Canadian Nuclear Safety Commission | Commission canadienne de sûreté nucléaire

Canada

APPLICATIONS OF PROBABILISTIC FRACTURE MECHANICS FOR PRESSURE TUBES WITH FLAWS

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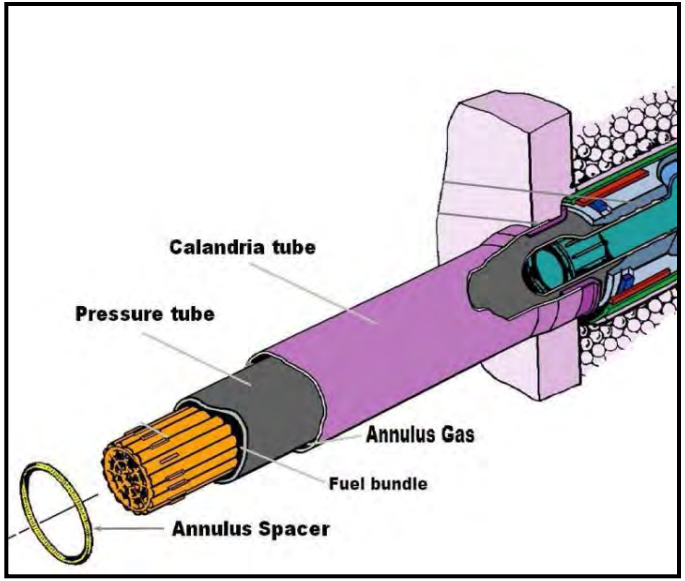
Outline

- Introductory information
- Probabilistic evaluations of CANDU reactor core, and probabilistic methodologies
- Efforts to increase confidence in probabilistic evaluations using probabilistic fracture mechanics
- Proposed path forward – engaging international experts under working group
- Concluding remarks

Fuel Channels in a CANDU Reactor

- A CANDU reactor has a channelized core with a large number of small diameter cold-worked Zr-2.5Nb pressure tubes
- Pressure tubes experience service-induced degradations and material property changes over operating time



Inspection Program and Fitness-for-Service

- Canadian licensees follow Clause 12 of CSA Standard N285.4, *Periodic Inspection of CANDU Power Plant Components*
- When inspection findings do not meet acceptance criteria (in CSA N285.4), operators use CSA Standard N285.8, *Technical Requirements for In-Service Evaluation of Zirconium Alloy Pressure Tubes in CANDU Reactors*, to demonstrate continued fitness-for-service

Degradation Mechanisms Related to Volumetric Flaws

- Major service-induced pressure tube degradation mechanisms related to volumetric flaws include:
  - debris fretting flaws, which are created when foreign materials are trapped between a fuel bundle and the pressure tube; they are mostly developed at the beginning of reactor operation
  - bearing pad fretting flaws due to fretting between the fuel bundle and pressure tube
  - crevice corrosion flaws related to localized corrosion affected by lithium

Evaluation of Inspection Findings

- Continued fitness-for-service of inspected pressure tubes with volumetric flaws is demonstrated on a deterministic basis
- Methodologies typically involve but are not limited to demonstration of acceptable margins to crack initiation from a volumetric flaw by two of three known crack initiation mechanisms: delayed hydride cracking (DHC) and fatigue
  - deterministic methodology for hydrided region overload (HROL) is under development
- Followed by the evaluations for entire reactor core

Evaluations for Reactor Core Related to Flaws

- Clause 7 of CSA N285.8-15 requires the following flaw-related evaluations for the reactor core
  - evaluation of in-service conditions for protection against fracture
  - assessment of degradation mechanisms related to flaws
  - evaluation of leak-before-break (LBB)
- Either probabilistic or deterministic approaches are allowed by the standard

Major Components of Probabilistic Core Evaluation

- Postulation of degradation mechanisms related to flaws over the evaluation period
- Evaluation of crack initiation from DHC, fatigue, and HROL
- Increase in size of the crack growing by DHC
- Leak detection, sequence of events from reactor shutdown to a cold and depressurized state
- Best estimate of pressure tube failure frequency per year

Proposed Allowable Frequencies of Failure

- Establishing risk-informed rather than risk-based allowable failure frequencies
  - while reactor safety features are redundant and credited, higher failure frequencies can satisfy risk criteria based on probabilistic safety goals
- Proposed allowable frequencies of Table C.1 of CSA N285.8-15 amendment are limited by class of the event (i.e., design basis accident)

Maximum allowable failure frequency from all degradation mechanisms (H_{all-ig})				
Number of known in-service pressure tube degradation mechanisms, g				
g = 1	g = 2	g = 3	g = 4	g = 5
0.01000	0.00500	0.00333	0.00250	0.00200

Probabilistic Leak-Before-Break

- Probabilistic leak-before-break (PLBB) methodologies used by Canadian nuclear industry
  - method 1 PLBB – based on evaluation of the limiting pressure tube in reactor core with sequentially postulated through-wall cracks (TWCs)
  - method 2 PLBB – based on integrated probabilistic core evaluation of crack initiation and LBB

Industry-Proposed Acceptance Criteria for PLBB

- PLBB is demonstrated if the conditional probability of pressure tube rupture given a TWC is less than
  - 0.10 for the limiting pressure tube in reactor core (i.e., Method 1 PLBB)
  - 0.05 for entire reactor core (i.e., Method 2 PLBB)

Arguments for Industry-Proposed PLBB Acceptance Criteria

- Proposed acceptance criteria consider recent estimates of frequency of through-wall cracks (F_{TWC})

$$P\left(Failure \middle| TWC\right) \times F_{TWC} \leq H_{all-ig}$$

- Procedures in response to a leaking pressure tube event are established and in place
- Pressure tube leak detection capabilities should be adequate for frequency of through-wall cracks

Probabilistic Fracture Protection

- Probabilistic fracture protection methodology developed by the Canadian nuclear industry is under review by the CNSC
  - methodology involves probabilistic evaluation of reactor core
  - industry-proposed acceptance criteria are intended to meet the intent of the design basis for CANDU pressure tubes

Uncertainty Analysis

- Proposed Annex G for CSA N285.8-15 amendment was developed to provide the requirements for treatment of uncertainties
  - triggered when the estimate is higher than half of the acceptance criterion
- Uncertainty analysis has yet to be completed for any probabilistic evaluations for pressure tubes

Quality Assurance for Computer Codes

- Implementation of the reactor-core based probabilistic methodologies into computer programs result in complex codes and extensive programming efforts
- The requirements for computer codes outlined in CSA N286.7 should be satisfied
- Benchmarking of the computer codes used for probabilistic evaluations of the reactor core is challenging
  - limited number of qualified computer codes and users
  - limited international cooperation in this area

Numerical Convergence of Simulations

- Simulation time can be considerable, despite recent substantial improvements in the computational power of professional computers
- Ongoing activities to develop the criteria for numerical convergence of Monte Carlo simulations
  - requirement for a minimum number of simulations
  - limit the number of simulations when the best estimate is distant from the acceptance criterion

Reporting and Verification

- Detailed reporting requirements for probabilistic evaluations should be established
  - level of reporting details for evaluations varies
- Improved confidence would be obtained through the development of best practices, including reporting requirements
- CNSC performs regulatory compliance inspections for additional review of important inputs and assumptions

Validation Challenges

- Challenges in validation of probabilistic methodologies and computer codes for pressure tubes
  - low frequency of pressure tube failures in Canada
  - limited information available for any events that occurred abroad
- Common approaches for validation of probabilistic methodologies should be developed
  - considerable efforts required

Guidelines on Best Practices

- Probabilistic evaluations utilizing probabilistic fracture mechanics have many common features
- Best practices for assessments involving probabilistic fracture mechanics evaluations should be established
  - beneficial for the regulators and the nuclear industry
  - sharing experience is desired

Statistically-Based Models

- Assumption is made that statistically-fitted experimental data from laboratory tests conservatively bounds operating pressure tubes; or, at least, the test conditions were a realistic simulation of operating conditions
- Mechanistic understanding of physical phenomena is required to increase confidence in statistical models while reducing model form uncertainty

Surveillance and Testing Programs

- Probabilistic evaluations for pressure tubes involve many distributed inputs projected into the future
- The limited amount of available experimental data raises concerns over the accuracy of model predictions and the confidence associated with estimates
- The ability to obtain additional experimental data is limited because it relies on the removal of a small sample of surveillance pressure tubes, artificial aging of material, and limited testing facilities

Common Challenges and Path Forward

- Probabilistic methodologies using fracture mechanics recently find more applications in licensing frameworks
- Probabilistic methodologies utilizing fracture mechanics have many common features regardless of specific applications
- An international working group on probabilistic methodologies using probabilistic fracture mechanics should be created to exchange information and develop common approaches

Concluding Remarks

- Validation of assumptions, probabilistic models and probabilistic methodologies require considerable effort
- To validate models and assumptions, choosing the appropriate frequency of surveillance, testing and inspection activities is critical
- Uncertainty and sensitivity analysis performed for newly introduced probabilistic methodologies are necessary to provide supporting arguments and confidence for their licensing applications

Concluding Remarks (cont'd)

- Establishing risk-informed rather than risk-based acceptance criteria requires considerable effort
- Guidelines for best practices for probabilistic methodologies and evaluations involving probabilistic fracture mechanics, as well as probabilistic computer code validation, should be internationally supported
  - increase confidence in the estimates from probabilistic evaluations
- An international working group should be established

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Thank you!

Any questions are welcomed!

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