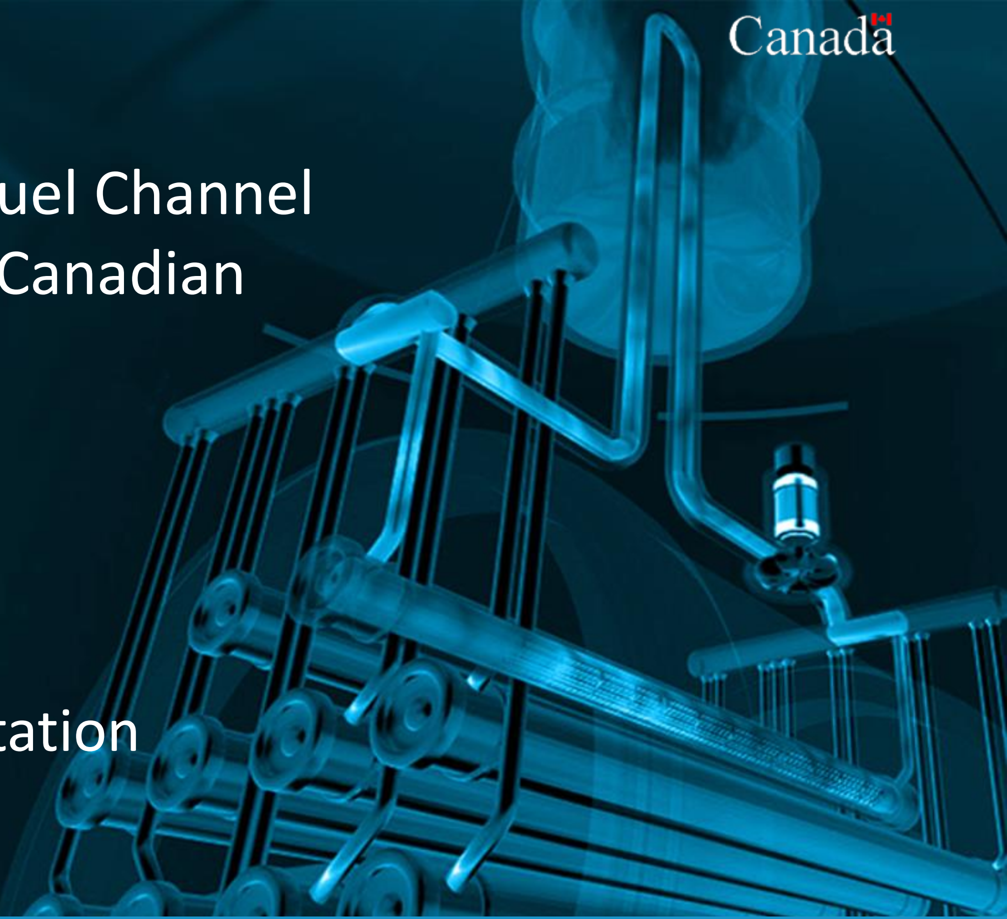
Canadian Nuclear Safety Commission
Commission canadienne de sûreté nucléaire

Canada

Technical Update on Fuel Channel Fitness-For-Service in Canadian Nuclear Power Plants

Commission Meeting, January 23 2018

CMD 18-M4



CNSC Staff Presentation

Purpose

In relation to aging management of existing operating facilities, CNSC staff presents the science behind fuel channel fitness-for-service assessments in support of technical information for Regulatory recommendations.

Previous CMDs

Pressure tubes have been mentioned during several NPP Re-Licensing Hearings; the following is a list of CMDs that provided detailed technical information:

- CMD 13-H2.A: Supplemental CNSC staff submission recommending Hold Point for OPG-Pickering (in connection with request to operate beyond 210,000 EFPH)
- CMD 14-H2: CNSC staff submission regarding OPG-Pickering request to remove 210,000 EFPH Hold Point
- CMD 14-M15: OPG/BP technical briefing regarding PT fitness-for-service
- CMD 14-M15.1: CNSC staff submission regarding PT fitness-for-service
- CMD 17-M12: CNSC staff submission (follow-up) regarding Commission Meeting Item: CANDU Safety Issues

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Outline

- Overview of the CANDU fuel channel
- Some useful concepts
- Degradation of pressure tubes (“PT”)
- Regulatory oversight of PT degradation
  - Example 1 - PT flaws
  - Example 2 - reduced PT fracture toughness
- CNSC evaluation of requests for extended PT operation
  - Timeline of licensee requests for extended operation
  - Operation beyond 247,000 EFPH: area of regulatory focus
- Summary

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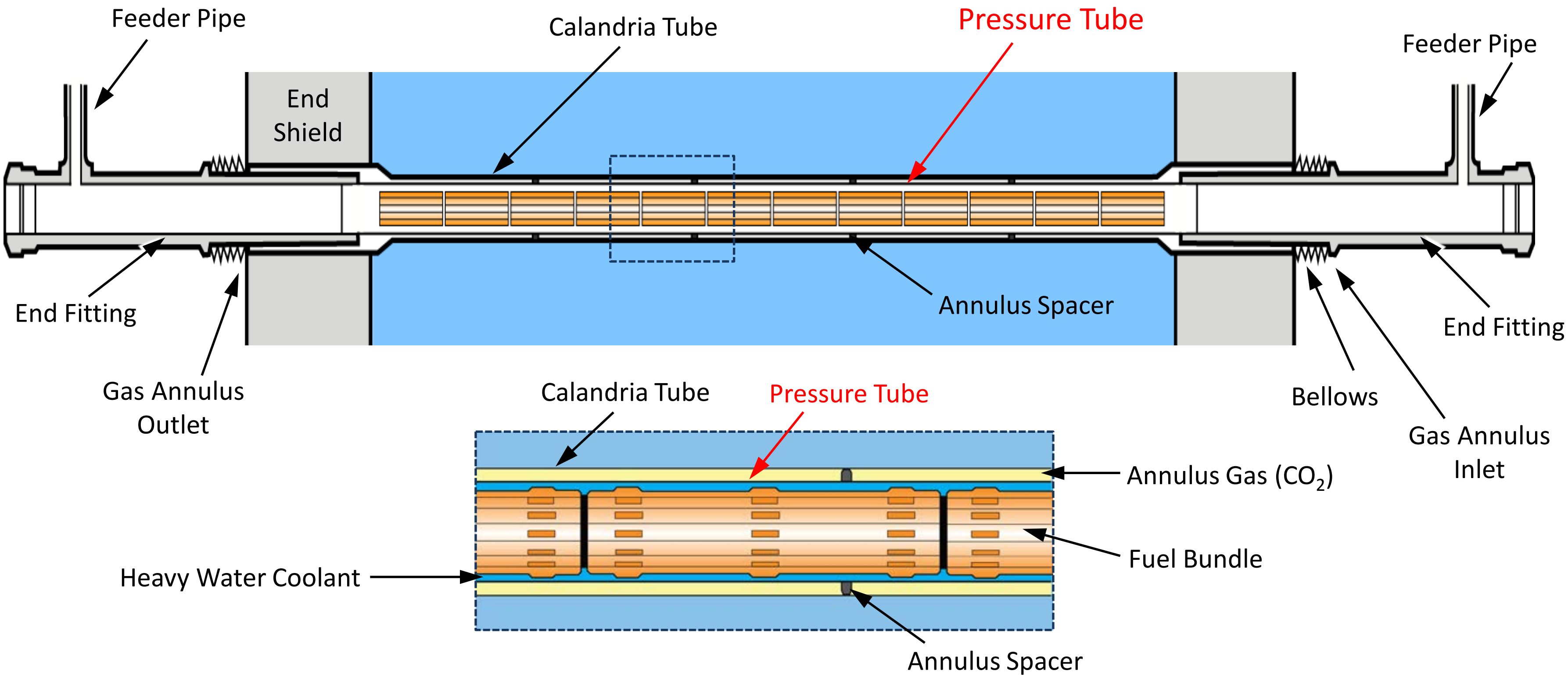
OVERVIEW OF THE CANDU FUEL CHANNEL

CANDU Fuel Channel (FC)



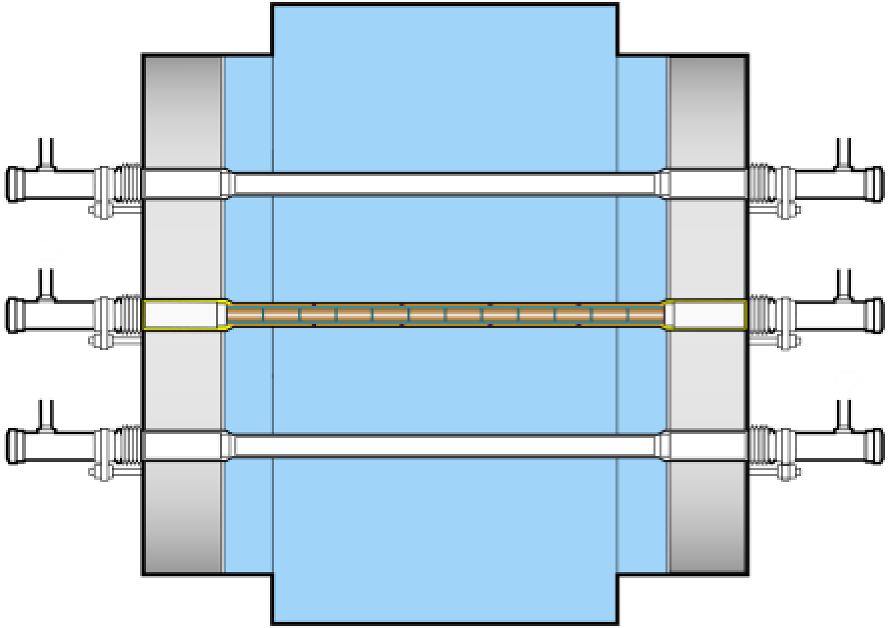
CANDU Fuel Channels (2 of 2)

Pressure Tubes

- 380 to 480 per core
- Horizontal orientation
- Zirconium-2.5 wt.% Niobium
- Dimensions
  - 5.94 m in length
  - Inside diameter 103.4 mm
  - 4.2 mm wall thickness

Normal Operating Conditions

- ≈250°C (inlet) to ≈310°C (outlet)
- ≈11 MPa (inlet) to ≈10 MPa (outlet)



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THECHNICAL CONCEPTS

Some Technical Concepts

Before describing the basis for pressure tube (PT) assessments, it is useful to review a few concepts:

1. Fitness-for-Service of pressure tubes
2. Hydrogen/deuterium in pressure tubes
3. Units for reactor operating time

Concept #1
Fitness-for-Service of PTs (1 of 2)

- Pressure tubes form part of the pressure boundary of the Primary Heat Transport System
- Structural integrity of the Heat Transport System is an important element of CANDU safety case
  - Under Normal Operating Conditions, PTs contain the high-pressure, high-temperature primary coolant
  - During (postulated) Design Basis Accidents, PTs keep the fuel cool

Concept #1
Fitness-for-Service of PTs (2 of 2)

- For these reasons, PT design must support an extremely low probability of failure under all reactor operating conditions:
  - Pressure tubes are designed not to leak
  - Pressure tubes are designed to resist propagation of a through-wall crack to the point of PT rupture

Goal of fitness-for-service: ensure PTs continue to meet the design intent

Concept #1
Pressure Tube Evaluations

CNSC requirement:

Licensee must demonstrate acceptable performance of 100% of pressure tubes over future period

Fitness-for-Service assessments based on results from periodic inspections	**30%** of pressure tubes
	+
Risk assessments* based on CNSC-accepted Models	**70%** of pressure tubes

✓ **100% of PTs assessed against defined acceptance criteria**

* Examples: Leak-Before-Break (Slide 22) and fracture protection (Slide 28)

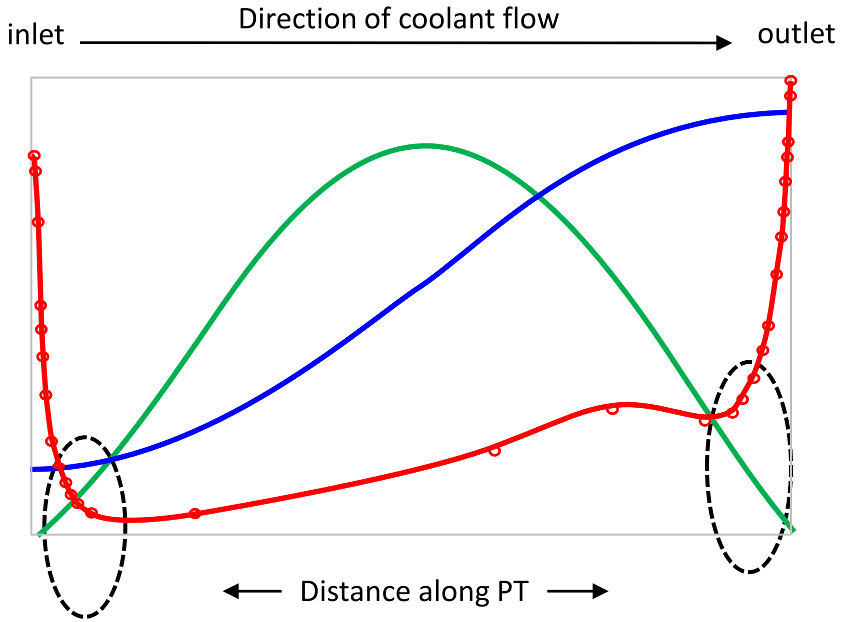
Concept #2

Hydrogen/Deuterium

- While three hydrogen isotopes are important to CANDU operation, only two affect PTs
- Every PT contains some **hydrogen (H)**, originating from its manufacture
- In the presence of hot heavy water coolant, PTs corrode to form zirconium oxide. This releases **deuterium (D),** a fraction of which is absorbed by the tube
- By convention, H and D concentrations are reported as milligrams per kilogram of PT material (or parts-per-million, PPM)
- Every PT contains both H and D. The two are often combined and reported as a single value: hydrogen-equivalent (Heq) concentration
  - For convenience, the term “Heq” will be used throughout this CMD

Concept #2

Factors Influencing Heq Level Along a PT



🟩 Fast neutron flux

🟦 Coolant temperature

🟥 Deuterium concentration

- - - - *Areas where potential reduction in fracture toughness requires enhanced regulatory focus to ensure safety margins are maintained*

Concept #3

Units for Reactor Operating Time

- Reactor operating time is described in two ways:
  - ***Hot Hours*** (HH) – includes all periods when the Heat Transport System exceeds ≈200°C
    - Since PTs corrode at these temperatures, Hot Hours is a useful metric for comparing Heq levels
  - ***Effective Full Power Hours*** (EFPH) – captures only those periods when fuel is undergoing fission
    - Since PTs irradiated by fast neutrons during such periods, EFPH useful for tracking degradation arising from neutron damage e.g. PT elongation
- Example: 1 calendar year = 8760 Hot Hours ≈ 7890 EFPH*

* Varies by station, and operating circumstances

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DEGRADATION OF PRESSURE TUBES

Degradation of Pressure Tubes due to aging

- PTs located in reactor core are exposed to high temperatures, high pressure and intense radiation fields
- Leads to in-service degradation

1. PT deformation
- Elongation
- Reduction in wall thickness
- Increase in diameter
- PT sag

2. Calandria tube-to-LISS contact

3. PT corrosion

4. PT flaws

5. Degradation of annulus spacers

6. Changes in PT material properties

(fracture toughness of particular interest)

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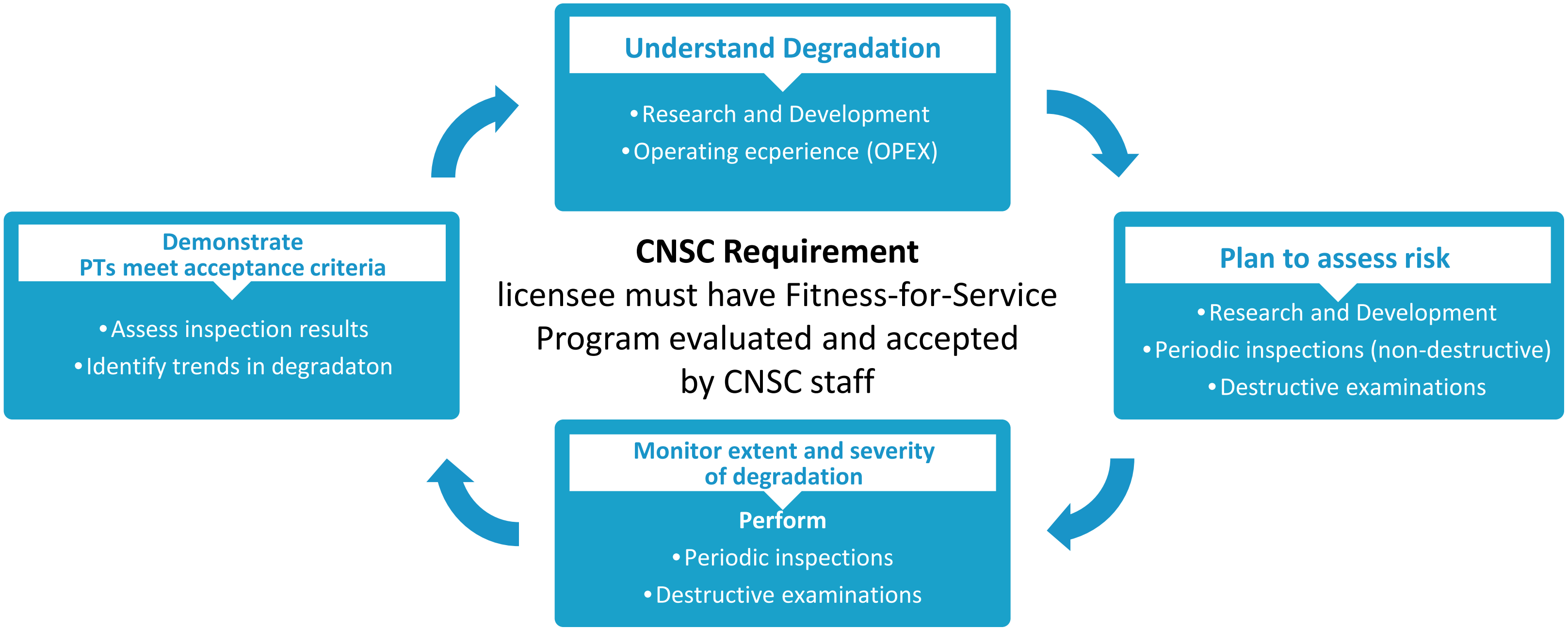
REGULATORY OVERSIGHT

Regulatory Oversight of PT Degradation



Understand Degradation

- Research and Development
- Operating ecperience (OPEX)

Plan to assess risk

- Research and Development
- Periodic inspections (non-destructive)
- Destructive examinations

Monitor extent and severity of degradation

Perform

- Periodic inspections
- Destructive examinations

Demonstrate PTs meet acceptance criteria

- Assess inspection results
- Identify trends in degradaton

CNSC Requirement
licensee must have Fitness-for-Service Program evaluated and accepted by CNSC staff

CNSC Staff’s Management of Risk – Two Examples

Two examples of staff’s regulatory oversight of PT degradation:

- Flaws in PTs
- Declining PT fracture toughness

Example 1

PT Flaws (1 of 3)

Progression of flaw degradation:

- Flaw initiated in pressure tube
- Flaw develops into crack (e.g. Delayed Hydride Cracking)
- Crack propagates through the PT wall -> primary coolant leakage
- Crack extends axially along PT ***(predictable rate, by design)***
  - **Leak-Before-Break:** reactor cooled and shut-down before PT crack reaches "Critical Length" (point of instability)
  - **Break-Before-Leak:** crack reaches Critical Length before reactor can be shut-down

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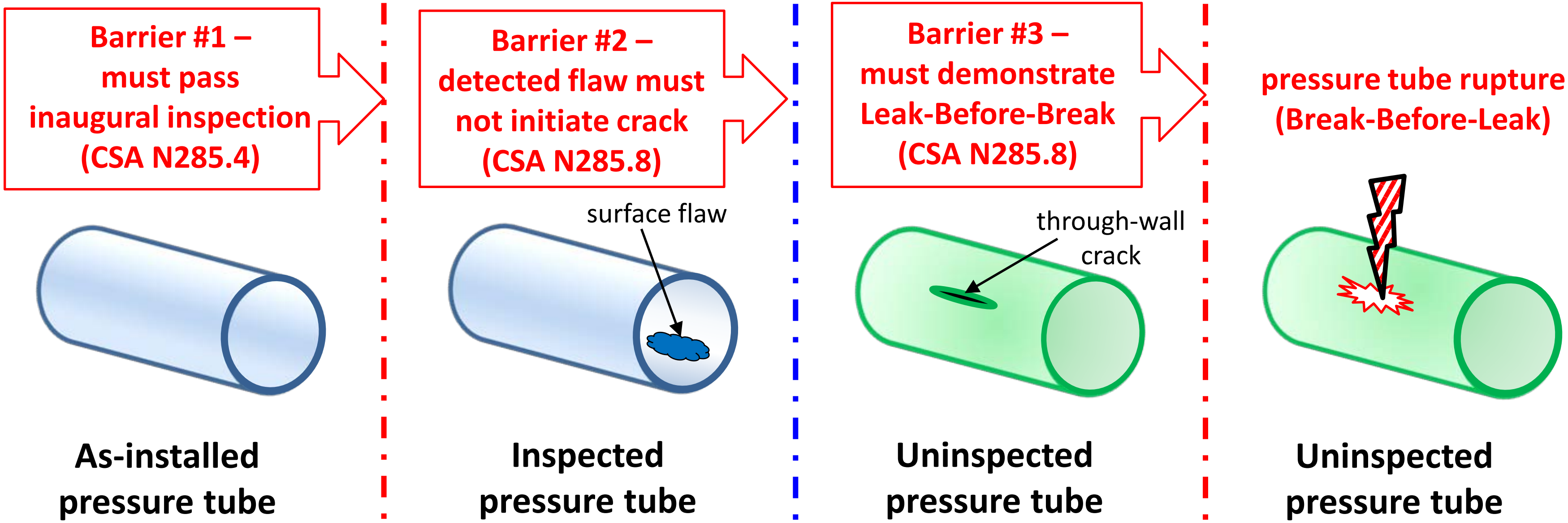
Example 1

Safety Case for PTs (2 of 3)



Barrier #1 – must pass inaugural inspection (CSA N285.4)

Barrier #2 – detected flaw must not initiate crack (CSA N285.8)

Barrier #3 – must demonstrate Leak-Before-Break (CSA N285.8)

pressure tube rupture (Break-Before-Leak)

As-installed pressure tube

Inspected pressure tube

Uninspected pressure tube

Uninspected pressure tube

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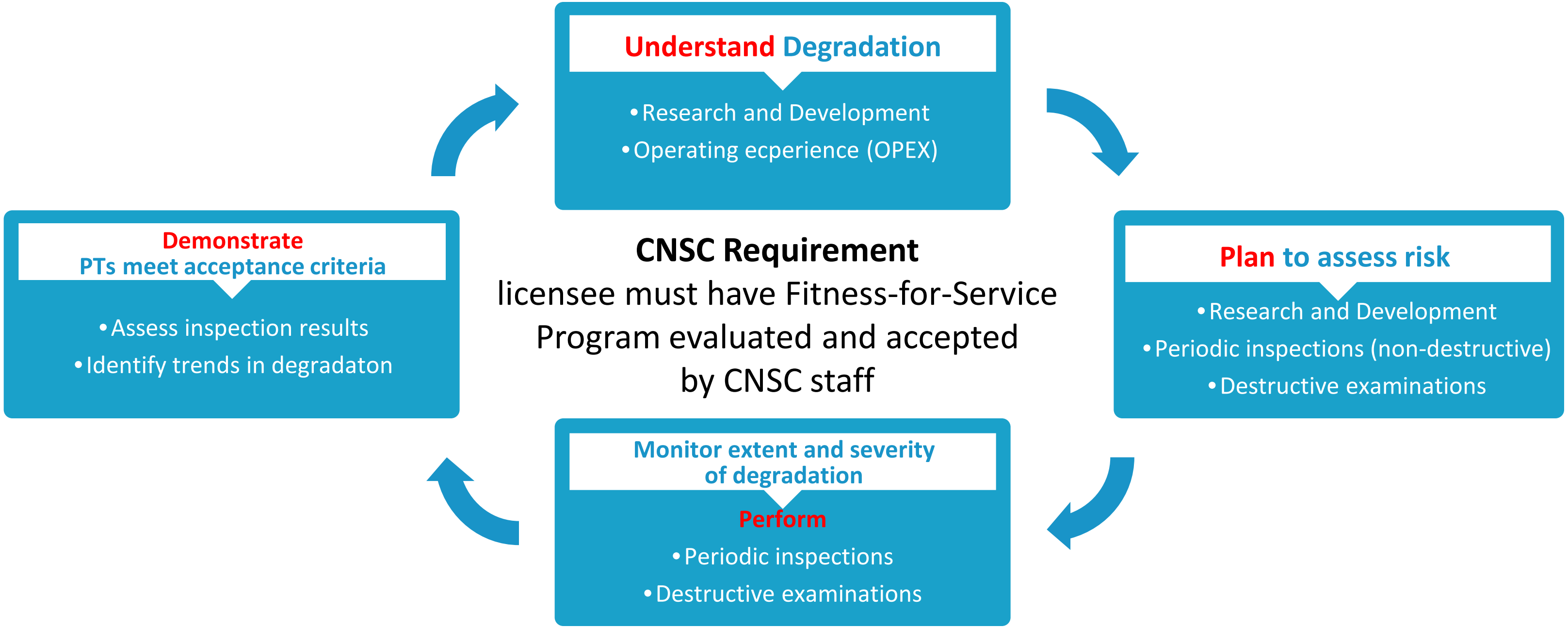
Recalling Slide 20



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Example 1
PT Flaws (3 of 3)

Requirement	Regulations	Licensee actions to address requirements
Understand	REGDOC-2.6.3	Industry research and development; fuel channel Condition Assessments
Plan	CSA N285.4 (per licence Condition Handbook)	Periodic Inspection Program (PIP); fuel channel Life-Cycle Management Plan
Perform	CSA N285.4, CSA N285.8 (per licence Condition Handbook)	Periodic inspections; PT material surveillance; research and development
Demonstrate acceptance criteria met	CSA N285.4, CSA N285.8, REGDOC-2.6.3 (per licence Condition Handbook)	Fitness-for-service assessments; follow-up inspections; research and development

Example 2

Fracture Toughness (1 of 5)

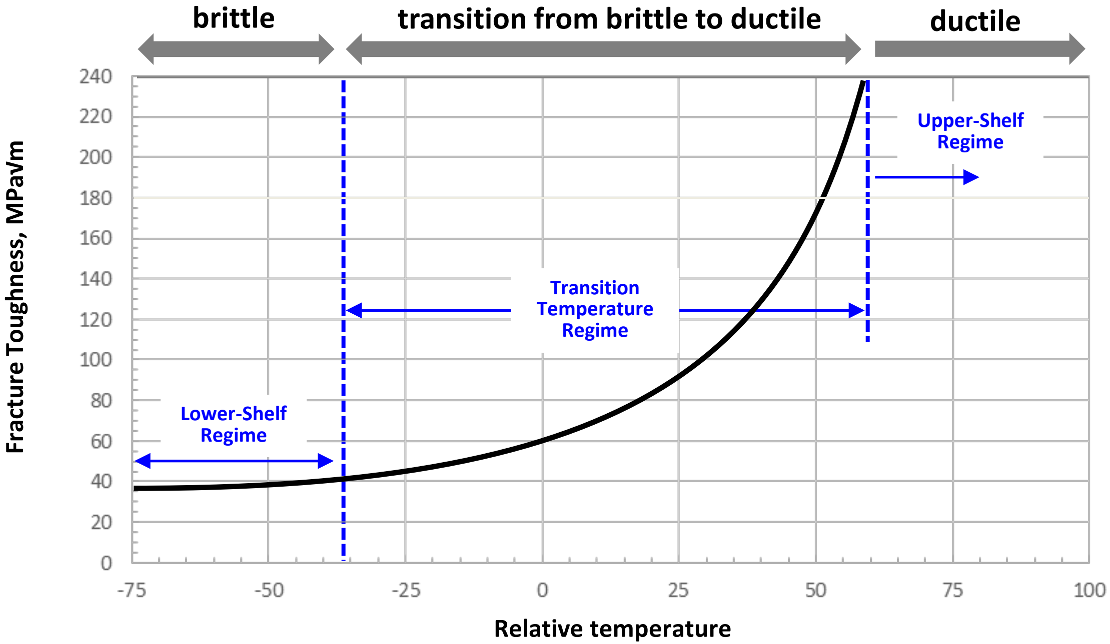
Definition* - resistance a material will offer to a growing crack

- Fracture toughness vital for quantifying risk posed by postulated PT cracks (uninspected PTs)
- Unique situation
  - Unlike PT flaws (which can be identified and monitored in-situ), fracture toughness cannot be measured in in-service pressure tubes
  - Can only confirm toughness of a tube once it has been removed
  - **To predict behavior of operating pressure tubes, licensees must rely on models**
- Industry relies on two forward-looking toughness Models
  - Statistical upper-shelf model: predicts PT toughness at $\geq 250^{o}$C
  - **Cohesive Zone-based Model**: predicts toughness for lower-shelf and transition regimes

* Carter & Paul, ***Materials Science & Engineering*** ASM International, © 1991

Example 2

Fracture Toughness (2 of 5)



- Relationship between lower-bound toughness and temperature
- Based on destructive tests of irradiated samples of LWR pressure vessel steel
- Three regimes of fracture behavior

Example 2

Fracture Toughness (3 of 5)

- Periodic (destructive) examination of PTs has confirmed adequate fracture toughness over the near-term i.e. successful demonstration of Leak-Before-Break
- However, research and development has demonstrated that PT toughness has, and will continue to decline as Heq levels increase
- To ensure PTs can perform their design function
  - Under Normal Operating Conditions (≥250°C) PTs must be ***fully ductile*** to respond to anticipated loads under (postulated) Design Basis Accidents. That is, 100% of the pressure tubes in a core must exhibit upper-shelf behavior
  - During reactor heat-up/ cool-down (35°C to 250°C), transition behavior of PTs must be known, and fracture toughness must be adequate

See Slide 26

- Impact of decreased toughness during heat-up/cool-down is addressed in the following Slide

Example 2

Fracture Toughness (4 of 5)

Heat Transport System heat-up/cool-down envelope*

- ***Regulatory requirement*** – licensee must operate the Heat Transport System (HTS) so as to maintain integrity of pressure-boundary components
  - To address this for pressure tubes, licensees establish a “envelope” within which operators must maneuver pressure and temperature during reactor start-ups and shut-downs
- The upper-bound of the envelope is defined using a ***PT fracture protection assessment***. Assuming a through-wall crack in an uninspected PT, the assessment calculates the maximum operating pressure beyond which the crack would be unstable
- Fracture toughness is a key input
  - Until recently, Heq levels were low enough that PT toughness remained high. This ensured a reasonable safety margin between the heat-up/ cool-down envelope and the maximum allowable Heat Transport System pressure
  - However, PT toughness has decreased as Heq levels increased. licensees can adjust their heat-up/cool-down envelopes to stay below revised maximum pressure values, but safety margins must be demonstrated as adequate
- Since PT toughness is affected by Heq levels only when temperatures fall within the heat-up/cool-down range, ample safety margins are expected to exist under Normal Operating Conditions (i.e. PT temperature >250^{o}C)

* see Appendix

Example 2

Fracture Toughness (5 of 5)

- Regulatory requirements similar to Slide 24

✓ licensee activities involve similar level of effort and focus compared to those devoted to fitness-for-service assessments (e.g. PT flaws)

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CNSC EVALUATION OF EXTENDED PT OPERATION

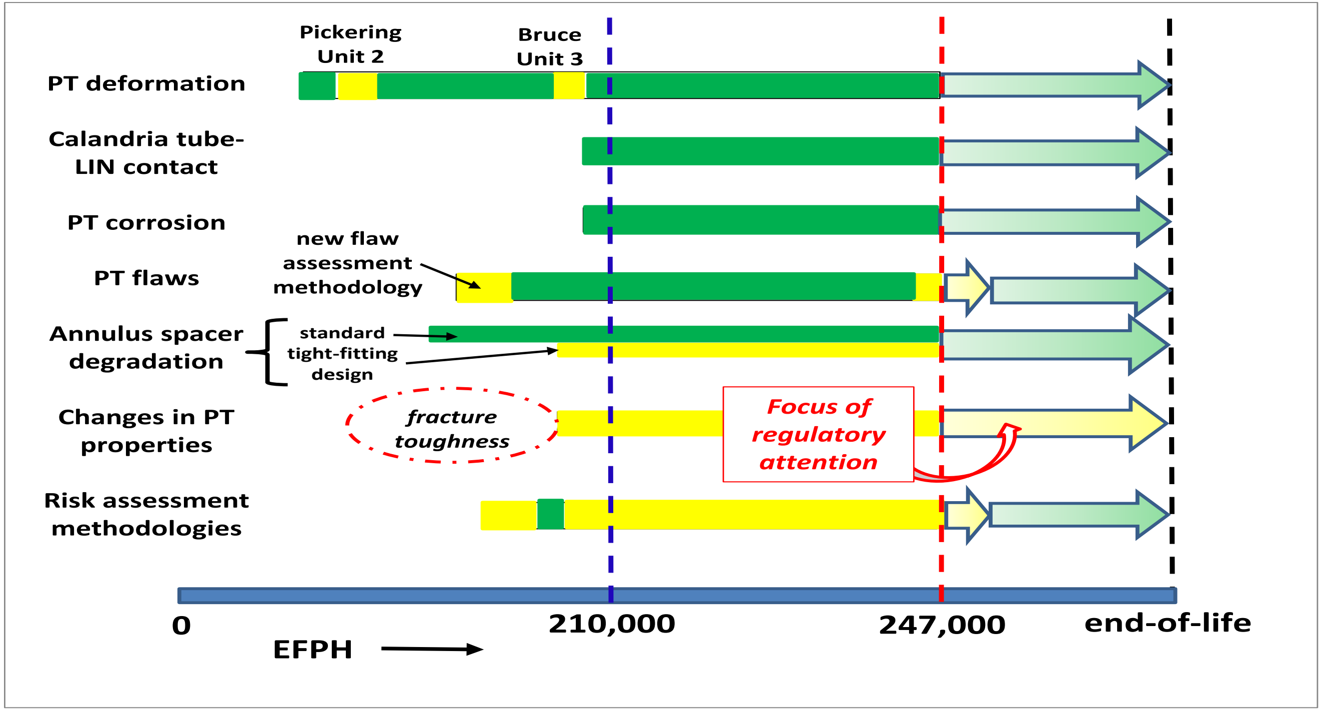
CNSC Evaluation of Proposals for Extended PT Operation (1 of 2)

Existing PROL

- 🟩 licensee provisions satisfactory
- 🟨 Enhanced regulatory scrutiny required

Requested PROL

- ➡ Staff anticipates satisfactory licensee performance
- ➡ Staff anticipates continued need for enhanced scrutiny



CNSC Evaluation of Proposals for Extended PT Operation (2 of 2)

Operation beyond 247,000 EFPH ?

- CNSC staff evaluating licensee progress on outstanding issues from Slide 31

Issue	Status in 2014 (prior to 210,000 EFPH)	Current status
Degradation of tight-fitting annulus spacers	Limited data; modest understanding of degradation phenomena	***Additional data collected; improved understanding of phenomena; FFS guidelines have been drafted***
Methodologies for PT risk assessments	New methodologies proposed; limited practical experience	***Two methodologies accepted for use; regulatory decision on third is pending***
Fracture toughness	Limited validation of, and limited experience using two new Models	***Development and validation of new Model? handling of uncertainties?***

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SUMMARY

Summary (1of 2)

PT degradation mechanisms

- ***CNSC expectation* -** licensees must have an in-depth understanding of PT degradation phenomena, based on extensive research and development and an effective OPEX program
- ***CNSC requirement*** – licensees must routinely inspect PTs to monitor the incidence and severity of known (and emerging) degradation mechanisms
- ***Comprehensive and effective regulatory oversight***
  - Reviews of licensee fitness-for-service assessments, risk assessments, Type II inspections, periodic reviews of the state of industry technical knowledge
  - Clear, well-documented expectations (REGDOC-2.6.3, N285.8 Compliance Plans)
  - Effective Compliance Verification Criteria (CVC) in the Licence Conditions Handbook
  - Regular updates to the Commission (Annual Regulatory Oversight Report)

Summary (2 of 2)

Reduction in fracture toughness

- On-going, dedicated industry research and development program
- ***Regulatory expectations have not changed***: licensees must demonstrate PTs are, and will remain capable of meeting the design intent (*extremely low probability of failure*)
- For acceptance by CNSC staff, models must conservatively predict PT toughness over range of EFPH and Heq concentration shown in the Appendix

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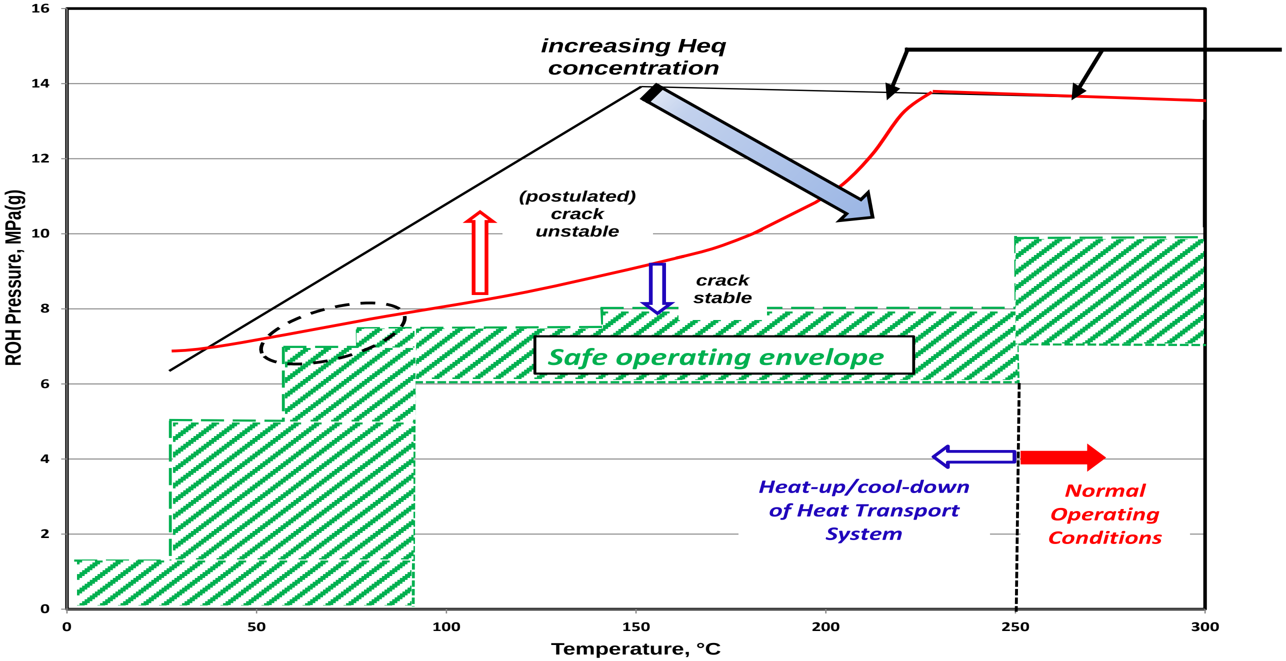
APPENDIX

APPENDIX
Typical Heat Transport System Heat-Up/Cool-Down Envelope



Maximum allowable Heat Transport System pressure

APPENDIX
Canada’s Pressure Tube Population

Station	Number of fuel channels	Existing cores		Refurbished cores	
		Original PTs began service	EFPH (as of Dec. 2017)	New PTs began service	EFPH (as of Dec. 2017)
Pickering Units 1 & 4	390	(1983), (1993)	**134,000**		
Pickering Units 5 - 8	380	1982 – 1985	**237,000**		
Darlington Units 1, 3, 4	480	1990 – 1993	**196,000**		
Bruce Units 1 & 2	480			Fall 2012	**35,000**
Bruce Units 3 & 4	480	1977 – 1978	**211,000**		
Bruce Units 5 - 8	480	1984 - 1987	**233,000**		
Point Lepreau	380			Fall 2012	**35,000**

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APPENDIX
In-Service Degradation of Fuel Channels (1 of 2)

Type of degradation	Potential risk	How do licensees manage the risk
PT deformation		
• Elongation	Potential for inadequate fuel channel support (*e.g. postulated earthquake)*	Periodic inspections. Fuel channel maintenance
• Reduction in wall thickness	Potential reduction in margin-to-rupture (*postulated design basis accident)*	Periodic inspections
• Increase in diameter	Potential reduction in margin to fuel dry-out (*postulated design basis accident*)	Periodic inspections. Ensure adequate provisions for avoidance of fuel dry-out
• PT sag	Potential contact between pressure tube and calandria tube (CT)	Periodic inspections. Shift annulus spacers (as required)

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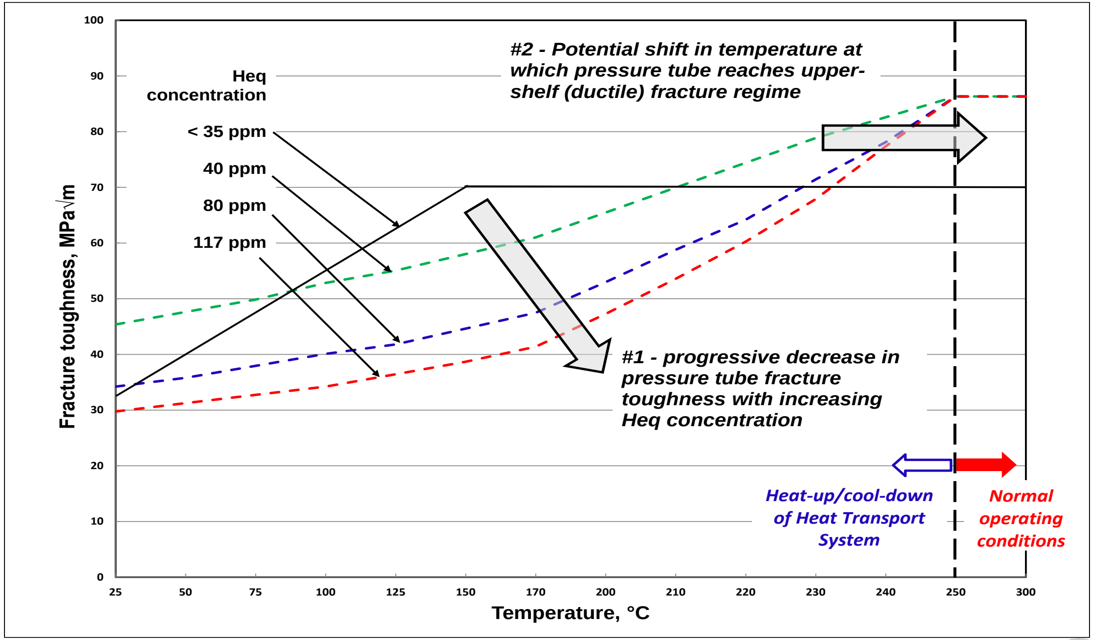
APPENDIX
In-Service Degradation of Fuel Channels (2 of 2)

Type of degradation	Potential risk	How do licensees manage the risk
Fuel channel sag	Potential contact between CT and liquid (poison) injection nozzles	Periodic inspections. Re-positioning nozzles
PT corrosion	Reduction in PT wall thickness	Periodic inspections
PT flaws	Delayed Hydride Cracking (DHC) can initiate at flaws	Periodic inspections. Assess risk of DHC initiation
Degradation of annulus spacers	Potential contact between PT and calandria tube	Periodic inspections (gap). Periodic material surveillance
Changes in PT material properties	Key mechanical properties (e.g. fracture toughness) diverge from values assumed in PT safety case	Periodic removal of PTs for destructive examination

APPENDIX
Impact of Increasing Heq Concentration on PT Fracture Toughness
(Lower-Shelf & Transition Temperature Regimes)



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APPENDIX
Projected Heq Concentrations for Ontario PTs: Near-Inlet

Station	Projections		
		June 2018	Target Service-life
Pickering-B	EFPH	234,680	289,000
	Heq, ppm	**38**	**55-60**
Darlington Units 1, 3, 4	EFPH	192,790	234,000
	Heq, ppm	**45**	**66**
Bruce-A (Units 3, 4)	EFPH	215,035	255,000
	Heq, ppm	**50**	(unknown)
Bruce-B	EFPH	229,260	298,000
	Heq, ppm	**40**	**70**

APPENDIX
Projected Heq Concentrations for Ontario PTs: Near-Outlet

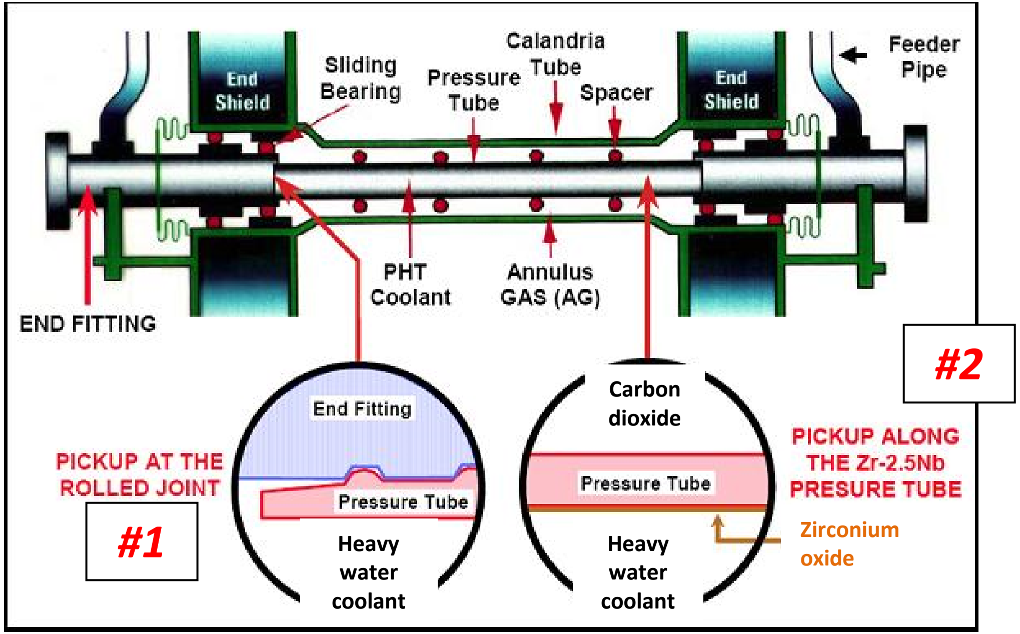
Station	Projections		
		June 2018	**Target Service-life**
Pickering-B	EFPH	234,680	289,000
	Heq, ppm	**55**	**82**
Darlington Units 1, 3, 4	EFPH	192,790	234,000
	Heq, ppm	**52**	**127**
Bruce-A (Units 3, 4)	EFPH	215,035	255,000
	Heq, ppm	**71**	**105**
Bruce-B	EFPH	229,260	298,000
	Heq, ppm	**90**	**160**

APPENDIX
Attributes of an Acceptable Model

1. The model should (preferably) be founded on a mechanistic understanding of the phenomenon, and/or based on experimental evidence
2. The model must be verified and its predictions validated prior to use
3. Model inputs and assumptions must be identified and justified
4. Model uncertainties must be quantified
5. To focus improvements to the model, a sensitivity analysis is invaluable
6. Forward-looking models must be periodically re-validated

APPENDIX

Sources of Deuterium Uptake



PICKUP AT THE ROLLED JOINT

#1

PICKUP ALONG THE Zr-2.5Nb PRESURE TUBE

#2

APPENDIX

Sources of PT data

Periodic (CSA-mandated) / In-Service Inspection programs (licensee-initiated, part of Licensing Basis)

- Frequency: typically 2 to 3-year intervals (planned outages)
- Scope: 10 PTs (CSA minimum); mix of uninspected and previously inspected tubes
- Non-destructive examinations include PT dimensions, PT-CT gap, flaws etc.
- Heq concentration

Material surveillance (CSA requirement)

- Frequency: typically 2 to 4-year intervals
- Remove one PT (plus annulus spacers if possible)
- Destructive examinations: Heq, PT material properties (e.g. fracture toughness)

Research and Development

- 35+ years of dedicated effort that continues within Canadian industry