

Ultrasonic testing procedures for volumetric and surface inspection of CANDU pressure tubes

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Abstract

Fuel channel pressure tubes are critical components at the heart of the CANDU reactor core which require periodic inspection to demonstrate continued fitness for service. A CANDU reactor 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 inside diameter, 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.

Ontario Power Generation; Inspection & Maintenance Services Division operates a variety of inspection systems to perform volumetric and surface nondestructive examinations of the pressure tubes. At the core of those systems is an ultrasonic probe module which contains several ultrasonic probes interrogating inspected tube from several angles and with various wave modes at the same time. The ultrasonic inspection system utilizes high frequency ultrasound (10 MHz and 20 MHz) in order to achieve high degree of detectability of small flaws and high accuracy of flaw sizing. The inspection is performed in three phases:

- Inspection system calibration
- ultrasonic flaw detection
- sizing of detected flaws

Detection of the flaws is performed using several criteria, including signal amplitude criterion. Sizing is performed using a variety of B-scans acquired with various probes in both pulse echo and pitch catch configurations. The flaw depth sizing accuracies achieved are in 20 to 40 microns range for certain flaws.

The pressure tube 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.

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. 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.

Unlike single vessel PWR or BWR reactors, a CANDU reactor consists of several hundred smaller pressure vessels – called pressure tubes.

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

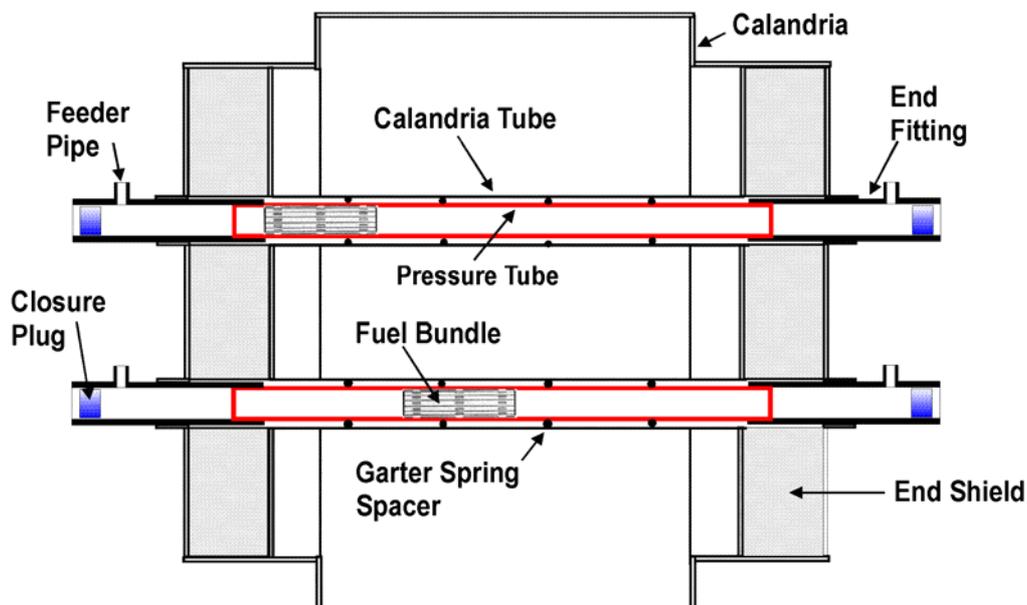


Figure 1 Simplified schematic of CANDU reactor core

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. It is currently being implemented for use.

The vast majority of the pressure tube inspections are being conducted under In-Service Inspection Programs. 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 integrity at an acceptable level. 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 ultrasonic inspection 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 testing methods and procedures

The ultrasonic inspection of pressure tubes 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 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 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.

4.2 Ultrasonic flaw detection

Once calibrated, the reportability and investigation threshold is established at 50% of the calibrated levels. Certain areas of the pressure tube may have this threshold lowered even further, to 20% due to non uniform stress field in the area.

To put the calibration notch size 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 material and pressure tube OD. The second normal beam probe is calibrated using back wall echo and is used for flaw detection based on amplitude drop.

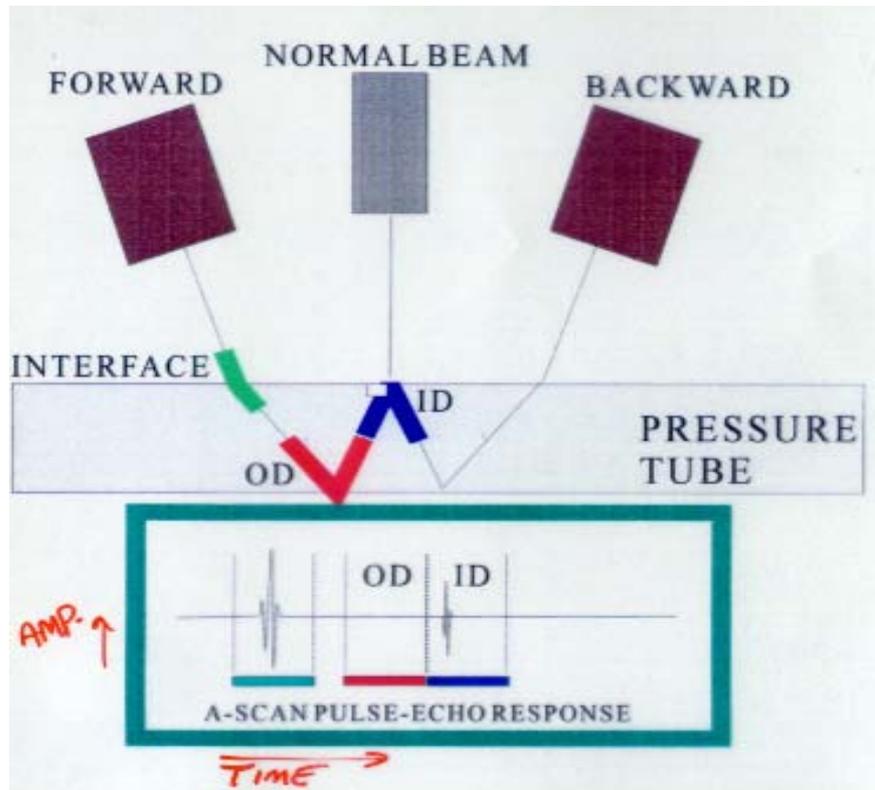


Figure 2 Probe cluster – axial probe pair

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

Shear Wave probes:

Three gates (see Figure 3) 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 visual plots. 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. Figure 3 is an example of a flaw flagging on signal amplitude.

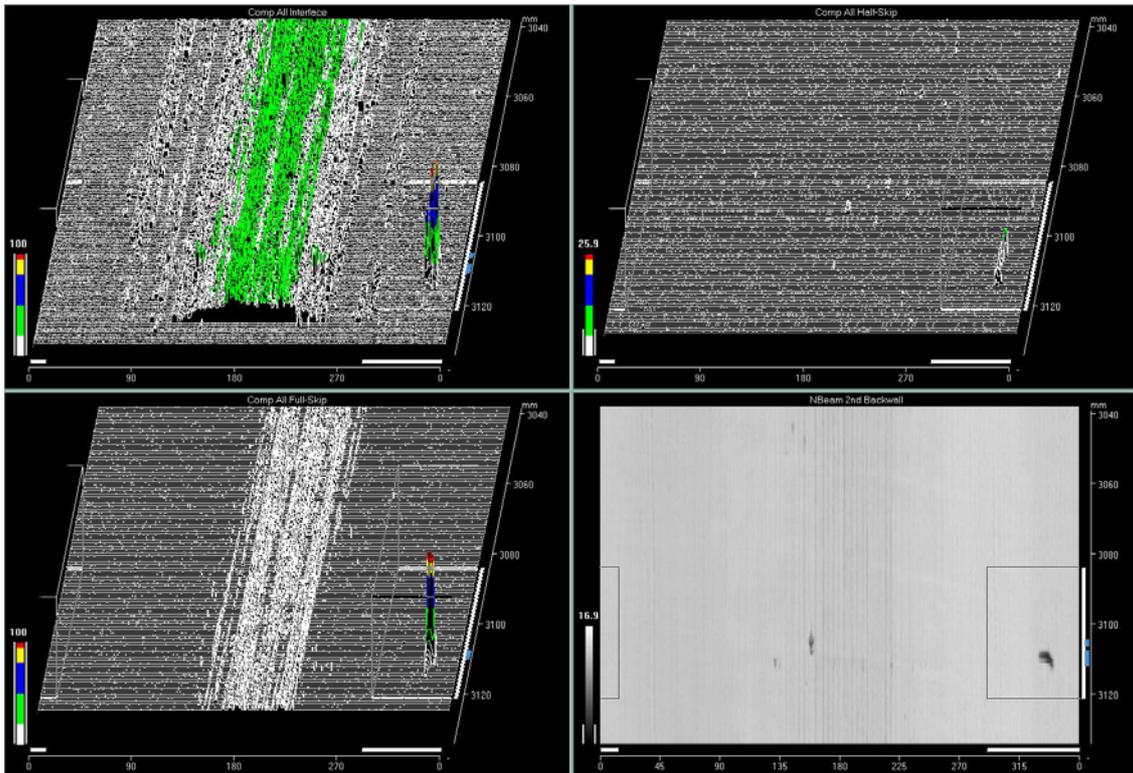


Figure 3 Indication flagging on signal amplitude

10 MHz Normal Beam probe:

The data acquisition gates are set up to monitor material range between Interface and First Back Wall, between First and Second Back Wall, Second Back Wall and Third Back Wall. Each of these gates has its specific purpose, but over the years we have learned to specifically respect Normal Beam Second Back Wall amplitude drop as a very potent flaw detection and analysis tool.

The 15 MHz material probe (ANDE only):

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. In order to illustrate difficulties associated with manufacturing of such probes, it is worth noting that the beam skew is considered acceptable within +/- 0.5°, and probe must be capable of working at least 200 hours in the reactor.

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. B-scan is usually defined as collection of A-scans stacked together to form an image, which resembles a cross section of the material being inspected.

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 volumetric flaws
- c) 15 MHz Normal Beam material probe for volumetric 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 with all four shear wave probes

Additionally a Pitch Catch Shadowing scan, collected during the detection scan is being used for flaw depth sizing and characterization. The Pitch Catch Shadowing scan is not a B-scan – the data is collected as a highest voltage signal in a gate.

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.

With the exception of the 20 MHz probe, which is installed in the inspection head specifically to perform the B-scans, all other probes used for B-scans are the same probes also used for the detection scan.

A short discussion of the various B-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. The probe beam converges and diverges relatively quickly so it does not achieve good penetration through the tube material. 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. In the assessment process, the reactor owner provides sufficient evidence to the regulatory body, that the pressure tube is fit for service. Only upon acceptance of such evidence can the fuel channel be returned to service. Such evaluations require very detailed and accurate flaw measurements and profiling.

See Figure 4 for demonstration of 20 MHz probe capabilities. It shows 10 cent coin (Canadian) scanned in water using the 20 MHz probe

Figure 5 provides image of a 0.31 mm deep debris fret sized by the 20 MHz Normal Beam B-scan.



Figure 4 10 cent coin (Canadian) scanned in water using 20 MHz probe. Image reversed.

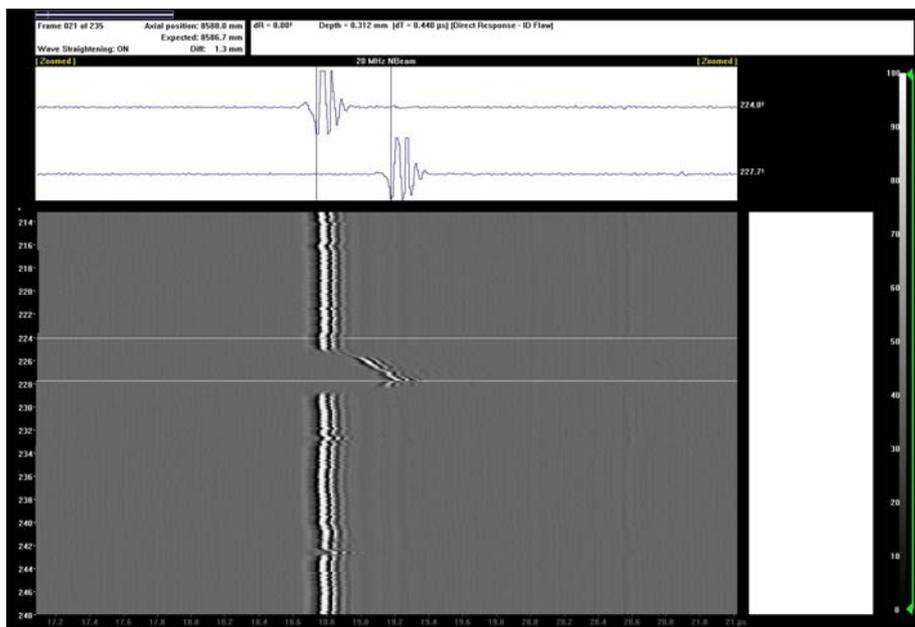


Figure 5 Depth sizing of a 0.31 mm deep flaw using 20 MHz B-scan

b) 10 MHz Normal Beam probe for volumetric flaws

This transducer has much improved penetration capabilities, when compared to the 20 MHz transducer, 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. The probe beam is not as highly focused as the 20 MHz probe beam and subsequently, lateral resolution of the method is worse than that for the 20 MHz transducer.

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

This probe has been designed to provide improved volumetric and OD flaw sizing. It is a highly focused 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. 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. Currently, pure diffracted signals are not used for these measurements, but rather small signals reflected from facets of the flaw are used. Use of focused shear wave probes makes this method very sensitive to small reflectors. The probes employed have 6 dB beams in the order of 0.75 to 1.0 mm which makes them extremely sensitive to reflections coming from even very small reflecting surfaces. Normally the Pitch Catch B-scans are performed by both probe pairs, circumferential and axial in order to maximize available information.

Figure 6 is an example of sizing a 0.31 mm flaw using Pitch Catch B-scan



Figure 6 Sizing of flaw using Pitch Catch B-scan

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. The dimensions of the shadow depend on many factors; some of them are tied to 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.

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.

In order to estimate actual measurement accuracies achieved a structured B-scan Verification Program has been conducted. During the program a number of scans were collected on a variety of notches. These have been later independently analyzed by several analysts. Such an approach allowed for testing of the complete system including actual inspection equipment and procedures, and human performance factor. Achieved accuracies have not deviated much from the theoretical limit. On a number of

measurements (2500 data points) it has been proven that the ID flaws can be 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. As mentioned above this also includes impact of human factor as the tests included several data analysts. The verification project has also proven that there is a tendency in the system (that includes the data analyst making the final call) to slightly, but consistently, oversize measured flaws.

4.5 *Ultrasonic data analysis and reporting*

As mentioned before, pressure tube inspection is performed in two phases: phase 1 is primarily an amplitude based inspection for flaw detection, phase 2 consists of flaw sizing and characterization scans. Preliminary evaluation of 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. It focuses on the completeness and quality of the collected data. The reactor down time is extremely expensive, so economy dictates that on channel time becomes minimized. The current practice calls for final data analysis and flaw sizing and characterization to be done off channel. The basic idea is to minimize the amount of analysis and decision making performed by the Data Acquisition crew while on-channel. This allows for significant on reactor time savings and minimizes the potential for mistakes and errors which could be made while working under pressure and to very tight and demanding schedules. An additional benefit resulting from that is better predictability of on channel times which allows for better utilization of station resources due to better planning. The data acquisition crew is responsible for performing a detection scan and for performing local sizing and characterization scans when required as per CSA N285.4, and typically more conservative OPG-IMS procedures. The first pass analysis is done by the Flaw software which flags indications requiring sizing and characterization scans. This software function is assisted and verified by “manual” review of collected channel data. Certain channel areas are automatically pre-selected for sizing and characterization scans based on experience or potential for presence of flaws. The procedures are fairly conservative in the selection of areas for detailed sizing and characterization scans which significantly minimizes potential for channel revisits. The off line data analysis process (Figure 7) is subject to a rigorous QA system which includes the following features:

- All analysis activities are performed by personnel certified to respective national (CGSB) standards (a minimum level II UT for ultrasonic data and Level II ECT for Eddy Current data required) and internal IMS certification program
- All analysis software has been tested and verified to comply with the requirements. Only tested and verified software functions are used for analysis.
- All data is analyzed independently by two independent analysis streams. Each of the analysis streams is done independently deriving the results from the raw data.
- The two sets of results are reconciled by a third qualified analyst. Correlation is done as per very rigid procedure imposing strict tolerances on allowable measurement discrepancies.

- In addition to this, certain categories of flaws undergo even more demanding process (Phase II Analysis) which increases assurance that critical flaws have been handled appropriately. This process typically includes technical support and possibly third party involvement in the data analysis. Typically, very complex flaws or flaws which impose very strict limits on reactor operation are subject to this process.

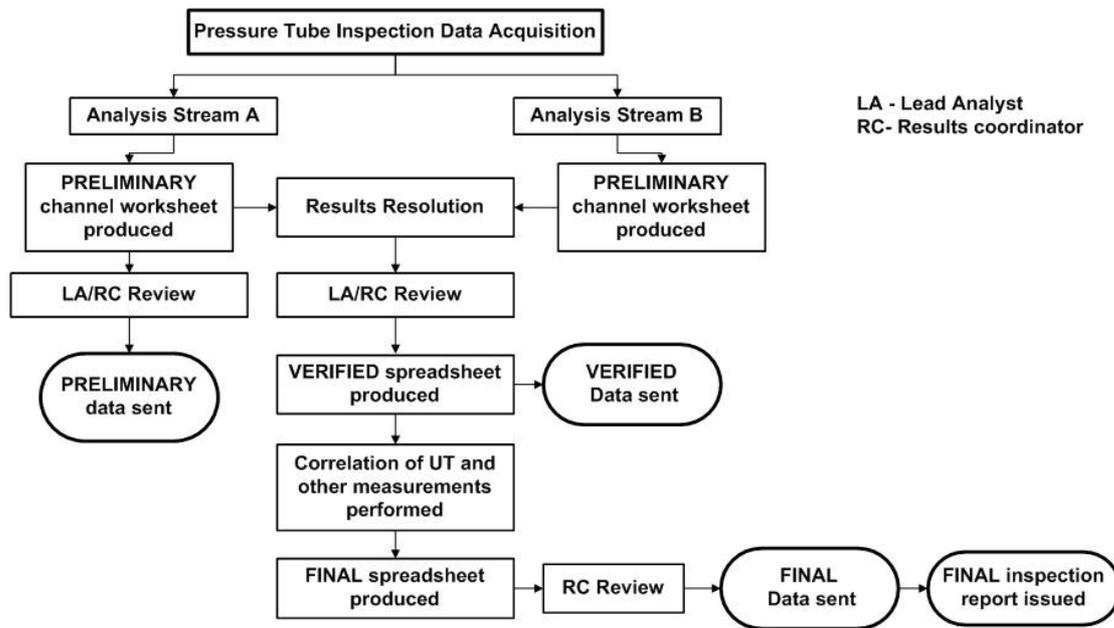


Figure 7 Flowchart describing “off line” data analysis process

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.