Assessment of Structural Integrity of Pressure Tubes during Cold Pressurization

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Abstract

Presently, double melted, cold worked and stress relieved Zr-2.5% Nb alloy pressure tubes are employed in some of Indian Pressurized Heavy Water Reactors (IPHWRs) where initial hydrogen content is limited to 25 wppm. Over a period of time, part of hydrogen/deuterium released by the corrosion reaction (metal-coolant reaction) between the Zr-2.5%Nb alloy and D2O may be picked up by the pressure tubes which further embrittles the pressure tube material at lower temperatures. Structural integrity of the irradiated pressure tubes of these reactors during cold pressurization is studied. Studies have been performed to ensure that there is no unstable crack growth and Delayed Hydride Cracking (DHC) during cold pressurization of pressure tubes. For these calculations, reported lower bound fracture toughness properties for the double melted Zr-2.5%Nb irradiated pressure tube material have been used. The calculations indicate that the applied stress intensity factor for the postulated part through wall flaw in the pressure tube is less than the threshold stress intensity factor for DHC initiation. Pressure tubes also meet the required factor of safety for the stability of a postulated leakage size crack in case of cold pressurization and the operator has sufficient time to take the necessary action before the crack reaches the critical size. The paper brings out the details of the safety assessment carried out for the pressure tube during cold pressurization.

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1. Introduction

Double melted, cold worked and stress relieved Zr-2.5% Nb alloy pressure tubes are being employed in some of the Indian PHWRs where the initial hydrogen content is limited to 25 wppm. The double melted pressure tube ingots had no specified limits of trace elements such as Chlorine, Phosphorus and Carbon, which influence the fracture properties of the tubes [1]. These pressure tubes were manufactured by following the route of extrusion-
double pilgering with intermediate stress relieving [2].

Over a period of time, part of hydrogen/deuterium released by the corrosion reaction (metal-coolant reaction) between the D₂O and Zr-2.5%Nb alloy may be picked up by the pressure tubes. Owing to its high mobility, deuterium/hydrogen easily gets distributed in the metal. The diffusion of deuterium/hydrogen in the pressure tube takes place from low stress to high stress, high concentration to low concentration and high temperature to low temperature region of the pressure tube. Initially, hydrogen gets dissolved in the alpha-phase metal; at higher concentrations and lower temperatures, hydride precipitates are formed in the metal matrix. The maximum amount of hydrogen which can be retained in solid solution without precipitation of hydrides is called as Terminal Solid Solubility (TSS). TSS of hydrogen in Zirconium alloys is observed to increase with increase in temperature and it follows the Arrhenius equation with temperature [3]. As solubility of hydrogen is low at lower temperature, hydrogen present in excess of solid solubility limit precipitates out as hydride phase. Being brittle, the presence of substantial quantities of hydrides can cause embrittlement of the host matrix resulting in decrease in ductility, impact energy or fracture toughness. Diffusion of hydrogen in front of the crack tip and then precipitation can lead to Delayed Hydride Cracking (DHC) if stress intensity factor is more than a threshold value [4].

High energy neutrons also embrittlement the Zr-2.5%Nb pressure tube materials. The embrittlement is due to bombardment of neutrons which creates collision cascades that can produce point defects and dislocations in the materials. Embrittlement of pressure tubes due to high energy neutrons saturates after fluence of around 2e25 n/m² [5].

Cold startup of the reactor can be carried out following either hot pressurization or cold pressurization procedures. The hot pressurization scheme imposes restrictions in carrying out the leak search of PHT system for detecting external leaks especially while checking the integrity of the system after repairs. It also imposes to operate the reactor with Emergency Core Cooling System (ECCS) in blocked condition till the pressure at reactor outlet header reaches a pressure of 5.5 MPa. Hence, cold pressurization scheme is employed at these reactors, where the system is pressurized at room temperature upto 5.8 MPa, then the system is heated to 250°C and afterwards the pressure is raised gradually to operating pressure of 8.7 MPa at ROH. In view of this, safety assessment of the irradiated double melted pressure tubes has been carried out to ensure that it is prevented from unstable crack growth and Delayed Hydride Cracking (DHC) in case of cold pressurization. These studies have been carried out based on reported lower bound fracture toughness properties of double melted Zr-2.5%Nb irradiated pressure tube material.

2. Methodology

In case of pressure tubes, the maximum principal stresses are in hoop direction during all the operating conditions and as such, stability of axial part through wall flaw and axial through wall crack is demonstrated in the present study.

2.1 Stability of Postulated Axial Part Through Wall Flaw

The dimensions of the postulated axial part through wall flaw are governed by the inspection limits. The flaw is postulated as surface planar flaw at worst location (maximum tensile stress near rolled joint at PT inlet) and in most critical direction. The calculations for the flaw have been carried out for fracture initiation and Delayed Hydride Cracking (DHC).

2.1.1 Calculation of Applied Stress Intensity Factors

The stress intensity factor \( K_I^a \) calculations for the postulated axial part through wall planar flaws are carried out using Eq.(1) [6]:

\[
K_I^a = \left[ p \left( \frac{r_i}{w} + 1 \right) F_p + \sigma_{h}^{res} F_m \right] \left( \frac{\pi a}{Q_1} \right)^{1/2}, \quad \ldots (1)
\]

where, ‘p’ is the internal pressure of pressure tube, ‘\( r_i \)’ is inner radius of pressure tube, ‘a’ is depth of postulated part
through wall flaw, ‘w’ is wall thickness, ‘$F_p$’ is geometry correction factor for the stress intensity factor for an internal axial part through wall flaw under internal pressure loading, $\sigma_{h}^{res}$ is rolled joint residual hoop stress, ‘$F_m$’ is geometry correction factor under membrane stress loading and $Q_1$ is the flaw shape parameters defined as $Q_1 = 1 + 1.464 \left( \frac{a}{c} \right)^{1.65}$ [6].

2.1.2 Evaluation of Pressure Tube for Plastic Collapse Load

A postulated axial part through wall flaw is evaluated for the plastic collapse load. The expression used for the plastic collapse evaluation for axial flaw is represented by Eq.(2) [6]:

$$\sigma_h = \sigma_f \left[ \frac{1 - \frac{a}{w}}{1 - \left( \frac{1}{M} \right) \left( \frac{a}{w} \right)} \right], \quad \ldots(2)$$

where, $M = \left[ 1 + 1.255 \left( \frac{c^2}{r_m w} \right) - 0.0135 \left( \frac{c^2}{r_m w} \right)^2 \right]^{1/2}$, $\sigma_f$ is the flow stress defined as $\frac{\sigma_a + \sigma_y}{2}$, ‘$r_m$’ is the mean radius of the pressure tube and ‘$c$’ is axial half length of postulated flaw[6].

2.2 Stability of Postulated Through Wall Flaw

Deterministic approach has been used to demonstrate that the leakage size crack has sufficient margin against the critical crack size. It needs to demonstrate that in the event of the DHC initiation and growth of leakage size through-wall crack in a pressure tube, the operator has sufficient time, to shut down and depressurize the reactor in a controlled manner till the leakage size crack becomes critical crack. The methodology followed for the deterministic analysis is in line with CSA Standard N285.8-05 [6], and is summarized below:

$$2C_{ULB} = \frac{2C_{CLLB}}{FOS} \ldots \ldots \ldots (3)$$

where,

- $2C_{ULB} =$ upper bound length of growing through-wall leakage size crack
- $2C_{CLLB} =$ lower bounds of length of the critical crack length
- $FOS =$ Factor of safety

The critical crack length ($CCL$) is a function of lower bound fracture toughness ($K_c$), flow stress ($\sigma_f$) and hoop stress ($\sigma_h$), which in turn depend on the pressure and temperature as follows [6]:

$$CCL = \frac{K_c^2 \pi}{8 \sigma_f \sin \left( \frac{2M_1 \sigma_h}{2 \sigma_f} \right)} \ldots \ldots \ldots (4)$$

where, the hoop stress ($\sigma_h$) depends on the pressure $p$ and residual stress $\sigma_h^{res}$:

$$\sigma_h = p \left( 1 + \frac{r_1}{w} \right) + \sigma_h^{res} \ldots \ldots \ldots (5)$$

where, the tensile residual stress due to rolled joint $\sigma_h^{res}$ is considered as zero for the through wall crack and the flow stress ($\sigma_f$) is a function of temperature $T$ in K [6]:

$$\sigma_f = 1004.5 - 1.1995 \times (T - 273) \ldots \ldots \ldots (6)$$

and the bulging factor ($M_1$), is given as:

$$M_1 = \sqrt{1 + 1.255 \left( \frac{CCL^2}{r_m w} \right) - 0.0135 \left( \frac{CCL^2}{r_m w} \right)^2} \ldots \ldots \ldots (7)$$

where, $r_m$ is mean radius of the pressure tube.

The allowable fracture toughness ($K_{call}$) is calculated after considering the FOS as per USNRC [7]:

$$K_{call} = \frac{K_{lower \, bound}}{\sqrt{2}} \ldots \ldots \ldots (8)$$
The maximum allowable pressure \( p_c \) at any temperatures during pressurization is calculated using Eq.(9) [6]:
\[
p_c = \left( \frac{w}{w+r_f} \right)^{\frac{2\sigma_f}{\pi H}} \cos^{-1} \left[ \exp \left( -\frac{\pi K^2_{eq}}{8\sigma_f} \right) \right] \quad \ldots \ldots \ldots \quad (9)
\]

2.3 Crack Growth Due to Delayed Hydride Cracking

The DHC growth velocity of Zr-2.5%Nb un-irradiated pressure tube material of Indian PHWRs as a function of temperature is given as in Eq.(10) [8]:
\[
V_{DHC} = 0.019 \exp \left( -\frac{54200}{RT} \right) \text{m/s} \, \ldots \ldots \ldots (10)
\]
where, \( T \) is temperature in \( K \). The axial DHC growth velocity of irradiated Zr-2.5%Nb pressure tube material is represented in Eq.(11) [9]:
\[
V_{DHC} = 5.2 \times 10^{-3} \exp \left( -\frac{41445}{RT} \right) \text{m/s} \, \ldots \ldots \ldots (11)
\]

2.4 Failure Assessment Diagram: R-6 Method

Failure Assessment Diagram (FAD) method uses two ratios: brittle fracture and plastic collapse to evaluate whether a crack may cause a structural failure. The axes of the FAD chart use the non-dimensional ratios \( L_r \) (plastic collapse ratio) on the x-axis, and \( K_r \) (brittle fracture ratio) on the y-axis as shown in Fig.1. The example evaluation points inside the FAD curve indicate acceptable cracks, and the evaluation points above the FAD curve are unacceptable cracks that indicate a predicted structural failure. An evaluation point on the FAD curve is considered as critical crack, which has been used to determine the critical crack size.

\[
K_r = \begin{cases} 
(1 - 0.14L_r^2)[0.3 + 0.7 \exp(-0.65L_r^2)] & \text{for } L_r \leq L_r^{max} \\
0 & \text{for } L_r > L_r^{max}
\end{cases} \quad \ldots \ldots \ldots (12)
\]

![Figure 1: Schematic of a Failure Assessment Diagram](image)

Option-1 failure assessment diagram is used in the present evaluation. It is derived from the lower bound fit of experimental results and it is independent of material and geometry [10]:

\[
K_r = \begin{cases} 
(1 - 0.14L_r^2)[0.3 + 0.7 \exp(-0.65L_r^2)] & \text{for } L_r \leq L_r^{max} \\
0 & \text{for } L_r > L_r^{max}
\end{cases} \quad \ldots \ldots \ldots (12)
\]
2.5 Tensile Residual Stresses at the Rolled Joint Area

Pressure tubes are rolled into end-fittings at both the ends, which results in tensile residual stresses near the rolled joint. The residual stress level depends on the as rolled residual stress level and the amount of in-reactor stress relaxation due to creep. Zero clearance rolled joints are employed in these reactors, such that initial tensile residual stresses are minimum near the rolled joint region [11]. The maximum tensile residual stresses near rolled joint are limited to 150 MPa for zero clearance rolled joint [12]. The tensile residual stresses are also expected to be relaxed by around 40% within three years and one pressure-temperature cycle.

The Zr-2.5%Nb pressure tube material also undergoes tensile residual stress relaxation due to thermal creep and irradiation. Moreover, if a through wall flaw is considered near the rolled joint region then it can be considered that the residual stresses are no more present as the residual stresses are secondary in nature and tensile residual stresses are limited to a very short distance (~20 mm) in the pressure tubes.

3. Deliberations

3.1 Four tight fit garter springs are employed between pressure tubes and concentric calandria tubes. Therefore, it is assumed that there will not be any contact between pressure tubes and low temperature calandria tubes during the service life of the reactor and as such, there will not be any blister formation in the pressure tubes [11].

3.2 For cold worked Zr-2.5 Nb irradiated pressure tube material, the lower bound values of the threshold stress intensity for the DHC initiation for an axial flaw is 4.5 MPa√m [6].

3.3 Initial hydrogen concentration in double melted pressure tubes is limited to 25 wppm. Maximum hydrogen pick rate is reported to be 1 wppm/year. It has also been reported that further reduction in fracture toughness of the pressure tube at room temperature is not significant when hydrogen content is further increased from 25 wppm to 200 wppm [13]. The fracture toughness properties of pressure tube considered in the present study are corresponding to the saturation fluence >10^{25} n/m^2 for Zr-2.5%Nb pressure tube material.

3.4 As per USNRC requirement, the minimum leak detection capability should be 1/10th of the minimum expected leak rate. The pressure tubes of these reactors are provided with sensitive closed loop Annulus Gas Monitoring System (AGMS) for leak detection with leak detection capacity 30 gm/hr [14].

3.5 Delayed Hydride Cracking (DHC) velocity at room temperature is negligible 2.83e-7 mm/sec or 1.02e-3 mm/hr [8 & 9].

4. Fracture Properties And Flaw Sizes

4.1 Irradiated S-07 pressure tube from KAPS-2 reactors indicated fracture toughness between 26-39 MPa√m. These data are corresponding to 17 wppm of hydrogen content and after 8 FPYs of reactor operation [15]. Rodgers et.al. also reported lower bound fracture toughness for the < 100% re-melted pressure tube material as 35 MPa√m from rising pressure burst tests. These data are also corresponding to 35 wppm of hydrogen and saturated fluence >10^{25} n/m^2 [16]:

\[ K_c = \begin{cases} 
72 & \text{if } (T - 273) > 150 \\
27.6 + 0.296 \times (T - 273) & \text{if } (T - 273) \leq 150
\end{cases} \quad \text{(13)} \]

The present study has been carried out considering the lower bound fracture toughness (K_c) of 26 MPa√m for double melted irradiated Zr-2.5%Nb pressure tube material.

4.2 Pressure tubes are thoroughly examined during PSI and ISI for presence of any flaw during initial phase and also during reactor operation. The present specification for the pressure tubes is such that defect size of upto 2% of wall thickness is acceptable. As such, in the present study a flaw size of \(a=0.0664 \text{ mm}\) and \(c=3*a=0.1992 \text{ mm}\) is considered as the postulated part through wall flaw [7].
4.3 Hundreds of measurements of crack shapes in pressure tubes at different stages of their growth in reactors show that most of the cracks initiated at a point and the average crack length at wall penetration \( L \) was ‘3.6w’, with a upper bound of ‘4w’ [17]. Accordingly, calculations are presented for ‘4w’ and ‘5w’ leakage size cracks.

5 Results and Discussion

5.1 Postulated Part through Wall Flaw

5.1.1 The applied stress intensity factors for postulated part through wall flaw in the pressure tube and corresponding factor of safety with respect to fracture toughness of irradiated material are as shown in Fig.2&3 respectively. Calculations are carried out for residual stresses upto 150 MPa considering the rolled joint residual stresses for fresh tube and then relaxation due to creep. It is found that the postulated part through wall flaw meets the minimum factor of safety requirement for the crack initiation.

\[ K_{IIH} \] is the threshold stress intensity factor below which crack do not grow, even though a quantity of hydride is accumulated at the crack tip under stress. In the present calculation as seen from the Fig.2, the applied stress intensity factor is found to be lower than the threshold stress intensity factor for the crack initiation in the hydride platelet \( (K_{IIH}) \). Hence, DHC initiation of the part through wall flaw can also be ruled out.

5.1.2 The plastic collapse load of the pressure tube with the presence of postulated part through wall flaw is calculated. It was observed that there is no significant change in the plastic collapse load for the pressure tube with presence of postulated flaw, it is found to be same as that of a pressure tube without any flaw.

5.2 Postulated Through Wall Flaw

5.2.1 In the present study, the CCL calculations are based on FAD diagram as shown in Fig.4, where locus of through wall crack is plotted and CCL was identified where it crosses the failure assessment line.
Figure 4: Locus of through wall crack in the failure assessment diagram (FAD)

Figure 5 shows the critical crack length (CCL) calculations at different ROH pressures considering the room temperature fracture toughness properties of irradiated and saturated Zr-2.5%Nb pressure tube material. End of life increase in diameter and reduction in thickness of the pressure tubes due to irradiation and thermal creep have also been considered in the calculations. The available factor of safety with leakage size cracks w.r.t. the critical crack size at different ROH pressures is as shown in Fig.6. Leakage size cracks of size ‘4w’ and ‘5w’ meet the required factor of safety against the CCL.

5.2.2 Maximum allowable pressure at 25 °C is calculated as per the expression given in Eq.9 and found to be 8 MPa at the inlet of the pressure tube, which is more than the cold pressurization pressure of 5.8 MPa.

5.2.3 The DHC velocity at 25 °C is negligible, hence, operator has sufficient time for leak detection, identification and depressurization of the pressure tubes after the leak starts during cold pressurization.
6. Conclusions

Structural integrity of the irradiated double melted pressure tubes during cold pressurization is studied. Studies have been performed to ensure that there is no unstable crack growth and during cold pressurization of the pressure tubes. For these calculations, reported lower bound fracture toughness properties for the double melted Zr-2.5%Nb irradiated and hydrided pressure tube material have been used. The calculations indicate that the postulated part through wall flaw at the most critical location meets the required safety factor against the growth of the postulated flaw. The postulated flaw will not even initiate through the hydride platelet so the DHC initiation can also be ruled out. Pressure tubes meet the required factor of safety for the stability of a leakage size crack in case of cold pressurization and operator has sufficient time to take the necessary actions before the crack becomes critical. It is safe to pressurize the reactor at room temperature i.e. 25 °C up to 8 MPa at pressure tube inlet.

7. References

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