An Improved Measurement of Internal Diameter, Wall Thickness and Crack Detection of Irradiated Zr-2.5%Nb Pressure Tubes by Immersion Ultrasonic Testing

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ABSTRACT

Zr-2.5%Nb Pressure tube undergoes deformation during irradiation in Pressurized Heavy Water Reactor (PHWR) due to presence of high temperature, high stress and fast neutron flux. This deformation is caused by irradiation creep and irradiation growth [1] and is manifested as changes in length, diameter and wall thickness of the pressure tube. Dimensional measurements during post-irradiation examination (PIE) on the pressure tubes removed from the reactor provides valuable data for developing models for predicting the useful life of the pressure tubes. Hoop stress is mainly responsible for increase in internal diameter (creep) though, it also depends on several other parameters like temperature, fluence, texture, cold work, grain shape and size etc. Hoop stress is determined by coolant pressure, internal diameter and wall thickness. Coolant pressure is an operational variable while; the other two parameters viz-internal diameter and wall thickness are affected by irradiation over a long time. To estimate the changes in wall thickness (WT) and internal diameter (ID), ultrasonic testing technique have been developed in-house. Pressure tube wall thickness and corresponding internal diameter measurement was done by immersion ultrasonic testing. It was found that diameter creep increases from inlet to outlet end and wall thickness decreases. Pressure tube wall thickness reduced as a result of nodular corrosion on the outer surface. In case of failed pressure tube, crack detection is carried-out inside the shielded cask tilted and filled with water, using two UT probes for the axial and circumferential flaw. The length from one end of the tube could be found-out which gives in-sight for the further examination around that point in-side the hot-cell. The crack length was estimated by 6 dB drop technique.

Keywords: PHWR, Zr-2.5%Nb, pressure tube, internal diameter, wall thickness, ultrasonic testing.

1. Introduction:

High temperature and high-pressure heavy water coolant flows through the pressure tubes (PT) over years of reactor operation. High pressure coolant generates tensile Hoop stress inside the PT wall, subjecting it to expand outwardly aided by high temperature. Hoop stress is mainly responsible for increase in internal diameter (creep) though, it also depends on several other parameters like temperature, fluence, texture, cold work, grain shape and size etc. Hoop stress is determined by coolant pressure, internal diameter and wall thickness. Coolant pressure is an operational variable while, the other two parameters viz internal diameter and wall thickness are affected by irradiation over a long time. It also under goes irradiation enhanced creep and growth both axially and diametrically. In-case of nodular corrosion, there is reduction in wall thickness due to outer thick layer of ZrO$_2$ (mainly monoclinic) which is reflected in UT examination. Irradiated Zr-2.5%Nb pressure tube P-18 was received for detailed post irradiation examination. To estimate the diametral creep, changes in wall thickness (WT) and internal diameter (ID) have been measured by ultrasonic testing technique developed in-house. Also, using the probes for the axial and circumferential crack detection, any presence of defect in P-18 was tried. The details of the technique, probe arrangement and the results are discussed in this paper.
2. Old probe holder and measurement set-up:

Two 10 MHz normal beam immersion transducers looking in opposite directions were fitted along the diameter line inside an annular perspex cylindrical probe holder shown in Fig 1 [2]. To keep probe holder in the center inside the PT, four spring loaded steel ball rollers were used for easy entry and smooth movement of the probe assembly. The ultrasonic beam gets reflected back from ID surface, and a part of it enters wall of the pressure tube to be returned from OD surface. Water path in front of the two probes are added to the distance between the probe to estimate ID of the pressure tube. Thus at the same circumferential location ID and WT measurements are carried out simultaneously. One set of ID measurement is accompanied by two wall thickness readings. The probe holder is rotated by 90° to get another ID measurement and two more wall thickness readings.

The pressure tube removed from the reactor is around 5.1 meter long. We had to develop a 6 meter long telescopic handle to cover the entire length. Six numbers of 1 meter long stainless steel tubes of different diameters with end stoppers were assembled giving smooth sliding movement over each other. Small grub screws were provided to lock the fully expanded segmental tubes to make a 6 meter long handle shown in Fig. 2. Permanent markings were inscribed at intervals of 50 mm on each segment to be visible at a distance away from the shielding cask end. The pushing of the telescopic handle in-side the pressure tube was done manually. After the completion of the measurement of ID and wall thickness, another probe holder containing two probes (line focus, 27° inclined probe, 10MHz), one for axial flaw and another for circumferential flaw were inserted for finding any flaw.

3. New probe holder and measurement set-up:

In the new-probe holder, the same probe holder contains all the diameter, wall thickness and defect detection probes as shown in the Fig.3 (a). Fig.3 (b) shows the probe arrangement for the ID and wall thickness measurement.
From Fig.3(b), two diameters are calculated using following formula:

\[ ID-1 = X1 + wp1 + wp2 \]  \[ ID-2 = X2 + wp3 + wp4 \]

Where, \( X1 \) is the distance between the probes \( p1 \) and \( p2 \)
\( X2 \) is the distance between the probes \( p3 \) and \( p4 \)

A step block is there inside the probe holder to accurately measure the water velocity at the temperature when the measurement is being carried-out using probe \( p5 \). For all the four probes, four wall thickness measurements are made available.

Regarding the insertion of the telescopic assembly containing the probe head, all its parts are shown in the Fig.4. The movement of the probe head is motorized, exact distance at which the probe is positioned is known through the optical encoder. The tilt of the head can be adjusted by the special arrangement as shown in the figure. Rotation can also be given.
4. Calibration

The UT probes were calibrated using Zr-2.5% Nb PT spool piece with machined steps and a two channel ultrasonic testing machine with an accuracy of ten microns. Ultrasonic velocity in water was used to measure water path (WP) for a known internal diameter to find the distance between the two probes. For pressure tube wall thickness, ultrasonic velocity in Zr-2.5% Nb alloy was set and confirmed by measuring wall thickness at known locations. Corrections were provided for phase reversal effects. The signal appearing first is from water/metal ID interface and latter two are from OD of the pressure tube. The defect size is also calibrated using the standard notches made in the Zr-2.5% Nb spool piece.

4. Measurements

The irradiated pressure tube was transferred to PIED pressure tube cask for UT examination. To hold water and also protect workers from harmful radiations, the shielding cask was carefully tilted (~15°) using overhead crane. The lower bottom ends of cask were sealed leak tight by a common rubber bung having drainage tube and a valve. Water was filled in the cask ensuring full immersion of pressure tube. The probe holder was introduced from the top open end of the cask. The extra 1-meter water near the open end provided shielding from direct radiations. The measurements were taken at every 25 mm distance.

5. Result

The measured thickness and internal diameter readings were plotted against pressure tube length. Thickness reduction is observed from inlet to outlet end in Fig. 5. Wall thinning is clearly seen on the pressure tube towards 1 m from the hot end. The ID variation is shown in the Fig. 6, which shows the increase in diameter towards the hot end. There were no cracks observed in the pressure tube. The maximum diameter was found to be 84.03 mm and the lowest wall thickness was 3.20 mm. There were no cracks found in any of the locations along the length of the pressure tube.
6. Discussion

The P-18 pressure tube was heavily nodule at the hot end side as shown in the Fig.7. The nodular oxide was basically found to be ZrO$_2$ which is monoclinic in nature. So, as Zr is converted to ZrO$_2$, the wall thickness is reduced which is reflected in the ultrasonic measurement. So, the lowest thickness was found to be 3.20 mm which was also confirmed by metallographic examination.

As, temperature increases towards the outlet end, so there is a trend of increase in diameter towards the hot end and maximum at around 4000 mm from the cold end. This is due to the increase in the in-reactor deformation mechanisms with both temperature and fluence. As the fluence again reduces towards the hot-end, so the diameter increase is reduced at the hot end. There were no cracks observed in the pressure tube at any location. In the metallographic examination also, there was no crack beneath any of the nodule (typically shown in Fig.8).
7. Conclusions

1. An improved ultrasonic testing technique has been developed and used to measure simultaneously ID, wall thickness and defects of irradiated pressure tube.
2. Measurement on irradiated pressure tube P-18 indicates a maximum diametral increase of 1.2 mm which is for ~4.8 EFPY indicating diametral deformation rate of 0.25 mm/year.
3. The lowest thickness was found to be 3.20 mm towards the hot end of the pressure tube and also later confirmed by metallography. The reduction in wall thickness was found to be due to the nodular corrosion.
4. There were no cracks observed which is later confirmed by metallography.
5. With this improved set-up, fast and reliable data on ID, wall thickness and crack detection can be easily carried-out with the minimum man-rem consumption.

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References: