Ultrasonic Measurement of Internal Diameter and Wall Thickness of Irradiated Zr-2.5%Nb Pressure Tube from KAPS-II Reactor

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Abstract

In Indian Pressurized Heavy Water Reactors (PHWRs), Zr-2 pressure tubes were replaced by Zr-2.5%Nb tubes, made through cold pilgering route. Low corrosion rate and low H/D pickup, favoured selection of Zr-2.5%Nb alloy. Wall thickness of pressure tubes was reduced to 3.32 mm due to higher strength of Zr-2.5%Nb alloy, while retaining the internal diameter. The present pressure tubes are operating at higher hoop stress due to reduced wall thickness. The channel S-07 from KAPS-II reactor was removed after 8 Effective Full Power Years (EFPY), to carry out detailed Post Irradiation Examination (PIE). Internal diameter and corresponding wall thickness were measured by an innovative ultrasonic testing technique. It was found that diametral creep was more in a location, where initial wall thickness was lowest.

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 long duration. It also undergoes irradiation enhanced creep and growth, both axially and diametrically. An irradiated Zr-2.5%Nb pressure tube S-07 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.

The Zr-2.5%Nb pressure tubes are estimated to operate continuously for 30 years, due to lower corrosion and H/D pick up. If total hydrogen does not exceed 30 ppm, it may have adequate load carrying capacity. Diametral increase causes flow bypass around the fuel bundles and hence, may result in fuel failures. The increase in pressure tube length (elongation) may lead to problems for the support at the ends and feeder pipes. Creep sag and increase in diameter may cause an early CT/PT contact, for blister formation. Hence, creep rate is one of the factors, determining the life of pressure tubes. Diametral creep due to Hoop stress is dependent on local internal diameter and wall thickness, around a particular circumference. These two parameters have been measured by ultrasonic testing technique and results are discussed in this paper.
Probe holder design

To determine the actual hoop stress \( H = PD/2t \) around a particular circumference, it is essential to measure WT and ID both on the same circumference, to determine local Hoop stress. The two fabrication parameters may vary from inlet to outlet end in a pilgered tube. Two 10 MHz normal beam immersion transducers, facing in opposite directions, were fitted along the diameter line, inside an annular perspex cylindrical probe holder, shown in Fig. 1. To keep the 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 the 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\(^\circ\) to get another ID measurement and two more wall thickness readings.

The pressure tube removed from the reactor is around 5.1 meter long. A 6-meter long telescopic handle was fabricated, to cover the entire length of the irradiated pressure tube. Six 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 as 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 6-meter long stainless steel pipe is filled with water from the top open side, for ultrasonic coupling of the probes.

![Fig. 1: Schematic probe arrangement](image1)

![Fig. 2: Probe holder with telescopic handle](image2)

![Fig. 3a: Typical signal for single probe](image3a)

![Fig. 3b: Typical signals for two probes](image3b)
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 calculate 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 / PT ID interface and the latter two are from OD of the pressure tube. Typical signal waveforms are shown in Fig. 3a. & 3b. for single and double probes respectively.

Measurements

A 6 meter long S.S. pipe of 116 mm OD was used inside a shielding cask to hold the irradiated pressure tube to ensure complete immersion of the 5.1 meter long irradiated PT in water (Fig. 4a). To hold water and also protect workers from harmful radiations, the shielding cask was carefully tilted using overhead crane. The lower bottom ends of S.S. pipe and cask were sealed leak-tight by a common rubber bung, having drainage tube and a valve (Fig. 4b). Water was filled in the S.S. pipe ensuring full immersion of the pressure tube. The probe holder was introduced from the top open end of the S.S. pipe, projecting out of the cask. Measurements were taken at every 50 mm distance, inside the pressure tube.

Result

The measured diameter and thickness readings were plotted against pressure tube length. Internal diameter was found to have increasing trend from inlet to outlet end. But, there is an abrupt increase in the ID distinctly seen around 3.2 meters from inlet end as seen in Fig. 5. The as fabricated ID at the peak region was found to have increased by ~0.9 mm after 8 EFPY. Thinning was also observed in the pressure tube from inlet to outlet end (Fig. 6). A localized wall thinning is clearly seen in the same region (peak ID) on the pressure tube, around 3.2 meter from inlet end and spanning over 600 mm length. ID and WT both plotted together can be seen in Fig. 7 which shows the kink in ID, corresponding to the wall thinning. It was not clear whether the peak in ID and wall thinning were irradiation-induced or from the manufacturer’s side, at the time of measurement.
As fabricated ID were also plotted and compared with data generated during PIE. It is seen that as fabricated ID was on the upper end of specification as shown in Fig. 8. But, a slightly higher initial ID that is still within specified range, may not cause a localized peak in diameter creep. The increase in ID up to 0.9 mm does not account for so much wall thickness reduction due to creep, from constancy of volume consideration, unless a lower WT existed from the very beginning. The reason behind diametral creep is Hoop stress, which is determined not only by ID but also by WT.

The level of hoop stress is determined dominantly by initial wall thickness than by initial diameter. It is the lower wall thickness from manufacturing, which raises the hoop stress deterministically and causes higher diametral expansion. As a result of which, the lower wall thickness region gets thinned down more, by in reactor creep. The initial lowest wall thickness 3.452 mm was further reduced to 3.4 mm, after 8.0 EFPYs of operation in the reactor core. The final wall thickness profile is the result of initial WT profile superimposed by thinning, due to addition of thermal and irradiation diametral creep, which is more from center to outlet end. Higher temperature and fast neutron flux enhance the diametral creep more towards outlet end.

Since, two wall thickness readings were available at the end of the diameter line, it was possible to calculate outer diameter as well. The wall thickness readings were added to the respective ID to get outer diameter. The difference between final ID & OD is not as much as that in initial ID & OD (Fig. 10).
This shows that outer diameter is not increasing as much as internal diameter, due to compensation by wall thinning. This information is useful for removable AHWR type pressure tube.

**Conclusion**

1. Ultrasonic testing technique has been developed and used, to measure simultaneously ID & wall thickness of irradiated pressure tubes, to evaluate the effect of hoop stress and irradiation on creep.
2. Measurement on irradiated pressure tube S-07, indicates a maximum diametral increase of 0.9 mm at a location 3.2 meter from inlet end; where as tabrical lower wall thickness reduced further.
3. Cold pilgering route of manufacturing gives thickness variation all along the pressure tube. At the location where minimum thickness occurred during manufacturing, higher hoop stress lead to enhanced diametral creep. The proper selection of thickness and control of its variation is very important.
4. The reason for localized enhanced diametral creep in S-07 pressure tube from KAPS-II is lower initial wall thickness, though it was under specified range of manufacturing.