Measurement of Internal Diameter of Pressure Tubes in Pressurized Heavy Water Reactors using Ultrasonics

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Abstract

The Pressure Tube in Pressurized Heavy Water Reactors (PHWRs) undergoes dimensional changes due to the effects of creep and growth as it is subjected to high pressure and temperature, which causes Pressure Tubes to permanently increase in length and diameter and to sag because of weight of fuel & coolant (heavy water) contained in it. These dimensional changes are due to prolonged stresses under high temperature & radiation. Pressure Tube stresses are evaluated for both beginning and end of life for accounting the Pressure Tube dimensional changes that occur during its design life. At the beginning of life, the initial wall thickness and un-irradiated material properties are applied. At the end of life, Pressure Tube diameter and length increases, while wall thickness decreases. Material strength also increases during that period. The increase in Pressure Tube diameter results in squeezing of garter spring spacer between the pressure and calandria Tubes. It also causes unacceptable heat removal from the fuel due to an increased amount of primary coolant that bypasses the fuel bundles. This reduces the critical channel power at constant flow. Hence the periodic monitoring of pressure Tube diameter is important for these reasons. This is also required as per the applicable codes and standards for In-Service Inspection of PHWRs. Mechanical measurement from ID of the Tube during periodic monitoring is not practically feasible due to high radiation and inaccessibility. This necessitates the development of NDT technique using Ultrasonics for periodic in-situ measurement of ID of pressure Tubes with a BARC made remotely operated drive system called BARCIS (BARC Channel Inspection system). The development of Ultrasonic based ID measurement techniques and their actual applications in PHWRs Pressure tubes are being discussed in this paper.

Key Words: Ultrasonic velocity, Heavy water, In-situ Calibration, Stepped reference block, Coolant Channel

Introduction

The Pressure Tubes in Pressurized Heavy Water Reactors (PHWRs) undergo dimensional changes due to the effects of irradiation creep and growth. This causes permanent increase in length and diameter of pressure Tube and also sag that occurs from the weight of the fuel bundles and coolant contained in it. The increase in diameter may lead to fuel failure due to in-sufficient cooling caused by the coolant bypassing the fuel bundle. Squeezing of garter spring spacer between the pressure and Calandria Tubes may create safety issues. The coolant bypassing the fuel bundles also reduces the critical channel power at constant flow. Thus, the diameter expansion turns out to be a major life limiting parameter for the reactor Pressure Tubes. Hence periodic monitoring of pressure Tube diameter is necessary during In-Service Inspection (ISI) and also during pre-service inspection (PSI) for baseline data. Mechanical measurements from inside the Tube are difficult due to high radiation and inaccessibility. The presence of heavy water as coolant helps the use of Ultrasonic immersion based techniques for periodic in-situ measurement of Internal Diameter (ID) for pressure Tubes along with a remotely operated drive system (BARC Channel Inspection System) BARCIS. Since the Ultrasonic velocity is highly dependent upon temperature of the medium, in which they are travelling; a provision has been made for in-situ compensation for velocity variation in heavy water flowing through PT under measurement. This paper describes the development of UT based two techniques viz. full wave rectified flank method & negative half wave rectified peak method for PT ID measurement with in-situ ultrasound velocity compensation required to maintain measurement accuracy. It also discusses our experiences gained during ID measurements carried out at different reactors (for both types of PHWRs; 220MWe & 540 MWe PHWRs).

EXPERIMENTAL SET UP:

BARCIS Inspection head for ID measurement has been designed with three 10 MHz immersion spot focused probes; two probes are used for measurement of water path kept at diametrically opposite to each other (180° apart) and the third probe is used for calibration, kept at a fixed distance from a stepped reference reflector as shown in Fig 1. First ID is measured at 12 locations of the reference standard piece where it is mechanically measured using two axis co-ordinate measuring machine (CMM) and the calibration is done using calibration probe and stepped reference reflector by observing the difference between first and second echo using digital Ultrasonic flaw detector having multiple gates and minimum reading accuracy 0.01 mm (Fig 2). At the calibration velocity the water paths are measured by the other two probes meant for actual measurement. (fig.3) Then the ID value measured by mechanical method is subtracted from the summation of two water paths measured by two measurement probes. It gives us the value of probe-to-probe face distance within the inspection head and this value will be constant during all measurements. Probe to probe face distance is not possible to measure by mechanical measurement due to the geometrical layout & probe positions. For measurement of water paths in full wave rectified flank measurement method; the difference between 1st & 2nd interface echoes are measured and in negative half wave rectified peak measurement method the difference between initial pulse and first interface echo is measured. Since the Pressure Tube (PT) is filled with heavy water; during ID measurement inside the coolant channel, there is a need in the inspection head to have a reference calibration probe to measure in-situ calibration velocity. Since the ID value is required with high accuracy, Ultrasonic flaw detector is required to get the water path reading at least with 10 microns reading accuracy as mentioned above.

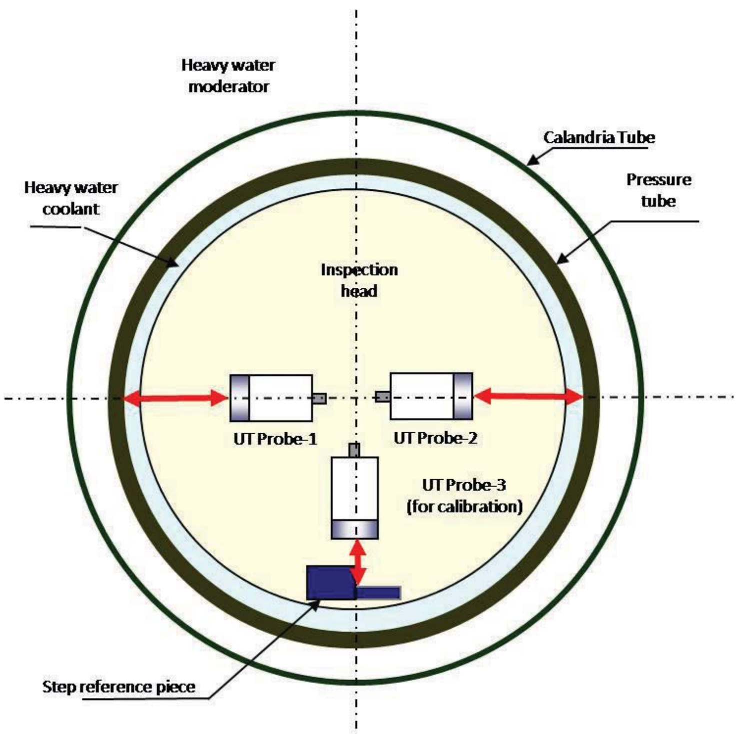

Fig.1: Schematic of Ultrasonic probes arrangement for ID measurement

Fig.2: Echoes from Stepped Reference Block

Fig.3: Water Path Measurement by Ultrasonic Probe

Since actual measurements are done in the channel filled with heavy water, calibration of Inspection heads are also carried out using virgin heavy water before putting into the actual channel. Measurement of Ultrasonic velocity at each measurement location within the channel compensates the Ultrasonic velocity in heavy water at the channel temperature and all measurements within the channel are taken with the measured Ultrasonic velocity in both the techniques.

Measurement Methodology:

$$D = \left(\frac{TOF_1}{2} + \frac{TOF_2}{2}\right) \times v + x \qquad (1)$$

D = Diameter of Pressure Tube, in mm

TOF1 = Ultrasound Time of Flight from probe 1, in μs

TOF2 = Ultrasound Time of Flight from probe 2, in μs

v = Ultrasound velocity in liquid (viz. Heavy water) medium, in mm/μsec

x = Probe to probe face distance for probe 1 & probe 2, in mm

Velocity calibration from stepped piece,

$$v = z/\left(\frac{TOF_{s2}}{2} - \frac{TOF_{s1}}{2}\right) \qquad (2)$$

v = calibration velocity, in mm/μsec

z = step distance from reference piece, in mm.

TOFs1 = Ultrasound Time of Flight from surface 1, in μs

TOFs2 = Ultrasound Time of Flight from surface 2, in μs

Possible errors during ID measurement:

1) Mechanical configuration of the stepped surface such as chamfering, surface roughness, degree of parallelism etc
2) Ultrasonic instrument settings
3) Errors in measurement of probe to probe face distance
4) Variation in light water/heavy water velocities
5) Distance between stepped reference piece used for calibration and reference ultrasonic probe.

Features to achieve the measurement accuracy:

The difference in thickness of two stepped reference block was made to ~18 mm. This will ensure the increased accuracy of water path measurements which is the range of 15-20 mm during actual inspection.

The surfaces of reference block for in-situ velocity measurement has been smoothly polished. In order to achieve sharp stable echoes; the surface finish of the reference target is made of the order of 0.1 micron or better and two stepped surfaces parallelism is maintained within 10 microns.

The water distance measured by probe is adjusted in such a way that first interface and second interface echoes are having almost equal heights in flank method. This significantly contributes increase in measurement accuracy.

ID measurement in calibration Tube piece is made by two axis coordinate measuring machines where inaccuracy is negligible and minimizes errors in ID values used during calibrations.

Calibration is done before putting the inspection heads into the channel. Inspection heads are calibrated using both light water and heavy water and ID values obtained are compared with mechanical measurement ID data of calibration Tube piece (which is done by two axis coordinate measuring machines). The difference between ID by mechanical measurement and ultrasonic measurement during calibration is always of the order of $\pm$ 50 microns.

Considering all other uncertainties in the measurement, the overall accuracy of ID measurement system achieved is approx. $\pm$100 microns.

Calibration Procedure:

First the velocity in the calibration media (first light water, then heavy water) is determined using reference probe with the help of stepped reference block. The reference probe distance from the stepped block is adjusted in such a way that the amplitudes of echoes from the two interfaces of stepped block is almost same (max variation of $\pm$ 5% FSH) at any gain (dB) in flank method when put in heavy water during calibration.

Similarly in negative half wave rectified peak method, the distance between initial pulse & 1st interface echo is measured and in this method the echo amplitude can be kept at any height on the screen. Probe to probe face distance is measured in both light water and heavy water during calibration at minimum 3 locations and the difference between these measurements cannot be more than $\pm$ 30 microns in both flank and peak method.

The calibration spool of Pressure Tube is around 500mm long. At the centre of the Tube four axial locations (min 50mm apart) are marked as P, Q, R and S. At each axial location, 3 circumferential orientations viz; 6 – 12 O' clock, 4 – 10 O'clock and 2 – 8 O'clock are marked with respect to a fixed reference. All these points are defined as calibration locations and there are 12 such calibration locations in calibration spool.

First the calibration is to be done using light water. At first calibration location, probe to probe distance is determined. This is done by measuring water path at that location using two measurement probes at reference velocity set as mentioned above. The sum of the water path by both measurement probes is to be subtracted from the ID value measured by mechanical method. This probe to probe face distance is a mechanical parameter and remains constant irrespective of media and calibration locations. The measurement of this probe to probe distance is thus repeated at other two locations. The difference of these measurements should not vary by more than $\pm 30\mu m$ (microns) as mentioned earlier. The mean of probe to probe face distance measured in heavy water is used during actual ID measurement within the Pressure Tube in both the methods.

After that in remaining 9 calibration locations, using average probe to probe face distance determined above, ID values by Ultrasonic method are calculated and they are compared with mechanical ID measurement values. The difference of ID determined by UT method and mechanical method does not vary by more than ±50μm for any calibration locations.

The distance between the measurement probes and the ID of the tube is adjusted in such a way that the amplitudes of the first and second interface echoes shall be almost same (max variations ± 5% FSH at any gain level) in flank method. In velocity measurement interface echoes from two steps shall be kept within the width of 'A' and 'B' gates respectively and difference in the beam path between the gates measured in flank/edge mode. In water path measurement, 1st and 2nd interface echoes are kept within gates A and B respectively (gate threshold level to be kept at 40 % FSH for both the gates) and their differences are measured in flank/edge mode. Measurement of Velocity of Ultrasound in Light Water was carried out using negative half-wave rectification on the echo signals received from two steps of the reference block. Two Gates used one each on the two echo signals from the step reference block. Measurement of reference velocity using Peak method of water path measurement, by entering the precise step difference measured mechanically. Then the distance between initial pulse & 1st interface echo is measured and in this method the echo amplitude can be kept at any height on the screen.

Measurement of Probe Face-to-Face distance was carried out in the Calibration tube by measurement of water paths of Probe-1 and Probe-2 and subtracting sum of the two water paths of Probe-1 and Probe-2 from the Calibration tube ID. Water path measurement of Probe-1 and Probe-2 at each location was carried out using Peak Measurement mode with one gate on the First Interface (S-A mode in the UT equipment) of the negative half-wave rectification echo signal received from ID of the tube.

Measurement of Internal Diameter was carried out in horizontal condition in both 3-9 O'clock and 6-12 O' Clock orientation in the Test Set Up for 2%, 4% and 5% diametrical creep tube samples by both the methods. The ID at each location was calculated by summation of Water paths of Probe -1, Probe-2 and Probe Face to Face distance.

During calibration, the temperature of the water should be measured. Similar exercise of calibration is repeated (in exactly the same manner as in light water) using virgin heavy water in a calibration tank and data are to be tabulated in a similar format. The accuracy level required for probe to probe face distance measurements and ID measurements at 9 other locations shall be same as of light water calibration.

For validation of technique for higher diameter pressure tubes in the actual coolant channel, experiments were also carried out using 2%, 4% & 5% creep ID standards and accuracy of ID measurements were found to be approx. ±100 microns as described in Para 7.0(Results & discussions). All calibrations are to be done using full length signal cable and four drive tube cables, which simulate the actual condition during inspection. All the parameters of equipment controls are to be recorded and used during actual inspection for setting of Ultrasonic equipment.

RESULTS AND DISCUSSION:

This ID measurement technique has been successfully used in various Pressurized Heavy Water reactors (PHWRs). This has also been deployed in both types of Indian PHWRs viz. 220 MWe & 540 MWe. Measurements were generally done at 3-9 O'clock orientation and also at 6-12 O'clock orientation in a cross section with a close spacing (100 mm) between two successive measurements for ID in the hot region (where diameter increase is expected to be higher) to find out the maximum

Flank Mode ID Measurement

Sr. No.	Inspection Head Type and No.	Diametrical Creep (Tube Sample Size)	Maximum variation between UT ID and Mechanical ID (in mm)
1	220 MWe NDG-12-10	2%(84.15mm)	+0.03 /-0.03
2		4%(85.80mm)	+0.07/-0.03
3		5%(86.60mm)	+0.08/-0.13
4	540 MWe BDG-12-06	2%(105.50mm)	+0.01/-0.08
5		4%(107.60mm)	+0.10/-0.07
6		5%(108.60mm)	+0.11/-0.01

Peak Mode ID Measurement

Sr. No	Inspection Head Type and No.	Diametrical Creep (Tube Sample Size)	Maximum variation between UT ID and Mechanical ID (in mm)
1	220 MWe NDG-12-10	2%(84.15mm)	-0.03 /-0.05
2		4%(85.80mm)	+0.04/-0.01
3		5%(86.60mm)	+0.05/-0.04
4	540 MWe BDG-12-06	2%(105.50mm)	-0.04/-0.07
5		4%(107.60mm)	+0.08/+0.01
6		5%(108.60mm)	+0.09/-0.11

diameter in the channel. At other than the hot region, axial spacing between two successive locations is 200 mm. The difference in ID values at 6-12 O'clock and 3-9 O'clock orientations at same axial location was also observed and found to be very less as can be seen from the graph (Fig -4) given below. This ensures that de-centering errors of Inspection head in the channel was also negligible. This was also successfully carried out for 540 MWe PHWRs at TAPS 3&4 .Apart from that at rolled joint region & liner tube region where possibility of increase in diameter is very less, ISI values are almost matching with installed data within max. difference of ±50μm (microns). This ensures the required accuracy obtained from our ID measurement technique.

The two techniques (Flank and Peak) were simultaneously employed in K-04 channel of KGS-1 and the data obtained by both the methods were compared and plotted as graph (fig 5 & 6). The RF waveforms for both types of UT signals were captured and analyzed (fig 7). It has been observed from RF waveform analysis that negative half wave rectified peak method gives better accuracy than full wave rectified flank method.

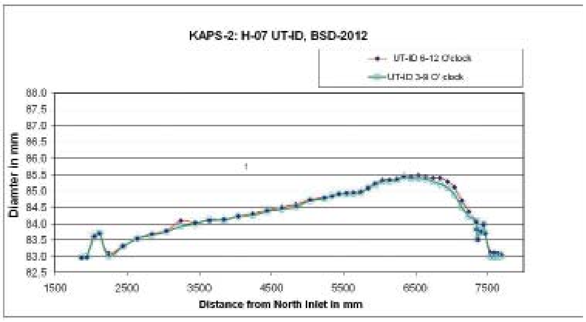

Fig. 4: UT-ID for Channel H-07 KAPS-2

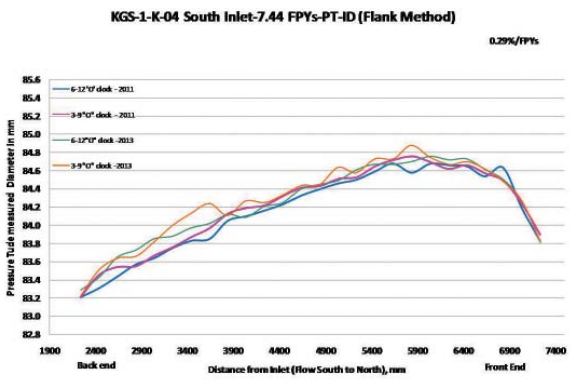

Fig. 5: UT-ID for Channel K-4 KGS-1 (Flank Method)

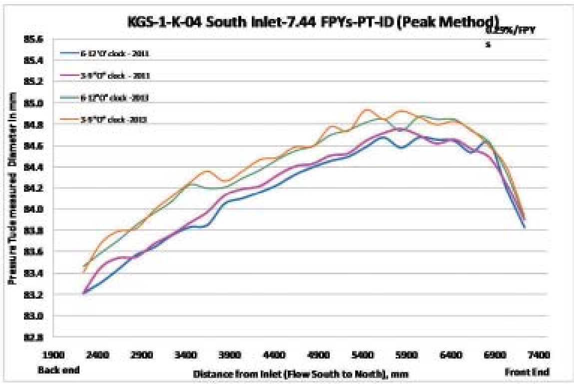

Fig. 6: UT-ID for Channel K-4 KGS-1 (Peak Method)

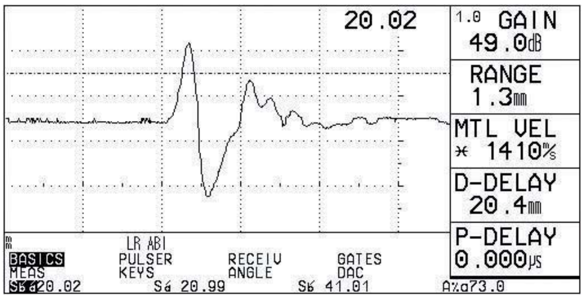

Fig. 7: RF Waveform

CONCLUSION:

ID measurement using our above mentioned techniques for all PHWR's (both 220 MWe and 540 MWe) was carried out successfully. From our experiences it is observed that ID measurement of Pressure Tube in in-situ condition is possible with this probe arrangement and digital Ultrasonic flaw detector. We also make the provision of in-situ calibration with the help of calibration probe and stepped reference reflector at fixed distance for compensation of Ultrasonic velocity in heavy water at the channel temperature. The inspection head has been designed in such a way that it can measure the ID of Pressure tube at any circumferential and axial locations for monitoring the growth of diameter due to high temperature irradiation and creep with required accuracy. It also helps in determining ovality of Pressure Tube. The results obtained from different reactors are highly encouraging and presently it is regularly used during Pre-Service & In-Service inspection of any 220 MWe & 540 MWe PHWRs.

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