On the Failure Assessment Diagrams for CANDU-6 Pressure Tube Structural Integrity Analysis

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ABSTRACT

The core of a CANDU-6 pressurized heavy water reactor consists of some hundred horizontal pressure tubes that are manufactured from a Zr-2.5%Nb alloy and that contain the fuel bundles. These tubes are susceptible to a damaging phenomenon known as Delayed Hydride Cracking (acronym – DHC). The Zr-2.5%Nb alloy is susceptible to DHC phenomenon when there is diffusion of hydrogen atoms to a service-induced flaws, followed by the hydride platelets formation on the certain crystallographic planes in the matrix material. Finally, the development of a hydrided regions at the flaw-tip will happened. These hydrided regions are able to fracture under stress-temperature conditions (DHC initiation) and the cracks can extend and grow by DHC mechanism. Some studies have been focused on the potential to initiate DHC at the blunt flaws in a CANDU reactor pressure tube and developed the methodology for structural integrity evaluations.

The methodology based on the Failure Assessment Diagrams (FAD’s) consists in an integrated graphical representation, where the fracture failure and plastic collapse are simultaneously evaluated by means of two non-dimensional variables (K_r and L_r). These two variables represent the ratio between the applied value of either stress or stress intensity factor and the resistance parameter of corresponding magnitude (yield stress or fracture toughness, respectively). Once the plotting plane is determined by the variables K_r and L_r, the procedure defines a critical failure line that establishes the safe area.

In the recent papers D.A. Scarth and T.E. Smith have presented a very interesting development of the Failure Assessment Diagrams in K* and L* format, somewhat different than K_r and L_r format, for evaluation of the DHC initiation at in-service flaws that are found during in-service inspection of CANDU reactor pressure tubes.

The present paper is focused on the experimental results of the tests carried out on the Zr-2.5%Nb samples, in order to produce the zones with reoriented hydrides at the blunt flaws-tip. The zones with reoriented hydrides at the flaws-tip have been realized by means of cyclic thermal treatment on the Zr-2.5%Nb samples, under adequate values of the applied tensile stress. From the metallographical photos examinations, the depth and shape magnitude measurements of “zones with reoriented hydrides” (ZRH) at the notch tip have been performed. The experimental results are compared with those pointed out from theoretical stress functions analysis at the notch tip. Based on the ZRH characteristics an “effective blunt flaw” will be defined and implications on FAD’s shape are mentioned.

KEY WORDS: CANDU pressure tubes, Zr-2.5%Nb alloy, DHC-Delayed Hydride Cracking, reoriented hydrides, FAD-Failure Assessment Diagrams

INTRODUCTION

Romania has only one NPP into operation. It is a CANDU 6 reactor located in the Cernavoda site. Construction of five CANDU 6 reactor units started at Cernavoda in 1980 and stopped at different stages of advancement following the 1989 political changes. Subsequently, it was decided to concentrate on the completion of the first two units. In 1991, the Romanian Electricity State Company (RENEL) signed a contract with a Western Consortium (AECL and Ansaldo), transferring to it the responsibility to complete the construction of Unit 1 and to commission and manage its initial operation. The national industry participated in the construction of conventional systems under a qualification program supervised by the Consortium. Operating responsibility was transferred from the Western Consortium to RENEL, with commercial operation starting in July 1997 under the conditions of a provisional operating license issued by the Regulatory Body.

The Cernavoda reactor uses natural uranium as fuel and heavy water as the coolant and moderator. It is based on a standard CANDU 6 design developed in Canada in 1979 and is similar to NPP’s in operation at Point Lepreau and Gentilly 2 in Canada. In a CANDU 6 reactor the moderator and the coolant are separated by two concentric tubes, the pressure tube and the calandria tube. The pressure tubes (380) and the calandria tubes are housed in a cylindrical tank (calandria) that contains heavy water moderator at low pressure, surrounded by a concrete reactor vault containing light water for biological and thermal shielding. At INR Pitesti is currently unfolding a research program for CANDU fuel channels.

Zirconium alloys are largely used in the nuclear industry because of their low neutron capture cross-section and excellent corrosion and mechanical properties. The calandria contains D_2O moderator at 70° C and is penetrated by fuel channels each 6 m long. In a fuel channel there is a pressure tube containing fuel bundles and coolant D_2O agent at a pressure of 10 MPa. The temperature domain is from 260° C at inlet to 310° C at outlet. The space between the pressure
tube and the calandria tube is filled with annulus gas and separation of tubes is assured by four located garter spring [1].

In a CANDU 6 reactor the pressure tubes are made from cold-worked Zr-2.5%Nb alloy. A pressure tube has a wall thickness of 4 mm and an inside diameter of 103 mm and is rolled into the end fittings. Over time, these tubes are susceptible to a slow corrosion process, which also leads to a gradual pickup of deuterium in the tubes. When the hydrogen plus deuterium concentration in the tube exceeds the terminal solid solubility (TSS), the tubes are susceptible to a crack initiation and propagation process called delayed hydride cracking (DHC).

Delayed hydride cracking is a multistep, diffusion-controlled crack propagation process. The DHC process consist in diffusion of the hydrogen (or deuterium) atoms to a high tensile stress region of the tube, such as at crack or notch tips loaded by tensile hoop stress. If the hydrogen concentration at these locations exceeds the TSS for hydride precipitation, hydrides with platelet normals parallel to the applied tensile stress direction will form and grow. When the crack/notch tip hydride grow to a critical size, fracture of “radial” hydrides will occur and the described process would repeat itself. [2]

In-service wear of pressure tubes in CANDU reactors has been caused by fuel bundle scratching during refueling, bearing pad fretting, crevice corrosion at fuel bundle bearing pad positions and debris fretting. Debris fretting is a known in-service flaw mechanism in CANDU reactors that cause pressure tube flaws with depths exceeding the acceptance level (0.15mm) of CSA Standard N285.4 [1]. The debris marks primarily occur during early operation, because construction debris such as metal turnings left in the primary heat transport system (PHTS) can get trapped in the fuel and cause pressure tube fretting damage. The majority of debris fretting damage observed to date in CANDU pressure tubes has been localized, shallow (less than 0.5 mm deep), blunt notches with low stress concentration [1] as illustrated in Figure 1.

The hydrides would be expected to form when these tubes are cold and the intent of many studies is to establish the maximum depth of debris frets and hydride reorientation conditions such as the fact will no lead to DHC initiation.

The paper presents the FAD’s in the form developed for Zr-2.5%Nb pressure tube by the D.A. Scarth and T.E. Smith [3]. The FAD’s are designated to evaluate the potential of DHC initiation at blunt flaws during normal operating conditions. Also, the paper presents the experimental results of tests that has been carried out to produce hydrides reorientation phenomenon at the blunt flaw-tip, measurements of zones with reoriented hydrides (ZRH) depths on metallographical photos and comparison between its fitness with stresses analyses at notch-tip. Finally, it is proposed a reevaluation of a blunt flaw with its reorientation zone as an “effective blunt flaw”. The “effective blunt flaw” length is defined as sum of the real blunt flaw depth and ZRH depth. The experimental results and “effective blunt flaw” assumption are used in the Failure Assessment Diagram format and influence on the Failure Assessment Curves shapes are discussed.

METHOD OF ANALYSIS

Failure Assessment Diagrams for Blunt Flaws in CANDU Pressure Tubes

The Zr-2.5%Nb alloy is susceptible to a DHC phenomenon when there is hydrogen atoms to a service-induced flaw, precipitation of hydride platelets on appropriately oriented crystallographic planes in matrix material, and development of a hydrided region at the flaw root. When the bulk hydrogen concentration is sufficient such that hydrides from the surrounding of flaw-tip does not dissolve at the peak temperature in a heat up cool down thermal cycle then the hydride ratcheting conditions are realized. As a consequence, the hydrided region will grow in size with each cycle.

The hydrided region has a structure that exhibits certain characteristics somewhat different from surrounding zirconium alloy matrix. The discrete nature of hydrided region establishes the basis for using process-zone methodology for modeling DHC initiation [3]. The process zone methodology uses the type of representation in order to describe relaxation due to plasticity at a stress concentration and such zone is referred to as a strip yield zone. A hydrided zone that exits at a flaw-root, together with the neighboring region that is fracturing, could be viewed as a single entity [3].

The Failure Assessment Diagram for DHC initiation from blunt flaws was developed from closed form Mode III process-zone. The anti-plane strain, Mode III process-zone simulation of DHC initiation at the two-dimensional blunt

Fig. 1 Debris fretting damage as blunt flaw in CANDU pressure tube [1]
surface flaw with a semi-elliptical cross-section in a semi-infinite solid (Figure 2), under a Mode I uniform applied tensile stress, was described in the Scart’s paper [3].

This model was used to develop the Failure Assessment Diagrams for DHC initiation, because the Mode III solutions have simplicity and can prove insight of how the various both material and geometrical parameters interact for DHC prediction by means FAD’s. The failure assessment diagram was developed in terms of $K_r$ and $L_r$, that are defined:

$$K_r = \frac{\sigma^a \sqrt{\pi c}}{K_{III}}$$

and

$$L_r = \frac{\sigma^a}{p_c}$$

where:

$\sigma^a$ = applied nominal stress;
$c$ = notch depth;
$K_{III}$ = threshold stress intensity factor for delayed hydride cracking initiation at a crack;
$p_c$ = threshold stress for delayed hydride cracking initiation at a planar surface.

The relationship for FAD diagram with $K_r$ and $L_r$ terms has the following form [3]:

$$K_r = \frac{\pi L_r}{8 \ln \left( \sec \left( \frac{\pi}{2} \left( 1 + \left( \frac{\rho}{a} \right)^{1/2} \right) \right) \left( L_r - 1 + \left( \frac{a}{\rho} \right)^{1/2} \right) \right)^{1/2}}$$

where:

$\rho$ = flaw root radius

For the special case when $\frac{\rho}{c} \rightarrow 0$ (the semi-elliptical flaw degenerates into a crack) Eq. (3) simplifies to relation from fracture mechanics [4]:

$$K_r = \frac{\pi S_r}{8 \ln \left( \sec \left( \frac{\pi}{2} S_r \right) \right)^{1/2}}$$

where the significance of variables are: $K_r$ means K ratio and $S_r$ means stress ratio

$$K_r = \frac{K_I}{K_{eff}}$$

and

$$S_r = \frac{\sigma^a}{\sigma_c}$$

$K_I$ = the stress intensity factor for Mode I loading;
$K_{eff}$ = the effective plane strain fracture toughness;
$\sigma_c$ = the collapse stress.
An application of relation (4) has been performed by Kuroda, M. and collaborators for analysis of the fracture behavior of hydrided Zircaloy-4 cladding tubes [5]. The FAD in $K_r - L_r$ format shows a strong geometry dependence, therefore a FAD in $K^* - L^*$ format was developed by Scart, D.A. and Smith, T.E.[3], as follow

\[
K^* = \frac{\pi L^*}{\lambda \left( 8 \ln \sec \left( \frac{\pi}{2} \left( 1 + \left( \frac{a}{c} \right)^{1/2} \right) L^* - \frac{1}{1 + \left( \frac{a}{c} \right)^{1/2}} \right) \right)^{1/2}} + \frac{\rho}{c}\]

where:

\[
L^* = \frac{\sigma^u}{p_c}\]

and

\[
K^* = \frac{1 + \left( \frac{a}{c} \right)^{1/2}}{\frac{\lambda}{K_r} + 1 \left( \frac{a}{c} \right)^{1/2}}
\]

with $\lambda$, a parameter.

DHC initiation is evaluated by plotting the assessment point given by the coordinates:

\[
K^*_0 = \frac{\sigma_p}{p_c} \left( \frac{\lambda}{K_r} \right) \cdot \frac{K_{II}}{\sigma_p (\pi \rho)^{1/2}}
\]

and

\[
L^*_0 = \frac{\sigma^u}{p_c}
\]

with the applied peak flaw-tip stress $\sigma_p$ calculated on the elastic basis.

In this paper, after experimental determining of characteristics for ZRH at blunt flaw-tip, it will assess the influence of a defined “effective blunt flaw” on the failure assessment curve described by Eq. (7).

**Stress Functions at the Blunt Flaw-Tip**

Characterization of the stress state at blunt flaw requires a different treatment than for the field at sharp cracks or smooth surface [2,3]. Characterizing the stress state at a blunt notch by $K_n$, such as is appropriate for a sharp crack, would overestimate the stress level, whereas adopting an applied far-field stress would underestimate it. We suppose that a blunt flaw could be approximated by a notch with a half-elliptical shape under axial load (Figure 2). If the depth of the notch $c$ is small compared with the specimen width in the x-direction, then the stresses in the vicinity of the notch can be directly obtained by the methods of elasticity theory [2]. A local yielding around the notch tip will occur when the far-field applied stress $\sigma^u$ is greater than the stress $\sigma^u_n$, resulting in a plastic zone whose size increases with increasing of the applied stress. According to the slip-line theory [2] and based on the Tresca yielding criterion the tensile stress in the y-direction inside the plastic zone my be given by

\[
\sigma_{yy} = \sigma_{yy}^u \left[ 1 + \ln \left( 1 + \frac{r}{\rho} \right) \right]
\]

where $\sigma_{yy}$ is uniaxial yield stress.

The elastic stress concentration factor for a blunt flaw, with a semi-elliptical surface, in a finite thickness solid is given by [3]

\[
k_f \left( \frac{c}{\rho} \right) = 1 + 2 \cdot F \left( \frac{c}{\rho} \right)^{1/2}
\]

where $t$ is thickness of specimen and $F(c/t)$ is the geometry correction factor for the stress intensity factor for a crack with the same planar dimensions as the blunt flaw. For membrane loading conditions [3]
\[
F\left(\frac{c}{t}\right) = F_m\left(\frac{c}{t}\right)
\]
and
\[
F_m\left(\frac{c}{t}\right) = 1.122 - 0.23\left(\frac{c}{t}\right) + 10.55\left(\frac{c}{t}\right)^2 - 21.71\left(\frac{c}{t}\right)^3 + 30.38\left(\frac{c}{t}\right)^4
\]

For elastic domain at the tip notch it can be used the following stress function
\[
\sigma_{yy} = \sigma^a \cdot k_i \left(\frac{c}{\rho}, \frac{c}{t}\right)
\]

In our experiments the hydrided specimens have been loaded in tensile stress and therefore we will assess the stress functions from the notch-tip up to opposite sample edge by Eqs. 12 (plastic zone) and 16 (elastic zone).

**EXPERIMENTAL PROCEDURE FOR HYDRIDE REORIENTATION**

Hydrides are always present in Zr-2.5%Nb pressure tubes at room temperature, while in the range operating temperature, hydrides formatted only when hydrogen equivalent concentration Heq (the sum of the H concentration in a new tube plus half ppm concentration of the D picked up during service) is greater than the terminal solid solubility (TSS) at operating temperature. The TSS in operating pressure tubes is about 40 to 70 ppm, depending on the tube temperature. For tubes fabricated before 1990, 5-15 ppm of H is a typical range for the H concentration (up to 25 ppm of H was allowed). Recent improvements in the manufacturing process of Zr-2.5%Nb pressure tubes have significantly reduced the H concentration (less than 5 ppm). During reactor operation the heavy water flowing through pressure tubes slowly corrodes their inside surface and increases their oxide thickn

5% of the D produced from corrosion.

The samples used in experimental works have a V notch on a single face, with 60° angle between its planes. In order to obtain the hydrided specimens at different levels of hydrogen concentration has been used an electrolytic method. The electrolytic method consists in the following steps:

- a hydrided layer was deposited on the Zr-2.5%Nb specimen surface in a 0.1 H₂SO₄ electrolyte at 90°C by means of 100-mA/cm² current density;
- a heat-treatment at 400°C was applied to diffuse the hydrogen into the samples body.

It was obtained the hydrogen concentrations in 30-70 ppm range. As shown in the Figure 3, all hydrides from transversal-radial section are only oriented in the circumferential direction. The hydrides platelets are majority orientated in the circumferential direction because the Zr-2.5%Nb pressure tubes are highly textured.

To perform the hydride reorientation phenomenon were used the specimens prepared from the circumferential direction of the pressure tube, having a “V” type notch (c=0.2 - 0.3 mm depth, radius \(\rho = 0.07-0.1\) mm), in the same domain as in [3].

The sequences of the experimental procedure were:

- increasing of the tensile load on specimens up to defined stress (far from yielding conditions);
- maintaining of the constant designed load;
- applying of a thermal treatment, Figure 4;

After thermal treatments it was carried out metallurgical examinations and measurements of lengths zones with reoriented hydrides at flaws-tip.

In order to start the reorientation mechanism of the hydrides in the Zr-2.5%Nb specimens, from circumferential direction in radial direction of the pressure tube is necessary a tensile stress greater than 240 MPa at flaw-tip at 270°C temperature.

![Fig. 3 Hydrides at notch-tip in a Zr-2.5%Nb samples with 60 ppm H (magnification is 200x).](image)

![Fig. 4 Thermal treatment for hydride reorientation](image)
Some of typical zones with hydrides reorientation at flaws tip are illustrated in Figures 5, 6, 7, and 8.

From examinations of previous metallographical photos one can see a circular shape of zones with reoriented hydrides at blunt flaws tip. Also, it has been performed the measurements of the zone depths.

RESULTS

The basic characteristic measurements of some tested samples are presented in Table 1. It is obvious that depths of zones with reoriented hydrides are related to many factors: root radius, notch depth, applied tensile stress, thickness of specimens, etc. We tried to correlate the reoriented depths with stress functions due to applied stresses for designed configurations. Through representation of stresses at notch-tip (plastic and elastic evaluations) and also representation of reorientation stress (≈ 240 MPa) on the same graph one could deduct the “analytical” results for depths of the zones with reoriented hydrides. In the following graphs one can see predictions for depths of reoriented zones (Figures 9-12).
Fig. 9 Stress functions ahead at blunt flaw-tip for Probe #1: \(H_r=0.05\text{mm}\) (depth of the reorientation zone)

Fig. 10 Stress functions ahead at blunt flaw-tip for Probe #2: \(H_r=0.07\text{mm}\) (depth of the reorientation zone)

Fig. 11 Stress functions ahead at blunt flaw-tip for Probe #3: \(H_r=0.13\text{mm}\) (depth of the reorientation zone)

Fig. 12 Stress functions ahead at blunt flaw-tip for Probe #4: \(H_r=0.17\text{mm}\) (depth of the reorientation zone)

Table 1. Characterization of the zones with reoriented hydrides and comparison between measured (metallographical) and predicted (stresses graph) values

<table>
<thead>
<tr>
<th>Probe #</th>
<th>(\rho) (mm)</th>
<th>(c) (mm)</th>
<th>(t) (mm)</th>
<th>(c/\rho)</th>
<th>(c/t)</th>
<th>(\sigma^a) (MPa)</th>
<th>(\sigma_{ys}) (MPa)</th>
<th>(H_r) (mm) measured</th>
<th>(H_r) (mm) predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.07</td>
<td>0.2</td>
<td>0.62</td>
<td>2.85</td>
<td>0.32</td>
<td>79.11</td>
<td>584</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>0.08</td>
<td>0.17</td>
<td>0.52</td>
<td>2.125</td>
<td>0.326</td>
<td>94.33</td>
<td>584</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>3</td>
<td>0.09</td>
<td>0.27</td>
<td>0.57</td>
<td>3.0</td>
<td>0.473</td>
<td>77.44</td>
<td>584</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>4</td>
<td>0.10</td>
<td>0.27</td>
<td>0.55</td>
<td>2.7</td>
<td>0.49</td>
<td>79.54</td>
<td>584</td>
<td>0.15</td>
<td>0.17</td>
</tr>
</tbody>
</table>

The \(K_{IC}\) parameter of \(\delta\)-hydride Zr-\(\text{H}_1.6\) was measured and resulted about 1-3 MPa.m\(^{1/2}\) values. Therefore we consider that hydried region in front of flaw-tip are very brittle. Some tensile tests, performed on the samples discussed above, have carried out up to the final fracture. The cracking front started at notch-tip, moved through ZRH in a brittle manner (normal to stress direction), and after that it exhibited a ductile propagation (situated in 45° angle to stress direction), Figure 13. Taking into account these facts we would define an “effective blunt flaw” with length equal sum from real notch depth and ZRH depth. The root radius of the “effective blunt flaw” is supposed equal with half of the ZRH depth.
This assumption was incorporated in Failure Assessment Curves described by Eq. 7. In the Figures 14 and 15 are illustrated three curves: for a crack ($\rho \rightarrow 0$), for real blunt flaw with characteristics of Probe #1 and Probe #4 and as well as for the “effective blunt flaw”.

We have to mention that FAD defined [3] for assessment of blunt flaws could be useful in domain $L^* > 0.4$. By using of the “effective blunt flaws” characteristics the curves become operative for $L^* > 0.3$, so the applicability is extended.

This assumptions must be proved and our future experimental programs will deal with both defining conditions for DHC initiation from blunt flaws having ZRH at notch-tips and agreement between theoretical and experimental predictions.

CONCLUSIONS

1. The experimental tests for obtaining of the zones with reoriented hydrides at blunt flaw tip in the Zr-2.5%Nb samples were performed. From metallographical analysis it was obtained characteristics of zones with reoriented hydrides at blunt flaw tips. A comparison with resulted predictions from stress analyses at notch-tips showed a good agreement.

2. Based on the embrittlement properties of mentioned zones, an “effective blunt flaw” assumption was proposed and consequences on the Failure Assessment Diagrams for DHC evaluations at blunt flaws were established.

REFERENCES

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