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Inspection of CANDU Reactor Pressure Tubes Using Ultrasonics

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Abstract

Fuel channel pressure tubes are critical components of the CANDU reactor core which require periodic inspection to demonstrate continued fitness for service.
Ontario Power Generation; Inspection & Maintenance Services Division has been operating a variety of inspection systems to perform volumetric and surface nondestructive examinations of the pressure tubes. Since the early days, ultrasonics was selected as the preferred method of inspection. Several ultrasonic transducers are employed to perform inspection from different directions and at various angles at the same time. The ultrasonic inspection system utilizes immersion, focused transducers operating at high frequencies (10 MHz and 20 MHz) in order to achieve high degree of detectability of small flaws and high accuracy of flaw sizing.
The inspection could be divided into the following phases:

- System amplitude calibration
- Ultrasonic flaw detection
- Sizing of detected flaws

In addition to inspecting tube for flaws, data is collected allowing gauging measurements (diameter and wall thickness), pressure tube sag measurements and Garter Spring detection.
Detection of flaws is performed using several criteria, including reflector amplitude criterion.
Sizing is performed using a variety of fully digitized scans acquired with various probes in both pulse echo and pitch catch configurations. The sizing accuracies achieved are in 20 to 40 microns range for certain flaws.
Flaw evaluation is performed off line, using a variety of methods to display and analyze collected data.
The inspection systems in use by Ontario Power Generation and previously by Ontario Hydro have successfully inspected hundreds of pressure tubes in Canadian and foreign CANDU reactors over the last 20 years.

Keywords: CANDU; pressure tubes; flaws; inspection; ultrasonics

1. Brief description of CANDU reactor

Although the purpose of this paper is not to present CANDU design, basic knowledge of the reactor is required to understand issues related to structural integrity and inspection of the pressure tubes.
A CANDU reactor (Figure 1) consists of a large tank, the calandria, which is penetrated by several hundred horizontally mounted fuel channels containing natural uranium fuel bundles. The fuel channel consists of a 104 mm diameter (ID), 4.3 mm thick Zirconium - Niobium pressure tube, inserted into slightly bigger calandria tube, and two stainless steel end fittings at the ends of the fuel channel. The tubes are approximately 6.3 m long. Garter Spring spacers separate the two tubes preventing contact between the hot pressure tube and relatively cooler calandria tube. Heavy water coolant flows through the pressure tubes, removing heat from fuel bundles and transferring it to steam generators, where secondary circuit light water is being heated and converted into steam to run the turbine. During reactor operation, pressure tube material is subject to high pressure (up to 11.3 MPa), high temperature (up to 310 °C) and very high gamma and neutron radiation fields.

The calandria is filled with non pressurized heavy water acting as moderator.

CANDU reactors are currently operated by several Canadian and foreign utilities. In addition, a number of similarly constructed PHWR reactors of the same basic design are under operation in India and Pakistan

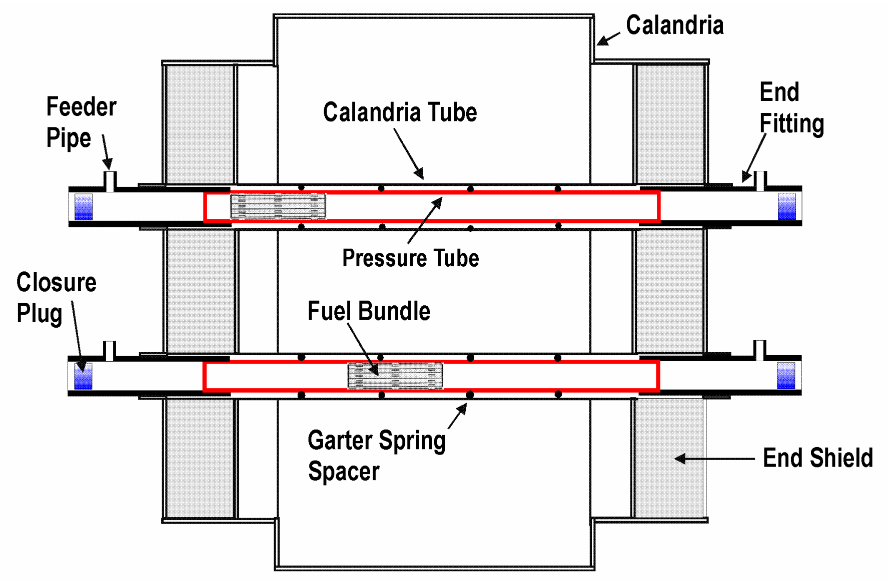

Figure 1 Simplified schematic of CANDU reactor core

2. Inspection requirements for NDE of pressure tubes

Inspection requirements for nuclear reactors in Canada are determined by two inspection programs:

- Periodic Inspection Program
- In-Service Inspection Programs

Periodic Inspection programs are mandated by Canadian Standard CAN/CSA-N285.4-94. The standard has been recently revised and issued as CAN/CSA-N285.4-05. The 2005 issue of the standard is not fully in effect yet (in Canada) but will be implemented within the next year. The vast majority of the pressure tube inspections are being conducted under In-Service Inspection Programs reflecting fuel channel life management strategies developed for specific plants and units. A number of degradation mechanisms have been identified during the many years of the CANDU program. Various fuel channel life management programs have been developed in order to gain better understanding of the pressure tube degradation phenomena and to maintain monitoring of pressure tube condition at an acceptable level. Currently, the number of inspections performed under In-Service Inspection Programs vastly exceeds the minimum level required by the standard.

3. Inspection Systems Currently Operated by OPG for inspection of Pressure Tubes

Inspection & Maintenance Services of OPG operates a variety of pressure tube inspection systems for the benefit of OPG and other utilities in Canada. The focus of this paper is on full length ultrasonic inspection of pressure tubes. Such inspections are accomplished using either of the two systems:

- ANDE (Advanced NDE)
- CIGAR (Channel Inspection and Gauging Apparatus for Reactors)

There are many differences in the delivery mechanisms, electronic and computer hardware and productivity rates but basic pressure tube inspection capabilities and procedures remain the same for both systems.

Basic capabilities of the inspection systems provide the following:

a) Ultrasonic volumetric inspection of pressure tube material
b) Flaw characterization by ultrasound
c) Flaw characterization by flaw replication
d) Garter Spring location by Eddy Current and UT techniques
e) Channel gauging (internal diameter and tube thickness measurements) by ultrasonics
f) Pressure tube sag profile
g) Visual inspection of pressure tube ID

This paper will focus on ultrasonic inspection capabilities of the Pressure Tube inspection systems.

4. Ultrasonic inspection of pressure tubes

The ultrasonic inspection of a pressure tube is performed in three phases:

- In channel system calibration
- Detection scan
- Sizing and characterizations scans

Detection scans are run in helical pattern. The helix pitch is adjustable by the operator. Currently used pitch for general flaw detection scans is a nominal 1 mm (0.9 mm+/-0.1 mm) through the full length of the pressure tube. The sizing and characterization scans may be done as helical or raster scans – depending on the system.

4.1 Ultrasonic system calibration

The flaw detection procedure is based on CSA N285.4-94 requirements. The 2005 edition of the standard introduces only minor changes. The requirement of the standard is to calibrate the inspection system on a variety of EDM notches. The calibration is achieved by setting the signals at a predetermined (100% FSH) amplitude level.
The shear wave probes are calibrated on 0.15 mm deep, 6 mm long and 0.15 mm wide notches. There are a total of 4 notches:

- two ID notches – one axial and one circumferential
- two OD notches – one axial and one circumferential

The Normal Beam (material) probe is calibrated on three Flat Bottom slots, machined from the OD of the tube. The slots are 1.5 mm long, 0.75 mm wide and are machined to 15%, 50% and 85% of the tube thickness.
The 2005 edition of the standard also added a need to verify system performance on so called PV (Performance Verification) notches.

4.2 Ultrasonic flaw detection

The reportability and flaw investigation threshold is established at 50% (-6 dB) of the calibrated levels for most of the pressure tube. Certain regions of the pressure tube may have this threshold lowered even further, to 20% (-14 dB) due to non uniform stress field in the area.
To put the calibration notch depth into perspective, it should be recognized that one paper sheet (copy paper) is approximately 0.11 mm thick.

For the general flaw detection scan, both pressure tube inspection systems currently employ four focused, immersion probes, 10 MHz nominal frequency and one or two normal beam probes. The shear wave probes are configured in such a way that the individual beams refract in the pressure tube material at 45 degree angle (refracted shear wave). The probes are grouped into a probe cluster (Figure 2). Two probes constitute an axial pair and two constitute a circumferential pair. All four beams meet at the same point on the pressure tube ID (full skip). Thus, any flaw is being looked at from four different directions by shear wave beams. Depending on the system there might be one or two more normal beam probes. One of them is calibrated on OD slots in pulse echo mode. This probe interrogates the pressure tube material and OD. The second normal beam probe is calibrated using back wall echo and is used for flaw detection based on amplitude drop.

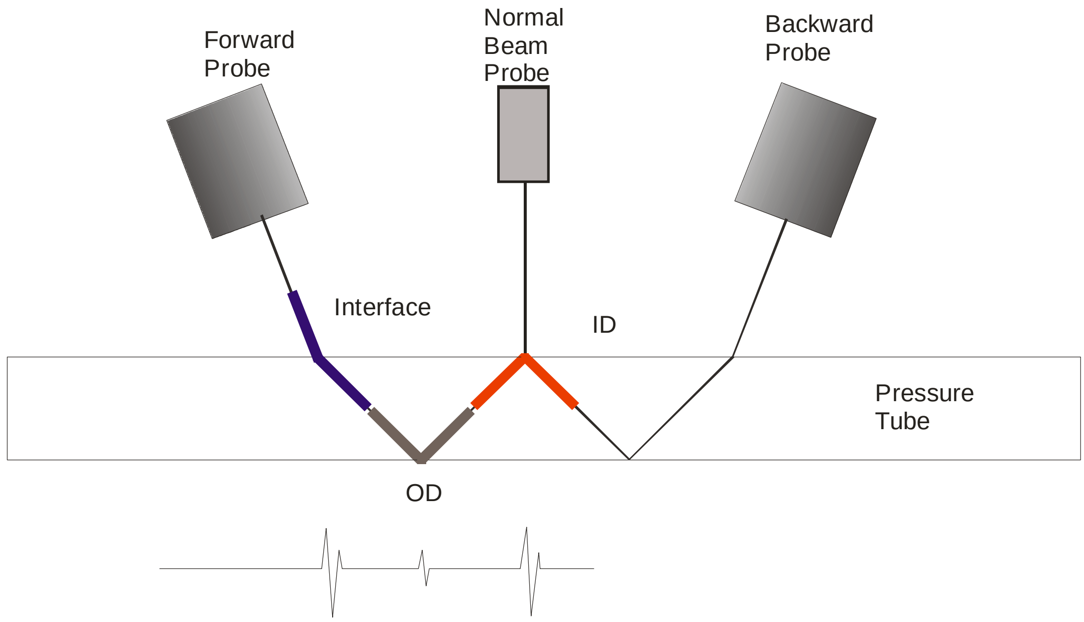

Figure 2 Probe cluster – axial probe pair

During the detection scans the data is acquired in a number of data acquisition gates. The gates are configured in the following way:

<u>Shear Wave probes:</u>
Three gates (see Figure 2) are set up in order to monitor the Interface, the OD (half skip) and the ID (full skip). Over every 0.1 degree of the rotary motion, the highest amplitude signal from each gate is being read by the instrument and sent to the Data Acquisition Computer. The computer processes the data, sends it for storage and displays in the form of plots (typically color coded by amplitude). The software used for this operation is OPG developed proprietary software. The software also performs some limited data analysis functions, by flagging indications which exceed preset thresholds and proposing a list of areas for sizing and characterization scans. These indications are then investigated by the data acquisition crew in order to verify whether additional scans are required.

<u>10 MHz Normal Beam probe:</u>
The data acquisition gates are set up to monitor material ranges between Interface and First Back Wall, between First and Second Back Wall and Second Back Wall. Each of these gates has its specific purpose. The Normal Beam Second Back Wall gate is used as a very potent flaw detection and analysis tool.

<u>The 15 MHz material probe (ANDE only)</u>:
This probe is gated between the Interface and 1st Back Wall. It is a very effective tool for detection and sizing of material and OD indications,

Ultrasonic transducers installed in the inspection head are manufactured to very strict requirements contained in OPG specifications. Probe relative sensitivity, bandwidth, centre frequency, beam skew and beam offset are strictly controlled. As an example the beam skew is considered acceptable within +/- 0.5°, and probe must be capable of working at least 200 hours in the reactor environment.

4.3 Sizing and characterization scans

Data collected during the detection scan is only used for detection and length and width sizing of the flaws. The depth sizing is primarily performed using B-scans collected in a flaw area.

The current inspection procedures require use of the following types of B-scans for pressure tube flaw characterization:

a) High frequency (20 MHz), highly focused Normal Beam probe for flaws open to the inside surface (ID)
b) 10 MHz Normal Beam probe for material and OD flaws
c) 15 MHz Normal Beam material probe for material and OD flaws (ANDE)
d) Shear Wave, Pitch - Catch (Time of Flight) B-scans with axial and circumferential probe pairs
e) Shear Wave, Pulse Echo B-scans performed individually by all shear wave probes

Additionally a Pitch Catch Shadowing scan is being used to assist in flaw depth sizing and flaw characterization.
As is often the case in ultrasonic inspection, one scan, mode or probe set up does not usually provide enough information to properly size and characterize a flaw. Careful analysis of all available data may assist in performing these tasks.

A short discussion of the various sizing scans and their applications for sizing follows below.

a) High frequency (20 MHz), highly focused Normal Beam probe for flaws open to the inside surface (ID)

The currently employed probe is a nominal 20 MHz, 10 mm focal length and approximately 6 mm crystal diameter transducer. This probe is installed in such a way, that it focuses at the ID surface. Due to the focusing it is extremely useful for interrogation of the water - metal interface area (tube ID). As more than 99% of all dispositionable flaws encountered in CANDU pressure tubes are ID surface flaws, this is the area of significant interest. The probe beam diameter in the focal spot is only about 0.5 mm (6 dB beam). Such narrow beams provide excellent lateral resolution capabilities. This is critical for the pressure tube inspection as relatively small flaws (0.15 mm or deeper) are subject to an engineering assessment according to the Standard. Such assessments require very detailed and accurate flaw measurements and profiling.

See Figure 3 for demonstration of 20 MHz probe capabilities. It shows 10 cent coin (Canadian) scanned in water using the 20 MHz probe

Figure 3 10 cent coin (Canadian) scanned in water using 20 MHz probe. Image reversed.

b) 10 MHz Normal Beam probe for volumetric flaws

This transducer has excellent material penetration capabilities, so the B-scans collected are used for evaluation of flaws in the material itself (not open to any of the surfaces) and some OD flaws. The collection gate is normally set up to cover several back wall indications. This probe is also used for very precise material thickness measurements in close proximity to a flaw.

c) 15 MHz Normal Beam probe for volumetric and OD flaws (ANDE).

This probe has been designed to provide improved volumetric and OD flaw sizing. It is a highly focused probe with an acoustic lens designed to provide an “elongated” focal zone which maintains almost uniform beam width through the pressure tube thickness.

d) Shear Wave, Pitch - Catch (Time of Flight) B-scans with axial and circumferential probe pairs

These B-scans accord an opportunity to look at the flaw from “below”, thus making it possible to characterize flaws which may not be open to the surface, tightly closed, undercut or contain accumulated oxide. Ultrasound travels through the pressure tube material in a “W” fashion from the transmitting to the receiving probe. A sound beam will reflect from the “bottom” of the flaw. This results in shortening of the ultrasound paths, thus enabling time shift measurement which occurs between bottom of the flaw and undisturbed area of the tube. The Pitch Catch B-scans are performed by both probe pairs, circumferential and axial in order to maximize available information.

e) Shear Wave Pulse Echo B-scans

These B-scans are useful for deeper flaws and composite flaws where a secondary flaw may propagate from the bottom of a primary flaw. The Pulse Echo B-scans are collected using the same probes as Pitch Catch B-scans.

f) Pitch Catch Shadowing

The Pitch Catch Shadowing scan is collected during the detection scan. In a probe pair one probe works as a transmitter and one as a receiver. Any flaw standing in the way of the through transmission beam will create a shadow (drop in the received signal amplitude). The dimensions and degree of the shadow depend on many factors; among them flaw depth. This method is generally used as confirmatory method. It is an excellent method for detection and sizing of flaws oriented at unfavorable angles to the shear wave pulse echo beams.

The B-scan data can be presented in a variety of formats and displays including 3D images

4.4 Sizing accuracies

The theoretical limit of the measurement accuracy is affected by system resolution. The resolutions currently implemented in our systems are quite high: 6 - 7 microns for 20 MHz Normal Beam probe, 14 microns for shear wave B-scans and 19-21 microns for the 10 MHz Normal Beam transducer. The resolution depends on sound velocity and digitization rate. Depending on the inspection system the digitization rate used may be either 100 MHz or 125 MHz.
The verifications programs conducted and accumulated experience indicates that the actually achieved accuracies have not deviated much from the theoretical limit. It has been proven that the depth of ID flaws can be reliably measured with accuracy of +/- 20 microns with the 20 MHz probe. The accuracy of the Pitch Catch methods is somewhat lower, but still results in an impressive +/- 40 microns. .

4.5 Ultrasonic data analysis and reporting

Initial evaluation of the collected data is done by the data acquisition crew, before coming off channel. This evaluation usually involves review of flagged indications (indications which exceeded preset threshold values) in order to establish whether further (sizing) scans are necessary. The current practice calls for detailed data analysis and flaw sizing and characterization to be done off channel by a dedicated data analysis team.

5. Summary and Conclusions

Ontario Power Generation, Inspection & Maintenance Services has operated various, remotely controlled inspection systems for inspection of CANDU reactor pressure tubes for the last 20 years. Such systems are unique to CANDU configuration. The main inspection method is ultrasonics. The inspection methods and procedures have evolved over the years leading to significant improvements in quality of the inspection. The evolution has also lead to more robust and reliable methods which allow for significant improvement in inspection times. Such improvement is critical in order to comply with tight outage schedules.