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Probabilistic Fracture Mechanics applied for DHC Assessment in the Cool-Down transients for CANDU Pressure Tubes

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Work overview

- The structural integrity assessment of CANDU fuel channels is based on the technical requirements and methodology stated in the Canadian Standard N285.8. Usually it works with fracture mechanics principles in a deterministic manner.
- However, there are inherent uncertainties from the in-service inspection, which are associated with those from material properties determination, so a necessary conservatism in deterministic evaluation should be used.
- Probabilistic approach, based on fracture mechanics principles and appropriate limit state functions defined as fracture criteria, is a promising complementary way to evaluate structural integrity of CANDU pressure tubes.
- To perform this, it is necessary to account for the uncertainties that are associated with the main parameters : flaws distribution and sizing, initial hydrogen concentration, fracture toughness, DHC rate, dimensional changes .
- Present work describes a probabilistic approach of pressure tube failure by DHC mechanisms during the cool-down cycles by using probabilistic fracture mechanics principles and the Monte Carlo method.

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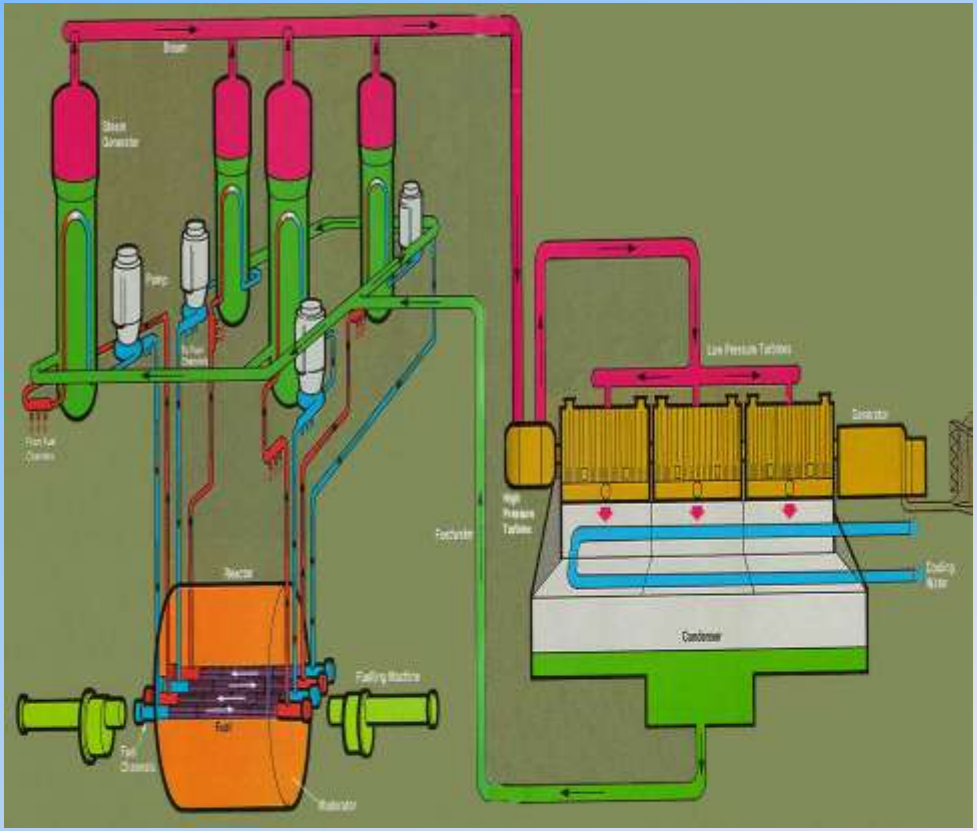
Short background on DHC (1)

CANDU 6 design

- 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.



Short background on DHC (2)

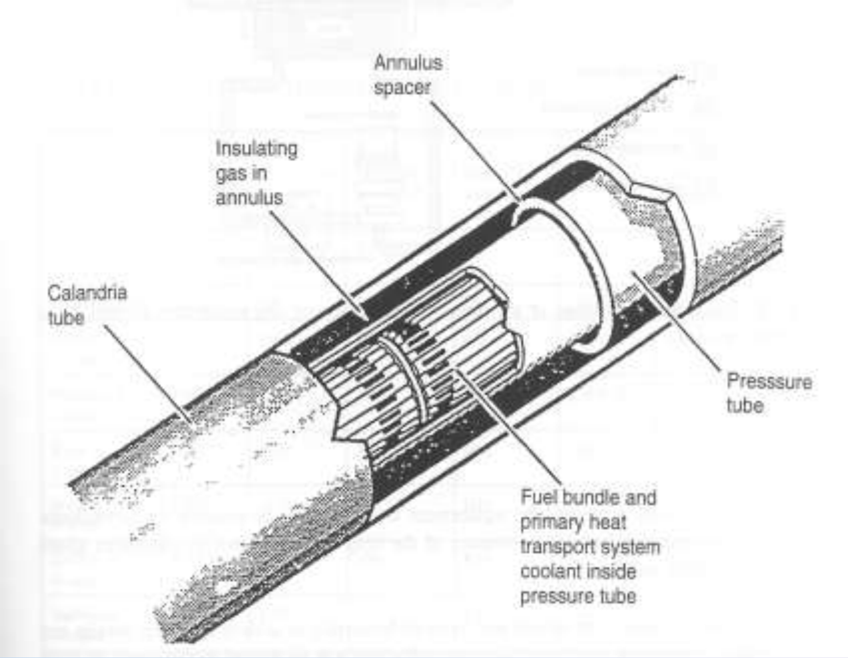
Fuel Channel Damage Mechanisms

- The main factors affecting CANDU P/Ts from fuel channels are:
  - Dimensional changes (irradiation creep and growth);
  - Hydrogen/Deuterium ingress in P/T (corrosion);
  - Fracture toughness reduction (embrittlement);
  - Service induced damage (scratches from refueling);
  - End fitting degradation .

Short background on DHC (3)

P/T - main characteristics

- P/T from fuel channel:
  - -12 fuel bundles
  - - coolant D2O (10 MPa pressure)
- The temperature range:
  - 260° C (inlet) - 310° C (outlet)
- Pressure tubes:
  - - cold-worked Zr-2.5%Nb alloy
  - - wall thickness = 4 mm
  - - inside diameter =103 mm



Short background on DHC (4)

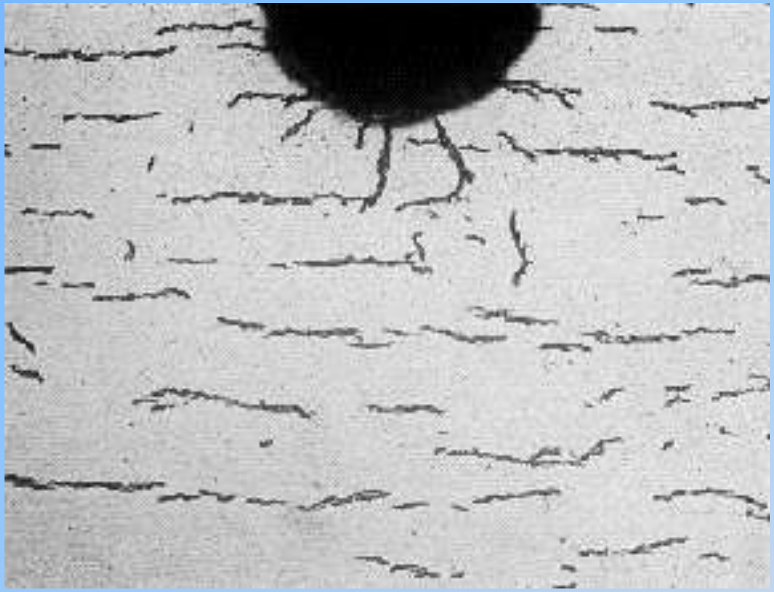
Deuterium ingress and DHC mechanism

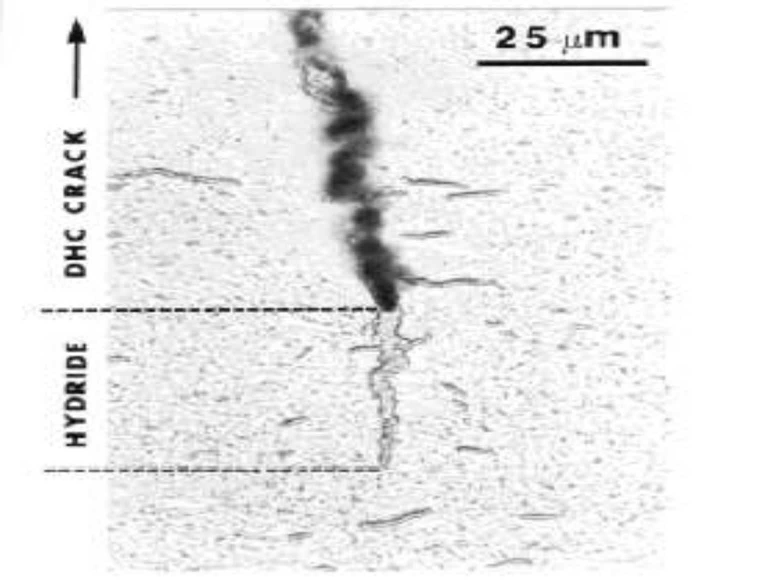
- Over time, CANDU P/Ts are susceptible to a slow corrosion process and gradual pickup of deuterium in the tubes.
- When the hydrogen/deuterium concentration exceeds TSS, the P/Ts are susceptible to a crack initiation and propagation process called DHC.
- DHC process consists in the diffusion of the hydrogen (or deuterium) atoms to a high tensile stress spots of the tube, such as at crack or notch tips loaded by tensile hoop stress.
- The in-service flaws are evaluated using fitness-for-service procedures to justify further operation of pressure tube containing the flaws.

Short background on DHC (5)

Steps of the DHC mechanism

1. - the crack/notch tip hydride grows to a critical size;
2. - the "radial" hydrides are fractured;
3. - the crack grows and the described process would repeat itself .



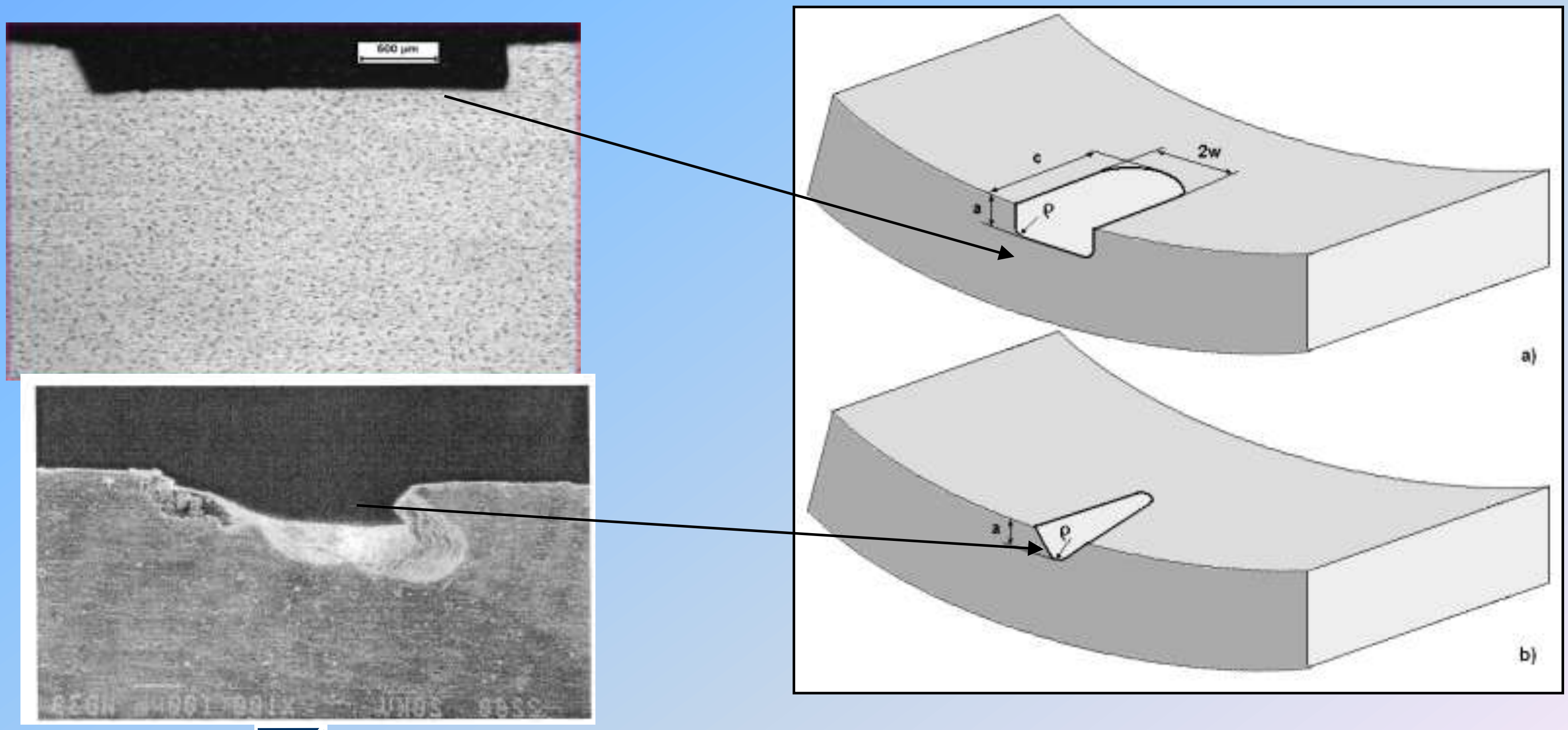


Short background on DHC (6)

Blunt flaws modeling and assessment

The flaws found during ISI of Zr-2.5%Nb CANDU P/Ts include:

- The fuel bundle bearing pad fretting flaws (BPF);
- The debris fretting flaws (DFF).



DHC crack growth model in cool-down cycles (1)
Past experience in the field

- The past operating experience of CANDU pressure tubes reveled that 8% of inspected tubes were affected by flaws larger than allowable limits, and 60% from these were made by debris or by bearing pad fretting.
- The blunt flaw tip is susceptible to hydride platelets formation due to hydrogen atoms diffusion towards the peak stress until the terminal solid solubility limit is reached.
- The hydride platelets are brittle and in the case of higher stress intensity factor, K_I, exceeding the threshold value, K_{IH}, the crack initiates and propagates by mechanism called DHC.

DHC crack growth model in cool-down cycles (2)

The formalism of structural reliability analysis

- In the fundamental case the reliability of a structure is determined by load effect variable(S) and a resistance effect variable (R). The limit state function is:

$$g(R,S) = R - S \le 0$$

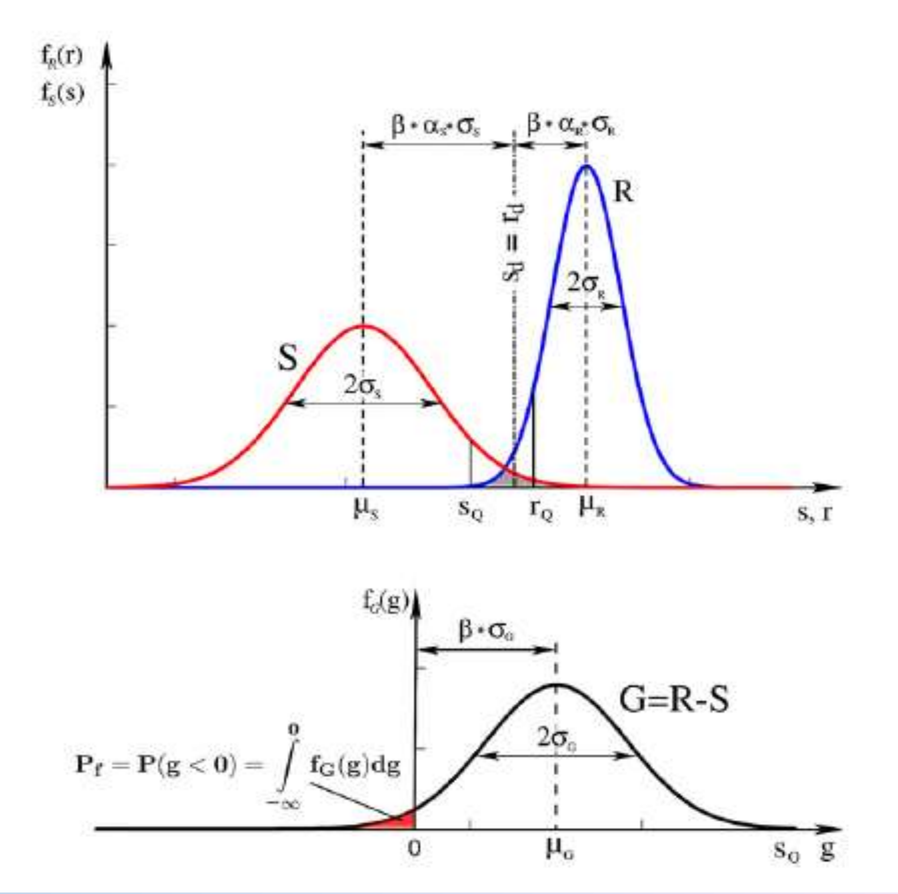
- With the pdfs pS(S) and pR(R) , the probability of failure is give by:

$$P_f = P\{R - S \le 0\} = \int_{-\infty}^{\infty} F_R(x)\, p_S(x)\, dx$$

  - with FR(x) is probability of resistance less than x.

- The safety index β is equivalent to the inverse variation coefficient of the limit state function:

$$\beta = \frac{\mu_g}{\sigma_g} = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}$$



DHC crack growth model in cool-down cycles (3)
Crack growth model

- In the present approach the model considers that the crack growth by DHC is realized during a each cool-down cycle in the pressure tube body region, where hydrogen concentration exceeds TSSD limit, starting from a initial surface flaw.

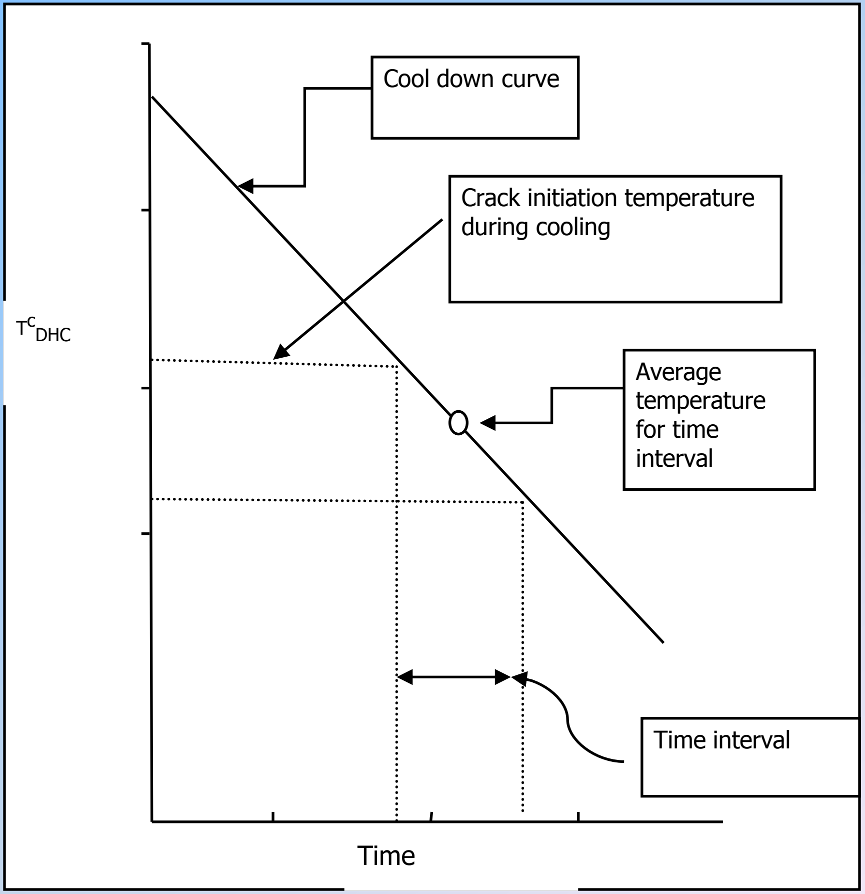
- In the first step of any structural integrity analysis of CANDU pressure tube it is important to define an evaluation period, at the end of which the technical requirements, as they are stated in standard [1], must be satisfied.

- The maximum value of evaluation period is 2 years (1 year ≅ 8760 hot hours); for sensitivity analysis reason, in the present work a maximum evaluation period of 3 years is considered too.

- *Ref. [1] CAN/CSA N285.8, Technical Requirements for In-Service Evaluation of Zirconium Alloy Pressure Tubes in CANDU Reactors, 2005*

DHC crack growth model in cool-down cycles (4)
Deterministic approach

- In the deterministic approach a surface planar flaw is analyzed in the actual location of pressure tube.
- The deterministic methodology has the following steps:
  - the number of cool-down transients, N_{tr}, are identified for DHC crack growth corresponding to evaluation period;
  - for reactor cool-down transient *j*, the temperature versus time relationship shall be determined, as illustrated;
  - the amount of crack growth by DHC for each cool-down cycle is obtained by integrating the isothermal crack growth rate equation according to the temperature versus time history.



DHC crack growth model in cool-down cycles (5)
Deterministic approach

- When K_I is greater than or equal to K_{IH}, DHC crack growth during the cool-down transient shall be evaluated in accordance with technical requirements.

- The dimensions of crack are calculated on both directions (radial and circumferential) and the crack growing by DHC is cumulated for all cool-down transients defined for the evaluation period.

- Finally, the acceptance criteria are verified as they are specified in Canadian Standard N285.8.

Material properties and derived quantities for probabilistic approach (1)

Geometry and material

- The present probabilistic approach, uses the deterministic and probabilistic quantities (provided by N285.8-05, and other from open literature).
- For geometry characteristics : the inner radius of pressure tube of 52.0 mm and wall thickness of 4.2 mm.
- Dimensional changes during normal operation are: the maximum wall thinning rate of 0.03mm/year and diameter increasing rate is 0.11 mm/year.
- The mechanical properties: Young's modulus of E=101.7 GPa at 50ºC and E=91.7 GPa at 300ºC, Poisson's coefficient ν=0.3.
- Flow stress is considered a probabilistic variable characterized as follows:
  - normal distribution of probability density function (pdf),
  - mean of 1063.3 MPa,
  - standard deviation of 55.4 MPa,
  - minimum value of 600 MPa, and
  - maximum value of 1400 MPa.

Material properties and derived quantities for probabilistic approach (2)
Quantities that influence DHC

- TSSD (terminal solid solubility for hydrogen dissolution)

$$TSSD = 8.19 \times 10^{4} \exp\left(-\frac{34500}{RT} \right) \quad (ppm)$$

- Equation gives the possibility to infer the T_{TSSD} temperature, but also of T^{c}_{DHC} temperature, from which starts the hydrides precipitating in continuously cooling, when the hydrogen concentration in the tube body is known.

Material properties and derived quantities for probabilistic approach (3)
Quantities that influence DHC

- K_{IH} (the threshold isothermal stress intensity factor for the onset of DHC from a crack); The lower-bound value of K_{IH}, is supposed to be a deterministic parameter, with value of K_{IH}=4.5 MPa√m.

- K_i (the lower-bound critical stress intensity factor for fracture initiation or lower-bound fracture toughness);.

- For fracture toughness, K_i, in the radial direction, the probabilistic modeling considers:
  - a log-normal distribution of probability density function,
  - with the mean of 67.0 MPa√m,
  - standard deviation of 12.0 MPa√m,
  - minimum value of 20.0 MPa√m,
  - and maximum value of 120.0 MPa√m.

Material properties and derived quantities for probabilistic approach (4)

Quantities that influence DHC

- For DHC crack growth rate in radial direction of pressure tube (Zr-2.5%Nb) the temperature dependence is given by

$$v_r\left(T\right) = v_{ro} \cdot \exp\left(-\frac{56098}{RT}\right)$$

  - probabilistic characteristics of v_{ro} : a log-normal distribution of pdf; mean of $5.30 \cdot 10^{-2}$m/s, standard deviation of $0.58 \cdot 10^{-2}$m/s, min value of $2.0 \cdot 10^{-2}$m/s ; max value of $14.0 \cdot 10^{-2}$m/s.

- In the case of axial direction the DHC crack growth rate depends on the temperature

$$v_a\left(T\right) = v_{ao} \cdot \exp\left(-\frac{41445}{RT}\right)$$

  - v_{ao} log-normal distribution of pdf; mean of $2.40 \cdot 10^{-3}$m/s, standard deviation of $0.48 \cdot 10^{-3}$m/s, minimum value of $1.0 \cdot 10^{-3}$m/s and maximum value of $5.0 \cdot 10^{-3}$m/s.

Material properties and derived quantities for probabilistic approach (5)

Other quantities

- Pressure of coolant with a value of 10.4 MPa, which is constant during the whole cool-down transient (conservative approach);
- The initial concentration of hydrogen characterized by:
  - a normal probability density function, with the mean of 8.3 ppm, the standard deviation of 2.65 ppm, the minimum value of 5.0 ppm and maximum value of 15.5 ppm;
- The deuterium up-take rate is constant of 1.2 ppm/year ;
- The initial crack shape ($a/2c$):
  - exponential probability density function, mean of 0.12, minimum value of 0.1 and maximum value of 1.0;
- The initial crack depth to wall thickness ratio (a/w):
  - log-normal probability density function, mean of 0.1, standard deviation of 0.08, minimum value of 0.01 and maximum value of 0.5.

Probabilistic model for P/T failure by DHC (1)

Limit state functions based on Canadian standard N285.8-05

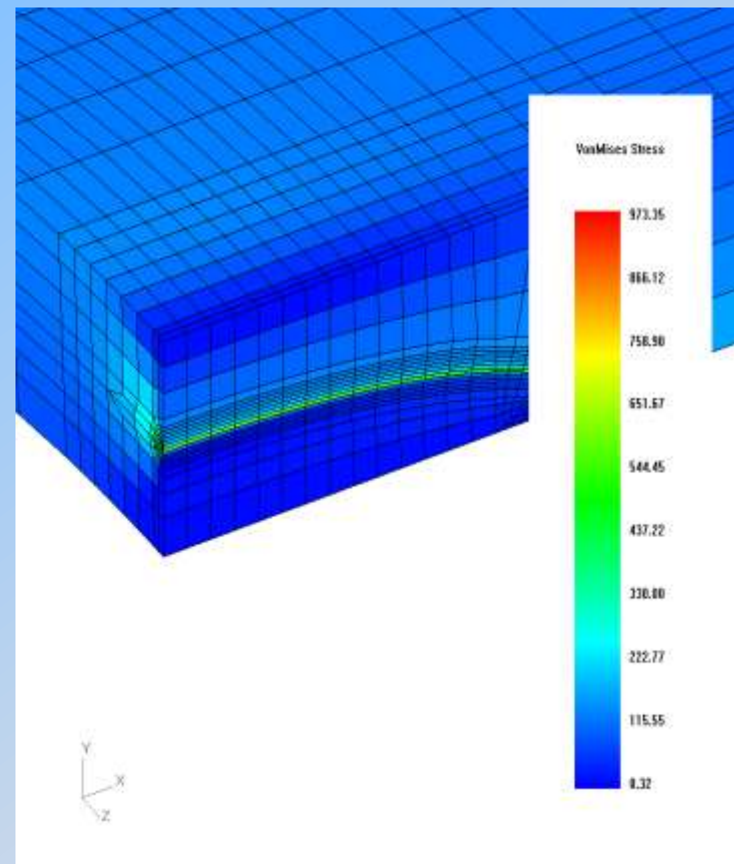
- The fracture initiation criterion, after crack propagation by DHC during a cool-down transient is given by the following limit state function:

$$g_1 \; K_I \; = \frac{K_i}{SF_{\;F}} - K_I$$

$$K_I = \left[p\left(\frac{r_i}{w} + 1\right) F_p + \sigma_h^{res} F_m \right] \left(\frac{\pi a}{Q}\right)^{1/2}$$

- To evaluate the plastic collapse condition in the case of a crack in the axial-radial plane, the criterion used is

$$g_2 \; \sigma_h^p \; = \frac{\sigma'_h}{SF_{\;C}} - \sigma_h^p$$



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Probabilistic model for P/T failure by DHC (2)

Limit state functions based on BP R6 and reserve factors in FAD

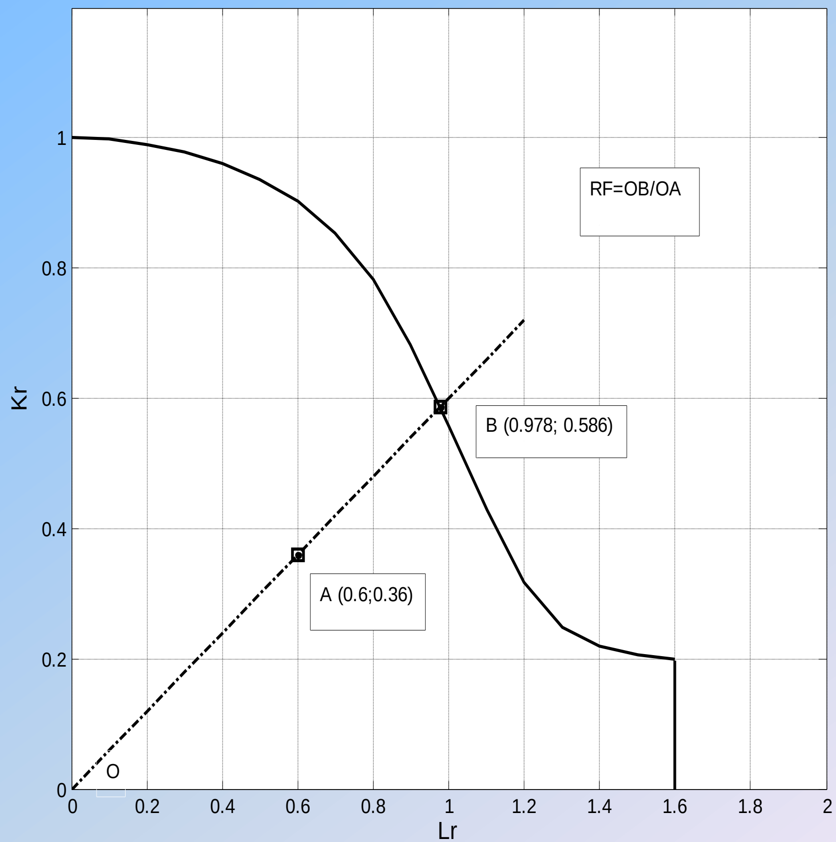
- The limit state function based on R6 failure criteria is build up with the help of reserve factors, and accounting the safety factor with the same vales of 3 as for g_1 and g_2, by the Equation:

$$g_3(RF) = 1 - \frac{3}{RF}$$

$$RF = \frac{OB}{OA} = \frac{\sqrt{\left(K_r^{FAC}\right)^2 + \left(L_r^{FAC}\right)^2}}{\sqrt{\left(K_r^{A}\right)^2 + \left(L_r^{A}\right)^2}}$$

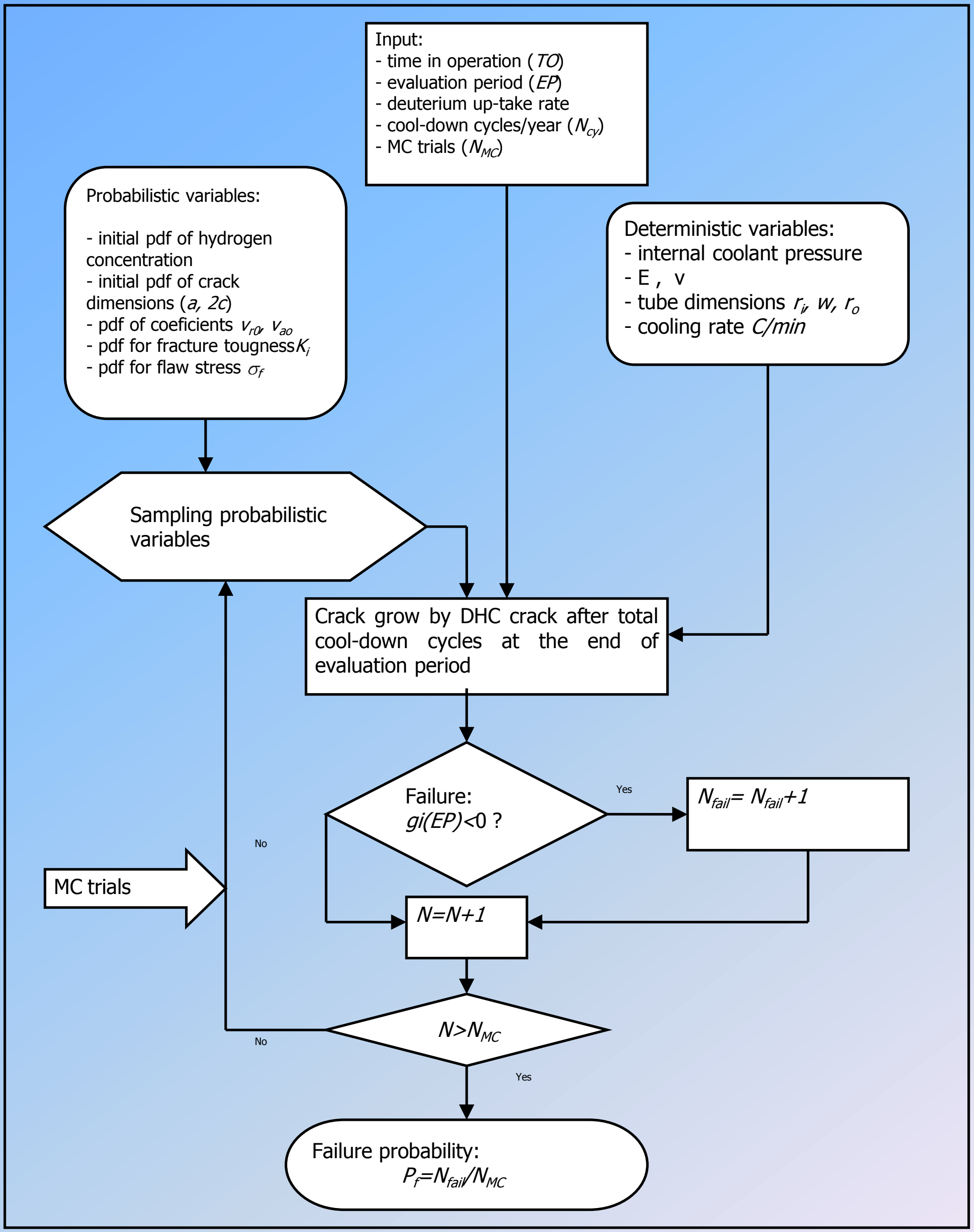
- The Option 1 general FAD

$$K_r = f_1(L_r) = \frac{\left[0.3 + 0.7 \cdot \exp\left(-0.06 L_r^6\right)\right]}{\sqrt{1 + 0.5 L_r^2}}$$



Probabilistic model for P/T failure by DHC (3)

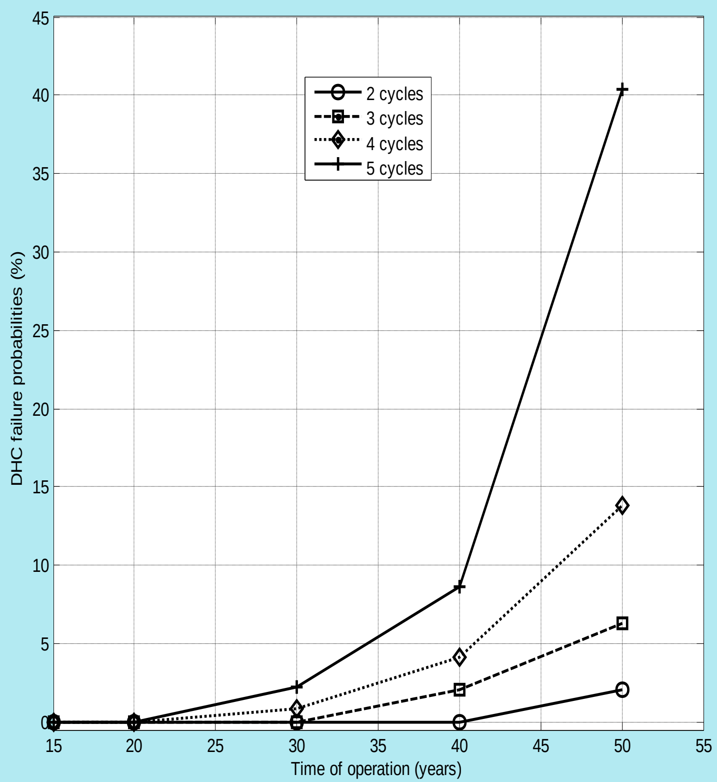
Flow chart

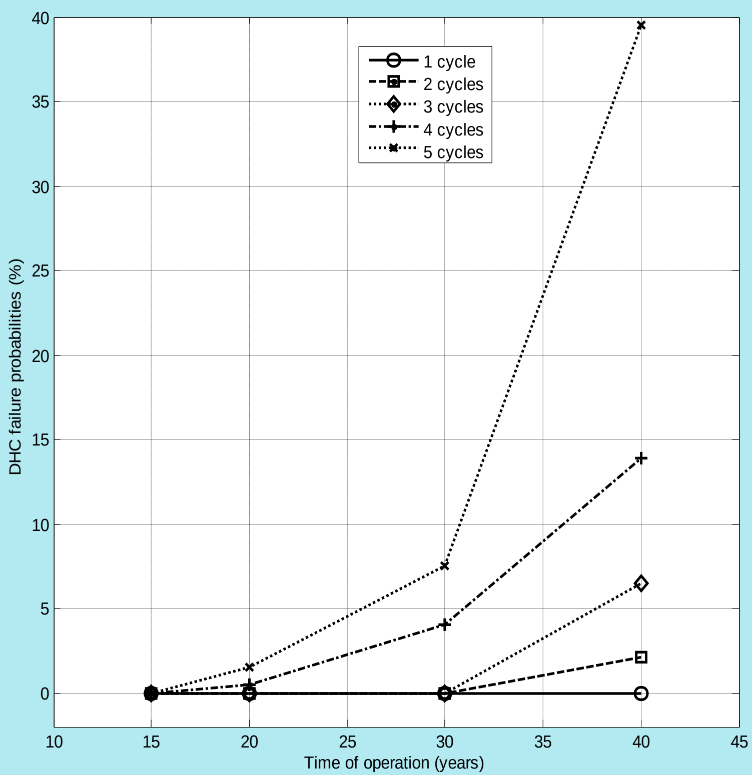


Results (1)

- The time in operation of pressure tubes, which provides the initial equivalent hydrogen concentration at the beginning of the evaluation period, has values in the range of 10 to 50 years.
- For the evaluation period, three values are considered here: 1 year, 2 years and 3 years, and the final dimensions of cracks, propagated by DHC.
- In terms of number of cool-down cycles, during a 30 years lifetime of pressure tubes the maximum value is around 250, and should be less than 3 cool-down cycles/year. However, the consequences of a number of 4 and 5 cycles /year are investigated here to obtain the tendency of probability of pressure tube failure.
- To obtain the convergent probabilities of failure the Monte Carlo number of trials used here is in the range of 10^4-10^6.

Results (2)

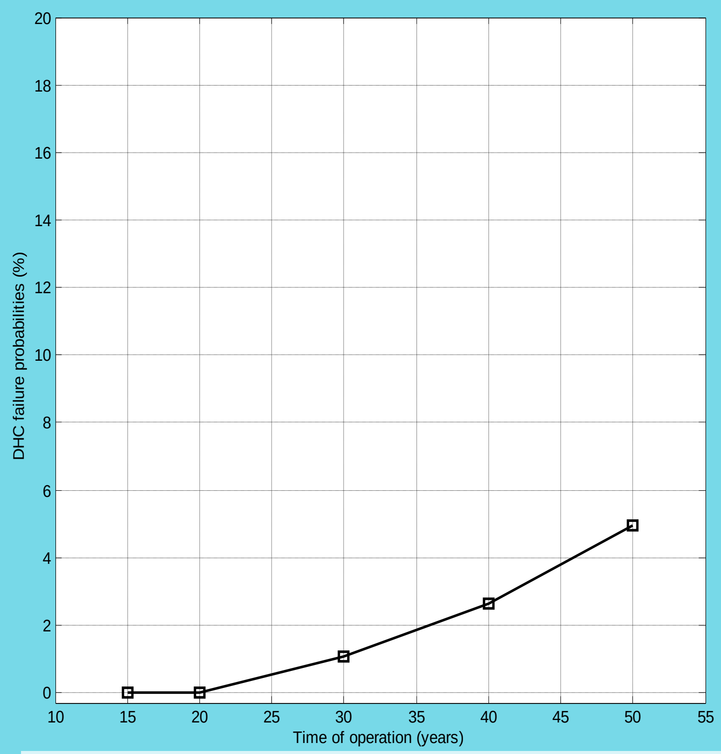




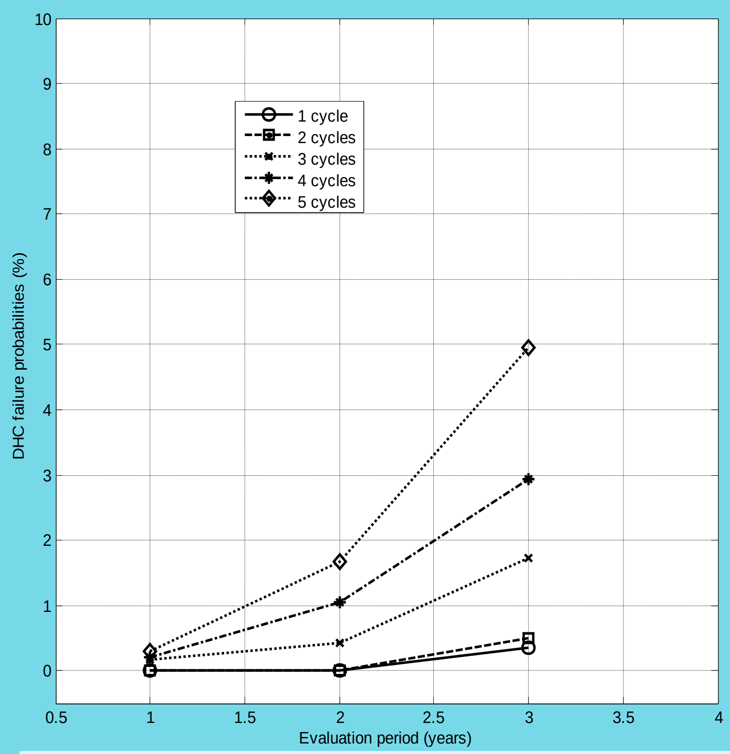
DHC failure probabilities versus time of operation, 2 years evaluation period, limit state functions defined in line with N285.8 requirements

DHC failure probabilities versus time of operation, 3 years evaluation period, limit state functions defined in line with N285.8 requirements

Results (3)



DHC failure probabilities versus time of operation, 3 years evaluation period, 5 cycles/years, limit state function based on reserve factors in FAD (R6)



DHC failure probabilities versus evaluation time, for 50 years operation period, limit state function based on reserve factors in FAD (R6)

Conclusions

- The paper develops a probabilistic approach of structural integrity for CANDU pressure tubes based on the probabilistic fracture mechanics principles and Monte Carlo method.
- The limit state functions, requested to characterize the DHC failure during cool-down cycles, are defined for unstable fracture and plastic collapse by using the technical requirements of Canadian standard N285.8-05 and the reserve factors in the FAD methodology from R6 British Procedure at the same safety factor.
- The values for deterministic and probabilistic variables are collected from open literature and Canadian standard and explicit exposed.
- The DHC failure probabilities are calculated for normal values of lifetime and evaluation period of CANDU pressure tubes, but also few more extension of them are investigated, for sensitivity and trend reasons.
- The results are in allowable prescript limits for CANDU pressure tube failure probabilities, and show a more conservative coverage by Canadian standard versus R6 methodology.

Thank you for your attention !