Evaluation and implementation of methodology for dispositioning flaws in Zr-2.5% Nb pressure tubes of CANDU® power reactors

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Outline of Presentation

• Introduction
  • Canadian Nuclear Regulatory Authority and Nuclear Power in Canada
  • CANDU Reactors and Pressure Tube Fuel Channels
• Delayed Hydride Cracking (DHC) and Volumetric Flaw Assessment (Process Zone Methodology-PZM)
• Regulatory Evaluation of PZM
  • Case-by-Case application
  • Trial Use
  • Long-Term Use
• Discussion and Summary
Mission: to protect the health, safety and security of persons and the environment; and implement Canada’s international commitments on the peaceful use of nuclear energy

Established May 2000, under the Nuclear Safety and Control Act; Replaced the AECB, established in 1946, under the Atomic Energy Control Act

Canada’s Independent Nuclear Regulator ~
70 Years Of Experience
Aging management is embedded/embraced in all levels of our regulatory framework.

* Requirements if referred to in the licence
Regulatory Requirements and related CSA Standards

**CSA N285.0-12**  
General requirements for Pressure Retaining Systems and Components for CANDU NPP  
including appendix: Materials requirements for Pressure Retaining Systems and Components for CANDU NPP (formerly CSA N285.6)  
ASME Boiler & Pressure Vessel Code, Section III, Div. 1

**CSA N285.4-14**  
Periodic Inspection of CANDU NPP Components (clause 12 specifies PIP requirements for pressure tubes)

**CSA N285.8-15**  
Technical Requirements for In-Service Evaluation of Zirconium Alloy Pressure Tubes in CANDU (fitness- for-service assessment guidelines)
Nuclear Power in Canada

Five Nuclear Power Stations
All CANDU (CANada Deuterium-Uranium) Design
Nuclear Power In Canada

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Typical share of nuclear energy in total electricity generation

- **Canada > 15%**
- **Ontario – 62.2%, 2013; ~50% in 20 years**
- **New Brunswick - 30%**

Canadian Nuclear Safety Commission

17th International Conference on Environmental Degradation of Nuclear Materials
CANDU is a special “P(H)WR”
CANDU Power Reactor

- Pressure tube type Pressurized Heavy Water Reactor (PHWR) with calandria vessel
- Major components of Primary Heat Transport System (PHTS):
  - Fuel Channels (380 - 480 FCs*)
  - Feeders Pipes (760 - 960 feeders*)
  - Steam Generators (4 – 12 SGs*)

* Number of component items differs
Fuel Channel: Rolled Joint, Coolant/PT reaction

The CANDU Fuel Channel

Pressure Tube dimensions
Length: ~ 6.4m
Inner diameter: 103.4 mm
Thickness: 4.2 mm
Typical Coolant in CANDU PHTS
-the operating conditions of a pressure tube

Inside: Pressurized Heavy Water (D$_2$O)
- ~ 250 to 315 °C;
- Outlet header pressure: 8.7 ~ 9.9 MPa
- pH$_a$: 10.2 ~ 10.8;
- Dissolved oxygen concentration < 5μg(O$_2$)/kg (D$_2$O);
- Neutron fluxes up to 3.7 x 10$^{13}$ n/cm$^2$ /s
- Fluences up to 3 x 10$^{22}$ n/cm$^2$ (in 30 years of 80% capacity)

Outside: dry CO$_2$ annulus gas, ~60 °C
Pressure Tube Degradation Mechanisms

• Delayed Hydride Cracking
  – Corrosion and Deuterium Ingress
  – Hydride precipitate
  – Flaws acting as stress raisers: Debris, Fuel-bundle Bearing Pad Fretting, crevice corrosion –potentially leading to DHC initiation (However, DHC has never been detected from a volumetric serviced-induced flaw)
  – Hydride Blisters, due to PT/CT contact, can initiate long DHC cracks and lead to PT rupture

• Irradiation Enhanced Deformation (Creep)
  – Axial growth, diametral growth, sag

• Changes in Material Properties: reduction in ductility and fracture toughness
  – Irradiation Embrittlement
  – Deuterium ingress
In-service induced flaws: Debris fretting

- Majority are shallow, blunt with a few exceptions
- Generally formed during commissioning / early operation by construction debris trapped by fuel bundles

Cross-section of Debris Fretting Flaw
In-service induced flaws:
• crevice corrosion

• Typical crevice corrosion profile from a sectioned ex-service pressure tube. The depth of this flaw is about 0.190 mm. Note the flaw is filled with oxide.
• Generally shallow and wide with a maximum depth observed below 0.4 mm, suggesting depth to be self-limiting
• Due to LiOH concentrating under localized boiling conditions which exist between fuel bearing pads and pressure tubes.
Hydrided Regions at a Notch Tip in a Zr-Nb DHC Initiation Test Specimen (Notch root radius is 0.10 mm)
DHC: Terminal Solid Solubility and Temperature

Corrosion Reaction:
Zr + 2H₂O → ZrO₂ + 4H

- fraction of hydrogen absorbed by base metal
- hydrides present when Terminal Solid Solubility (TSS) exceeded
- hydrides can potentially lead to fracture issues
- ensure hydrides are not present during reactor operation at power

source: AECL website: www.aecl.ca
A schematic illustration of a single step in DHC, starting with a notch under stress and hydride precipitation at the notch (top); fracture of hydride and crack extension from the notch (middle); followed by new hydride form at the cracked hydride tip (bottom), and the process repeats itself.
Volumetric Flaw Assessment for DHC Initiation
old Fitness for Service Guidelines (FFSG)

When no hydrides at sustained hot conditions:
- The allowable peak stress = 750 MPa,
  No restriction on thermal cycles

When hydrides predicted at sustained hot conditions:
- If peak stress < 623 MPa,
  Allowable thermal cycles = 80;
- If 623 MPa < peak stress < 750 MPa,
  Allowable thermal Cycles vary between 80 and 12;
- If peak stress > 750 MPa,
  Not acceptable.

The allowable flaw-tip stress is independent of flaw geometry. It is not clear how to deal with secondary flaws at the root of blunt flaws.
Volumetric Flaw Assessment for DHC Initiation
Process Zone Methodology-PZM*

- Based on “Strip Yield Model” to account the stress redistribution in the “process zone” (the hydrided region);
- DHC occur only when two conditions are met:

\[ v_T > v_c \quad ; \text{and} \quad \rho_H > \rho_c \]

Where, \( v_c \) is the critical process-zone (opening) displacement, and \( \rho_c \) is the critical stress level at the hydrided region, below which the hydrided region cannot fracture.

* See the references listed in the paper for detail.
DHC initiation test results of elastic peak stress from samples of a pre-irradiated pressure tube with various notch root radii under constant loading with the threshold peak stress predicted from elastic engineering process-zone model with $K_{IIH}$ values from that specific tube, (a); and the threshold peak stress from the lower-bound $K_{IIH}$ value in CSA N285.8 (b), respectively.
Regulatory evaluation and implementation of PZM

Comparison of flaw acceptance criteria for DHC Initiation Evaluations using old FFSG and “process zone” based CSA N285.8 standard

PZM /CSA N285.8
Old FFSG

Threshold peak stress for DHC varies with flaw root radius

Threshold peak stress 623 to 750 MPa, and varies with heat-up/cool-down cycles
Regulatory evaluation and implementation of PZM

Comparison of flaw acceptance criteria for DHC Initiation Evaluations using old FFSG and “process zone” based CSA N285.8 standard

Under PZM:

- Threshold peak stress of DHC is no longer a constant for flaws with different shapes (root radii);
- Sharper the flaw, higher the threshold peak stress;
- Secondary flaws can be evaluated;
- No thermal cycle restriction.

This would mean:

- A relaxation for flaw assessment and disposition;
- Stringent evaluation is needed before the regulatory application.
Regulatory evaluation and implementation of PZM
Case-by-case application and story of P12-IND1

- P12-IND1, a debris fretting flaw, was confirmed from an inspection.
- The flaw is of a depth 1.1mm from replica taken during inspection and it could not pass the old FFSG for DHC evaluation.
- It was the first flaw that the CANDU industry applied the PZM, and was found acceptable for continued operation without any restrictions.
- The licensee requested permission for allowing the tube return to service; committed to remove it as surveillance tube in a future planned outage.
- Other licensees showed interest in applying PZM.
Regulatory evaluation and implementation of PZM
Case-by-case application and story of P12-IND1

CNSC staff conducted a careful assessment of the disposition request and all supporting materials, which lead to:

- Recognizing the merits of PZM, particularly the scientific basis, also the significance in PT FFSA;
- Allowing P12 return to service, as a special case, not only considered the PZM assessment result but mainly based on other factors including the safety measures available if required, and under the conditions that the licensee shall:
  - Remove the tube at THE NEXT planned outage;
  - Conduct metallographic examination of the flaw, in addition to the Standard required surveillance measurements.
CNSC staff also decided:

- Request that the whole CANDU industry, mainly through the CSA N285 BTC, provide further discussion on the details of PZM as well as a third party review, independent from CANDU industry;

- Conducting a CNSC own regulatory Research and Support (R&S) project to seek independent expert opinions on PZM.
Regulatory evaluation and implementation of PZM  
Regulatory independent verification project

- **The Team:** the project was successfully contracted to CANMET-Materials, with a review team of well-known experts in physical metallurgy, fracture mechanics, finite element analysis and Zirconium alloys;

- **The objectives:** to seek expert opinions on PZM with respect to
  - the theoretical and engineering soundness of the methodology;
  - the relevance, objectiveness and completeness of the experiments for verifying the model.
  - the usefulness, practicality and accuracy of the model and the proposed procedure
Regulatory evaluation and implementation of PZM
Regulatory independent verification project

• The project was conducted by
  - Reviewing and assessing the documents provided by PZM proponent
  - Applying the model to typical cases of observed flaws and comparing pass/fail results with those of the method in the existing FFSG
  - Discussing, between review term and PZM proponents, the issues identified by the review team;
• Further information was provided by the proponent and reviewed by the team;
• The final findings and recommendations were presented to and discussed among all the stakeholders.
Regulatory evaluation and implementation of PZM
Regulatory independent verification project

Major outcomes of the project:
- Review team concluded that in general, the PZM is a well-developed methodology and is ready for trial use for prevention of DHC initiation in an engineering assessment with certain conditions.
  - The scientific basis behind the PZM was judged to be sound;
  - The accuracy of functions describing the stress intensity factor ahead of a flaw could be improved with the recommendations provided by the team.
Major outcomes of the project:

- Major concerns of the review team were related to the conditions of the materials used in the validating experiments, in particular whether they represent the operating situations where the PZM might be applied.

- The review team also pointed out some operating scenarios that would affect DHC initiation but were not considered by the proponents of PZM at that time.
Regulatory evaluation and implementation of PZM
Regulatory independent verification project

- CNSC staff’s own assessment
- Conclusions and the recommendations of the review team
- Progress in the CSA Technical Committee in incorporating the PZM into a CSA standard

Conditions for trial use of the PZM for a 36-month period
Regulatory evaluation and implementation of PZM
Trial use

Conditions for trial use PZM include:

- the evaluation period $\leq$ two calendar years;
- flaws assessed using the PZM shall also be assessed using the method in the FFSG; if failed by the latter,
  - the flaw shall be re-inspected after the two-year evaluation period and
  - any changes reported to the CNSC;
Regulatory evaluation and implementation of PZM

Trial use

Conditions for trial use of PZM include:

• a reserve factor of 0.90 shall be applied to the lower bound $K_{IH}$ of $4.5 \text{ MPam}^{1/2}$, until concern on the experimental data size is resolved;

• the bulk hydrogen equivalent concentration ($H_{eq}$) in the body of the pressure tube of the flaws assessed using PZM shall not exceed 45 ppm, until higher $H_{eq}$ samples are tested for validating the PZM;
Regulatory evaluation and implementation of PZM

Trial use

Conditions for trial use of PZM include:

- the licensee shall be requested to submit a plan for performing unit-specific core assessments, which was a new initiative for assessing integrity of the entire core of pressure tubes, and to submit plans for experimental programs to address DHC initiation under the influence of cyclic loading and hydrided region overload.
Regulatory evaluation and implementation of PZM

Trial use

Responses to trial use of PZM:

- The licensees of major CANDU power reactor operators applied the conditions during their trial use periods of the PZM.

- A number of R&D projects were initiated by the CANDU industry
  - to improve the model and
  - to address the issues identified by the review team.
Regulatory evaluation and implementation of PZM

Trial use

Parallel with the trial use of PZM:

- The industry third-party expert review provided positive comments on the suitability of the PZM for application to DHC initiation assessment.
- The pressure tube P12 was removed as requested:
  - The material properties met the relevant criteria;
  - No sign of cracking around the flaw was found from metallographic examination on twelve cross-sections of the flaw.
- Detailed presentations and discussions on issues related the PZM took place within the CSA Technical Committee.
- The CSA N285.8 Standard, *Technical Requirements for In-Service Inspection of Zirconium Alloy Pressure Tubes in CANDU Reactors*, which incorporated the PZM for assessing DHC of volumetric flaws, was officially published.
Examination of flaw P12-IND 1
Implementation of PZM Trial-Use Results:

Flaw-tip peak stress vs root radius for flaws detected from in-service inspections and assessed as volumetric flaws, in comparison with the acceptance criteria by the engineering process zone methods of CSA N285.8 and that by the previous FFSG. Different symbols indicate flaws observed from different stations.
Regulatory evaluation and implementation of PZM
Long-term use

Licensees are now granted the long term use of PZM which has been incorporated into CSA N285.8 standard, based on

- Progress by CANDU industry on the related R&D projects.
- The licensees complied with the conditions for the trial use, including the confirmation that
  - no changes were observed from flaws re-inspected that failed to pass the acceptance criteria of FFSG and
  - no sign of cracking identified from the metallographic examination of flaw P12-IND1.
Discussion

- Modern nuclear regulations are developed using science-based, risk-informed and technically sound regulatory practices that take into account scientific uncertainties and evolving expectations.

- Contracting expert third-party reviews on some safety-significant methodologies for NPP analysis/assessment is of the importance for maintaining the regulatory capacity for safety.
Discussion

- Philosophically, a positive requirement of regulatory due diligence would be an intelligent distrust of its licensees, a skepticism stubborn but not blind, of all demands from its licensees for the relaxation of regulations, and an emphasis upon the critical issues in every phase of the regulated facilities*.

* Borrowed from political philosopher Sidney Hook: “A positive requirement of a working democracy is an intelligent distrust of its leadership, a skepticism stubborn but not blind, of all demands for the enlargement of power, and an emphasis upon the critical method in every phase of social life.” (from an on-line open course offered by the Stanford University.)
Discussion

- A regulatory technical assessment would be essentially a process of searching for an appropriate and defendable balance between the conservatism of licensee’s approach and reality of the concerned issue, as the evolution of knowledge, operating experience and regulatory expectation.
Discussion

• A safe plant is an economical plant and safety is the sole responsibility of the operator of NPP, the licensee.
• Demonstrating and maintaining structural integrity of key safety significant components would be the most important basis for enhancing the serviceability of NPP.
Discussion

• Demonstrating structural integrity requires
  - enhanced understanding of
    • degradation mechanisms,
    • material properties with operation time and their values at
      the end of the target service life;
  - improved and reliable methodologies for fitness for
    service assessments (FFSA) that
    • realistically represent the operating conditions,
    • describe the degradation mechanisms and
    • contain sufficient conservatisms for the designed safety
      margin and for covering uncertainties of the used
      parameters and unknown degradations.
• Regulatory acceptance of a new methodology for FFSA would be based on the review of
  - The **scientific** **basis**,
  - The adequacy and/or the accuracy of **models/calculations** involved;
    but most importantly
  - The **validation** process and results, experimentally and/or based on operational experience including in-service inspection/surveillance results; this is also the area where regulatory restrictions might potentially arise.
Summary

This presentation briefly reviewed the process used by CNSC staff in evaluating and implementing the process-zone methodology for assessing volumetric flaws in Zr-2.5%Nb pressure tubes in CANDU reactors, in order to

- Emphasis that the methodology for FFSA is of the most importance for demonstrating the structural integrity of a nuclear SSC;
- Illustrate from regulatory staff’s perspectives, what areas are of concern in assessing a new method for FFSA and what measures or restrictions might be applied to account for its shortcomings;
- Demonstrates the due diligence applied by CNSC staff in implementing a new methodology for FFSA to minimize any potential uncertainties or risks that it might bring.
Acknowledgments

- The authors wish to express gratitude to colleagues of CNSC, the members of the review team and the members of CSA Technical Committees, for their roles in participating and / or in facilitating the regulatory evaluation and acceptance of the PZM and for their help in the preparation of this paper.

Thank You For Your Attention