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Post irradiation examination of reactor operated pressure tube S-07 of KAPS-2

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A B S T R A C T

An irradiated Zr–2.5% Nb pressure tube removed from Kakrapar Atomic Power Station unit #2 (KAPS-2) after eight effective full power years was subjected to post irradiation examination in BARC hot cells facility. The examination included visual examination of outer and inner surface, gamma scanning, measurement of internal diameter, measurement of oxide thickness on the inner surface and analysis of hydrogen content in the tube. Examination revealed satisfactory performance of the pressure tube in the reactor. The maximum oxide thickness on the inside surface was found to be less than 15 μm at 4 m from the inlet end and maximum hydrogen pick up at the peak location was 6 ppm. The maximum increase in internal diameter was 0.82 mm at 3.2 m from the inlet end.

1. Introduction

Zr–2.5% Nb alloy is considered better than Zircaloy-2 for use as a material for pressure tubes in the pressurized heavy water reactors [1–6]. Pressure tubes made of Zr–2.5% Nb alloy were first introduced in the Indian pressurized heavy water reactors (PHWR) at Kakrapar Atomic Power Station unit #2 (KAPS-2). All subsequent PHWR units have used Zr–2.5% Nb pressure tubes. Under a program of en-mass coolant channel replacement, Zircaloy-2 pressure tubes in several earlier reactors have been replaced by Zr–2.5% Nb tubes. The Zr–2.5% Nb pressure tubes used in these reactors are fabricated by Nuclear Fuel Complex, Hyderabad using pilgering route. The details of the method of fabrication are described elsewhere [7]. Since KAPS-2 is the lead reactor with pilgered Indian Zr–2.5% Nb pressure tubes, it was important to know its irradiation performance, hence a pressure tube removed from the core after 8.0 effective full power years (EFPY) of operation was taken up for post irradiation examination (PIE). The pressure tube selected was from S-07 position, based on the trace element concentration in the tube and the ease of its removal from the reactor core.

The pressure tube was transported to the hot cells facility at BARC in a shielded cask. After cleaning the pressure tube, the following examinations were carried out: visual examination of the outer and inner surfaces, internal diameter measurement, gamma scanning, hydrogen measurement, SEM examination of oxide morphology on inner surface and measurement of oxide layer thickness. The details of examination and the results obtained are presented in this paper.

2. Non-destructive examination

2.1. Visual examination

The visual examination of outer surface of the pressure tube was carried out using a scanning wall periscope. Visual examination of inner surface was performed using a radiation resistant camera. The camera was inserted in the pressure tube using a 7 m long scaled pusher rod holding the cable. All the features were video recorded and distance of each feature was measured on the scaled pusher rod.

2.2. Internal diameter measurement

The internal diameter measurement was carried out using three different methods. The details of measurements are described elsewhere [8].

2.2.1. Internal diameter measurement using three point micrometer

Internal diameter was measured using a digital pistol type three point micrometer with a 3 m long extension rod. Resolution of the measuring system was 0.001 mm and the uncertainty of measurement was ±0.005 mm. The micrometer was calibrated using a setting ring of 80.00 mm diameter. The micrometer head was inserted 2.5 m inside the pressure tube from the inlet end of the tube. The micrometer was moved gently inside the tube and the diameter measurements were taken at intervals of 150 ± 10 mm. The

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measurement was repeated from the outlet end of the pressure tube at the same intervals.

2.2.2. Internal diameter profile measurement using linear variable differential transformer (LVDT) probe

The internal diameter profile measurement over the length of the pressure tube was carried out using a specially designed internal diameter measuring gauge fitted with LVDT probes. The gauge was calibrated using a piece of pressure tube with five steps of internal diameter varying from 82.5 to 87 mm. The speed of the probe movement was set at 1.6 mm/s, generating about 3000 data points over the length of the tube.

2.2.3. Ultrasonic measurement

Immersion ultrasonic testing technique was used to measure wall thickness and corresponding internal diameter at different locations along the length of the pressure tube. Two 10 MHz normal beam immersion transducers positioned in opposite directions were fitted diametrically inside an annular perspex cylindrical probe holder. To keep the probe holder in the center inside the pressure tube, 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 the inner surface and a part of it enters wall of the pressure tube to be returned from the outer surface. Water path in front of the two probes are added to the distance between the probes to estimate the internal diameter of the pressure tube. Thus, at the same circumferential location the internal diameter as well as the corresponding wall thickness was measured simultaneously.

2.3. Gamma spectrometry

Gamma spectrometry was carried out on the irradiated pressure tube in order to evaluate the fluence distribution along the length of the pressure tube. The Cd–Zn–Te detector (having a resolution of 15 keV at 1332.5 keV) with 4 K multi channel analyzer (MCA) system was used for gamma spectrometry. The detector was calibrated using ^{137}Cs and ^{60}Co gamma source. The spectrum is shown in Fig. 1.

3. Destructive examination

3.1. Cutting plan for the pressure tube

The pressure tube was cut into rings and further sampled for destructive testing like different mechanical tests (ring tensile test, compact tension (CT), burst test, small punch test and ball indentation test), hydrogen analysis, metallography, scanning electron microscopy (SEM), transmission electron microscopy (TEM).

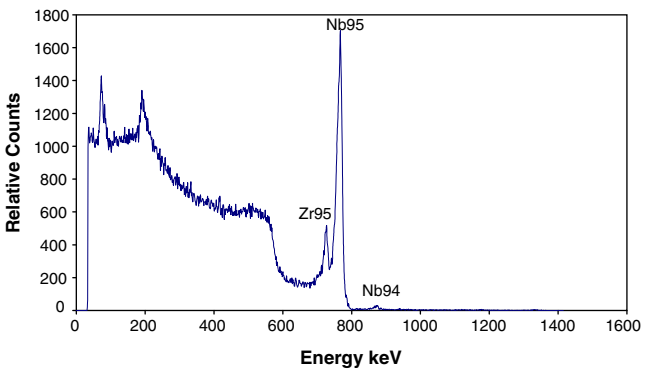

Fig. 1. Gamma spectrum of irradiated pressure tube.

3.2. Estimation of equivalent hydrogen (H_{eq}) content of pressure tube

Small samples were chopped from the pressure tube rings at identified locations. They were cleaned and analysed for H_{eq} using differential scanning calorimetry (DSC). A shielded DSC unit was used for the purpose. The DSC unit was calibrated using the standard In and Zn samples. The sample, along with the reference, was subjected to a linear heating program, under a constant flow of Argon. The reference material chosen was Al_2O_3. The derivative of the plot was used to identify the point of inflexion on the plot corresponding to the terminal solid solubility (TSS) temperature. Using the TSS temperature, the H_{eq} of the sample was evaluated using the calibration curve already generated.

3.3. Optical and electron microscopy

Transverse section samples were cut from 12 locations of the pressure tube along its length. They were subjected to the standard metallographic preparation of grinding and polishing before the examination. As-polished samples were examined to measure oxide layer thickness. The polished samples were chemically etched to reveal hydrides. The scanning electron microscopic (SEM) examination of the oxide layer was performed in the secondary electron as well as back scattered electron image modes. Hydride morphology and distribution were studied in optical microscope. Transmission electron microscopy was done on samples taken from 0.38, 2, 3.38 m from the inlet end. Disks of 3 mm diameter were prepared by jet thinning in a solution containing 80% methanol and 20% perchloric acid at a temperature of −40 °C.

4. Results and discussion

4.1. Visual appearance of outer and inner surface

The outer surface of the pressure tube had a typical dull dark brown color. Multiple longitudinal scratch marks of different length were observed throughout the length. A few circumferential scratch marks and garter spring marks were observed around the periphery of the tube. The features observed on the inner surface were longitudinal scratch marks, circumferential scratch marks, multiple patches, scraped locations, and bundle marks.

4.2. Diametral deformation

The results of diameter measurements by all the three techniques are presented together in Fig. 2. It is observed from data from all the three measurements that the maximum diameter is at 3.2 m from the inlet end. The maximum diametral change measured by three methods is found to be in the range 0.77–0.89 mm and the average value is 0.82 mm. A corresponding decrease in the wall thickness was observed by ultrasonic measurements as shown in Fig. 3. This location coincided with the as fabricated data of wall thickness as shown in Fig. 3. The change in diameter is within the design limit. This increase in diameter could be due to the long term effect of the higher hoop stress experienced by the pressure tube at this location.

The measured changes in the diameter and the wall thickness along the length of the pressure tube were analysed using various types of empirical correlations. The details of this analysis are given in Rath et al. [8]. It was found that following correlation for rate of deformation gives a good agreement between the measured and calculated diametral profile along the length of the pressure tube.

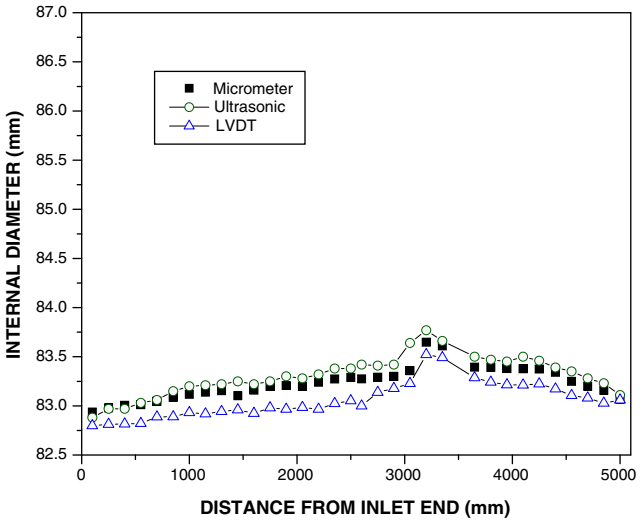

Fig. 2. Variation of internal diameter of the pressure tube along its length.

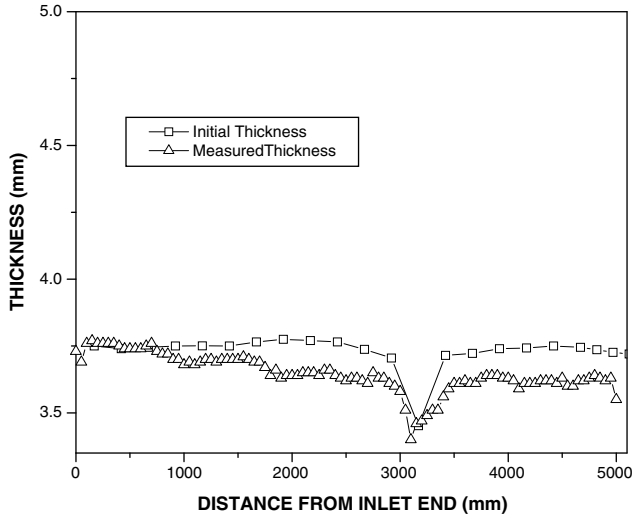

Fig. 3. Variation of wall thickness along the length of the pressure tube.

$$\text{Diametral strain rate } (\text{h}^{-1}) = 8.55 \times 10^{-14} \times \Phi^{0.85} \times \exp(-14000/\text{RT}) \times \sinh(B\sigma) \quad (1)$$

where B = 0.163, Φ = fast neutron flux, n/cm^2/s, $E > 1$ Mev, R = gas constant in cal/mol K, T = temperature, K and σ = hoop stress in kg/mm^2.

4.3. Hydriding

The typical hydride distribution observed in the transverse section of a sample taken from a location 4.5 m from the inlet end is shown in Fig. 4. Uniformly distributed, fine and randomly oriented hydrides were observed across the thickness.

The profile of H_{eq} along the length of the pressure tube is shown in Fig. 5. The maximum hydrogen content in the bulk samples of this tube was 16 ppm. The initial hydrogen content in the tube was reported to be 10 ppm. Hence the maximum hydrogen pick up determined is 6 ppm in 8 EFPY. The H_{eq} profile of a Zircaloy-2 pressure tube with an equivalent irradiation history is given in the figure for comparison. This indicates a better in-reactor performance of Zr-2.5% Nb pressure tube.

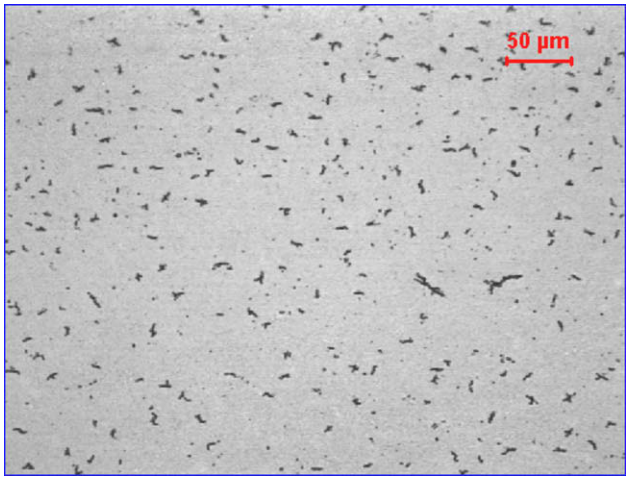

Fig. 4. Hydride distribution in the transverse section sample of the pressure tube at 4.5 m from the inlet end.

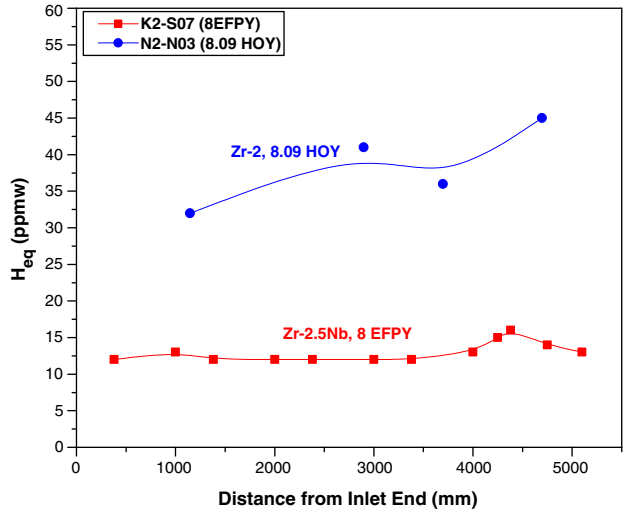

Fig. 5. H_{eq} along the length of the pressure tube.

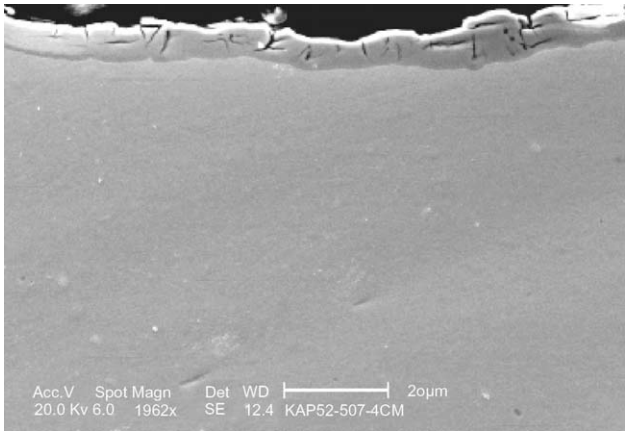

Fig. 6. Typical appearance of oxide layer at 1.38 m from the inlet end.

4.4. Oxidation on inner surface

Examination of as polished transverse section samples showed a continuous, adherent, dense oxide layer on the inner surface. The typical appearance of oxide layer is shown in Fig. 6. The SEM exam-

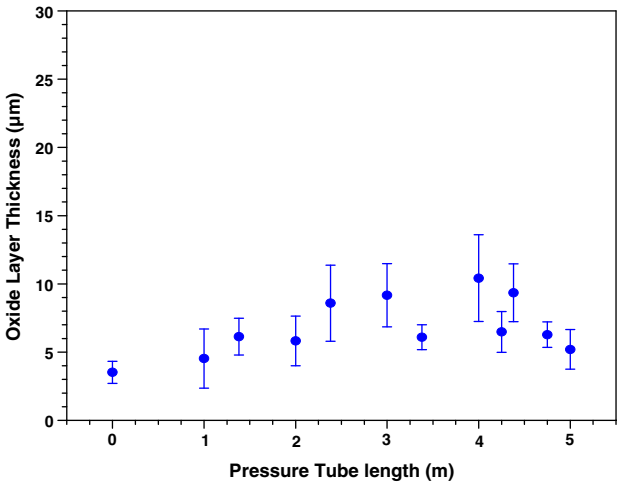

Fig. 7. The oxide layer thickness profile along the length of the pressure tube.

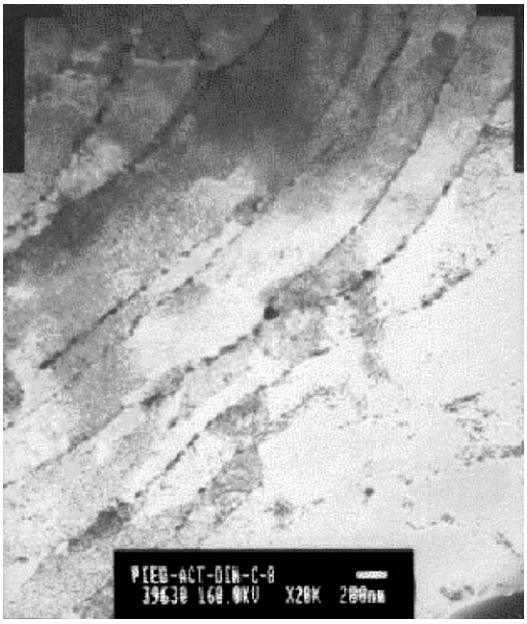

Fig. 8. Transmission electron photomicrograph of the irradiated pressure tube at 3.38 m from the inlet end.

ination of inside surface of the pressure tube showed presence of adherent oxide on the surface. Fine axial cracks were noticed on the oxide surface.

The oxide layer thickness profile along the length of the pressure tube obtained by SEM measurement is shown in Fig. 7. It shows that the oxide thickness is low at the inlet end but there is a continuous increase in the oxide thickness up to 4 m from the inlet end. Thereafter, the oxide thickness decreases up to the outlet end. The observed oxide thickness profile is a result of the combined effect of variation in the coolant temperature and fast neutron flux along the length of the pressure tube. Large scatter is observed in the measured values. The maximum oxide thickness was found to be 10.4 ± 3.9 μm at 4 m from the inlet end.

The TEM examination revealed elongated alpha grains with dispersed β-particles along the grain boundary. A typical microstructure of the tube material is shown in Fig. 8. The absence of a continuous beta phase surrounding alpha in the microstructure is beneficial from delayed hydride crack growth point of view.

5. Conclusions

1. PIE revealed satisfactory performance of Zr-2.5% Nb pressure tube irradiated up to 8 EFPY in PHWRs.
2. The maximum value of the oxide layer thickness on the inside surface of the pressure tube was less than 15 μm and the maximum hydrogen pick up at this location was 6 ppm.
3. There was a increase in the internal diameter of the pressure tube along its length. The maximum value of the increase was 0.82 mm at 3.2 m from the inlet end. There was a decrease in wall thickness at this location.
4. The measured changes in diameter and wall thickness of the pressure tube was analysed using various types of empirical creep correlations. An empirical correlation was established which gives a good agreement between the measured and calculated axial diametral profile.

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