Aspects of Inspection Qualification for CANDU Piping Welds.

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Abstract

The paper presents technical aspects of inspection qualification for ultrasonic in-service inspection of CANDU piping ferritic welds with outside diameter range between 172 mm to 660 mm and thickness range between 9mm to 80 mm. The OPG contribution to inspection specification is discussed and illustrated. Validation through the ENIQ concept of technical justification are presented for different aspects of UT conventional procedure; including crack skew/tilt issues, sensitivity setting, equipment substitution and technique development. ESBeam Tools was used to assess the coverage zone (inspection plan). Mock-up design and specific results are also presented. OPG has one of the most diverse sets of mockups for ferritic piping welds in the world (32 mock-ups grouped in 7 families with 200+ implanted flaws) as well as 15 bars with fatigue cracks (thickness 9 mm – 47 mm; crack height: 2.5 mm – 19 mm). Examples of UT amplitude response on different flaws for 20” sch 100 mock-up family are presented in the paper. The PAUT sizing procedure was developed in parallel with the UT conventional procedure qualification; following the same CIQB process. The following aspects are presented: technique selection, probe selection, ligament assessment, weld defect pattern display, sizing capability assessment, possibility and limitations of single-index semi-automatic scanning, short-comings of one-side PAUT examination, and tolerances on essential parameters. Flaw sizing methods based on ACG/TCG and noise-plus techniques are also presented and commented. The PAUT sizing procedure in both manual and semi-automatic modes is ready for the qualification process, based on experimental evidence from mock-ups and field data on economizer welds, on CIVA simulation and inspection plan coverage using ESBeam Tools. Technican training aspects are also presented and commented on.

Keywords: in-service inspection, ferritic piping welds, crack tilt/skew angle, inspection plan, inspection qualification, conventional UT, PAUT, weld defect pattern, length, height, ligament, CIVA simulation, ray tracing simulation, technician qualification

Problem Statement

The in-service inspection (ISI) activity for CANDU reactors is regulated by CSA 285.4 standard [1]. Clause 3.6(e) of CSA N285.4-05/09 assigns responsibility to the Licensees of a CANDU® nuclear plant for “performance demonstrations of the adequacy of the procedures and the proficiency of the personnel using the assigned equipment to detect and size flaws in representative samples”. CANDU OWNER GROUP (COG) established a qualification body-CIQB (Candu Inspection Qualification Bureau). Its structure, activities and specific issues were presented at San Diego, in 2006 [2]. By the mid 2008, all Canadian Nuclear Utilities were committed to qualify the ISI procedures for feeders, piping welds, steam generators tubes and pressure tubes. The qualification...
The qualification process is following ENIQ procedures and is mixing ASME XI for mock-ups defect distribution, procedure and personnel qualifications. The qualification process is based on inspection specification (IS), technical justification (TJ), detection/sizing procedure and training/qualification personnel procedure. Ontario Power Generation decided to qualify the detection based on conventional UT and sizing based on phased array ultrasonic technology (PAUT). During the pre-qualification process, OPG identified specific issues in the IS, such as skew angle for fatigue cracks, errors regarding flaw location and specific criteria for pass/fail of personnel. CIQB issued a revision of IS in Aug.2009 [3]. All Canadian CANDU Utilities signed by the end of 2009. OPG was designated as lead investigator of a joint program to qualify the detection and sizing procedures and personnel for ferritic piping welds.

This paper presents a summary of the following issues related to:
- CANDU ferritic piping welds distribution
- OPG mock-ups and implanted flaw distribution
- detection procedure conventional UT: amplitude comparison between weld defects and DAC level, effect of skew angle on crack detection, CIVA simulations – preliminary results, inspection coverage using ESBeam Tools, novel procedure for equipment compatibility
- sizing PAUT procedure: pattern, height, length, ligament
- one-side PAUT sizing
- index influence on flaw detection and sizing
- CIVA simulations on cracks and embedded flaws-preliminary results
- Technician qualification procedure

The reader should keep in mind the qualification process is just beginning, and the CIQB peer review could impact the final qualification outcome.

**CANDU Piping Welds and Mock-ups**

CANDU piping welds are made of ASTM 106 gr.B ferritic steel. Their dimensions range from between 173 mm x 9 mm to 660 mm x 80 mm. The component side is made of ferritic casting or forging (see Figure 1).

![Figure 1: OPG piping distribution (left) and welding components (right).](image)

The diversity of weld geometries, (including the counterbore) are presented in Figure 2 left. In general, the weld cap is ground and some of the weld roots are removed. The degradation mechanism during service is typically a circumferentially oriented fatigue crack, straight or with a tilt following HAZ, and a skew angle no greater than 10 degrees (see Figure 2 right).

During a 20-year period, OPG acquired a large variety of welded mock-ups and test pieces based on the following projects:
- IQ [2008 – on going]: Inspection Qualification – 15 mock-ups + 26 test pieces

The total number of implanted flaws in 26 mock-ups is greater than 200.

The welded mock-ups for MUVE were made by Sonaspection (UK) and the ones for PPS and IQ were made by Flaw Tech (USA). While MUVE and PPS projects were focused on manufacturing defects, the IQ project is focused on detection and sizing of fatigue cracks. Figure 3 presents the implanted defect distribution on all OPG mock-ups.

Mock-ups fingerprint was performed by high sensitivity RT and TOFD for MUVE and by high-frequency, high sensitivity PAUT for PPS and IQ. All mock-ups were 100% RT by the manufacturer, according to ASME V-Art.2 (low sensitivity). Satellite defects were present in all mock-ups and evaluated. They have a negative contribution to flaw dimensions and to final results of the technicians (see Figure 4, as an example). Generally, the design flaws were within 20% tolerance for length, height, location and ligament. The implanted cracks were easy to detect. The MUVE mock-ups cracks have a rectangular shape. The IQ mock-ups cracks are elliptical, but satellite defects are changing the final shape, location and dimension. OPG machined test pieces with fatigue cracks from L-0 blades (GEIC Alstom-Darlington NGS) (paper Fr.2.B.1 of this conference). An example of a pipe segment containing a fatigue crack is presented in Figure 5. Other test pieces include the ligament parameters (location, tilt, and height), counterbore slope and width, crack-like EDM notches closer to mismatch, suck back, counterbore, root and/or rough inner surface.
Figure 4. Examples of satellite defects around the implanted defects.

Figure 5: Test piece with fatigue crack machined from L-0 blade (ref.4).

**Detection Procedure – Conventional UT**

The detection procedure of conventional UT is based on CSA 285.4 requirements and ASME V DAC sensitivity setting. Two shear waves probes of 2.25 MHz (either 60 & 70 or 45 & 60 degrees) are used to scan from both directions, where accessible. The DAC – 14 dB recording level provides enough sensitivity and avoids the false calls. Figure 6 and 7 present a comparison between amplitude of implanted flaws and the DAC level.

Figure 6: Amplitude comparison of LOF, slag, porosity and LOP vs DAC level.

Figure 7: Amplitude comparison of cracks vs DAC level
The effect of skew angle on fatigue cracks is illustrated in Figure 8. For skew angle < 10°, the amplitude drops by -6 to -8 dB versus the DAC level (still recordable/reportable).

![Figure 8: Example of crack skew angle on normalized amplitude.](image)

The sensitivity setting based on DAC-14 dB provides enough gain in reserve for detection of fatigue cracks with length x height > 18 x 3 mm. The amplitude of fatigue cracks with a skew angle up to 15 degrees is within recordable threshold.

The Canadian ISI Service Providers are using portable flaw detectors made by GEIT (USA/Germany), OlympusNDT (USA) and Sonatest (UK). An equipment compatibility procedure was developed and validated for different UT machines in combination with GEIT piezo-composite probes of 2.25 MHz (5 MHz) / 12.7-mm diameter. The system could be used without re-qualifying the procedure if the useful gain-in reserve from a side-drilled hole (+14 dB) on IOW block is > 6 dB and the location of the reflector is within +/-4 mm UT path reading. Other tolerances on essential variables, similar to ASME V-Art.4 Table T 421 and ASME XI-Appendix VIII-4000 are included in the detection procedure. The Technical Justification details in seven Appendices all Essential Parameters according to ENIQ documents. The Detection Procedure is focused on flaw location (surface-breaking or embedded, axial and circumferential position), flaw characterization (geometric such as root, counterbore, misalignment or weld defect) and maximum amplitude vs. DAC level. Length and height sizing will be performed by PAUT. Figure 9 presents results regarding compatibility of three flaw detectors on IOW. Figure 10 illustrates the results for two flaw detectors on implanted flaws of small length and height. The results concluded: all flaw detectors are compatible and the amplitude of the small implanted flaws is within +/- 2 dB variation. Length evaluation using -6 dB drop method is within +/- 2 mm vs the PAUT measurement.
Figure 9: Examples of compatibility evaluation on IOW block for three flaw detectors.

Figure 10: Gain sensitivity and length sizing for three flaw detectors on 6” sch 80 mock-up.

**PAUT – Flaw Pattern and Sizing Capability**

The removal of the weld crown facilitates the use of a L-waves PAUT probe on the weld center line. The combination of PAUT scanning in L- and T-waves led to specific flaw pattern and increases the sizing capability. Preliminary results were published during 2007-2008 period (ref. 5-6). The new PAUT results were focused on skew angle effect for detection and sizing, sensitivity setting, sizing capability (length, height, ligament) and evaluation of detection and sizing possibilities for one-side examination. The sensitivity study for one-side inspection of ECI weld (Emergency Coolant Injection) concluded the ACG/TCG is similar to mono-crystal sensitivity. Height sizing and flaw characterization require more gain, either by using an additional channel or by using the soft gain features. A combination of circumferential and axial scanning will conclude on flaw length, height, ligament, location and orientation. Some examples of flaw pattern are presented in Figure 11.
Figure 11: Examples of weld flaws and their location in the weld related to PAUT probe.

The skew angle effect on detection and sizing concluded PAUT probes, specifically L-waves, could detect and reliably size cracks for skew angle up to 30 degrees (see Figure 12).

Figure 12: Example of PAUT results for sizing skew crack. Top: LW; bottom:TW.

The preliminary results for sizing are presented in Figure 13. The results exceeds the IS requirements.
One-side examination limits the redundancy of sizing or flaw characterization. The weld defect may present only specular characteristics, and sizing based on echo-dynamic features is a must. The detection and sizing of service-induced fatigue cracks in the root, HAZ and counterbore area increases with pipe thickness. Figure 14 illustrates the sizing capability for different index values. Other PAUT parametric studies (results of which will be published later) were related to:
- length sizing using soft palette (saturated signals)
- probe frequency and pitch on sizing
- DDF vs optimization of active aperture
- axial and lateral resolution
- sizing accuracy for specular flaws (smooth and rough)

SIMULATION SOFTWARE

OPG purchased CIVA (CEA-France) for advanced simulation and ESBeam Tools (Eclipse Scientific-Canada) for inspection plan and ray tracing. Both applications show potential for procedure development, technical justification and explanation of specific indications in S-, B- and A-scans. ESBeam Tool package was included in detection procedure for inspection technique development. The CANDU piping welds could be grouped in 12 cases and diversified on thickness, diameter and access conditions, specific for each ISI patch. Examples of CIVA and ESBeam Tools simulations are presented in Figure 15. CIVA validation will be performed after the fall 2010-spring 2011 outages, beginning in May 2011.
Technician Qualification

Technician qualification is based on a specific procedure and testing process. Figure 16 illustrates the main activities and pass/fail criteria. The qualification process will be implemented after the qualification dossier is approved by CIQB.
Conclusions

The qualification process for CANDU ferritic piping is well-advanced and more activities will take place in the near future (Q4 2010 – 2011). OPG is leading the COG-JP tasks and the other Canadian Utilities are reviewing the documents and may contribute with mock-ups, reference blocks, UT equipment, and procedures, as specific tasks will require. This paper presented results of conventional UT-detection and PAUT sizing and flaw characterization. OPG considers the IS requirements met by the qualification dossier for conventional UT-detection and for PAUT sizing and characterization techniques.

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