam generator (a) and reactor coolant pump (b) installation

2.2. Ultrasonic techniques

Due to the weld configuration such as material and thickness, the inspection area shown in Fig. 7 is separated into three areas: the near-surface area A, the middle area B, the bottom area C. To inspect the whole weld it is necessary to use several focus TRL (Transmitter/Receiver Longitudinal) wave probes with different beam angles scanned over the surface (Table 2). In addition, a 0° longitudinal wave probe was used to monitor on the back wall reflection echos.

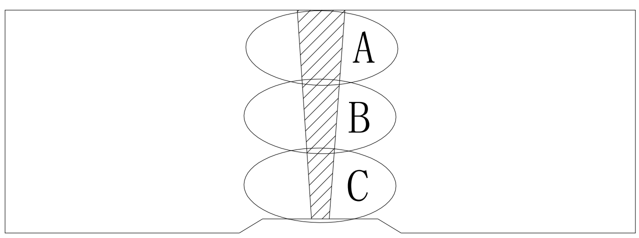


Fig. 7. Inspection area

Table 2. The parameters of probes for ultrasonic test

Probe	Frequency	Focus sound path	Crystal type

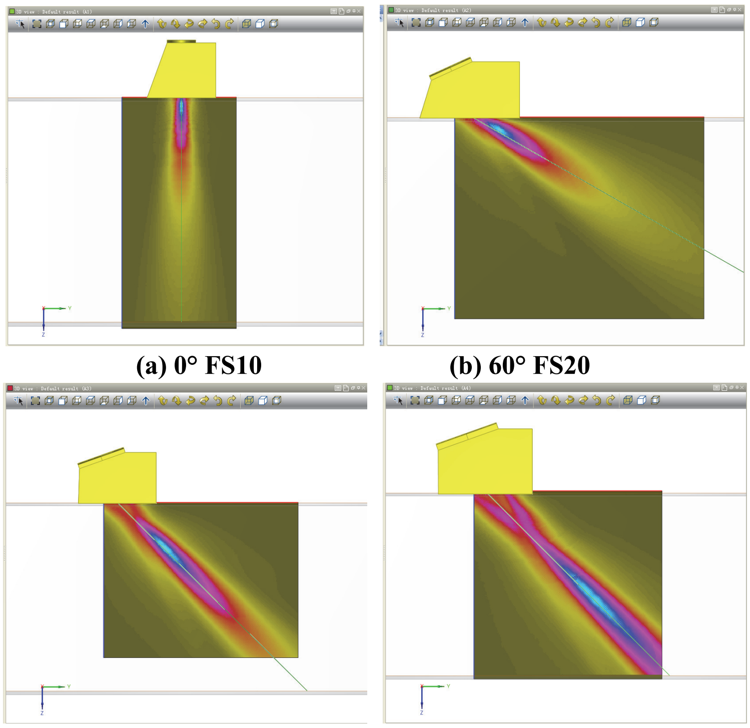
0°	1.5MHz	10 mm	TRL
60°	1.5MHz	20 mm	TRL
45°	1.5MHz	40 mm	TRL
45°	1.5MHz	90 mm	TRL
0°	2 MHz	/	Single crystal

Simulations were utilized for verify the parameters of ultrasonic techniques in relation to the material type and thickness. In this study, CIVA software was used to evaluate their ability to detect defects. The ultrasound simulation in the CIVA software includes two basic modules: Beam field predictions using the elastic-dynamics pencil method and defect response predictions using SOV, Kirchhoff and GTD models[6].

Obtained beams of the probes simulated are shown in Fig. 8. Theoretical focal depths as measured from these simulations, are 4 mm for the 0° FS10 probe, 10 mm for the 60° FS20 probe, 22 mm for the 45° FS45 probe and 58 mm for the 45° FS90 probe. Sensitivity was obtained by setting the reflection of 2mm side-drilled hole of different focus depths to 0 dB, respectively. Rectangular defects with 20 mm×5 mm, positioned in different depths, were used to simulate the cracks and the curves of the ultrasonic responses. The results appear as shown in Fig. 9-12 below:

- The inspection area of 0° FS10 can cover a range from 0 to 35 mm;
- The inspection area of 60° FS20 can cover a range from 0 to 30 mm;
- The inspection area of 45° FS40 can cover a range from 10 to50 mm;
- The inspection area of 45° FS90 can cover a range from 20 to 100 mm.

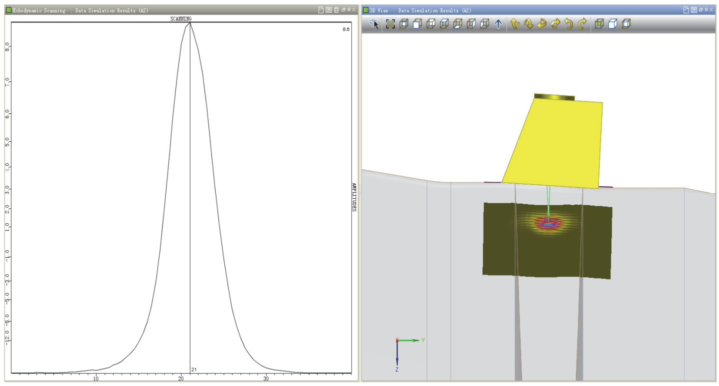
The results indicated that the probes are able to perform a full coverage examination of the inspection volume, and have sufficient sensitivity to the respective focusing area to meet the requirements of ultrasonic inspection of the austenitic stainless steel weld.



(a) 0° FS10 **(b) 60° FS20**

(c) 45° FS40 **(d) 45° FS90**

Fig. 8. Sound field simulations



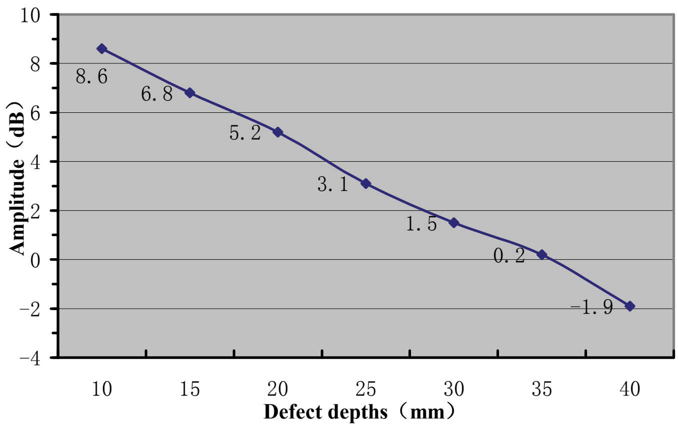
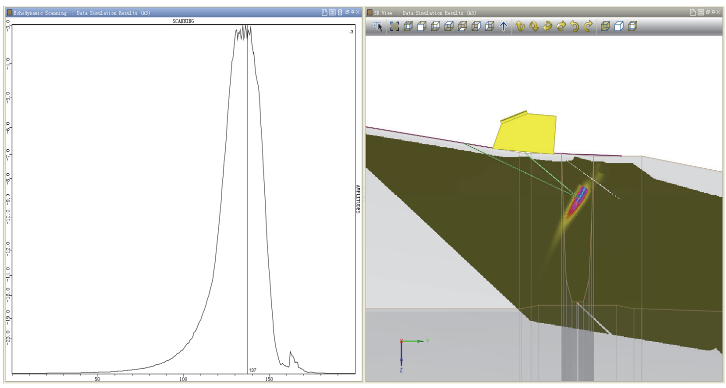


Fig. 9. Ultrasonic responses (0° FS10)



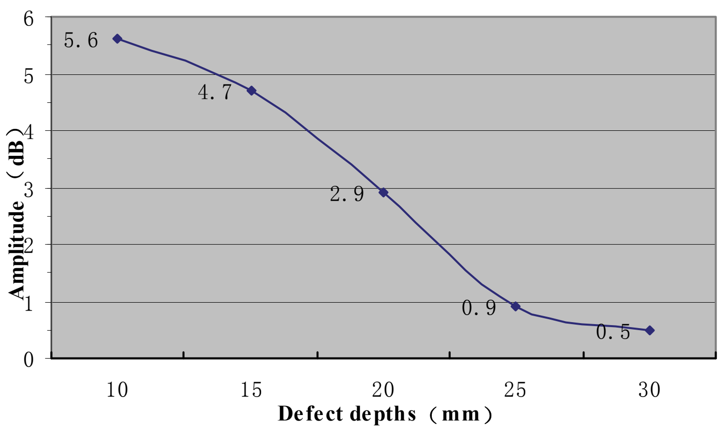


Fig. 10. Ultrasonic responses for different defect depths (60° FS20)

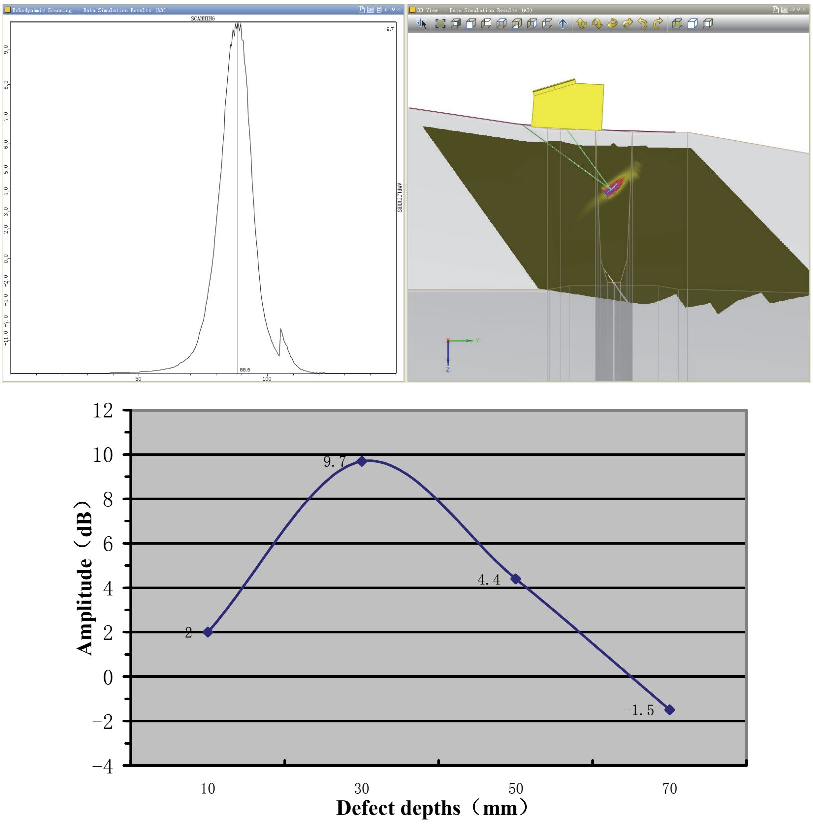
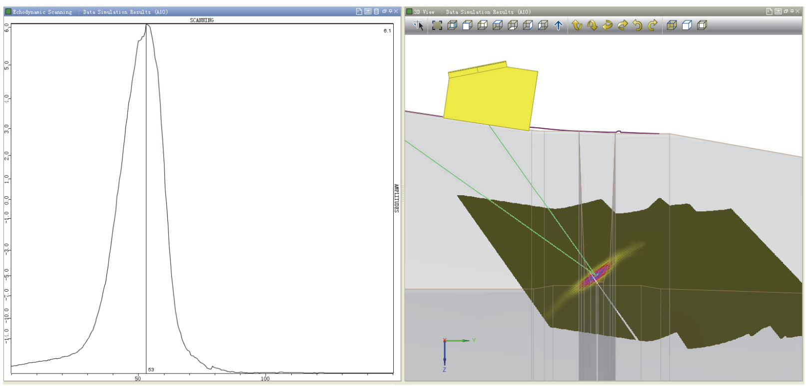


Fig. 11. Ultrasonic responses for different defect depths (45° FS40)



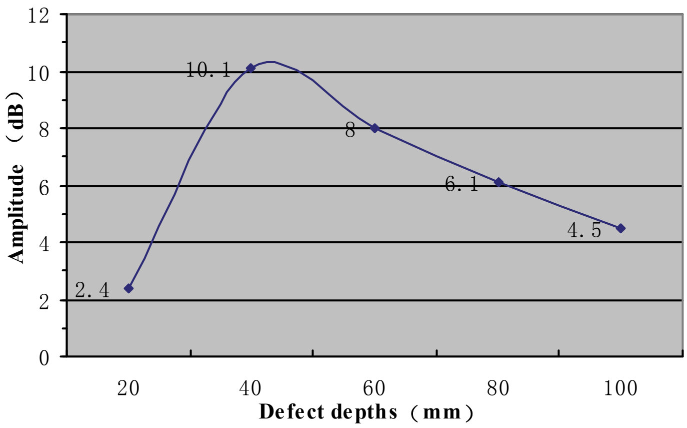


Fig. 12. Ultrasonic responses for different defect depths (45° FS90)

3. Inspection Qualification Progress

3.1 Methodology

The purpose of the qualification is to confirm that an inspection system has the ability to solve its required examination task. The qualification of the EPR reactor is carried out according to the RSE-M 2010 code. There are 3 types of qualification defined on the base of RSE-M Appendix 4.3: conventional, general and specific qualification.

- Conventional qualification. No defect is postulated, Evidence justifying the technique performance (detection, localization) to be compiled in a technical file.
- General qualification. Presence of defects is suspected. Evidence justifying the technique performance (detection, localization, characterization) by a combination of technical justification and practical tests based on realistic defects.
- Specific qualification. Presence of specific defects has been observed. Justifying evidence (detection, localization, characterization) by a combination of technical justification and practical tests based on real or similar defects.

Due to the main coolant line weld is one type of safety class 1 area of the main primary components, the qualification level is "special" type, determined by the China National Nuclear Security Administration (NNSA). The qualification of the main coolant line also adopted the ENIQ (European Network for Inspection Qualification) methodology as a complement to the RSE-M Appendix 4.3. The main steps of qualification are based on:

- Technical justification which include theoretical and laboratory evidences for the effectiveness of the inspection, and inspection procedures for the MCL welds examination must be qualified.
- Open and blind practical test on full-scale mock-ups, the mock-ups used for the qualification tests have a representative character in size, geometry and welding technology.

3.2 Demonstration of ultrasonic inspection

The qualification was performed with practical trail on an "open test" mock-up and finally validated on a "blind test" mock-up to verify the detection and sizing techniques.

The purpose of the open test is to verify the UT procedure and equipment capabilities. Figure 10 shows the open test mock-up for the MCL welds. The mock-up has the same dimensions and material with the components to be inspected in the nuclear power plant. Distribution of the flaws was implanted throughout the entire weld volume. The flaws were typical of those produced during welding fabrication, including cracks, inclusion, and porosity.

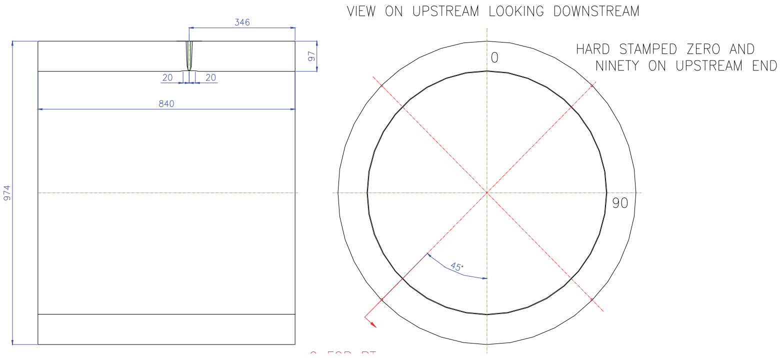


Fig. 13. Open test mock-up

Length and depth sizing of defects were performed by further evaluation after the data acquisition was completed. Length sizing was determined by using the drop-of-signal technique which sets the endpoints where the signal can be discriminated from the background noise. As for the height sizing, tip diffraction method was used by analysis the signals from the top and bottom edges of the flaw on the B-scan or D-scan image.

Practical example of defect sizing results on B-scan image was shown in Fig. 14. The results of the detected flaws are listed in the Table 3 The ASME BPV Code, Section XI, Appendix VIII [7], requires that the acceptable length sizing root mean square (RMS) is within 19mm and depth sizing is within 3mm. The error calculated shown in Table 4 present good enough for the requirement. The result showed good detection ability and acceptable sizing accuracy for full-scale mock-up. The inspection system was qualified and has been used on site in the site inspection of plant.

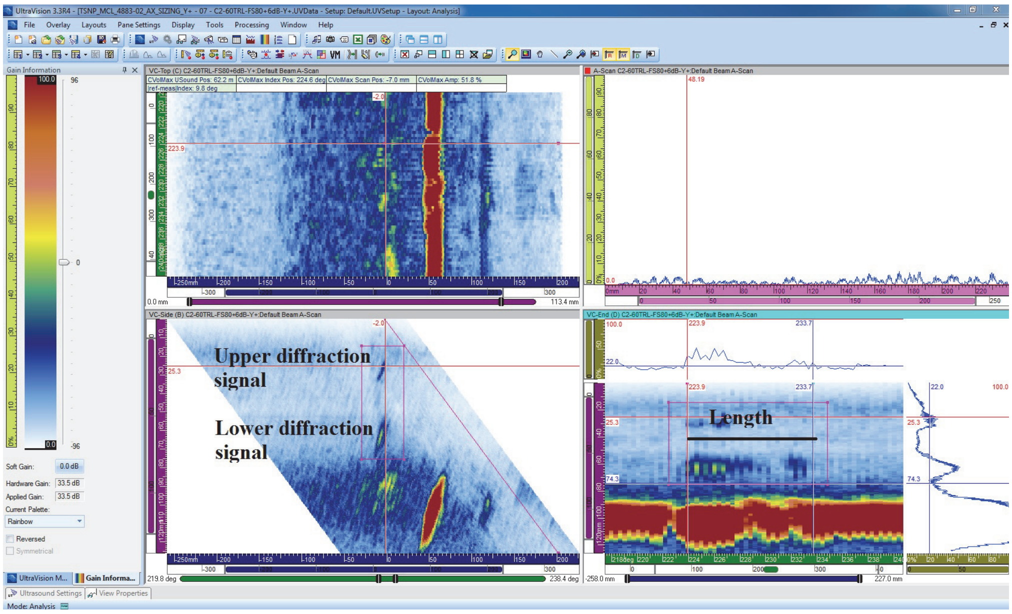


Fig. 14. Example of evaluation layout

Table 3. Flaw sizing results

No.	Defect	Actual value		Measured value	
		Length/mm	Height/mm	Length/mm	Height/mm
1	Crack	20	5	22	5.7
2	Crack	28	7	29	9.2
3	Crack	21	8	23	7.4
4	Crack	40	18	45	20.2
5	Crack	25	10	27	12.1
6	Crack	35	15	38	13.8
7	Crack	76	29	84	32.1
8	Crack	29	17	32	15.2
9	Slag inclusion	10	10	14	9.2
10	Porosity	30	10	33	12.3

Table 4. Root mean square error of defect measurement

Sizing technique	Calculated RMS error	ASME acceptable RMS error
Flaw length	3.75mm	19mm
Flaw depth	1.87mm	3mm

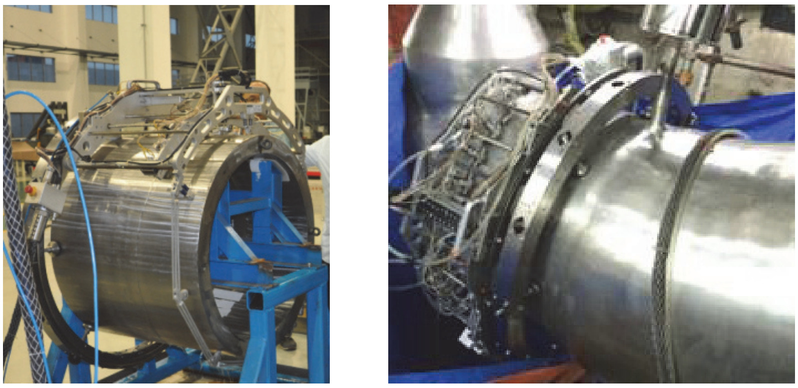


Fig. 15. Performance demonstration (a) and scanner installed on pipe at site (b)

4. Conclusion

Due to the coarse austenitic grain structure and limited access space, the ultrasonic inspection of MCL welds of the EPR plant represents a new challenge. In this study, a customized inspection system was successfully designed to perform automated ultrasonic examination from outside surface of the MCL welds. The scanner and the auxiliary fixtures were designed to deal with the difficult access conditions. The evaluation and experimental results confirm that used focus TRL techniques can cover a full range of inspection volume. Full-scale mock-ups were used to demonstrate detection and sizing capabilities. Performances of the inspection system had been verified according to the RSE-M code and local regulations.

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