Excellence through Collaboration

Probabilistic Fracture Protection Methodology and Acceptance Criteria for CANDU Zr-Nb Pressure Tubes

Doug Scarth and Leonid Gutkin
Kinectrics, Inc., Toronto, Ontario, Canada

Danny Mok and Chris Manu
Amec Foster Wheeler, Toronto, Ontario, Canada

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- Probabilistic core assessments of fracture protection
- Design-intent acceptance criteria for probabilistic fracture protection
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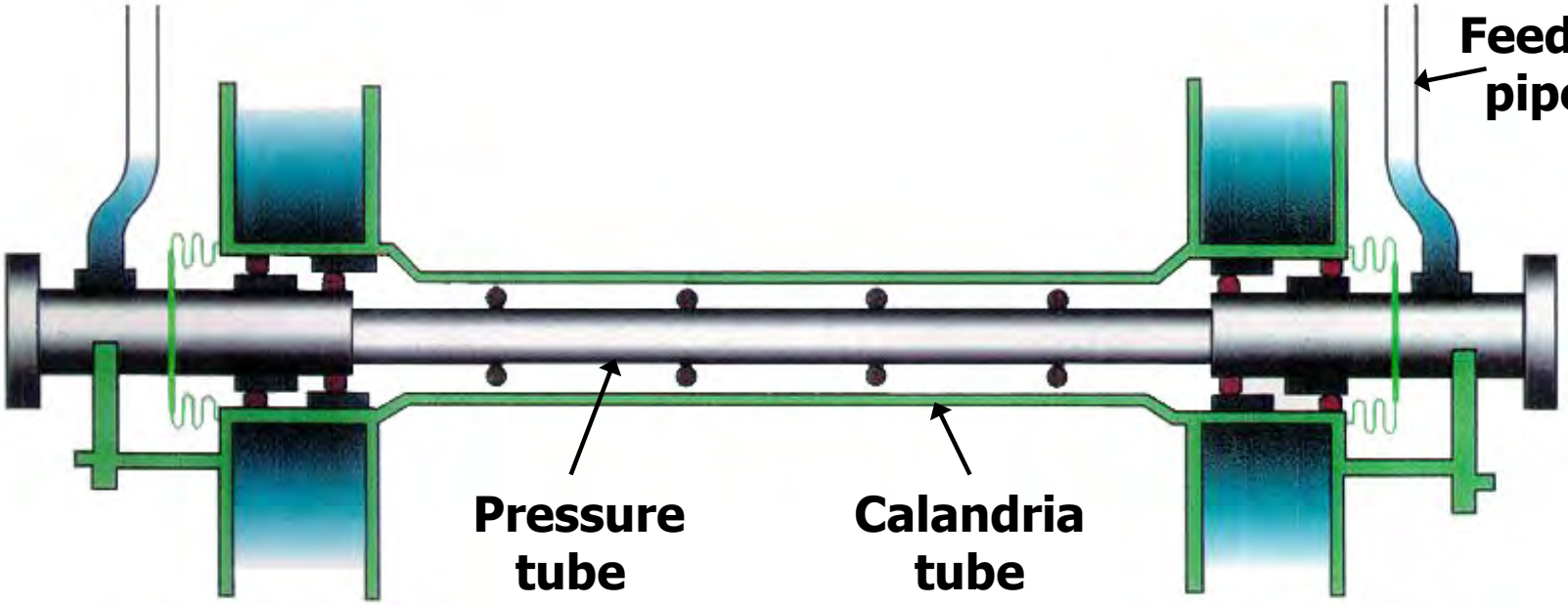
Introduction



CANDU Reactor Fuel Channel

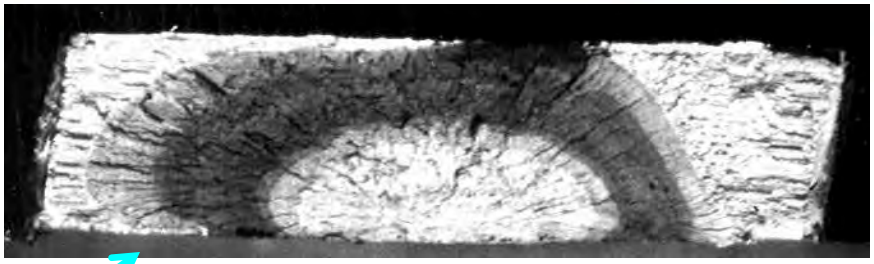
Introduction

- Requirements for pressure-temperature limits to protect against pressure tube rupture are provided in the *Canadian Standards Association* (CSA) Standard N285.8
  - Based on a stability evaluation of a postulated axial through-wall flaw for all ASME Service Level A, B, C and D loadings
- Deterministic evaluations contain safety factors on internal pressure to ensure a very low probability of pressure tube rupture
- Flaw stability evaluation is dependent on fracture toughness
  - Equivalent hydrogen concentration of pressure tubes is increasing with operating hours, and this results in a decrease in fracture toughness
- Compounding conservatisms based on using bounding values make deterministic evaluations more challenging

Introduction

- CSA N285.8 permits probabilistic evaluations of fracture protection
  - Alternate method to explicitly demonstrate a very low probability of pressure tube rupture
- Efforts are underway to develop a methodology and acceptance criteria for performing probabilistic evaluations of fracture protection
  - Proposed methodology based on probabilistic core assessments of flaws has been developed
  - Proposed acceptance criteria for probabilistic evaluations of fracture protection that meet intent of design basis for pressure tubes have also been developed

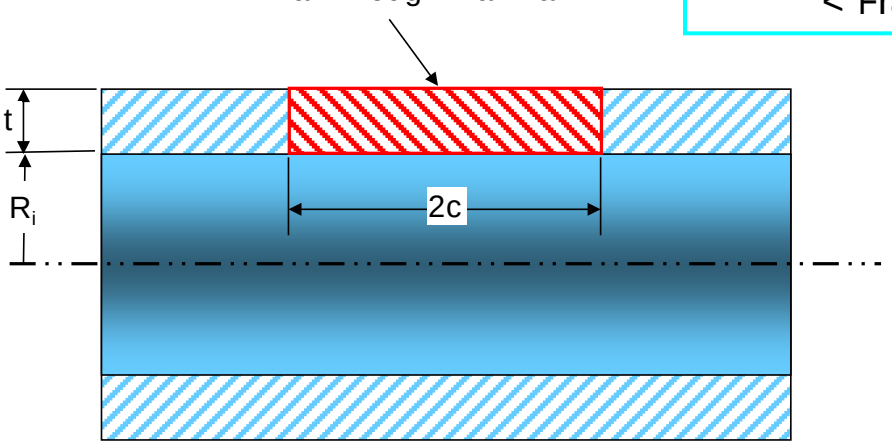
Background to Fracture Protection



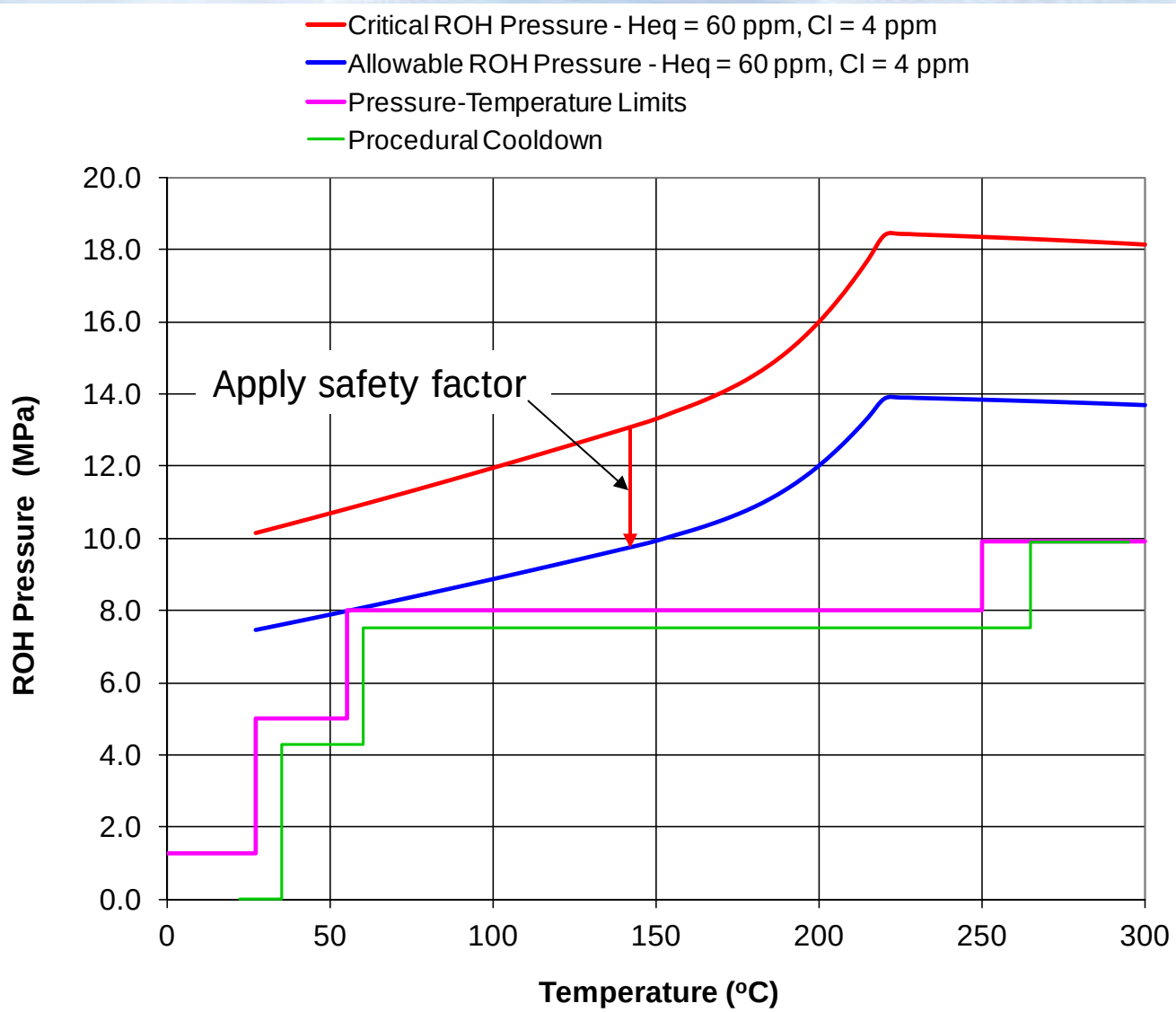
DHC Crack in Rolled Joint of Pressure Tube

Fracture Protection:

Applied stress intensity factor < Fracture toughness



Ex-Service Delayed Hydride Cracking (DHC) Crack and Postulated 20 mm Long Axial Through-Wall Flaw used in Deterministic Fracture Protection Evaluation



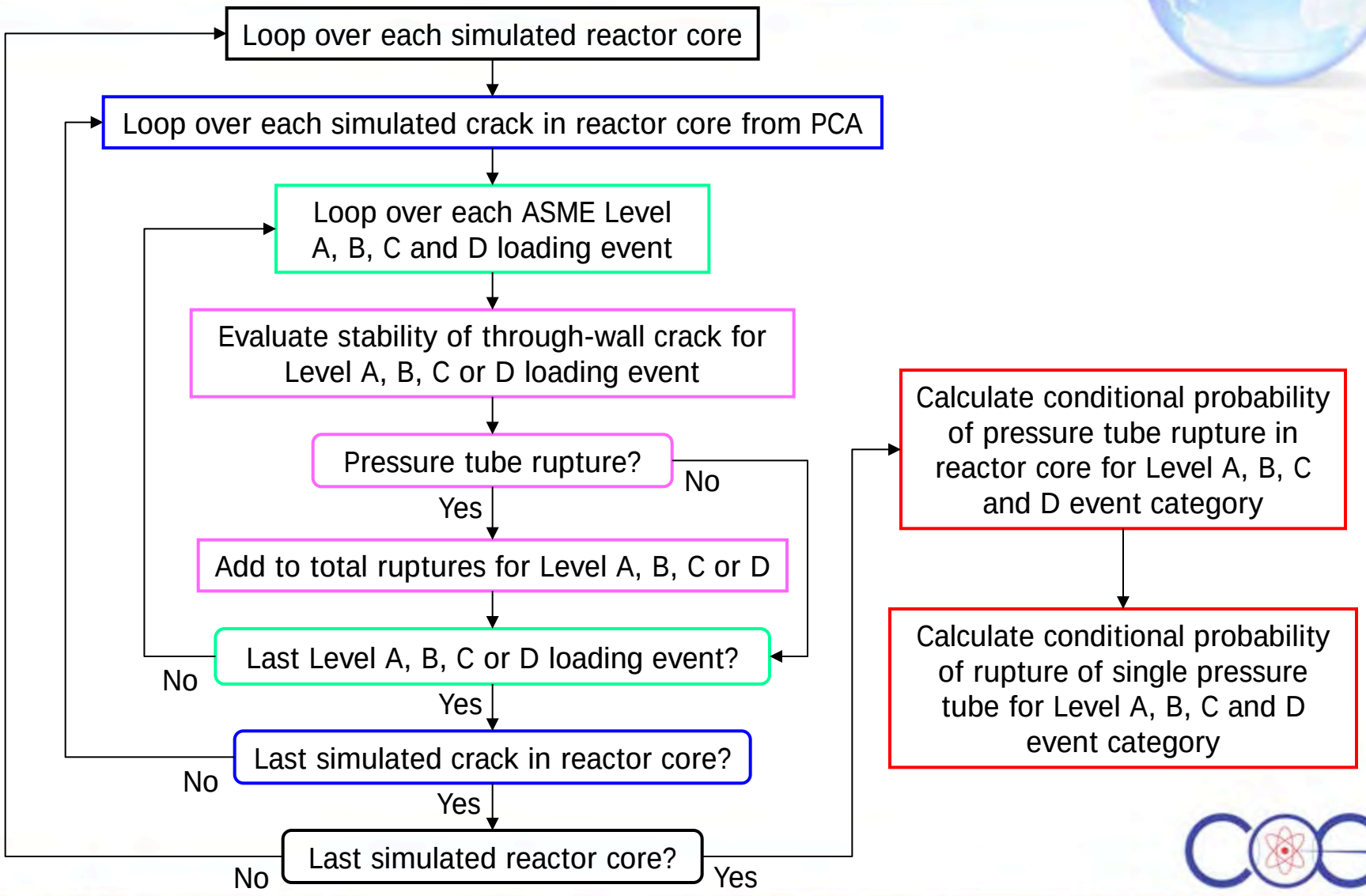
Development of Pressure-Temperature Limits for Reactor Heatup and Cooldown Based on Deterministic Criteria

Background to Fracture Protection

Comparison of Deterministic and Probabilistic Fracture Protection

Item	Deterministic Evaluation of Fracture Protection	Probabilistic Evaluation of Fracture Protection
Inputs (e.g. postulated flaw length)	Deterministic, bounding	Distributed, sampled statistically
Derived parameters from models (e.g. fracture toughness)	Deterministic, bounding	Distributed, sampled statistically
Acceptance criteria	Maximum allowable pressure = (critical pressure)/(safety factor)	Maximum allowable conditional probability of pressure tube rupture
Output	Critical pressure at flaw instability and allowable pressure	Conditional probability of pressure tube rupture

Probabilistic Core Assessments of Fracture Protection



Probabilistic Core Assessments of Fracture Protection

- Material properties and flaw attributes are randomly sampled from probability distributions and models using Monte Carlo method
- Key parameters sampled include:
  - Pressure tube dimensions
  - Yield strength, ultimate tensile strength, fracture toughness
  - Length and location of axial through-wall crack
  - Hydrogen equivalent concentration and chlorine concentration
- Stability of all simulated cracks in reactor core is evaluated for all Service Level A, B, C and D loading events using end-of-evaluation-period conditions
- Frequencies of occurrence of transients are simulated
  - Frequencies of occurrence decrease from Level A to Level D

Design-Intent Acceptance Criteria for Probabilistic Fracture Protection

- Acceptance criteria for probabilistic evaluations of fracture protection that meet design intent of pressure tubes have been developed
- Maximum allowable conditional probability of pressure tube rupture was developed for entire reactor core
- Maximum allowable conditional probability of rupture of a single pressure tube was also developed
  - Ensure that conditional probability of rupture of any single pressure tube does not make a disproportionate contribution to probability of pressure tube rupture for reactor core
- Acceptance criteria are not applicable to manufacturing flaws or hydride blisters

Design-Intent Acceptance Criteria for Probabilistic Fracture Protection

Review of design intent of pressure tubes – based on ASME B&PV Code

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ASME B&PV Code design rules are based on a single component

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Design intent for a single pressure tube was extended to population of pressure tubes in reactor core to develop *Reactor Core-based* acceptance criteria

↓

Acceptance criteria are in terms of:

- Maximum allowable conditional probability of rupture of any pressure tube in the reactor core
- Maximum allowable conditional probability of rupture of a single pressure tube in the reactor core

Development of Acceptance Criteria for Reactor Core

Design-intent maximum allowable frequency of a single pressure tube rupture, $f_{all}[\mathrm{PT_{rupt}}]$

Number of pressure tubes in reactor core, N_{PT}

Frequency of formation of axial through-wall flaw in reactor core based on OPEX, F_{TWF}

Require:

Frequency of pressure tube rupture = design-intent maximum allowable frequency

$$Pr_{all}\left[\mathrm{PT_{rupt}} \mid \mathrm{TWF}\right] = \frac{N_{PT}}{4}\frac{f_{all}[\mathrm{PT_{rupt}}]}{F_{TWF}}$$

Maximum allowable conditional probability of rupture for reactor core, $Pr_{all}[\mathrm{PT_{rupt}}|\mathrm{TWF}]$

Development of Acceptance Criteria for Reactor Core

- Design-intent maximum allowable frequency of rupture of a single pressure tube, $f_{all}[PT_{rupt}]$, was taken from work related to the ASME Code
- Cumulative probabilities of failure over one year that are implicit in ASME Code deterministic acceptance criteria are:
  - 10^{-7} through 6×10^{-6} for reactor pressure vessels
  - 10^{-6} for piping welds
- A cumulative probability of 10^{-6} over one year was used for pressure tubes
  - Corresponding implicit frequency of pressure tube rupture is 10^{-6} events per pressure tube year
  - $f_{all}[PT_{rupt}] = 10^{-6}$ events per pressure tube year

Development of Acceptance Criteria for Reactor Core

- Since entire population of pressure tubes in reactor core is evaluated, calculated conditional probability of pressure tube rupture for reactor core will reflect an integrated value for all pressure tubes
  - Tube-to-tube variability in the conditional probability of pressure tube rupture
- To address tube-to-tube variability, frequencies of rupture for all Service Level A, B, C and D loadings were combined into a total frequency that must not exceed design-intent maximum allowable
  - Reduces allowable conditional probability by factor of 4

Development of Acceptance Criteria for Reactor Core

- Frequency of formation of an axial through-wall flaw, F_{TWF}, was estimated based on OPEX with Canadian CANDU plants using reliability acceptance testing methodology
- No service-induced through-wall leakage has been detected in current vintage of operating pressure tubes
- Estimate of F_{TWF} is based on postulate that one axial service-induced through-wall flaw had previously formed in a pressure tube
- Upper-bound estimate of F_{TWF} is 0.0116 events per equivalent full-power reactor year at the confidence level of 95%

Development of Acceptance Criteria for Reactor Core

Calculated and Recommended Maximum Allowable Conditional Probabilities of Pressure Tube Rupture for Reactor Core

Reactor Type	Number of Pressure Tubes in Reactor Unit, N_{PT}	Allowable Frequency of Rupture of Single Pressure Tube, $f_{all}[PT_{rupt}]$ (per pressure tube year)	Calculated Allowable Conditional Probability of Pressure Tube Rupture, $Pr_{all}[PT_{rupt}\|TWF]$	Recommended Allowable Conditional Probability of Pressure Tube Rupture, $Pr_{all}[PT_{rupt}\|TWF]$
Bruce A, Bruce B or Darlington	480	1.0×10^{-6}	0.0103	0.01
Pickering	390	1.0×10^{-6}	0.0084	0.01

Development of Acceptance Criteria for a Single Pressure Tube

Frequency of formation of axial through-wall flaw in a single pressure tube based on OPEX, f_{TWF}^{PT}

Design-intent maximum allowable frequency of a single pressure tube rupture, $f_{all}[PT_{rupt}]$

Require:

Frequency of pressure tube rupture = design-intent maximum allowable frequency

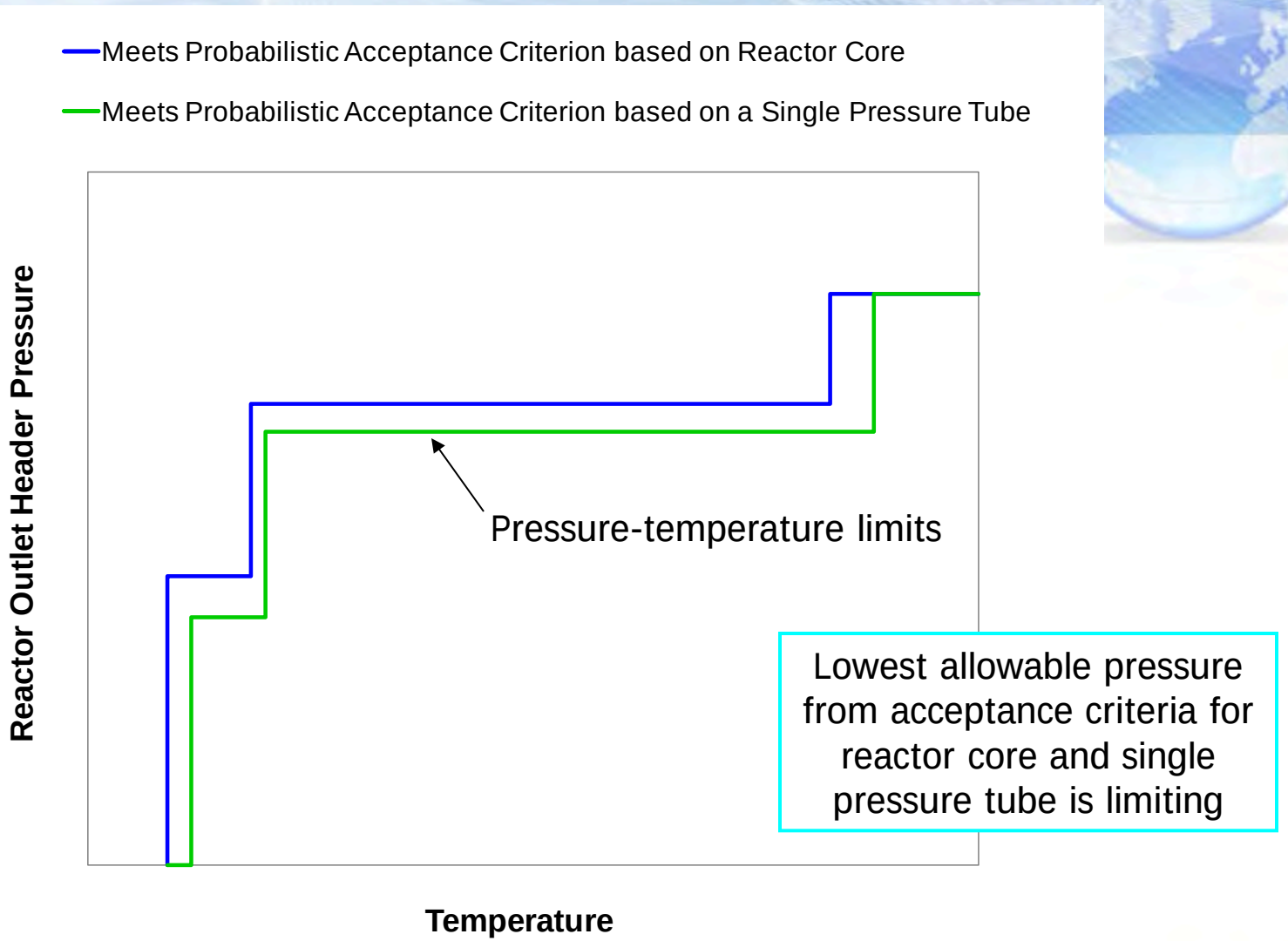
$$Q_{all}\left[PT_{rupt} \mid TWF\right] = \frac{f_{all}\left[PT_{rupt}\right]}{f_{TWF}^{PT}}$$

Maximum allowable conditional probability of rupture of a single pressure tube, $Q_{all}[PT_{rupt}|TWF]$

Development of Acceptance Criteria for a Single Pressure Tube

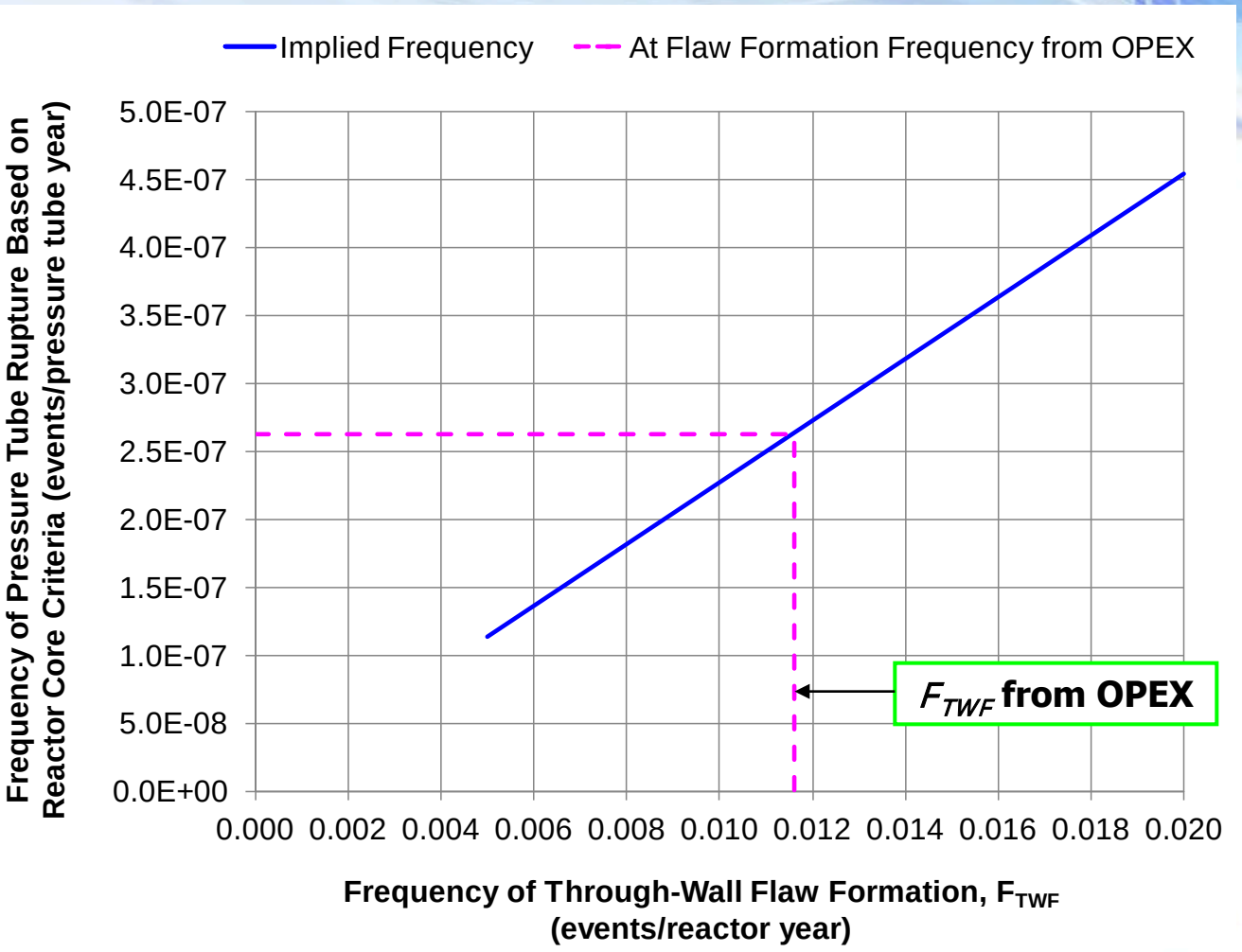
Calculated and Recommended Maximum Allowable Conditional Probabilities of Rupture of a Single Pressure Tube

Reactor Type	Allowable Frequency of Pressure Tube Rupture, $f_{all}[PT_{rupt}]$ (per pressure tube year)	Calculated Allowable Conditional Probability of Pressure Tube Rupture, $Q_{all}[PT_{rupt}\|TWF]$	Recommended Allowable Conditional Probability of Pressure Tube Rupture, $Q_{all}[PT_{rupt}\|TWF]$
Bruce A, Bruce B or Darlington	1.0×10^{-6}	0.0380	0.04
Pickering	1.0×10^{-6}	0.0380	0.04



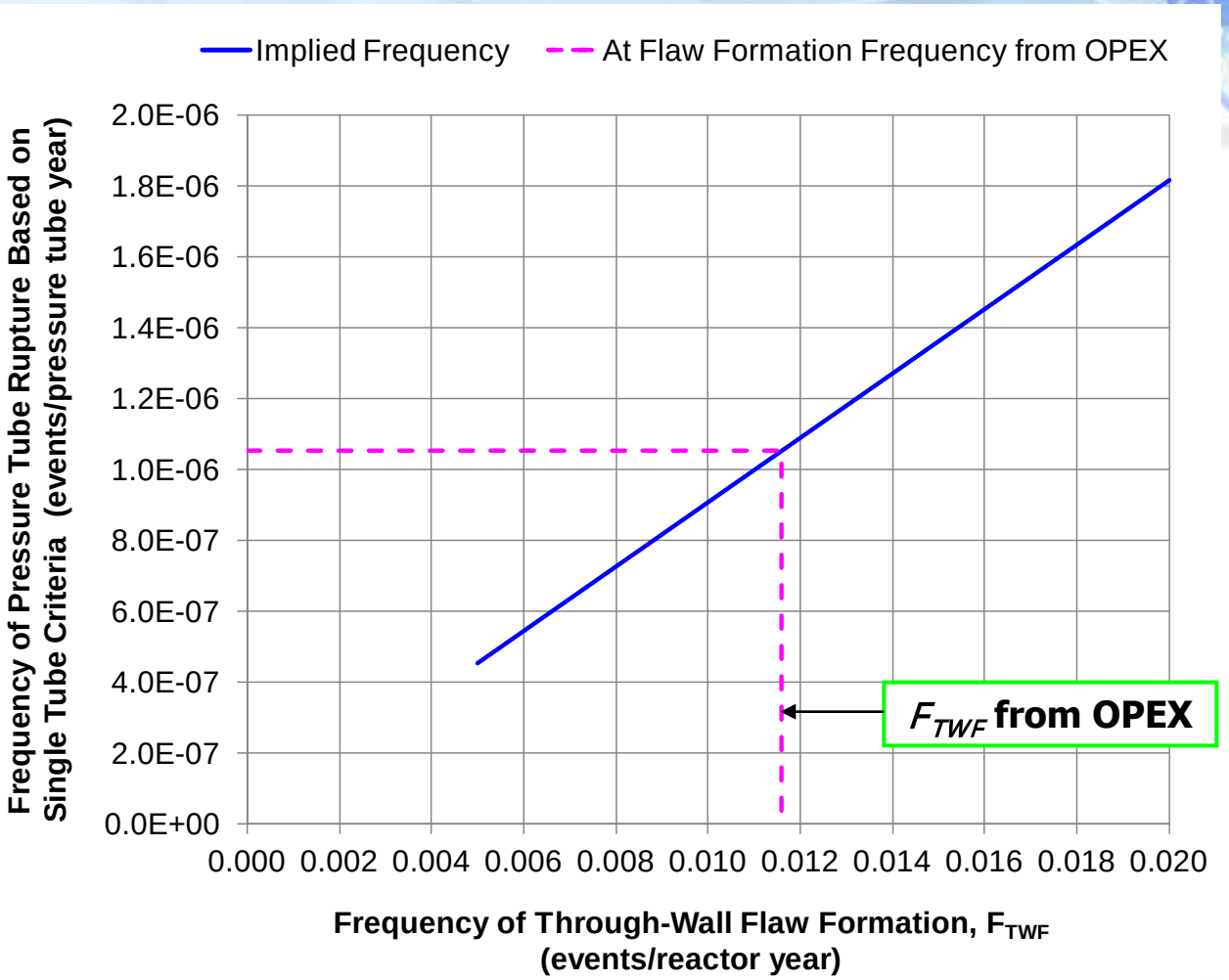
Schematic of Development of Pressure-Temperature Limits for Reactor Heatup and Cooldown Based on Probabilistic Criteria

Implied Frequency of Pressure Tube Rupture – Reactor Core Acceptance Criteria



Implied Frequency of Pressure Tube Rupture Based on Allowable Conditional Probability of Pressure Tube Rupture for Reactor Core

Implied Frequency of Pressure Tube Rupture – Single Pressure Tube Acceptance Criteria



Implied Frequency of Pressure Tube Rupture Based on Allowable Conditional Probability of Rupture of a Single Pressure Tube

Summary

- Acceptance criteria for probabilistic evaluations of fracture protection that meet design intent of pressure tubes have been developed
- Maximum allowable conditional probabilities of pressure tube rupture, given an axial through-wall flaw, for Service Level A, B, C and D loadings are
  - 0.01 for entire reactor core
  - 0.04 for rupture of a single pressure tube
- Probabilistic acceptance criteria are considered to provide an assurance of meeting design intent of fracture protection that is equivalent to that of the deterministic acceptance criteria

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