Overview of Improvements in Work Practices and Instrumentation for CANDU Primary Heat Transport Feeders In-Service Inspections

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Abstract

The Canadian nuclear industry has developed in recent years many advanced non-destructive inspection techniques to be applied safely in hazardous environments. Automated systems, manual tooling and specialized software modules have been designed since early 2000s to provide complete and very efficient fitness for service inspection of primary heat transport system carbon steel feeder pipes. These techniques deal with complex geometries, difficult access and radioactive environment. Complementary NDE techniques, namely Ultrasounds, eddy current, phased-array UT and automated scanners are used. This presentation describes the improvements in inspection practices and the advanced data analysis features.

Keywords: Feeders, ultrasound, automated, NDT, carbon steel, PHT, eddy current

1. Introduction

CANDU feeder piping is a main component of the Primary Heat Transport System (PHTS) that carries the primary coolant from the fuel channels to the steam generators. Feeder piping is composed of an outlet section that transmits the heated coolant to the steam generators, typically at 310°C, and an inlet section, typically at 265°C, that returns the coolant to the fuel channel for the next heating cycle. The connection between the feeders and the fuel channels is made via a Grayloc fitting located at the extremities of an end-fitting assembly.

Several in-service degradation mechanisms have been observed on CANDU feeder piping system. These mechanisms can be divided into two categories: wall thinning and cracking [1].

Wall thinning occurring on the inside surface of feeder piping have been postulated as a degradation mechanism in the mid-1990s. Concerns about feeders were prompted by the discovery of considerable amounts of magnetite precipitated in the cold leg of steam generators. While some corrosion was expected in the design of the PHTS, the amount of material recovered from the steam generators surpasses predictions and excessive feeder thinning became a concern. The mechanism has been identified as Flow Accelerated Corrosion (FAC) and later confirmed on mostly all operating CANDUs. Most thinning occurs on outlet feeders immediately downstream of the Grayloc fitting. Localized thinning could occur on Grayloc welds and at various points around the circumference of tight-radius bends and elbows. FAC is a transport mechanism that can be explained as follow: hot coolant exiting the fuel channel is unsaturated in magnetite (an iron oxide film on the inside surface of feeder pipes) and the coolant will dissolve the magnetite film until it reaches saturation. When the coolant passes through the steam generators, magnetite will precipitate as the coolant temperature decreases until the magnetite concentration reaches equilibrium. After several years of operation under these conditions, outlet feeders have thinned and the steam generator tubes fouled up.
The second mechanism is related to a form of intergranular cracking degradation. Feeder cracking was first observed on a CANDU-6 and occurred at outlet tight-radius bends. It was believed in the early 2000's that cracks, which are axially oriented, were initiated from the inside but later inspection found cracks initiated on the outside surface as well. From all the data collected during destructive post-examination of removed feeders, two failure mechanisms have been postulated: Intergranular Stress Corrosion Cracking (IGSCC) assisted by hydrogen for inside initiated cracks, and Low Temperature Creep Cracking (LTCC) assisted by hydrogen for outside initiated cracks. Both mechanisms would not be active without the contribution of stresses, and in the case of feeder bends, residual stresses from bending was the necessary condition to propagate an incipient crack. Not all CANDUs are at risk and only those stations with none stress-relieved bends are susceptible to feeder bend cracking.

Feeder cracking was also observed in one instance in a closure weld (joint between the upper and lower feeder assemblies welded on site). The crack was the result of a defective weld repair in which cracking propagated and merged within the boundary of the repaired heat affected region. It is postulated that the mechanisms involved in weld cracking are the same as for bend cracking and here the residual stress field originated by the localized full penetration repair weld. It is unknown if the crack was present immediately after the repair but it is believed that its growth took several years because FAC was observed along the inside surface crack opening. It is not believe that a residual stress pattern that can propagate a crack exists in unrepaired welds so the affected population is restricted to repaired welds made during fabrication.

These degradation mechanisms affect primarily the carbon steel outlet feeder pipes immediately downstream of the Grayloc connection. In-service inspections on feeder pipes are performed on a regular basis in all Canadian CANDU reactors. Efforts have been made by the industry in developing tools and work practices to improve data reliability and reduce dose intake by inspectors. Each station has specific configuration and accessibility issues that make universal tool design a difficult task.

The feeder non-destructive inspection tooling developed to date for these issues can be divided into four categories:
- Thinning at tight radius bend area;
- Cracking at tight radius bend area;
- Thinning at Grayloc weld area;
- Cracking at Grayloc weld area;

The main purposes for tool development are to improve the following:
- Meeting the requirements of the industry Feeder Inspection Specification
- Inspection reliability
- Radiation exposure
- Efficiency

For both manual and automated tooling, operating experience has showed that personnel qualification and training is of primary importance for a successful inspection campaign.
2. Thinning – Feeder Bends

2.1 Initial Developments

Feeder thinning measurement began with using ultrasonic thickness gauge and repeated inspections showed that the extrados of the bends was the thinnest areas on the feeder pipes. Templates with spacing grids improved the repeatability of the results, but this process was slow and could be applied only to a limited scope.

Ontario Hydro then developed a probe assembly which consisted of four (4) ultrasonic probes with water wedges, and an encoder for axial positioning. Multiple scans were required to cover the extrados region. This tool was hand operated and efficient for feeders with easy access. It was around that time that it was found that the thinning would be life-limiting for some feeder bends, and more accurate NDT technique would be needed for repairs planning.

2.2 MÉTAR bracelet

In 1998, Hydro-Québec contracted IREQ to develop an inspection system that would be easy to use, reduce strain on the operator and also facilitate data collection on second bends [2][3]. Space constraints, data quality as well as robustness were also taken in consideration. IREQ developed a multi-transducer scanner that meets all these requirements and is still used by the industry today. The MÉTAR (Mesure d’Épaisseur des Tuyaux d’Alimentation du Réacteur) bracelet is a mechanical assembly that clamps on the feeder and consists of a collar made of fourteen (14) 10 MHz, 4mm ultrasonic transducers mounted on individual water wedges. A wire going through all the wedges and a spring load keep the probes aligned perpendicularly to the feeder outer surface. An encoder providing axial position is mounted in front of the probe assembly. The METAR bracelet is manufactured under license by Zetec.

This tool requires the use of a remote data acquisition unit (RDAU) with at least 14 channels. Typically, a phased-array unit with 32, 64 or 128 channels is used for this application. The phased-array board trigs each transducer sequentially at a predefined axial spacing. The collected data represent a rectangular map of the scanned area with grid resolution of 6mm circumferentially (distance between each probe) and 1mm axially (data recording resolution). The software displays a top, side and end view of the feeder pipe thickness profile. The accuracy in the thickness direction is based on the digitizing frequency of 100 MHz and is basically of 0.03mm. The accuracy can be increased to the micron using digital signal processing techniques. This is the approach the industry took in order to measure thinning rate from repeated inspections and produce the data (thickness and thinning rates) used in fitness-for-service analysis and in the prediction of end-of-life.

Although it is still the main feeder thinning tool used today, the MÉTAR bracelet has some limitations;

- Manually driven: Requires a probe operator to move the bracelet on the reactor face. Inspection area limited to operator’s reach;
- Operator dependant: Data quality and reliability greatly affected by operator’s skills;
- Inconsistent signals: Water column may be hard to maintain, especially with the egg shape cross-section of certain feeder bends;
- Equipment failures: Sensitive equipment, especially the encoder and transducers.

2.2 MÉTAR version 2 bracelet

A second version of the MÉTAR bracelet was developed by Zetec to alleviate some limitations. The original MÉTAR had limited effectiveness for the intrados region and some issues with water resistance of the encoder needed improvements. This new bracelet uses the same principles as the original MÉTAR but has the following modifications:

- Modified clamping mechanism which can be operated with one hand;
- Water resistant magnetic encoder;
- Improved spring load on probe assembly.

The second version of the MÉTAR bracelet provides only limited improvements to the inspection technique. Although it provides a better coverage in the intrados area of feeder bends, it still has the same limitations as the original MÉTAR bracelet.

2.3 Future Development

Zetec has worked hard over the past 3 years to develop a mechanical tooling that incorporates new technologies in order to offer another approach to feeder inspection.

The prototype tool named “V3” is designed to perform thickness measurement of in-situ feeder tubes, covering the area near the Grayloc weld (2 mm near each welds) and up to 2 meters after the first 2-3 bends.

The tool is designed to record UT measurements, in a single scan, to cover 360°, all around the feeder (intrados, extrados, cheeks), in bends and on straight feeders. The tool should be able to cross weld caps and to fit within tight clearance (16 mm in nominal configuration and down to 8 mm using an optimized low profile configuration).
The combination of a flexible probe with a rigid frame gives enough flexibility to cover many configurations (i.e. going over weld cap, crossing tight radius bend without straight section, supporting ovality of feeders up to 8%...) but also allows to obtain an accurate positioning of each individual UT element which is required to obtain reliable and repeatable UT data.

Figure 2 New generation bracelet concept
3. Thinning – Grayloc Weld Area

3.1 SixPack bracelet

Wall thinning adjacent to the Grayloc weld became an issue after the discovery of some thinned areas. Thinning is the result of two factors: FAC that attacks the protective magnetite oxide layer, and grinding of the root weld cap during fabrication of the component. To minimize flow turbulence induced by the presence on an internal weld ridge, the weld root was grinded flush before installation. Pre-installation radiography showed that in some cases, excessive grinding may have occurred and left localized thinned areas. Local thin areas adjacent to Grayloc welds may have resulted from a combination of grinding adjacent to the weld at fabrication and subsequent FAC during service.

The weld cap and the taper profile of the Grayloc hub make thickness measurement very difficult in this area. To effectively collect thickness data around the full circumference of a feeder pipe in the region adjacent to welds, OPG developed a hand-held tool consisting of a water wedge housing 6 tiny transducers. The tool nicknamed the 6-pack, has the transducer spaced by 2.5mm in the axial direction and are slightly offset in the circumferential direction to allow a tight packaging. The 6-Pack includes a trailing encoder to trig the data-acquisition unit at regular interval of the order of 1 to 2 mm. To ease the operation, a magnet helps keeping the tool in place while the operator shifts hands during a full 360˚ scan.

The 6-Pack provided critical data to assess the conditions of pipe material adjacent to a weld and in particular the Grayloc weld region. The 6-Pack had some inherent limitations that make data collection difficult. The quality of the data is highly dependable on the probe operator and any mishandling along the circumferential scan, and particularly when the tool is located on the back side of the pipe, can cause the lost of the water column or the encoder to slip and abort the data-collection. Another intrinsic limitation caused by the geometry is that backwall signal from outmost transducers are lost in the intrados region due to the curvature of the pipe that makes the ultrasonic beam slightly off the normal incidence condition required for thickness measurement. The axial positioning of the 6-Pack is controlled by the operator and there is no ways to ensure the scanner was always abutting the weld cap for the entire scan. This raises the issue with repeatability with respect to positioning along the expected scan path.

3.2 GAIT Tool

COG funded the development of a tool that can alleviate the difficulty of manual scanning and allow a precise scan path along the circumference of a feeder pipe. The Grayloc Area inspection Tool (GAIT) is a manually-feed driving mechanism that revolves on the feeder pipe axis a wall thickness measurement head. The tool fits on top of the Grayloc flange and a lever closes the driving mechanism firmly around the grayloc hub. The driving mechanism consists of a push-tube that revolves the measurement head along a track by as much as 400˚ in order to scan the pipe material adjacent to the weld. An encoder monitors the push-tube movement and translates this information into a circumferential position around the feeder pipe.
The measurement head as 8 small ultrasound transducers packaged in a similar way as the 6-Pack. The head is mounted on a gimbal and is spring loaded. The transducer layout is such that 6 equidistant inspection lines are covered. The two additional transducers are to supplement data for the outmost transducer when scanning the intrados region. These additional transducers are tilted by 4.5° in order to produce a normal incidence condition on the pipe outside surface in the intrados region and capture wall thickness data next to the weld cap.

The GAIT tool is an evolution of the 6-Pack and makes scanning repeatable and reduces loss of water column or encoder position.

3.3 GRAVIS – Thinning

The next step into automation was to motorize the Grayloc thinning inspection. The tool development funded by COG was for a 2-axis motorized tool for Gayloc weld volumetric inspection. Hydro-Québec decided to extend the scope of the tool by adding a thinning measurement head so the tool could perform the same inspection as the GAIT. The measurement head selected had 8 transducers in a configuration similar to the GAIT inspection head but with a totally different couplant feeding design. The tool is fully automated and the operator responsibility is to install the GRAVIS by pushing the Grayloc flange adaptor against the flange bolt heads. From there, the inspection is entirely controlled by the data-acquisition operator from a remote location.
The GRAVIS with a wall thickness measurement head has been the tooling used at Gentilly-2 station since 2008. The inspection results are repeatable and the rescan rate caused by operator handling has been reduced to nearly zero.

3.4 Future Development – Thickness Measurements on Grayloc Weld

With the improvement of tools and results quality, trending shows thinner wall measurements as the probes get closer to the weld cap. This suggests that there may be thinner wall under the weld cap. It is therefore necessary to develop a tool that could measure under the Grayloc weld.

New features of the UltraVision software allow for adaptive focal laws, which provide the ability to inspect rough and wavy surfaces [4]. A 7.5 MHz, 64 elements, with pitch of 0.7mm probe was used on a test piece with three (3) different weld profiles.

The figures below illustrate the difference in results inspecting the 3 zones using specific adapted focal laws for each zone. The improvement in backwall signal to noise ratio is higher than 12dB. In all cases shown here, 6 elements were used per focal law in linear scanning configuration. Scanning sensitivity is 12 dB and 6 dB of soft gain were added for analysis. The non-adapted focal laws are displayed on the left; the adapted focal laws results are displayed on the right.

Other development projects have also made progress to inspection thickness under the Grayloc weld, namely OPG’s FP6 and AECL’s CAPT tool.
Figure 6 Zone 1 weld thickness profile.

Figure 7 Zone 2 weld thickness profile

Figure 8 Zone 3 weld thickness profile
4. Cracking – Feeder Bends

4.1 Manual Bend Cracking Inspection

Following the online failure of an outlet feeder in 1996, the CANDU industry responded by developing an inspection method addressing this degradation mechanism. The initial inspection zone was the bend area between the 3 and 9 o’clock positions centered on the extrados (12 o’clock). The first bend is in most cases accessible for manual inspection from the extrados. An inspection method and procedure addressing the COG inspection specifications was developed by the industry and validated using real flaws from removed feeders. The procedure was then qualified using cold bent feeder pipes containing thermal fatigue cracks (TFC) implanted at various locations in the area of interest. Several laboratory tests and the inspector qualification program conducted by each utility showed that the procedure is very effective in finding axially oriented internal surface breaking flaws near the intrados region with scanning passes centered on each side of the extrados [5].

In 2003, feeder inspection campaign detected feeder bends with cracks located in the second bend. Upon removal of the bend, non-destructive examination found additional cracking on the outside diameter (OD) of the second bend extrados. This crack was found in a different location and bend type than the previously cracked feeders and was outside of the COG inspection specification scope. The inspection procedure was updated and a special attention was also paid to scanning second bends because the extrados is not easily accessible for manual scanning. Alternate scanning techniques were experimented to alleviate the accessibility problem and thus expand the scope of the inspection procedure to include second bends.

The manual procedure was further improved following operating experience and the latest revision which was qualified by the CQIB in March 2010 is COG-JP-00-003-V18, Rev. 5.

4.2 Bend Cracking Crawler

Hydro-Quebec started the development of a manual data-recording method and in parallel, a motorized inspection system addressing the COG Inspection Specification. The main objective of these projects was to reduce the dose taken by the limited number of available level 2 ultrasonic operators. This is achieved using level 1 probe operators on the reactor face to manipulate transducers during manually recorded scanning and bracelet installation during motorized crawler inspections.

The first generation of the bend cracking crawler (BCC) had four in-line transducers, two running on each side of the extrados, aimed toward the intrados. The drive motors were mounted on top of the crawler which fit between the end fittings of adjacent channels during scanning. The design is such that transducers are as close as possible to the cheeks and move together in an 18 mm raster motion. An inspection procedure making use of the unique features of a digital data-acquisition instrument and a motorized scanner was developed. The main improvement resides in the precise flaw positioning offered by an encoded device. The procedure was validated using a set of cold bent feeder pipes containing thermal fatigue
cracks. Several blind tests were conducted using trained and qualified HQ technicians with no flaws missed.

In early January 2004, the COG decided to use the motorized crawler to inspect second bends that are difficult to access using the manual technique. The crawler had to be modified to access the second bends and to include the extrados in the inspection scope. Two modifications were undertaken. First, the two probes near the extrados were inverted to cover the upper half of the bend; secondly, the motors were relocated in order to reduce the overall height of the scanner to no more than 20 mm. Moving the motor made the crawler capable of accessing areas where the hand cannot reach and gave enough clearance to all second bends on a CANDU 6.

The main benefit of motorizing the inspection is repeatability of inspection results which are totally independent of operator skills or access constraints. The manual technique calls for 3 scans performed twice with an index of 10 mm between each pass. Each manual scan is intentionally repeated to increase the probability that the operator did not skip any areas. The crawler provides the capability of four simultaneous passes in one scan, two passes toward the extrados and two passes directed toward the intrados. The crawler does not require scanning redundancy because the motors are controlled electronically and the inspection sequence cannot skip positions.

After the successful performance demonstration, the industry selected Zetec to manufacture a rugged version of the latest crawler prototype. The commercial versions were made available in February 2006. Commercially available crawlers were used at PLGS and G2 during their 2006 to 2009 outages and on a trial basis at Darlington in 2009. The BCC procedure was qualified by the CIQB in 2010.

![Figure 9 Bend-Cracking-Crawler on feeder sample](image)
4.3 Eddy Current Bend Crawler

In 2005, several feeder bends were removed because the inspection techniques are very sensitive and artefacts such as inclusion in the base material or internal flow lines can results in an ultrasonic response above the disposition threshold. To avoid this situation, the industry developed a series of verification techniques to discriminate between real cracks from less minor reflectors. One verification method is a conventional wet fluorescent magnetic test applied for OD indications located on the extrados. For ID indications, the use of an ultrasonic amplitude-based comparison was developed to assess the reflectivity of a flaw from both sides. It was demonstrated experimentally that flow lines do not reflect sounds very well in both direction and that a simple comparative amplitude-bases test can differentiate real cracks from other artefacts.

For OD cracks located on second bends, which makes the extrados facing the reactor, the access does not allow any visual technique to be applied. The industry developed a magnetic rubber replica procedure but it was found difficult under real condition to deploy. Hydro-Québec developed an eddy current sensor that can be mounted on the BCC and perform an automated surface examination on inaccessible second bend extrados. Results on mock-up samples with TFC prove to be an effective and repeatable technique for OD initiated cracks.

5. Cracking – Feeder Welds

5.1 Manual Weld Inspection

The weld crack was found in a field weld, an area not easily accessible for inspection. The proposed approach was to monitor all full penetration repairs on Grayloc welds. A conventional 2 fixed angles shear wave technique was not appropriate because of the close proximity of the first bend that made raster scanning unreliable. The only technically-sound approach was to use a phased-array probe and use its beam deflection capability to scan the volume of the Grayloc weld. With a phased-array probe, raster scanning became unnecessary and simplified the volumetric inspection of the weld.

Figure 10 Grayloc weld cracking inspection

A contact phased array ultrasonic (UT) examination procedure was developed by COG for the detection of circumferential flaws in CANDU PHT system Grayloc hub welds. This technique provides a full volumetric weld inspection for circumferentially oriented flaws,
360° around the weld circumference, by multiple line-scanning performed from the pipe side over the entire circumference. The inspection is done manually using specially designed alignment jigs and either an encoded delivery tool design by Eclipse Scientific, or the GAIT tool with the appropriate gimble. The procedure was developed and tested on nominal feeder pipe and on thinned cross-section samples representative of removed feeders. The wall thickness is measured and used during analysis.

![Figure 11 Clip tool for manual Grayloc weld inspection with alignment jig](image)

### 5.2 GRAVIS – Weld Cracking

Automating the volumetric inspection of the Grayloc weld was a project funded by COG. The objective of the project was to design a 2-axis motorized scanner to deliver a phased-array probe to perform multiple circumferential scans with a small axial index. The advantage of this type of multiple line scan is to collect sufficient data along the axial axis in order to assess the echodynamic response of a suspicious indication. To discriminate between a crack and a side-wall lack of fusion, the echodynamic of a reflector is compare to the calibration notch. It is expected that a crack would normally propagate in a direction normal to the surface and its echodynamic should be similar to the calibration notch. This behaviour was compare against flawed samples and a known lack of side-wall fusion defect found in-service and it proved right. A lack of side wall fusion signal would peak at a high refracted beam angle while totally vanishing at lower angles.

The Grayloc Area Volumetric Inspection System was design and manufactured by Zetec according to COG specifications. The GRAVIS is a general purpose pipe scanner with a mounting adaptor for the Grayloc flange, the Grayloc hub for shop-floor inspections or a pipe-to-pipe weld clamp. The motorized unit is fixed on the mounting adaptor and provides motion of the probe holder in the orbital and axial directions. Then, a spring loaded probe holder developed specifically for the application – wall thinning or volumetric inspection – is affixed on the motorized unit.

Calibration of the phased-array probe is performed with the probe in hand. The operator must scan several blocks to validate the wedge delay, elements, and create TCG curves for each angle. Once the calibration is completed, the probe is mounted on the GRAVIS and inspection can commence.
To get a simple mechanical system, cable handling is performed by the operator. He must carefully manage the cable as the probe orbits around the feeder pipe. Operating the GRAVIS involves a certain amount of dose to the operator, but the quality of the data and the capability of the procedure to discriminate geometric indication from real crack offset the dose taken by the operator during the data-acquisition phase.

The collected data is analysed on-line and the entire volume of the weld is characterized in the matter of 1 or 2 minutes. Thanks to the feature of the software that creates 3-D views of the weld and the necessary top and side view for rapid identification of suspicious indications. Indication are then characterized in terms of amplitude and echodynamic in order to classify them as either an indication with vertical extension, which would likely be a crack, or a tilted indication which would be more likely a lack of side-wall fusion defect type. Any flaw acceptable in terms of amplitude (as per CSA N-285.4) or echodynamic would be revisited at the next outage to verify if any growth is observed.

![Figure 12 GRAVIS configured for weld cracking inspection.](image)

6. Conclusions

This paper described an overview of the improvements in work practices and tooling for a challenging non-destructive evaluation application. The use of automated tooling at Gentilly-2 vastly improved the feeder inspection data quality and reliability, worker’s safety and production rate, while reducing the dose intake by tooling operators. Furthermore, inspection results become independent of operator skills and human errors.

However, since these tools are more complex to operate, extensive training programs in simulation environment are required for efficient use of the instrumentation controls by the acquisition personnel. Automated NDE tooling has proven to be highly effective but only when such training are performed.

Future development in thickness measurements tooling should allow nuclear operators to similarly improve the efficiency of their planned outages for feeder thickness and cracking inspections.
References


