36th Annual Conference of the Canadian Nuclear Societyand 40th Annual CNS/CNA Student Conference
Toronto Marriott Downtown Eaton Centre Hotel, Toronto, ON, Canada, June 19-22, 2016

CONDITIONAL PROBABILITIES OF PRESSURE TUBE RUPTURE DURING LIMITING DESIGN BASIS TRANSIENTS AT REACTOR EARLY LIFE AND LATE LIFE

C.C.S. Manu[1], D.H.B Mok[1] and D. Pun-Quach[1]
[1]Major Component Engineering, Amec Foster Wheeler
christopher.manu@amecfw.com, danny.mok@amecfw.com, dan.punquach@amecfw.com

Abstract

The CSA Standard N285.8 requires evaluation of the service conditions for protection against pressure tube fracture using either a deterministic or probabilistic evaluation. Based on the results of a full core deterministic fracture protection evaluation, it is possible to identify limiting locations in the reactor core, i.e., the location at which it is most challenging to demonstrate fracture protection. The conditional probability of failure for a particular design basis transient, given a through-wall flaw, can be calculated at the limiting location. The ratio of the probabilities of rupture between reactor early life and late life could be used to investigate the effect of plant ageing on the stability of a postulated pressure tube crack. The results of an example calculation for a representative heatup/cooldown transient and a representative limiting Level C design basis transient are discussed in this paper.

1. Introduction

The Canadian Standards Association (CSA) Standard N285.8 "Technical requirements for in-service evaluation of zirconium alloy pressure tubes in CANDU reactors"[1] requires evaluation of the service conditions for protection against pressure tube fracture. The standard allows for either deterministic or probabilistic evaluation of fracture protection. Since it is deterministically challenging to demonstrate protection against through-wall penetration due to subcritical flaw growth for the entire core, a 20mm long through-wall flaw has been historically postulated for the deterministic evaluation of fracture protection for operating CANDU® pressure tubes. A full core deterministic fracture protection evaluation can be used to assess fracture protection under all service loading conditions along the entire length of each pressure tube of the core. Based on the results of the full core deterministic fracture protection evaluation, the limiting locations can be identified in the reactor core, i.e., the location at which it is most challenging to deterministically demonstrate fracture protection for a particular design basis transient assessed at a particular evaluation time. The conditional probability of failure for a particular design basis transient, given a through-wall flaw, can be calculated at the limiting location. This conditional probability of failure can be calculated for reactor early life conditions and late life conditions. The ratio of the probabilities of rupture between reactor early life and late life could be used to investigate the effect that plant ageing has on the stability of a postulated pressure tube crack. The results of an example calculation for a representative heatup/cooldown (HU/CD) transient and a representative limiting Level C design basis transient are presented and discussed in this paper.

2. Methodology

2.1 Full Core Deterministic Fracture Protection Evaluation

The evaluation of pressure tube fracture protection is primarily dependent on the pressure tube fracture toughness. Zr-2.5Nb pressure tube fracture toughness for a through-wall flaw is dependent on temperature, chlorine concentration and hydrogen equivalent concentration[1].

Fracture protection can be conservatively evaluated deterministicallyby postulating a through-wall flawat the pressure tube inlet (location of highest pressure), and applying bounding pressure tube dimensions and hydrogen equivalent concentrations in the evaluation [2].

To remove some of the conservatisms in the deterministic fracture protection evaluation, a full core deterministic fracture protection evaluation can be performed. In a full core deterministic fracture protection evaluation, the entire core is evaluated deterministically using location specific inputs where available. As such, the bounding internal pressure, pressure tube dimensions and hydrogen equivalent concentration are not artificially combined at a single postulated location. In a particular channel, the maximum pressure, most bounding pressure tube dimensions and minimum fracture toughness (maximum hydrogen equivalent concentration) may respectively be located in the inlet end, in the body of tube and in the outlet end of the channel.

The full core deterministic fracture protection evaluation postulates a 20 mm long axial through-wall flaw at regular intervals along the entire length of all of the pressure tubes in the reactor core. The critical pressures for flaw stability for each temperature condition of each design basis transient are calculated using the location specific hydrogen equivalent concentration ($[H]_{eq}$) and pressure tube dimensions at the end of the assessment period. The allowable pressures are calculated using the critical pressures and the appropriate safety factors. Deterministic fracture protection is demonstrated when the location specific applied pressures for each of the Service Loading conditions remains below the calculatedlocation specific allowable pressures.

The evaluation is complete when all the pressure tubes in the core are assessed (each pressure tube is assessed along its entire length). The limiting axial location is the location at which the margin between the allowable pressure and the applied (i.e. design basis Service Level transient) pressure is a minimum. The limiting location for each of the design basis transients may not necessarily be the same.

The critical pressurefor flaw stability is given by equations (1) and (2)[1].

$$P_c = \left(\frac{w}{w+r_i}\right)\left(\frac{2\sigma_f}{\pi M}\right)\cos^{-1}\left[e^{\left(\frac{\pi K_c^2}{8c\sigma_f^2}\right)}\right] \tag{1}$$

$$M = \sqrt{1 + 1.255\left(\frac{c^2}{r_m w}\right) - 0.0135\left(\frac{c^2}{r_m w}\right)^2} \tag{2}$$

Where, w = wall thickness of the pressure tube,r_i = inner radius of the pressure tube r_m = mean radius of the pressure tube,c = half length of the postulated axial through-wall flaw, σ_f = pressure tube transverse flow stress, M = bulging factor for the postulated axial through-wall flaw, K_c = pressure tube fracture toughness.

Deterministic fracture protection evaluations have been successfully used to define reactor operating envelopes, and thus have a good track recordfor providing operating CANDU reactors with adequate protection against pressure tube fracture which could occur due to the presence of an undetected severeflaw. However, the use of safety factors in deterministic assessment along with use of appropriate lower-bound and upper-bound inputs may lead to potentially restrictive assessment results (even with the full core deterministic fracture protection evaluation approach) due to the stack-up of conservatisms. It is generally accepted that probabilistic assessments, in which inputs may be treated as distributed quantities, provide a more representativeindication of component reliability and remaining life.

2.2 Probabilistic Fracture Protection Evaluation

An advantage of probabilistic assessments is the ability tobetter quantify component reliability. However, challenges of probabilistic assessments can include the determination of an appropriate acceptance criteria andthe establishment of assessment methodology. Therefore, it may also be useful to consider assessing how theprobability of pressure tube rupture increases due to reactor ageing. If the assumptions and calculation methodology are kept consistent, and multiple evaluation times are considered, it is possible to assess how the probabilities of rupture change over time.

For the example problem presented in this paper, the probabilistic fracture protection evaluation was executed as follows. Based on the results of the full core deterministic fracture protection evaluation, the limiting locations in the reactor core can be identified. The conditional probability of failurefor a particular design basis transient, given a through-wall flaw, can be calculated at the limiting location.The probabilistic fracture protection evaluation wasperformed using a Monte Carlo simulation in which the distributed (stochastic) variables in the evaluation were randomly sampled from their respective distributions. The simulated sets of variables were assessed using the deterministic fracture protection evaluation methodologyand the results of all the realizations were analysed.

The estimated conditional probability, $\hat{P}$, of a pressure tube failing to demonstrate fracture protection for a particular design basis transient,conditional upon having a through-wall flaw,is defined as the probability of the applied pressure, $P_{applied}$, exceeding or being equal to the critical pressure, P_c, for the limiting condition of a design basis transient. Since the sampling was performed using Monte Carlo simulation, the standard deviation, σ, of $\hat{P}$ is given as per equation (4).

$$\hat{P} = P\left(P_{applied} \geq P_c\right) \tag{3}$$

$$\text{with,} \quad \sigma = \sqrt{\frac{\hat{P}(1-\hat{P})}{N_{sim}}} \tag{4}$$

2.3 The Effect of Irradiation on the Fracture Properties of Pressure Tubes

The effect of irradiation on the fracture properties (fracture toughness, yield stress and ultimate tensile strength) of Zr-2.5Nb pressure tubes has been studied [3]. It was concluded that the fracture properties of pressure tubes saturate, i.e., do not change much with continued irradiation, after about half of year of irradiation in a typical CANDU reactor (in the high flux region of the core). In the ends of the pressure tubes where the flux is significantly lower saturation of fracture properties takes longer;approximately within about 2.5 years depending on the flux value. Therefore, using fully saturated fracture properties for the calculation of early life fracture protection is considered to be a reasonably valid approximation.

3. Example Problem and Results

An example problem was executed for discussion purposes.

The inputs used in the probabilistic fracture protection evaluation performed in this paper are summarized in Table 1. Monte Carlo simulation was used to perform the probabilistic fracture protection evaluations documented in this paper as Monte Carlo simulation can be used to estimate moderate to large failure probabilities [4].

Table 1: Inputs Used in the Sample Probabilistic Fracture Protection Evaluations

Input	Probabilistic EL	Probabilistic LL
Fracture toughness	As per CSA N285.8-15 (distributed) K_c is a function of $[H]_{eq}$, [Cl] and Temperature.	As per CSA N285.8-15 (distributed) K_c is a function of $[H]_{eq}$, [Cl] and Temperature.
$[H]_{eq}$	Tube specific initial concentration (non-distributed)	Appropriate $[H]_{eq}$ predictive model(distributed)
[Cl]	Appropriate [Cl] model (distributed)	Appropriate [Cl] model (distributed)
PT WT	As-installed (distributed)	Appropriate PT WT predictive model (distributed)
PT ID	As-installed (distributed)	Appropriate PT ID predictive model (distributed)
YS	Fully irradiated transverse YS (distributed)	Fully irradiated transverse YS (distributed)
UTS	Fully irradiated transverse UTS (distributed)	Fully irradiated transverse UTS (distributed)
Through-wall flaw length	20mm (non-distributed)*	20mm (non-distributed)*
Frequency of Transient Occurrence	Each assessed transient is assumed to occur at least once during the evaluation interval**	Each assessed transient is assumed to occur at least once during the evaluation interval**
Location in Reactor Core	Limiting location determined deterministically	Limiting locationdetermined deterministically

EL – Early Life; LL – Late Life; $[H]_{eq}$ – Hydrogen equivalent concentration; [Cl] – Chlorine concentration; PT WT – Pressure Tube Wall Thickness; PT ID – Pressure Tube Inner Diameter; YS – Yield Stress; UTS – Ultimate Tensile Strength.
* The through-wall flaw length could be treated as a distributed quantity, however, for the sake of simplicity the through-wall flaw length used in traditional deterministic fracture protection evaluations, 20mm, was used in the example problem presented in this paper.
** Assuming that a specific design basis transient occurs at least once during the evaluation interval is a simplifying assumption. For the HU/CD transient, this is a realistic assumption. However, for level C service loading transients this is overly conservative.

3.1 Early Life Conditional Probability of Pressure Tube Rupture

The estimated conditional probability of a pressure tube failing to demonstrate fracture protection during early life, $\hat{P}_{EL}$, is calculated for use as a baseline result. $\hat{P}_{EL}$was calculated at the location in the reactor core where it was most challenging to demonstrate fracture protection deterministically under early life conditions.$\hat{P}_{EL}$is defined as the conditional probability of the applied pressure, $P_{applied}$, exceeding or being equal to the critical pressure calculated under early life conditions, P_c^{EL}, for the limiting condition of a design basis transient.

A sample early life full core deterministic fracture protection evaluation was performed at 0 EFPH. The result of the early life full core deterministic fracture protection evaluation is quite intuitive; it is most challenging to demonstrate fracture protection during early life at the pressure tube inlet for both the

HU/CD and limiting level C transients. This is because the pressure of the primary heat transport system is the highest at the pressure tube inlet, pressure tube dimensions are approximately uniform along the length of the pressure tube at early life and the hydrogen equivalent concentration at early life is below 30ppm along the length of the pressure tube (for a given temperature, fracture toughness is expected to be approximately uniform along the length of the pressure tube). Therefore, at early life, it will be most challenging to demonstrate fracture protection at the pressure tube inlet due to the pressure loading being the highest at the pressure tube inlet. Assuming that the inlet pressure is constant for all pressure tubes, it will be equally challenging to demonstrate fracture protection for all pressure tubes in the reactor core.The limiting conditions, at the pressure tube inlet (the limiting location in the reactor core), of the HU/CD transient were found to be 75°C and 8.84MPa. The limiting conditions, at the pressure tube inlet (the limiting location in the reactor core), of the limiting level C transient were found to be 28°C and 11.49MPa.

A sample probabilistic fracture protection evaluation was performed at early life (0 EFPH) at the limiting location with the inputs listed in Table 1. The results of the early life probabilistic fracture protection evaluation are presented in Table 2.

Table 2:Sample Early Life Probabilistic Fracture Protection Results

Transient	N_{sim}	$\hat{P}_{EL}$	σ
HU/CD	100,000	~0*	N/A
Limiting Level C	10,000	0.027	0.00162

* On the order of 10^{-5} or less.

The early life conditional probability of failing to demonstrate fracture protection for the HU/CD transient is approximately 0. The deterministic evaluation of the HU/CD transient at early life has considerable margin even with the applied 1.3 safety factor. In the probabilistic evaluations, safety factors are not applied, i.e., applied pressure is compared to critical pressure in order to evaluate the pressure tube through-wall flaw stability. In the early life probabilistic evaluation of the HU/CD transient, no ruptures were predicted with 100,000 simulations. For assessments where the probability of failure is found to be extremely small, the realizations predicting rupture should be carefully reviewed to ensure that the simulated input variables have physically meaningful values.The early life conditional probability of failing to demonstrate fracture protection for the limiting level C transient wascalculated to be 0.027. Note that in general, level C service loading transients are expected to be rare events, thus assuming at least 1 occurrence of the transient in the evaluation interval is overly conservative.

3.2 Late Life Conditional Probability of Pressure Tube Rupture

The estimated conditional probability of a pressure tube failing to demonstrate fracture protection during late life, $\hat{P}_{LL}$, can be compared to $\hat{P}_{EL}$ to assess the increased likelihood of failing to demonstrate fracture protection. $\hat{P}_{LL}$ was calculated at the location in the reactor core where it was most challenging to demonstrate fracture protection deterministically under late life conditions. $\hat{P}_{LL}$ is defined as theconditional probability of the applied pressure, $P_{applied}$, exceeding or being equal to the critical pressure calculated under late life conditions, P_c^{LL}, for the limiting condition of a design basis transient.

The full core deterministic fracture protection evaluation for late life was performed at 245,000 EFPH. It was found that it was most challenging to demonstrate fracture protection deterministically at the pressure tube (pressure tube identity not disclosed in this paper) outlet for the HU/CD transientand in the body of tube region, approximately 3.6m from the inlet burnish mark, for the limiting level C transient.The limiting conditions of the HU/CD transient were found to be 75°C and 7.62MPa. The limiting conditions of the limiting level C transient were found to be 40°C and 11.66MPa.

A sample probabilistic fracture protection evaluation was performed at late life (245,000 EFPH) with the inputs listed in Table 1. The results of the late life probabilistic fracture protection evaluation are presented in Table 3.

Table 3:Sample Late Life Probabilistic Fracture Protection Results

Transient	N_{sim}	$\hat{P}_{LL}$	σ
HU/CD	100,000	~0*	N/A
Limiting Level C	10,000	0.076	0.00265

* On the order of 10^{-5} or less.

The late life conditional probability of failing to demonstrate fracture protection for the HU/CD transient is approximately 0 for the same reasons discussed for the results in section 3.1. The deterministic evaluation of the HU/CD transient at late life had sufficient margin with the applied 1.3 safety factor such that the probabilistic evaluation resulted in a probability of approximately 0.In the probabilistic evaluation of the HU/CD transient, no ruptures were predicted with 100,000 simulations. The late life conditional probability of failing to demonstrate fracture protection for the limiting level C transient was calculated to be 0.076.

3.3 Effect of the Number of Simulations Performed

The numerical stability of the results was investigated by varying the number of simulations performed. An example of such an investigation performed (1,000, 10,000 and 100,000 simulations) for $\boldsymbol{\hat{P}_{LL}}$ for the limiting level C transient is shown in Figure 1.

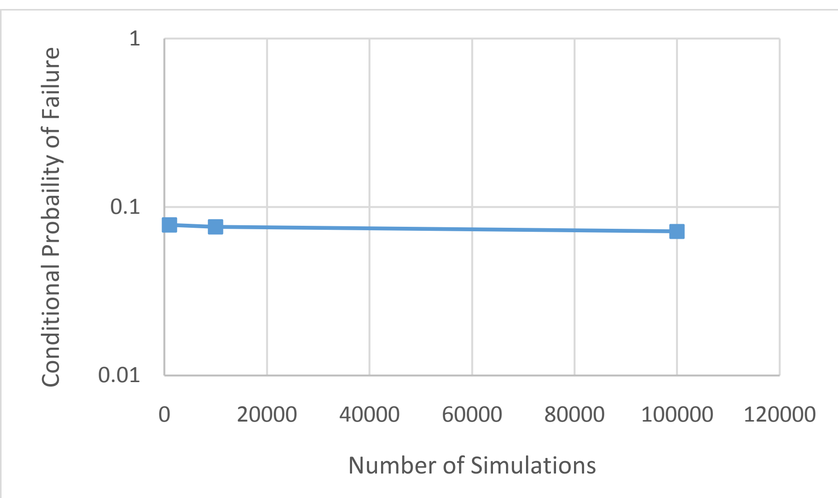

Figure 1: Effect of Varying the Number of Simulations

As seen in Figure 1, this probabilistic assessment does not require many simulations for the results to stabilize. All results presented in this paper are from assessments performed with 10,000 simulations unless otherwise stated.

3.4 Discussion

Sample probabilistic fracture protection evaluations were performed at the limiting locations in the reactor core for early life and late life conditions. The ratio of the late life to early life conditional probabilities, n_p, can be calculated to infer the increased likelihood of failing to demonstrate fracture protection due to pressure tube ageing, see equation (5) and Table 4.

$$n_p = \frac{\hat{P}_{LL}}{\hat{P}_{EL}} \tag{5}$$

Table 4:Sample Probabilistic Fracture Protection Results

Transient	n_p
HU/CD	N/A[1]
Limiting Level C	2.8

[1] Division by 0.

Table 4 shows that it was not possible to calculate $n_p$for the HU/CD transient as $\hat{P}_{EL}$was equal to 0 for the HU/CD transient. Therefore, the approach of calculating $n_p$cannot be applied to cases where significantmargin exists in the assessment. However, it is likely that such cases canbe successfully assessed deterministically, even at late life.

Table 4 shows that n_p was found to be 2.8 for the limiting level C transient.Therefore, due to pressure tube ageing, it is approximately 2.8 times more likely that a pressure tube would rupture due to a20mm through-wallflawexposed to the limiting level C transient in late life as compared to early life. The n_p value of 2.8 is difficult to put into perspective without reviewing similar results from various other probabilistic assessments, however, it is the authors' opinion that an $n_p$of 2.8 is a better than expected result given the 245,000 EFPH of ageing.

The sample evaluations performed assumed that every assessed transient occurred at least once during the evaluation interval, i.e., it was assumed that every postulated through-wall flawwas exposed to at least one occurrence of each assessed transient. However, if this assumption were changed the results of the assessment would be impacted. For further discussion, another sample evaluation will be considered solely for the limiting level C transient. If the probability ($P_{occurrence}$) of the limiting level C transient occurring was assumed to be 0.01 instead of at least 1, the results would be as per Table 5. It can be seen that the probability of transient occurrence significantly impacts $\hat{P}_{EL}$and$\hat{P}_{LL}$, however, in this case n_p remains unchanged.

Table 5:Sample Probabilistic Fracture Protection Results for the Limiting Level C Transient with Varying Assumptions

$P_{occurrence}$	$\hat{P}_{EL}$	$\hat{P}_{LL}$	n_p
1	0.027	0.076	2.8

0.01	0.00027	0.00076	2.8

A benefit of calculating n_p is that n_p is not as sensitive to assessment assumptions and methodology as $\hat{P}_{LL}$ since in the calculation of n_p, $\hat{P}_{LL}$ is normalized by $\hat{P}_{EL}$. Also, $n_p$provides insight into the effect that pressure tube ageing has on the stability of postulated cracks.

4. Conclusions

Deterministic fracture protection evaluations have been successfully used to define primary heat transport operating envelopes for CANDU reactors. However, the use of safety factors in deterministic assessment along with use of appropriate lower-bound and upper-bound inputs may lead to potentially restrictive assessment results due to the stack-up of conservatisms. It is generally accepted that probabilistic assessments, in which inputs may be treated as distributed quantities, provide a more representativeindicationof component reliability and remaining life. However, challenges of probabilistic assessments can include the determination of an appropriate acceptance criteria and methodology establishment. Therefore, when performing probabilistic pressure tube fracture protection evaluations it may also be useful to consider assessing the ratio of the late life to early life conditional probabilities of rupture, n_p, as it could be used to investigate the effect of plant ageing on the stability of postulated pressure tube cracks.

5. References

[1] Canadian Standards Association, N285.8-15, "Technical requirements for in-service evaluation of zirconium alloy pressure tubes in CANDU reactors", July 2015.

[2] P. Doddihal, D. Scarth, P. Mosbrucker, S. Xu, "Fracture Protection of CANDU Zr2.5-Nb Pressure Tubes with High Hydrogen Equivalent Concentration", Paper Number PVP2015-46000, Proceedings of 2015 ASME Pressure Vessels and Piping Conference, Boston, USA.

[3] Z.L. Pan, S. St Lawrence, P.H. Davies, M. Griffiths, S. Sagar, "Effect of Irradiation on the Fracture Properties of Zr-2.5Nb Pressure Tubes at the End of Design Life", Journal of ASTM International, Vol. 2, No.9, October 2005.

[4] J.M. Hammersley, D.C. Handscomb, "Monte Carlo Methods", Chapman and Hall, London, 1979.