FEEDER PIPING NDE – CURRENT CAPABILITIES AND FUTURE DIRECTION

G. Rousseau[1], K. Chaplin[2], T. Hazelton[3], P. Martin[4], and E. Choi[3]
[1]Hydro Quebec, Gentilly, Canada ; [2] AECL, Chalk River Laboratories, Canada; [3] Ontario Power Generation, Pickering, Canada; [4] New Brunswick Power, Point Lepreau Generating Station, Canada

Abstract: The primary heat transport system of a typical CANDU®-6 nuclear power reactor contains 760 feeder pipes. These feeders carry the coolant between the inlet or outlet headers and the individual fuel channels. Inspection requirements that developed in feeders in the 1990's led to rapid development of NDE technology to evaluate feeder integrity. The NDE technology had to deal with the complex and variable geometry of feeders and access constraints inherent in feeder inspections. The first feeder inspection requirement was ability to detect Flow-Accelerated Corrosion (FAC). This led to an evolution in wall thickness measurement techniques for feeders that is continuing. The leading edge technique for wall thickness measurement is the METAR Crawler that scans feeder bends with 14 wall thickness probes. This system uses motors to push the bracelet along the feeder bend. Second, cracking was detected in a feeder in 1997. This led to development of a specialized, manual inspection technique to deal with access problems. This technique has been extended to use a Hydro Quebec developed drive system to move the probes over a raster scan. The presentation will explain feeder degradation modes and the NDE developed to evaluate feeder integrity.

Introduction: The primary heat transport system of a CANDU-6 nuclear power reactor contains 760 feeder pipes. Feeders are made of A106B steel. These feeders carry the coolant, heavy water, between the inlet or outlet headers and the individual channels containing the nuclear fuel. Therefore, the feeder piping network is part of the pressure boundary and any leak is a major concern for the plant operation.

The feeder system is divided into two sections: the lower section connects to the fuel channel and pipe size ranges from 1.5 in up to 2.5 in, and the upper section that connects to the headers with pipe size between 2.0 and 4.0 in. The junction between the two sections is made by a field weld - all other welds were done on the shop floor and the crown and root caps were grounded flush wherever possible.

Two aging problems were discovered in the mid 90`s: thinning and cracking.

Results: Feeder Thinning. Concerns about the feeders were prompted by the discovery of considerable amounts of magnetite precipitated in the cold leg of steam generators. Some corrosion was expected in the design of the Primary Heat Transport System (PHTS) but the amount of material removed from the steam generators surpassed predictions and excessive feeder thinning became a concern.

Considerable feeder thinning was observed for the first time at the Point Lepreau reactor in 1995. The degradation mechanism identified is Flow Assisted Corrosion (FAC). Excessive thinning occurs on the inside of the feeder pipes, especially on the outlet elbows close to the exit of the pressure tube. This prompted generating stations to implement an inspection program to assess the extent of the problem.

Feeder thinning measurement began using an ultrasonic thickness gauge. Measurement showed that the thinnest spot is located on the extrados of the bends. For repeatability of measurement over the years, templates with a grid spacing of 19 mm were deployed at some plants. Using templates greatly improves positioning accuracy and results in better thinning rate trending but it is a slow inspection process and can be applied only to a small number of feeders for monitoring purpose.

The first development to improve inspection speed and coverage was achieved by Ontario-Hydro`s SIMD. Engineers developed a four-transducer probe array contoured to the outside surface of the feeder.

® CANDU – CANada Deuterium Uranium is a registered trademark of Atomic Energy of Canada Limited (AECL)

The hand scanner is made of two fingers mounted on a joint. Each finger holds two transducers and a miniature encoder located in the middle of the assembly provides axial position information. Coupling with the feeder pipe is done by a water column. In order to cover the whole extrados, an inspection requires 3 passes indexed circumferentially by 22.5 degrees. The SIMD scanner is very effective when the extrados is facing the operator. A precision of 0.06 mm was demonstrated. Reactor inspection results indicated that some 2-inch feeders would reach their minimum allowable thickness before the end of the life design. A precise date for repair was difficult to establish mainly due to uncertainty about the wall thickness of the original bends.

A second scanner was developed by Hydro-Québec to overcome some limitations of the SIMD hand scanner [1]. The MÉTAR bracelet is a mechanical device that clamps directly onto a feeder. It consists of 14 ultrasonic transducers, each mounted in its own shoe, and equally spaced in order to provide a coverage of 140 degrees on a 2.5 inch feeder. Each shoe has sufficient freedom to stay parallel to the entry surface while the bend is scanned, thus providing optimum coupling and perfect alignment with adjacent probes to deliver a precise thickness map of an elbow. The bracelet is designed to ease movement along the feeder pipe and an encoder provides axial positioning information. The main feature of the MÉTAR Inspection bracelet is that inspection results are independent of the operator. In most cases, inspection can be carried out with only one hand and requires little adjustment by the operator.

A multi-channel acquisition unit was adapted for the MÉTAR bracelet based on the R/D Tech FOCUS ultrasonic system and Tomoview data analysis software. The system features real-time B-scan from all 14 channels and provides a thickness map (C-scan) of the scanned area for rapid evaluation of minimum wall thickness. The RF waveform is recorded and the sizing technique is based on the zero-crossing method for accurate wall thickness measurement. On-line computer data anaysis software was developed for rapid evaluation of the thinnest spot. Using digital signal processing, it proved equivalent to a human analyst but at a much faster pace. Precision of wall thickness measurement was demonstrated better than +- 0.015mm for the 2.5 to 4.5 mm thickness range.

The MÉTAR technology is used to inspect the two bends next to the fuel channel connection. A motorized version was developed in order to reach bends too remote for manual inspection [2]. This MÉTAR crawler was extensively used in the upper feeder cabinet to determine if their life could be extended for another 25 years. These inspections, manual and motorized, confirmed that the FAC is mostly aggressive at the channel outlets, that boiling is a key parameter, and the thinning rate decreases with distance from the grayloc.

The successful NDE development program has permitted Utilities to manage FAC and either to mitigate thinning rate or plan feeder replacement on a feeder by feeder case.

Feeder Cracking: A feeder was found to leak in Dec. 1996 and the cause was a crack in an outlet feeder. The cracking was attributed to the fact that the channel was unlocked at both ends. This incident was thought to be isolated until another leak was found in March 2001. Feeder K16 was the leaker and an extensive ultrasonic inspection has found two more cracked feeders (Q08 and U15). An analysis done by AECL demonstrated that the four cracked feeders share similarities, i.e. that cracking was found at the same location (left cheek of 2 ½" outlet feeders near the grayloc fitting), that secondary cracks were present with a main crack that may have developed after coalescence of smaller stress corrosion cracks (SCC).

A detection technique was developed following the discovery of the first crack in 1996 [3]. Access limitation prevented full circumferential inspection using a range setting of two skips distance. A long range technique, called the rocking guided wave technique, uses a ¼" 5 Mhz transducer mounted on a flat 45 degree wedge. The beam is aimed toward the circumferential direction and the wedge is rocked back and forth in order to generate a range of refracted angle in the sample. The instrument range (metal path) is set to 225 mm in order to cover 360 degrees of pipe circumference. Calibration is done with a 5% EDM notch (0.35 mm deep X 10 mm long) located at 90 degrees (3.5-skip distance) away from the transducer and the scan gain is set at +14 dB. An additional 6 dB is added to compensate for water attenuation. To inspect a feeder, the transducer is centered on the extrados at about 150 mm above the grayloc weld. The transducer is moved in the axial direction toward the grayloc with a rocking motion to sweep through all the refracted angle range, and with a small skewing motion of the transducer in order to hit slightly misaligned flaws. Inspection required a minimum of 5 passes and typically takes 15 minutes to perform the detection scan.

In order to gain confidence in the inspection technique, the industry under Candu Owner Group (COG) umbrella held laboratory testing with two cracked feeders taken out of service. Both flaws were non surface breaking and the presence of SCC colonies was later confirmed by destructive analysis. Testing was done in a hot lab with feeders Q08 and U15 capped at both ends. The objective was to develop a common inspection procedure for all COG members.

Various scan patterns and techniques (monocrystal at various angles, phased-array, TOFD, creeping wave) were extensively tested. It became obvious from laboratory testing that the flaws are best detectable with a 45-degree contoured shoe and by performing a raster scan motion as close as possible to the cheeks. The first pass should be done with a circumferential offset of 20 mm from the extrados, and the second pass offset by 30 mm. The amplitude of the left to right motion (in the circumferential direction) has to be 15 mm or greater in order to cover a full skip. Technical reasons supporting this choice are that a contoured shoe makes it easier to keep the beam perpendicular to the flaw axis and improves coupling because of a better fit between the wedge and the entry surface. Because of the periodic nature of the V-path propagation of an angle shear wave, the transducer circumferential motion makes the ultrasonic beam axis sweep the entire surface of a flaw on every scan leg. This scanning method was adopted unanimously by COG members because it leads to repeatable detection of flaws.

The verification technique, whose purpose is to characterize the reflector found during the detection scan and to accept/reject it, was developed in order to dispose of the many geometric reflections occurring during a scan. Tests performed on Q08 and U15 led to the conclusion that the creeping wave method was adequate for verification of the presence of an ID indication and to measure its axial length. However, during qualification, a few cases showed that the creeping wave method had some limitations regarding its effective range and surface flatness. A standard ASME technique (two-skip 45 degree pulse-echo method) was adopted after several trials on mock up samples.

<u>Qualification</u>. The consequences of a feeder failure could have significant economical impact and the regulating body requested that the procedure (V18) be qualified. The qualification program was undertaken by Ontario-Hydro and a methodology similar ENIQ was followed. The qualification process involves several steps:

Inspection Specification (IS)
Laboratory testing to select an NDE method meeting the IS
Development of a procedure and a training program
Technical justification validating the NDE method
Review by an independent NDE expert team
Personnel and equipment qualification

The IS specifies that an internal 1 mm deep by 10 mm long thermal fatigue crack (TFC) is the defined sized crack (DSC) and therefore must be found with a high degree of confidence. The fabrication of such a flaw had to be verified and several samples containing 1X10 mm nominal TFC were produced.

Unfortunately, it was found difficult to produce such a small flaw repeatably. Another problem made TFC impractical because the process leaves secondary reflectors (weld defects) that make detection of TFC`s easier (which is not desirable in a performance demonstration) and sizing by TOFD unreliable (voids diffract more than the crack itself). As of today, producing a 1X10 mm ID TFC reliably has not been demonstrated and the industry may have to turn to electro-discharge machining (EDM) in order to have precise flaw size, knowing that this type of flaw is easier to find by an ultrasound technician.

Developing and verifying the ultrasonic procedure took 3 intensive laboratory sessions. Within 10 days of laboratory work, the inspection and training procedures were detailed and data collected proved that the technique applied by an average technician with adequate training can reliably find the DSC. Proving that the procedure meets the IS took much more time and effort. The technical justification required manufacturing samples in order to demonstrate that each aspect of the IS was verified experimentally. Designing the test samples, running blind tests and reviewing all the essential variables required a work load significantly greater than developing the procedure. The outcome of such effort was a positive review of all the evidences presented to the peer review team and only minor modifications were suggested.

The qualified procedure was used in the Fall of 2003 and Spring 2004 and small cracks with size in the order of the DSC were found twice.

<u>Motorization</u>. Inspection of the first bend is easily done by manual testing. However, after the discovery of a crack on a second bend in the Fall 2003, motorizing the inspection became a necessity to reach inaccessible bends, and to reduce radiation exposure for inspection in the upper feeder cabinet [4]. The objectives of the development were:

To make scanning independent of the operator
To guarantee a transducer overlap of 3 mm
To scan closer to the cheek
To alleviate the access problem on the less accessible cheek
To get encoded position on all scans in order to compare data between transducer.
To have an inspection method that can do both detection and disposition of OD scratches with the same scan.
To reduce inspection time and dose.

IREQ, which had developed several probe-delivery systems for Gentilly-2, was contracted. After reviewing V18 requirements, it was agreed to design a prototype that would have 4 transducers, two sets of two transducers on each side of the extrados. This arrangement would lead to a compact design with all probes in the same plane and full coverage achieved by moving each set of two probes simultaneously.

The main concern was the possibility of cross-talk because all transducers are located at the same axial position and fire along the same plane. It turned out that cross-talk was observed with the pair aimed at the extrados (the other pair, firing toward the intrados, are to far apart). Because the separation between both transducers is fixed, this geometric signal will depend on the pipe thickness and vary in amplitude during a scan. The inspection and analysis procedure dealt with this problem easily because there is no echodynamic accompanying such signal.

After several prototypes, a motorized design was achieved that provided good stability of all transducers, steady coupling on all probes, and repeatable inspection results. Once the crawler proved adequate for scanning straight pipe sections as well as type 6 feeder bends (2 ½" Schedule 80, 73° 1.5D bend), work was undertaken to develop an inspection procedure as close as possible to V18.

The inspection sensitivity is an important issue and we wanted to stay compatible with V18 as much as possible. Time-corrected gain (TCG) was tested under various conditions, pipe dry or filled with water, and the attenuation measured is 5 dB per skip for beam scattering and 2 dB per skip for attenuation by water in the tube. Gain settings in V18 are +14 dB for detection and DAC or TCG plus 8dB for ASME verification scan. Thus, a compromise between detection and verification scan could be made as follows:

Reference level is established with the ½ skip echo set at 80% FSH.
Linear TCG from ½ up to 3 ½ (pipe dry)
Constant gain after 3 ½ skips.
8 dB scan gain is added for scanning
6 dB is added to compensate for water attenuation

The axial and circumferential positions of an indication can be measured on all channels. This is possible because µTomoscan allows adjusting the offset position of each transducer independently. During a scan, the position of each probe is recorded with the ultrasound waveform. By choosing the ultrasound velocity correctly, the metal path is calibrated in circumferential distance. Then, to measure the axial position of a flaw, the analyst first reads the scanner axial position. Secondly, for the circumferential flaw position, the probe circumferential position is added to the metal path. This will provide the position as X mm from the grayloc, and Y mm in the circumferential direction from the extrados.

Calibration of four probes requires a special calibration block. To set the gain of all channels in one pass, a block with twenty one (21) EDM notches located at the appropriate position is required. Typically, gain and adjustments of four channels can be done in 30 minutes with the appropriate block. Verification that all channels are correctly set prior to an inspection is done with a feeder bend having a 1mm deep ID TFC located at 6 0-clock, and an OD EDM notch located at 12 0-clock. The ID flaw must be seen by all channels and the circumferential position must be +- 10 mm. This test consists of a performance demonstration that must be repeated each time any part of the acquisition system is replaced.

An analysis methodology was adapted to the crawler in order to deal with multiple false indications and to minimize on-reactor time. Data are collected in real time and on-reactor analysis consists of focussing the attention on data quality, coverage and a rapid detection of any reflectors that may be a linear flaw with length exceeding 10 mm. If any doubt or data quality is poor, a new scan is performed on the spot.

Off-line analysis consists of reviewing all the data by two independent analysts and any discrepancy resolved either by a third analyst or with a re-scan. To be called a crack, the signal must be observed on at least two channels, exhibit echodynamic, the flaw location must coincide within +- 10 mm axially and +- 10 mm circumferentially, and the flaw length must be at least 10 mm long. These criteria are necessary to resolve false indications from couplant or geometry. The analysis technique had no problem finding the crack in feeders N11 (found by manual testing in Spring 2004) and P09 (found by manual testing in Fall 2003), or any thermal fatigue cracks.

Future: A total of 10 cracks were detected by ultrasonic inspection since 1997 on a single CANDU 6 unit. Recently discovered flaws were relatively small (approximatively 10 mm long and 1 mm deep) and most probably young because they went undetected during their previous inspection. A key parameter for developing an inspection program and determining the frequency of inspection is the crack growth rate. Unfortunately, this parameter could not be evaluated with removed feeders. The only way this can be determined would be to monitor a flaw in-service. This idea, proposed by Alain Drolet, came from the fact that some plants already have thickness monitoring hardware installed. Crack monitoring of an in-service flaw is more challenging then thickness measurement because of the temperature effect on the sizing technique and the wedge. An in-service flaw monitoring program will be debated this year with the objective of getting more engineering data than what destructive analysis had supplied so far.

References:

1. "Hydro-Québec METAR Inspection Bracelet" , E. Lavoie, G. Rousseau, J. Lessard, A. Drolet; CNS 5th International Conference on CANDU Maintenance, November 2000.
2. "On the Development of the MÉTAR Family Inspection Tools ", E. Lavoie, G. Rousseau and L. Raynaud; CNS 6th International Conference on CANDU Maintenance, November 2003.
3. Assessment of Guided Wave Technique and Present Sizing Technique for In-Service Feeder Examinations, RPC Report No. EMR/97/170, Project No. 10004862/1, Rev. 3, April 15, 1998
4. " Development of Ultrasonic Techniques for Feeder Cracking Inspection at Gentilly-2", G. Rousseau, J-F. Coté, G. Lepage and E. Lavoie; CNS 6th International Conference on CANDU Maintenance, November 2003.