SAFETY ASSESSMENT OF K-11 PRESSURE TUBE OF KAIGA-2 REACTOR FOR THE OBSERVED FLAW DURING ISI-2010

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ABSTRACT

Pressure tube made of zirconium alloys is a major core component of Pressurized Heavy Water Reactors (PHWRs) which contain the fuel bundles and operate at high-pressure & high temperature conditions. Kaiga-1&2 reactors have cold worked Zr 2.5 wt% Nb as the pressure tube material. A flaw was observed in the K-11 pressure tube of Kaiga-2 reactor during the In-service Inspection (ISI) carried out using Ultrasonic Testing (UT). The safety of the pressure tube from the fracture mechanics consideration for the above observed flaw was evaluated. The evaluation of the flaw has been carried out for fracture initiation and for Delayed Hydride Cracking (DHC) initiation for various operating service loading conditions. The applied stress intensity factors have been compared with lower bound crack initiation fracture toughness of the material at the corresponding temperatures and with the applicable safety factors. The pressure tube with the measured flaw has also been checked for the plastic collapse loads for various operating service loading conditions. The effect of increase in stress due to diametral creep and thickness reduction from the initial thickness has also been considered for the end of life safety evaluation.

It was observed that the applied stress intensity factors are less than the threshold stress intensity factor for DHC initiation. The present flaw has been checked for the end of life condition of pressure tube and has been found to be safe. End-of-life Hydrogen equivalent in the tube is found to be less than the Terminal Solid Solubility for Hydrogen Dissolution (TSSD) and Terminal Solid Solubility for Hydrogen Precipitation (TSSP) at operating temperature. It ensures that there is no possibility of gross hydride formation in the pressure tube during normal operating conditions. There is no significant change found in the plastic collapse load of the pressure tube with present flaw size. From the above studies it is concluded that the flaw of the dimensions as observed during the inspection of the K-11 pressure tube will not further grow considerably for the operating loads as well as by DHC and there will be no impact of flaw on the plastic collapse load of the pressure tube which is found to be nearly same as that of a fresh tube.

Keywords: Safety assessment, Pressure tube, Stress intensity factor, Delayed hydride cracking

1. INTRODUCTION

Pressure tube made of zirconium alloys is a major core component of Pressurized Heavy Water Reactors (PHWRs) which contain the fuel bundles and operate at high pressure & high temperature conditions. Kaiga-1&2 reactors have cold worked Zr-2.5Nb alloy as the pressure tube material. The pressure tubes for 220 MWe PHWRs are approximately 5.4 m long, 82.6 mm inside diameter and 3.32 mm wall thickness. The heavy water coolant at about 290 °C and 9.5 MPa pressure (maximum) flows through the pressure tubes. There are 306 pressure tubes in 220 MWe Indian PHWR reactors. Each pressure tube (PT) is surrounded by a concentric calandria tube (CT). The calandria tube insulates the pressure tube from the cold moderator (Fig.1). The annular gap between the pressure tube and the calandria tube is maintained by garter springs. CO2 circulates through the annulus space between pressure tubes and calandria tubes. The annular gas is being monitored for any leakage either from pressure tube or calandria tube.
A semi-automated remote controlled channel inspection head known as BARCIS (BARC Channel Inspection System) has been used for in-service inspection of coolant channels of Indian PHWRs (Fig. 1) [1]. BARCIS inspection head contains various ultrasonic and eddy current transducers. A volumetric flaw indication was observed in the K-11 pressure tube of Kaiga-2 during the In-service Inspection (ISI) by ultrasonic examination using BARCIS. The pressure tube with the observed flaw is unconditionally acceptable as per CSA Standard N 285.4-09 [2]. Additionally, the safety of the pressure tube from the fracture mechanics consideration for the above observed flaw was evaluated to get further confidence. Conservatively, two equivalent planar flaws at the most severe location of the pressure tube are considered for the evaluation. The evaluation of the flaw has been carried out for fracture initiation and for Delayed Hydride Cracking (DHC) initiation for various operating service loading conditions. Presently, cold pressurization is carried out for primary heat transport system (Fig.2). Safety assessment of the pressure tube is carried out at every stage of cold pressurization. The applied stress intensity factors have been calculated and compared with lower bound crack initiation fracture toughness of the material at the corresponding temperatures and with the applicable safety factors. The pressure tube with the measured flaw has also been checked for the plastic collapse loads for various service loading conditions. End of life condition of the pressure tube was also assessed considering life of pressure tube as 16 years. The effect of increase in stress due to diametric creep and thickness reduction from the initial thickness has been considered for the end of life safety evaluation.

It is observed that the applied stress intensity factors are less than the threshold stress intensity factor for initiation of delayed hydride cracking. The stress intensity factors for the present flaw size have been calculated for the
end of life condition of the pressure tube. It is found that the end of life applied stress intensity factor is within the acceptable limits. End of life Hydrogen equivalent in the tube is also found to be less than the Terminal Solid Solubility for Hydrogen Dissolution (TSSD) and Terminal Solid Solubility for Hydrogen Precipitation (TSSP) at normal operating temperature, so there is no possibility of hydride formation in the pressure tube during normal operating conditions. There is no significant change found in the plastic collapse load for the pressure tube with present flaw size. From the above studies it is concluded that the flaw of the dimensions as observed during the inspection of the K-11 pressure tube will not further grow considerably during the operating loads as well as by DHC and there will be no impact of flaw on the plastic collapse load of the pressure tube which is found to be nearly same as that of a fresh tube.

2. DETAILS OF THE FLAW OBSERVED IN THE PRESSURE TUBE

In-service inspection of the pressure tube was carried out in K-11 pressure tube of Kaiga-2 after 7.09 full power years of operation as a part of the coolant channel ISI program. A semi-automated remote controlled channel inspection head known as BARCIS (BARC Channel Inspection System) has been used for in-service inspection of coolant channels of Indian PHWRs. BARCIS inspection head contains various ultrasonic and eddy current transducers. K-11 pressure tube was selected for inspection based on the criterion of high flux and low creep rate. A flaw was detected during the axial scanning of the pressure tube using a ultrasonic angle beam probe for volumetric examination. The existence of the flaw was confirmed by normal beam scanning. In addition to the ultrasonic examination, CT-PT gap measuring eddy current coil was also used to confirm the presence of flaw at the ID surface of the pressure tube. The axial position of the observed flaw was approximately 3.2 m from inlet and was located at 8 o’clock circumferential position. The details of the observed flaw are indicated in Table-1.

| Evaluation technique          | Flaw dimensions (mm) |                  
|-------------------------------|----------------------|------------------|
|                               | Depth    | Circumferential spread | Axial spread |
| Axial scan angle beam probe    | 0.18     | 4.3                  | ~ 1.5        |
| Normal beam probe             | 0.24     | 3.0                  | 1.5          |

3. METHODOLOGY

The dimensions of the flaw indicate that the flaw is a volumetric flaw. The possibility of bearing pad fretting flaw was ruled out because the bearing pad dimensions are 2.5 mm in circumferential and 25.5 mm in axial direction. In addition to this observation, the bearing pad material is Zr-4 which is softer than pressure tube material. The flaw could be due to fretting of debris stuck between fuel bundle and the pressure tube. The debris fretting type of flaws is analyzed for the threshold peak flaw tip stress for delayed hydride cracking initiation [3]. However, as with the present setup the flaw root radius could not be measured in the pressure tube, conservatively two part-through-wall sharp planar flaws have been assumed for the fracture mechanics analysis. The flaws are characterized as surface planar flaws, one in axial direction and another in circumferential direction. The calculations for the flaw have been carried out for fracture initiation and DHC initiation for various operating service conditions. The applied stress intensity factors have been compared considering applicable safety factors for the various service loading conditions with lower bound crack initiation fracture toughness of the material at the corresponding temperatures. The pressure tube with the measured flaw has also been checked for the plastic collapse loads for various service loading conditions. The effect of increase in stress due to 4 % diametral creep and a thickness reduction of 4.5 % from the initial thickness have also been considered for the end of life safety evaluation.
As against the observed volumetric flaw conservative dimensions of the hypothetical flaws are assumed for the fracture mechanics analysis. The dimensions of the hypothetical planar flaws considered for the fracture mechanics analyses are as follows:

**Dimensional details of hypothetical flaw in axial direction:**
- Depth of flaw \( a = 0.24 \) mm
- Axial length of flaw \( 2c = 1.5 \) mm

**Dimensional details of hypothetical flaw in circumferential direction:**
- Depth of flaw \( a = 0.24 \) mm
- Circumferential length of flaw \( 2b = 4.3 \) mm

In addition to the above, conservatively the hypothetical circumferential flaw is assumed to be located at the 6 o’clock position although the observed flaw is present at 8 o’clock position, because the bending stresses due to dead-weight are maximum at 6 o’clock position.

### 3.1 Calculation of Stress Intensity Factors

The stress intensity factors calculations for the equivalent hypothetical part through wall planar flaws are carried out using Eq. (1) & (2) for axial flaw \( (K^a_I) \) and circumferential flaw \( (K^{circ}_I) \) respectively [3]:

\[
K^a_I = \left[ p \left( \frac{r_i}{t} + 1 \right) F_p + \sigma_h^{res} F_m \right] \left( \frac{\pi a}{Q_1} \right)^{1/2}, \quad \ldots \ (1)
\]

\[
K^{circ}_I = \sigma_a \left( \frac{\pi a}{Q_2} \right)^{1/2} F_c, \quad \ldots \ (2)
\]

where, ‘\( p \)’ is the internal pressure of pressure tube, ‘\( r_i \)’ is inner radius of pressure tube, ‘\( t \)’ 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, ‘\( \sigma_a \)’ is total nominal axial stress on the pressure tube, ‘\( F_c \)’ is geometry correction factor for an internal circumferential part through wall flaw under membrane stress loading and \( Q_1 \) & \( Q_2 \) are the flaw shape parameters defined as \( Q_1 = 1 + 1.464 \left( \frac{a}{t} \right)^{1.45} \) & \( Q_2 = 1 + 1.464 \left( \frac{a}{b} \right)^{1.45} \) respectively. The distance between the observed flaw and rolled joint in the pressure tube is more than \( 5.2 \), therefore rolled joint residual stresses are not considered in the flaw evaluation.

### 3.2 Fracture Initiation Evaluation

The part through wall circumferential and axial flaws is evaluated for fracture initiation for level A, B and C service loading conditions. The applied stress intensity factors for axial as well as circumferential flaws are calculated and compared with the lower bound critical stress intensity factors for fracture initiation \( (K_{IC}) \) with applicable safety factors \( (SF) \) as represented in Table(2) [3]:

\[
K_I \leq \frac{K_{IC}}{(SF)_f}, \quad \ldots \ (3)
\]
Table 2: Applicable safety factors for various loading conditions

<table>
<thead>
<tr>
<th>Service level</th>
<th>$(SF)_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.0</td>
</tr>
<tr>
<td>B</td>
<td>2.7</td>
</tr>
<tr>
<td>C</td>
<td>1.7</td>
</tr>
</tbody>
</table>

The critical stress intensity factors for flaw initiation are calculated at various operating temperatures and during start up and shutting down of the reactor. The lower bound relationships of critical stress intensity factors in axial ($K_{IC}^a$) and circumferential ($K_{IC}^{circ}$) directions at various temperatures (in °C) used in the calculation are represented in Eq. (4) & (5) respectively [3]:

\[ K_{IC}^a = 26.3 + 0.022T \text{ MPa m}, \quad \ldots (4) \]
\[ K_{IC}^{circ} = 29.9 + 0.0647T \text{ MPa m}. \quad \ldots (5) \]

Stresses due to pressure and dead-weight have been considered for the circumferential flaw evaluation and stresses due to pressure have been considered for the axial flaw evaluation. The end of life condition of the pressure tube are calculated based on assumption of annual creep rate of 0.25 % and 4 % limit on the diametral creep to limit flow bypassing. For the end of life condition of the pressure tube (i.e. 16 years of life) with a diametral creep of 4 % and increase in the length of tube by 32 mm (2 mm/yr) are considered in the analysis. The creep will give a 4.5 % reduction in the thickness of the pressure tube after 16 full power years of reactor operation. Further the reduction in thickness and increase in diameter will result in 9 % increase in hoop stresses and 4.5 % increase in axial stresses. Stress intensity factors for the axial and circumferential flaws is increased in the same ratio respectively

3.3 Evaluation of Pressure Tube for Plastic Collapse Loads

A part through wall axial flaw and part through wall circumferential flaw are evaluated for the plastic collapse loads. The expression used for the plastic collapse evaluation with axial flaw is represented in Eq. (6) [3]:

\[ \sigma^*_h = \sigma_f \left[ 1 - \frac{a}{t} \right] \left[ 1 - \left( \frac{1}{M} \left( \frac{a}{t} \right) \right) \right], \quad \ldots (6) \]

where, \( M = 1 + 1.255 \left( \frac{c^2}{r_m t} \right) \left[ 1 + 0.0135 \left( \frac{c^2}{r_m t} \right)^{2/3} \right] \), \( \sigma_f \) is the flow stress defined as \( \frac{\sigma_u + \sigma_y}{2} \), \( r_m \) is the mean radius of the pressure tube, ‘a’ is depth of flaw and ‘t’ is thickness of the pressure tube. The expressions used for the plastic collapse evaluation with circumferential flaw for primary membrane stress and for primary membrane + bending stresses are represented in Eq.(7a) & (7b) respectively [3]:

\[ \sigma^*_m = \sigma_f \left[ 1 - \left( \frac{a}{t} \left( \frac{\theta_c}{\pi} \right) - 2 \left( \frac{\gamma}{\pi} \right) \right) \right], \quad \ldots (7a) \]
\[
\sigma_b = \frac{2\sigma_f}{\pi} \left[ 2\sin \eta - \frac{a}{t} \sin \theta_c \right] \tag{7b}
\]

where, \( \gamma = \sin^{-1} \left( \frac{a}{2t} \sin \theta_c \right) \), \( \eta = \frac{1}{2} \left[ \pi - \frac{a}{t} \theta_c - \pi \frac{\sigma^{\text{pl}}}{\sigma_f} \right] \) and \( \theta_c = \frac{b}{r_i} \).

### 3.4 Delayed Hydride Crack Propagation

Zr-2.5 Nb alloy pressure tubes are susceptible to failure by Delayed Hydride Cracking (DHC) \cite{4}. In DHC the crack propagation is governed by hydrogen diffusion to a high stress region within the bulk followed by hydride precipitation and subsequent hydride cracking when a critical length is reached \cite{5}. Like any other species Hydrogen also have tendency to migrate towards low chemical potential gradient i.e. low stress to high stress, high concentration to low concentration and high temperature to low temperature region. In DHC hydrogen is migrated to high stress gradient or to the region of stress concentration. Once the local Terminal Solid Solubility for Precipitation (TSSP) is exceeded, brittle hydride platelets are precipitated normal to the tensile stress and at the crack tip location. The precipitation of hydride continues at the crack tip until a platelet of critical size is formed. A hydride platelet of critical size cracks under concentrated stress leading to the growth of the crack. Again the process of hydrogen migration to the crack tip, hydrogen precipitation, hydride nuclei reorientation, critical hydride platelet formation and then growth of the crack is repeated. This crack growth is delayed by some time hence this phenomenon is called as DHC and it is a discontinuous process.

Once crack initiation by DHC has occurred, further continuous propagation of crack by DHC mechanism involves the repeated formation, growth and fracture of hydrides at the flaw tip. DHC propagation is possible if the Hydrogen equivalent concentration at the crack tip equals or exceeds the TSSP and the stress intensity factor is above threshold stress intensity factor for DHC initiation \((K_{IH})\). TSSP follows an Arrhenius type relationship and is defined as represented in Eq.8 \cite{3}:

\[
TSSP = 4.11 \times 10^4 \exp \left( \frac{28000}{RT} \right) \text{ [ppm]} \quad \ldots (8)
\]

### 4. RESULTS AND DISCUSSION

#### 4.1 Evaluation of Flaw in the Pressure Tube

The calculated values of applied stress intensity factors for the equivalent hypothetical planar flaws in the pressure tube for start up and shutdown loadings are given in Table-3 and for various levels of design loadings conditions are as given in Table-4. The critical stress intensity factors for flaw initiation at various operating temperatures are also brought out in Table-3&4. The effect of increase in stress due to 4 % diametral creep and a thickness reduction of 4.5 % from the initial thickness have also been considered for the end of life safety evaluation. For end of life condition the hoop stresses increase by 9.0 % and axial stresses increase by 4.5 %. The end of life applied stress intensity factors evaluations for various operating loading conditions are represented in Table-5.

### Table3: Planer flaw Evaluation of K11 pressure tube of Kaiga-2 for Startup and cold shutdown condition

<table>
<thead>
<tr>
<th>Sr.No.</th>
<th>Pressure (Mpa)</th>
<th>Temp (°C)</th>
<th>( \sigma_t ) (Mpa)</th>
<th>( K_i^a ) (MPaVm)</th>
<th>( K_i^{\text{Cir}} ) (MPaVm)</th>
<th>( K_{IC}^a ) (MPaVm)</th>
<th>( K_{IC}^{\text{Cir}} ) (MPaVm)</th>
<th>( K_{IH}^a ) (MPaVm)</th>
<th>( K_{IH}^{\text{Cir}} ) (MPaVm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.8</td>
<td>55</td>
<td>71.72</td>
<td>2.19</td>
<td>2.16</td>
<td>27.51</td>
<td>33.45</td>
<td>4.5</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>5.8</td>
<td>130</td>
<td>71.72</td>
<td>2.19</td>
<td>2.16</td>
<td>29.16</td>
<td>38.31</td>
<td>4.5</td>
<td>15</td>
</tr>
</tbody>
</table>
Table 4: Planer flaw Evaluation of K11 pressure tube in Kaiga-2 for various service levels

<table>
<thead>
<tr>
<th>Service Level</th>
<th>Pressure (Mpa)</th>
<th>Temp (°C)</th>
<th>$\sigma^a$ (Mpa)</th>
<th>$K_{Ia}$ (MPa√m)</th>
<th>$K_{Ia}^{cr}$ (MPa√m)</th>
<th>$K_{ICa}$ (MPa√m)</th>
<th>$K_{ICa}^{cr}$ (MPa√m)</th>
<th>$K_{IHa}$ (MPa√m)</th>
<th>$K_{IHa}^{cr}$ (MPa√m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level A</td>
<td>9.14</td>
<td>293</td>
<td>89.99</td>
<td>3.45</td>
<td>2.71</td>
<td>32.74</td>
<td>48.85</td>
<td>4.5</td>
<td>15</td>
</tr>
<tr>
<td>Level B</td>
<td>9.60</td>
<td>295</td>
<td>92.51</td>
<td>3.62</td>
<td>2.79</td>
<td>32.79</td>
<td>48.98</td>
<td>4.5</td>
<td>15</td>
</tr>
<tr>
<td>Level C</td>
<td>10.97</td>
<td>293</td>
<td>100.00</td>
<td>4.14</td>
<td>3.01</td>
<td>32.74</td>
<td>48.85</td>
<td>4.5</td>
<td>15</td>
</tr>
<tr>
<td>Design</td>
<td>10.40</td>
<td>300</td>
<td>96.88</td>
<td>3.93</td>
<td>2.92</td>
<td>32.9</td>
<td>49.31</td>
<td>4.5</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 5: Planer flaw Evaluation of K11 pressure tube in Kaiga-2 for various service levels at the end of life of 16 years of the pressure tube

<table>
<thead>
<tr>
<th>Service Level</th>
<th>Pressure (Mpa)</th>
<th>Temp (°C)</th>
<th>$\sigma^a$ (Mpa)</th>
<th>$K_{Ia}$ (end of life) (MPa√m)</th>
<th>$K_{Ia}^{cr}$ (end of life) (MPa√m)</th>
<th>$K_{ICa}$ (MPa√m)</th>
<th>$K_{ICa}^{cr}$ (MPa√m)</th>
<th>$K_{IHa}$ (MPa√m)</th>
<th>$K_{IHa}^{cr}$ (MPa√m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level A</td>
<td>9.14</td>
<td>293</td>
<td>89.99</td>
<td>3.75</td>
<td>2.83</td>
<td>32.74</td>
<td>48.85</td>
<td>4.5</td>
<td>15</td>
</tr>
<tr>
<td>Level B</td>
<td>9.60</td>
<td>295</td>
<td>92.51</td>
<td>3.94</td>
<td>3.91</td>
<td>32.79</td>
<td>48.98</td>
<td>4.5</td>
<td>15</td>
</tr>
<tr>
<td>Level C</td>
<td>10.97</td>
<td>293</td>
<td>100.00</td>
<td>4.50</td>
<td>3.14</td>
<td>32.746</td>
<td>48.85</td>
<td>4.5</td>
<td>15</td>
</tr>
<tr>
<td>Design</td>
<td>10.40</td>
<td>300</td>
<td>96.88</td>
<td>4.28</td>
<td>3.15</td>
<td>32.9</td>
<td>49.31</td>
<td>4.5</td>
<td>15</td>
</tr>
</tbody>
</table>

The applied stress intensity factor and the critical stress intensity factor for crack initiation shows the factor of
safety more than the required as brought out in Table-1. The applied stress intensity factors have been checked for the end of life condition and it is found that the factor of safety more than the required is present.

4.2 Delayed Hydride Crack Initiation

For cold worked Zr-2.5 Nb pressure tube material, the lower bound values of the threshold stress intensity for the DHC initiation for an axial flaw and circumferential flaw are $4.5 \text{ MPa} \sqrt{m}$ and $15 \text{ MPa} \sqrt{m}$ respectively [3]. It is observed that applied stress intensity factor for the present flaw size with various operating condition is not exceeding the threshold stress intensity factor for crack initiation in the hydrides.

DHC is a discontinuous crack growth process. There is continuous formation of brittle hydride platelet ahead of crack tip when the hydrogen equivalent concentration exceeded the terminal solid solubility limit at the temperature. Initial hydrogen concentration in the pressure tube is achieved to 4 ppm and it is observed that hydrogen/deuterium pick up rate of pressure tube is about 1 ppm/year. So the end of life (16 years) hydrogen equivalent in the pressure tube is considered as 20 ppm. End of life hydrogen equivalent in the pressure tube is found to be lower than the terminal solid solubility for hydrogen precipitation at the normal operating temperature [3].

4.3 Effect of Flaw on Plastic Collapse Loads

The plastic collapse loads of the pressure tube are calculated based on Eq.(6)&(7). It was observed that there is no significant change found in the plastic collapse loads for the pressure tube with present flaw size, it is found to be same as that of a pressure tube without any flaw.

The above studies indicate that (i) the flaw of the dimensions as observed during the inspection of the K-11 pressure tube will not further grow during the operating loads (ii) there is very remote possibility of hydride formation ahead of the flaw tip at operating temperatures (iii) there will not be any growth in the flaw in the hydrides platelets if formed and (iv) there is no impact of the observed flaw on the plastic collapse loads of the pressure tube which is found to be nearly same as that of a pressure tube without any flaw. It is concluded from the above studies that the observed flaw in the pressure tube will not grow considerably by the known propagating mechanisms. However, it is planned to inspect the pressure tube in the next bi-annual shutdown to confirm that the observed flaw is not growing further.

5. REFERENCES