Status Update: Condition of Pressure Tubes in Operating CANDU Reactors in Canada

Commission Meeting, January 21, 2021

CMD 21-M4

CNSC Staff Presentation

e-Doc 6367848 (PPTX)
e-Doc 6459353 (PDF)

Purpose

This CMD provides:

- A discussion of pressure tube fitness for service in the context of nuclear safety
- Insights into the extent of the regulatory oversight process related to pressure tube fitness for service
- An update on recent topics of interest identified by Commission Members

This CMD is provided for information only and there are no actions requested of the Commission

Primary Subject Areas

- Overview of pressure tube fitness for service requirements and regulatory oversight
- Status of pressure tube fitness for service in operating reactors
- Closure of Commission Action #20052
- Update on status of fracture toughness model following industry burst test BT-29

Outline

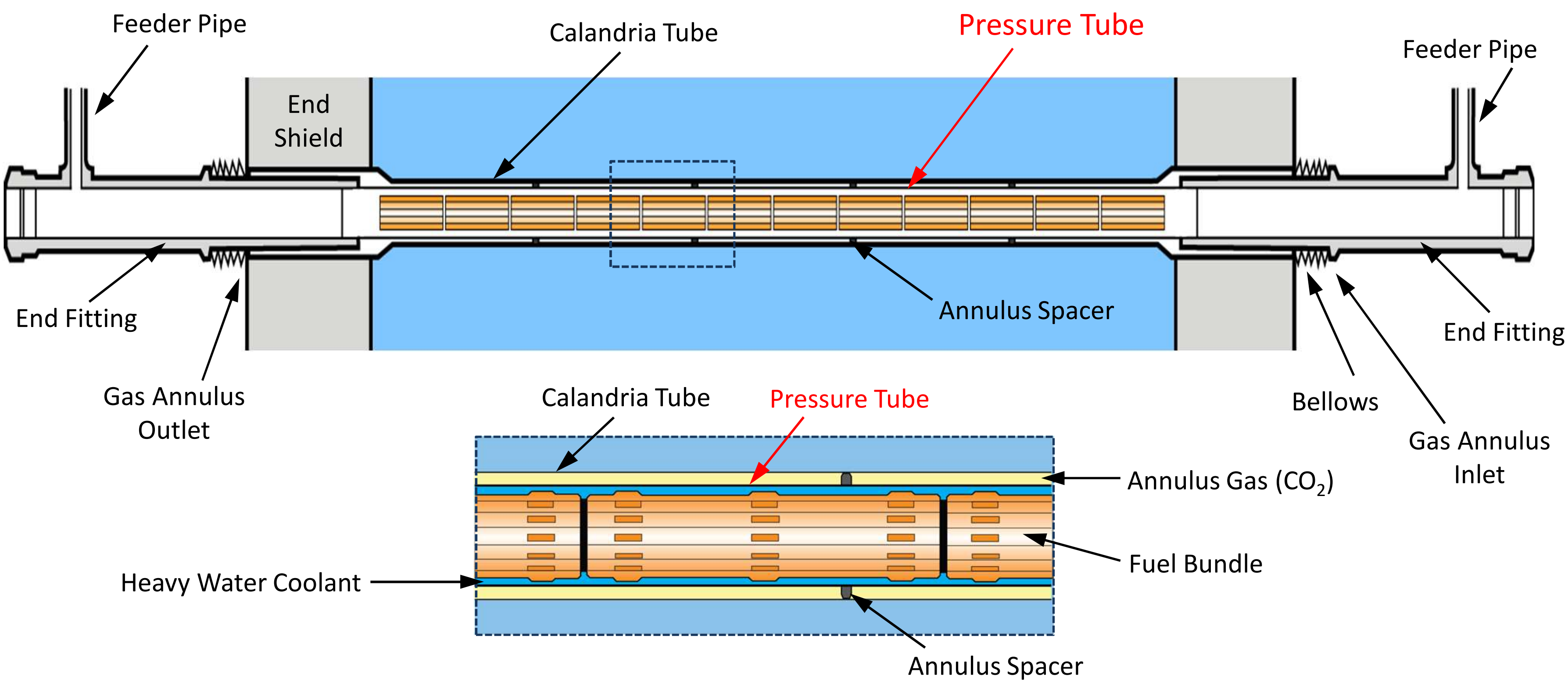
- Overview of the CANDU fuel channel
- Degradation of pressure tubes
- Safety Case for pressure tube operation
- Regulatory oversight of pressure tube fitness for service
- Status of operating pressure tubes
- Commission Action #20052
- Pressure tube burst test BT-29

Commission Meeting, January 21, 2021
CMD 21-M4

CANDU FUEL CHANNELS

e-Doc 6367848 (PPTX)
e-Doc 6459353 (PDF)

CANDU Fuel Channels (1/2)



Commission Meeting, January 21, 2021
CMD 21-M4

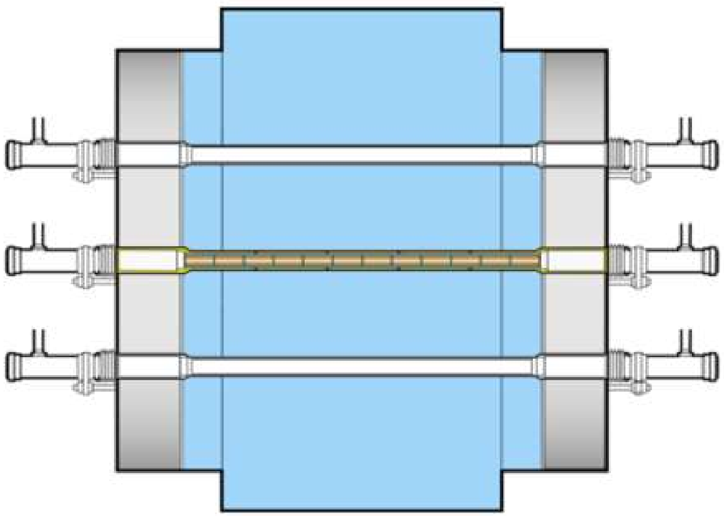
CANDU Fuel Channel (2/2)

Pressure Tubes

- 380 to 480 per core
- Horizontal orientation
- Zirconium-2.5 wt.% Niobium
- Dimensions
  - 6.3 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)



Commission Meeting, January 21, 2021
CMD 21-M4

DEGRADATION OF PRESSURE TUBES

e-Doc 6367848 (PPTX)
e-Doc 6459353 (PDF)

Degradation of Fuel Channels due to Aging

- Exposed to high temperatures, high pressure and intense radiation fields which result in:
  - dimensional changes
  - corrosion
  - changes in material properties
  - degradation of annulus spacers
- Flaws may be introduced due to interactions with fuel bundles

Commission Meeting, January 21, 2021
CMD 21-M4

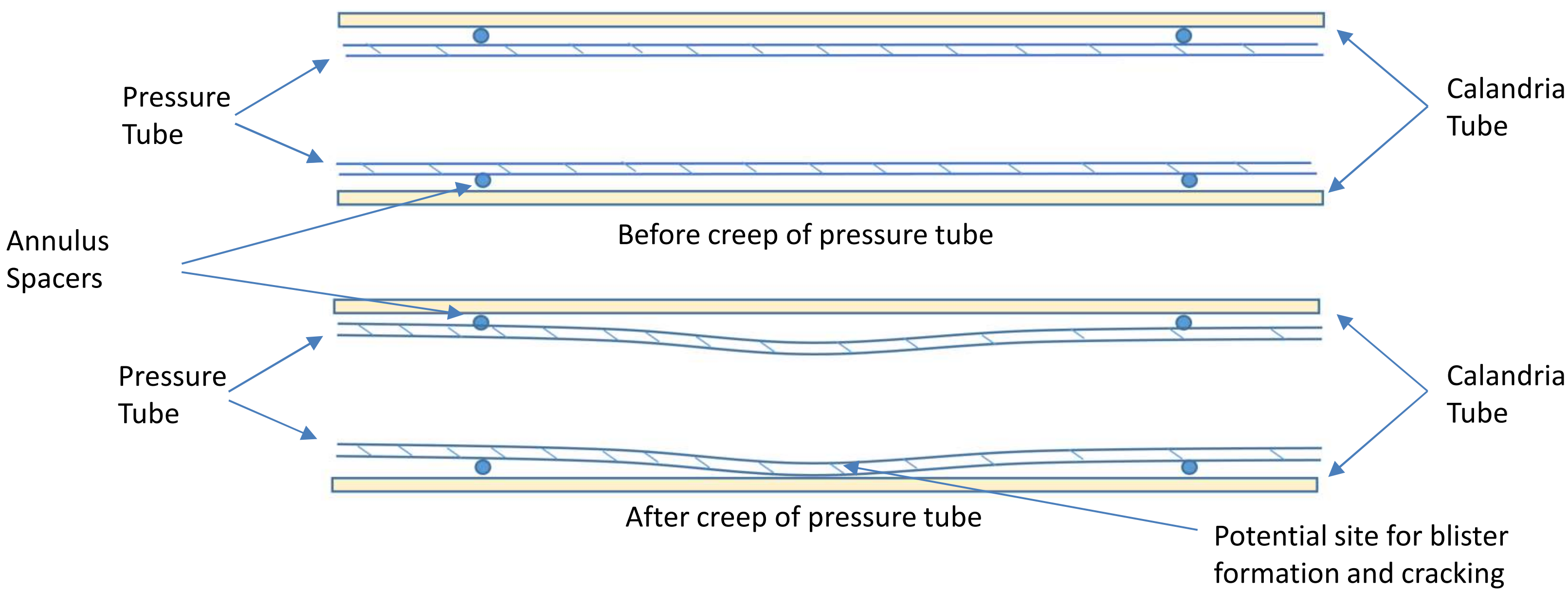
Dimensional Changes

Irradiation induced creep leads to

- pressure tube elongation
  - pressure tube sag
  - pressure tube to calandria tube (PT-CT) contact
- increase in diameter
- decrease in wall thickness

Commission Meeting, January 21, 2021
CMD 21-M4

PT-CT Contact



Corrosion

Corrosion of pressure tubes and end fittings

- not an integrity issue on its own because corrosion rates are low
- reduction in wall thickness considered with irradiation induced thinning
- increases hydrogen equivalent concentration

Commission Meeting, January 21, 2021
CMD 21-M4

Pressure Tube Flaws

Potential sites for crack initiation

- fuel bundle bearing pad frets
- debris frets
- crevice corrosion flaws
- scrapes from fuel bundles

No cracks observed in current Zr-2.5%Nb pressure tubes from service induced flaws

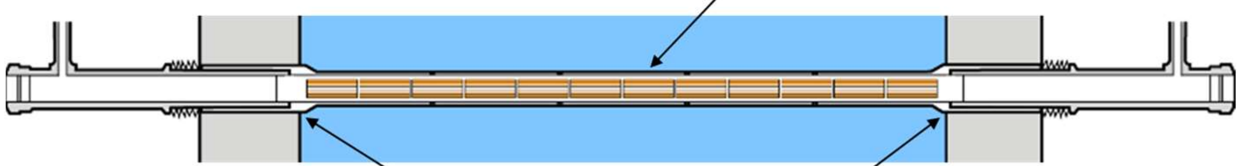
Material Property Changes

- Irradiation effects in pressure tubes
  - increase in yield and tensile strength
  - decrease in ductility and fracture toughness
  - increase in potential for crack initiation
  - increase in crack growth rates
- Irradiation effects in annulus spacers
  - increase in yield and tensile strength
  - decrease in ductility

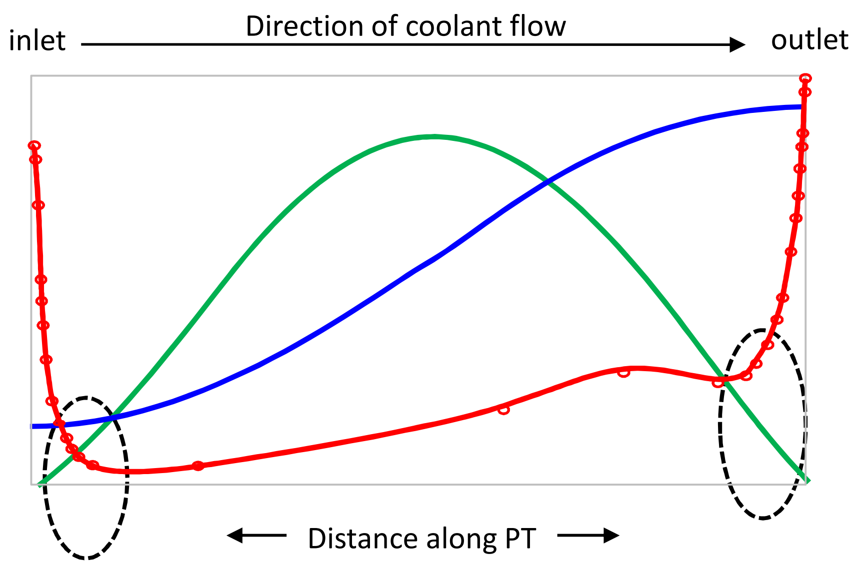
Commission Meeting, January 21, 2021
CMD 21-M4

Hydrogen in Pressure Tubes

- Pressure tubes contain some hydrogen (H), originating from manufacture
- In the presence of hot heavy water coolant, PTs corrode to form zirconium oxide
  - releases deuterium (D), a fraction is absorbed by the tube



Factors Influencing Deuterium Uptake



Fast neutron flux

Coolant temperature

Deuterium concentration

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

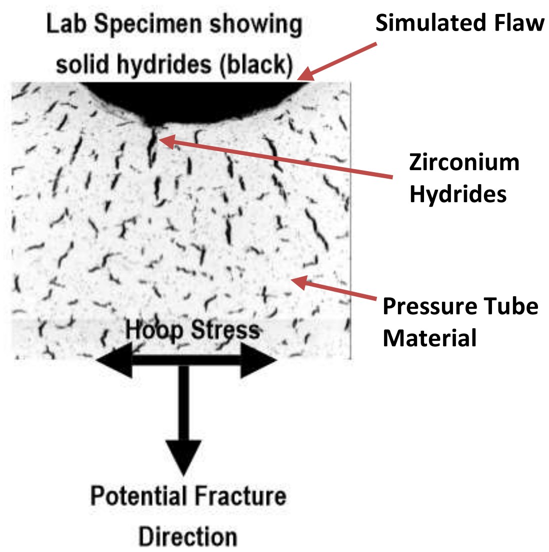
Hydrogen Equivalent Concentration

- H and D concentrations are reported as milligrams per kilogram of pressure tube material (or parts-per-million, PPM)
- H and D are combined and reported as hydrogen-equivalent (Heq) concentration
  - "Heq" will be used throughout this CMD
  - Heq = H_ini + ½ D
- Heq increases due to uptake of deuterium, D
- Licensees require to determine Heq in body-of-tube and rolled joint areas

Commission Meeting, January 21, 2021
CMD 21-M4

Impact of Heq

- Increased potential for formation of zirconium hydride precipitates since Heq increases with operating time
  - depends on temperature and Heq
- Higher Heq increases potential for crack initiation (i.e. due to delayed hydride cracking)
- Hydrides are brittle and can reduce fracture toughness depending on size, orientation and concentration



Example of zirconium hydride precipitates near a flaw in a laboratory specimen

Source: December 2002 AECL Presentation to the USNRC and CNSC, *Fracture Behaviour of Pressure Tubes*

In-Service Failure History - Canada

- Pickering A
  - 1973/4 delayed hydride cracking in overextended rolled joints
  - 1983 rupture caused by blister cracking from PT-CT contact for Zircalloy-2 tube
- Bruce A
  - 1982 crack initiated at a rolled joint
  - 1986 tube rupture due to manufacturing flaw during leak search

Issues that caused historical failures have been addressed

—

Safety systems responded to events as designed

Recent International Experience

- Indian Pressurized Heavy Water Reactors
  - Pressure tube leak in 2015 at Kakrapar Unit 2
  - Pressure tube rupture in 2016 at Kakrapar Unit 1
  - Safety systems performed as designed
  - Contaminants in annulus gas caused external corrosion of tubes and delayed hydride cracking
- CNSC staff reviewed the findings and concluded the Indian experience was not an issue for Canadian reactors.

Commission Meeting, January 21, 2021
CMD 21-M4

SAFETY CASE

e-Doc 6367848 (PPTX)
e-Doc 6459353 (PDF)

Defence-in-Depth

- Five Levels described in REGDOC 2.5.2, *Design of Reactor Facilities: Nuclear Power Plants*
- Primary Levels applicable for PT fitness for service
  - Level 1: prevent deviations from normal operation, and to prevent failures of structures, systems and components (SSCs) important to safety
  - Level 3: minimize the consequences of accidents by providing inherent safety features, fail-safe design, additional equipment and mitigating procedures
  - Level 4: ensure that radioactive releases caused by severe accidents are kept as low as practicable

Pressure Tube Design (Level 1)

- Part of the pressure boundary of the Primary Heat Transport System
- Heat Transport System is an important element of CANDU safety case
  - normal Operating Conditions: PTs contain the high-pressure, high-temperature primary coolant
  - postulated Design Basis Accidents: coolant circulation through the PTs keep the fuel cool
- Designed for a low likelihood of failure under all reactor operating conditions

Inspection and Aging Management (Level 1)

- Programs to assess tubes most likely impacted by aging mechanisms and evaluate inspection findings
- Evaluation of inspected pressure tubes against design margins
- Implement corrective actions if required
  - shortening operating intervals between outages
  - defuel channels
  - replace pressure tubes
  - permanent shut down

Safety Analysis (Levels 3 and 4)

- Rupture of a single pressure tube considered a Design Basis Accident for CANDU safety analysis
- Safety systems designed to mitigate consequences of a failure
- Design Basis Accident
  - frequencies of occurrence equal to or greater than 10^{-5} per reactor year, but less than 10^{-2} per reactor year
- Demonstrate that Core Damage Frequency and Large Release Frequency targets not exceeded in the event of a rupture

Commission Meeting, January 21, 2021
CMD 21-M4

Safety Case

- Level 1 Defence-in-Depth
  - programs to prevent pressure tube failures
- Level 3 Defence-in-Depth
  - safety systems to respond to pressure tube failures
- Level 4 Defence-in-Depth
  - barriers to prevent the release of radioactive materials

Extended Operation

- Extended operation refers to operation beyond 210,000 equivalent full power hours (EFPH)
- Safe operation is not limited to 210,000 EFPH
  - intended to ensure that reactors were economical to build and operate
  - based on conservative estimates for pressure tube deformation rates
- Safe operating life of pressure tubes based on design and fitness for service safety margins

Safe operation is not limited to 210,000 EFPH

Commission Meeting, January 21, 2021
CMD 21-M4

REGULATORY OVERSIGHT

e-Doc 6367848 (PPTX)
e-Doc 6459353 (PDF)

Regulatory Framework: Operating Licence

Licence Condition 6.1 – Fitness for Service

The licensee shall implement and maintain a fitness for service program.

Licence Conditions Handbook - Section 6.1

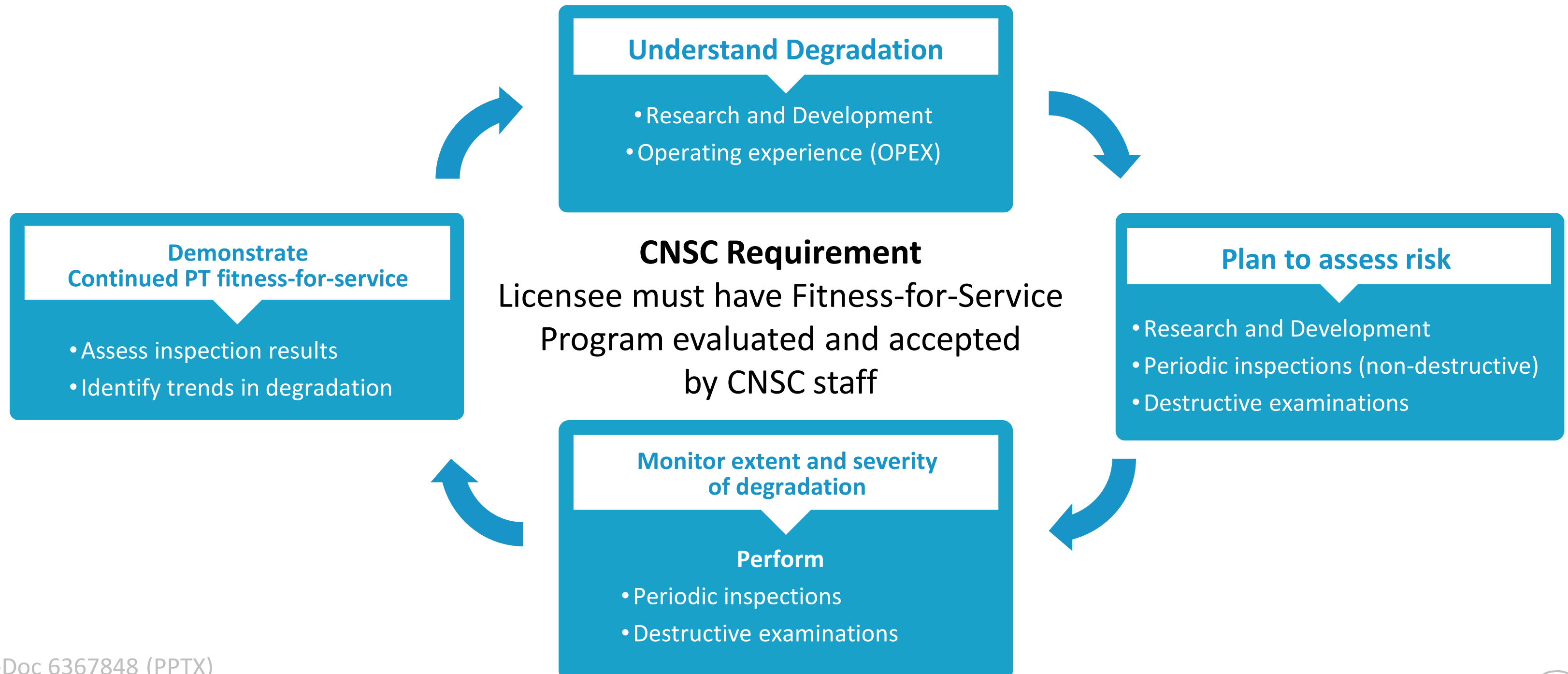
A fitness for service program includes the following elements:

- *aging management activities to ensure the availability of required safety functions of structures, systems and components (SSCs)*
- *periodic and in-service inspection programs to ensure that pressure-boundary components and safety-related structures are monitored for degradation*

Commission Meeting, January 21, 2021

CMD 21-M4

Regulatory Oversight of PT Degradation



Commission Meeting, January 21, 2021
CMD 21-M4

CNSC's Regulatory Oversight model

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

Regulatory Framework: Compliance

- REGDOC 2.6.3 – aging management requirements
  - life cycle management plans to manage aging
- CSA Standard N285.4 - requirements for periodic inspection programs
  - scope, frequency and methods
  - acceptance standards for inspection findings
  - disposition process requiring regulatory acceptance before reactor restart from an outage
- CSA Standard N285.8 - evaluation procedures
  - procedures for dispositioning inspection findings
  - fracture protection assessments
  - risk evaluations for the population of tubes that are not inspected

Regulatory Framework: Oversight

CNSC staff assess

- life cycle management plans
- periodic inspection programs
- outage reports and dispositions of inspection results
- fracture protection and risk evaluations
- important control room procedures and protocols

Extensive regulatory oversight for pressure tube fitness for service

Industry Challenges for Extended Operation

- Predicting material property changes beyond current operating experience
  - reliance on research and material surveillance
- Increasing irradiation induced creep increasing the potential for PT-CT contact
  - need for more inspections and maintenance activities
- Shift to probabilistic assessment methods for fracture protection and to evaluate uninspected population of pressure tubes
  - development of novel approaches

CNSC staff verify design and fitness for service margins maintained for extended operation

Evaluation Criteria Established in CVC

Compliance verification criteria establish safe operating margins:

- satisfy design margins for the assessment of detected flaws and fracture protection
- prevent PT-CT contact in tubes that may form hydride blisters
- demonstrate safety analysis goals not compromised by the uninspected population of tubes
- verify Heq and material property changes are bounded by predictive models

Safety margins must be maintained to operate pressure tubes

Commission Meeting, January 21, 2021
CMD 21-M4

PRESSURE TUBE EVALUATIONS

e-Doc 6367848 (PPTX)
e-Doc 6459353 (PDF)

Commission Meeting, January 21, 2021
CMD 21-M4

Inspected and Uninspected Tube Evaluations

CNSC requirement:

Licensee must demonstrate acceptable performance of pressure tubes for continued operation

Assessments based on results from periodic inspections and spacer relocation	**30%** of pressure tubes*
	+
Risk assessments based on CNSC-accepted Models	**70%** of pressure tubes

✓ **100% of tubes assessed against compliance verification criteria**

* Nominal
- actual percentages vary by station and expected degradation mechanisms
- exceeds minimum requirements of CSA Standard

Evaluation Process

- Pressure tubes evaluated against compliance verification criteria (CVC) after every inspection
- Fitness for service demonstrated for specified period
  - depends on evaluation procedure
- If CVC not met, corrective actions imposed on the licensee, for example:
  - reduce operating interval to next inspection
  - reposition spacers
  - defuel channel
  - replace pressure tube

CVC must be satisfied to operate pressure tubes

Evaluations Required for Inspected PTs

- Detected flaws
  - demonstrate no crack initiation prior to next planned inspection
- PT-CT contact
  - demonstrate no contact + hydride blister formation prior to next planned inspection
- Heq uptake
  - evaluate uptake rates
- Material surveillance
  - measure material properties and delayed hydride cracking growth rates

Reactor Core Evaluations (1/2)

- Fracture protection
  - demonstrate low likelihood of rupture of pressure tubes for design loads
  - establish pressure-temperature operating envelope for heat-up and cooldown
- Core assessments for flaws
  - assess likelihood of failure of tubes due to flaws (focused on uninspected tubes)

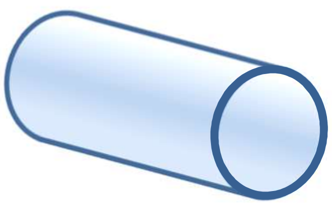
Reactor Core Evaluations (2/2)

- Leak-Before-Break (LBB)
  - demonstrate low likelihood of rupture in tubes that may contain zirconium hydrides at normal operating temperatures (focused on uninspected tubes)
- PT-CT contact
  - demonstrate low likelihood of contact and hydride blister formation prior to next planned inspection (focused on uninspected tubes)

Evaluation Process

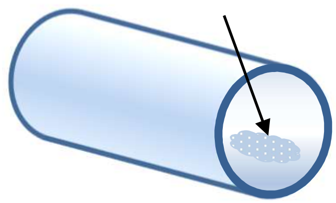
Multi-tiered evaluation approach for pressure tube fitness for service

Initial conditions → Inspected pressure tubes evaluated for potential cracking mechanisms → Uninspected PTs must have a low likelihood of failure → Maintain Safety Margins



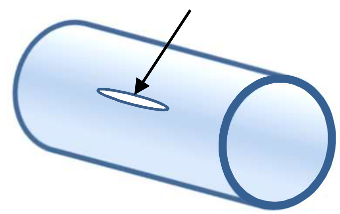
As-installed pressure tube
- must meet CSA N285.0 design requirements
- baseline conditions established for monitoring in accordance with CSA N285.4

surface flaw, PT-CT contact area

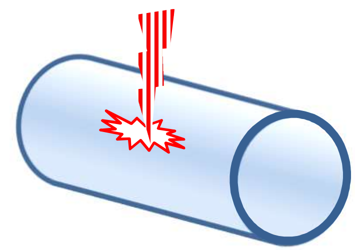


In-service pressure tube
- periodic inspection (CSA N285.4)
- detected flaws must meet CSA N285.4 acceptance standards
- prevent PT-CT contact
- otherwise, licensee must demonstrate tube remains fit-for-service (CSA N285.8)

through wall crack, PT-CT contact



Un-inspected pressure tube
- flaws?
- PT-CT contact?
- Heq concentration?
- fracture toughness?



Inspected pressure tubes
- cracking not permitted

Un-inspected pressure tubes
- low likelihood of failure

Commission Meeting, January 21, 2021
CMD 21-M4

STATUS OF PRESSURE TUBES

e-Doc 6367848 (PPTX)
e-Doc 6459353 (PDF)

Commission Meeting, January 21, 2021
CMD 21-M4

Pickering

Unit	Fitness for Service Evaluated to[1]	Next Planned Outage	Planned End of Operation
1	2023	2022	2024
4	2020	Outage underway[2]	
5	2021[3]	2022	
6	2020[3]	2023	
7	2022	2021	
8	2021	2021	

Units 2 and 3 shut down and in safe storage

(1) Calendar dates are approximate (depends on EFPH)
(2) When presentation prepared
(3) Evaluation under review when presentation prepared

Commission Meeting, January 21, 2021
CMD 21-M4

Darlington

Unit	Fitness for Service Evaluated to(1)	Next Outage	Planned End of Operation
1	2021	2021	2022
2	Tubes replaced prior to 2020 return to operation		
3	Refurbishment commenced September 2020		
4	2021	2021	2023

(1) Calendar dates are approximate (depends on EFPH)

Commission Meeting, January 21, 2021
CMD 21-M4

Bruce Power

Unit	Fitness for Service Evaluated to(1)	Next Outage	Planned End of Operation
1	2023	2021	Tubes replaced prior to restart in 2012
2	2022	2022	
3	2021	2021	2023
4	2023	2022	2025
5	2023	2022	2026
6	Refurbishment underway		
7	2021	2021	2028
8	2020	Outage underway(2)	2030

(1) Calendar dates are approximate (depends on EFPH) (2) When presentation prepared

Commission Meeting, January 21, 2021
CMD 21-M4

Point Lepreau

Fitness for Service Evaluated to[1]	Next Planned Outage	Planned End of Operation
2026	2024	Tubes replaced prior to 2012 restart

(1) Calendar dates are approximate (depends on EFPH)

Commission Meeting, January 21, 2021
CMD 21-M4

COMMISSION ACTION #20052

Purpose of Commission Action

- Provide information on industry models to predict fracture toughness and Heq in CANDU pressure tubes
- Discussion of model uncertainties
- December 2019 briefing note provided to Commission Members

Heq and Fracture Toughness Models

- Models used to predict specific behaviors
- Support planning the scope and frequency of inspections and surveillance
- Direct or indirect means to address CVC
  - direct: Measured Heq uptake compared to acceptable rates
  - indirect: Key input to fracture protection and LBB assessments
- Decline in fracture toughness with increasing Heq at temperatures below full power hot operation

Heq Measurement

- Majority of data from in-service scrape samples
  - small thin samples removed from tube wall analyzed with mass spectrometer
  - measurement accuracy 10% for low concentrations down to 1% for higher concentrations
  - in general, one future repeat measurement possible from same axial location
- Full thickness samples from removed material surveillance tubes
- Tube-to-tube variability in a reactor core
  - operational parameters affecting corrosion rates

Heq models must be bounding for pressure tubes

Heq Models

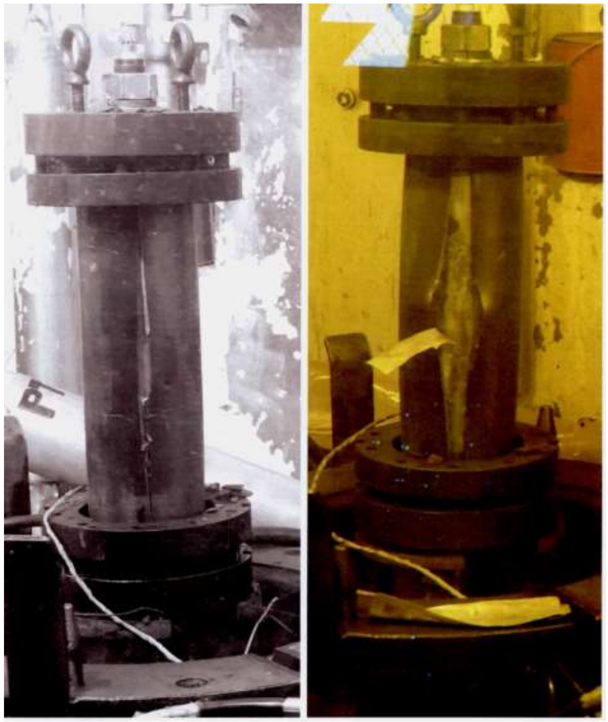
- Separate Rolled-Joint and Body-of-Tube models
  - "recalibrated" as required when new data obtained
- Deterministic model
  - statistical 95% upper bound fit to measurement data
  - used to evaluate condition of inspected tubes (flaw evaluations, contact assessments)
  - used to predict future Heq for licensing limit on fracture toughness model
- Probabilistic models
  - used for core assessments

Heq models updated as required

Commission Meeting, January 21, 2021
CMD 21-M4

Fracture Toughness Basics

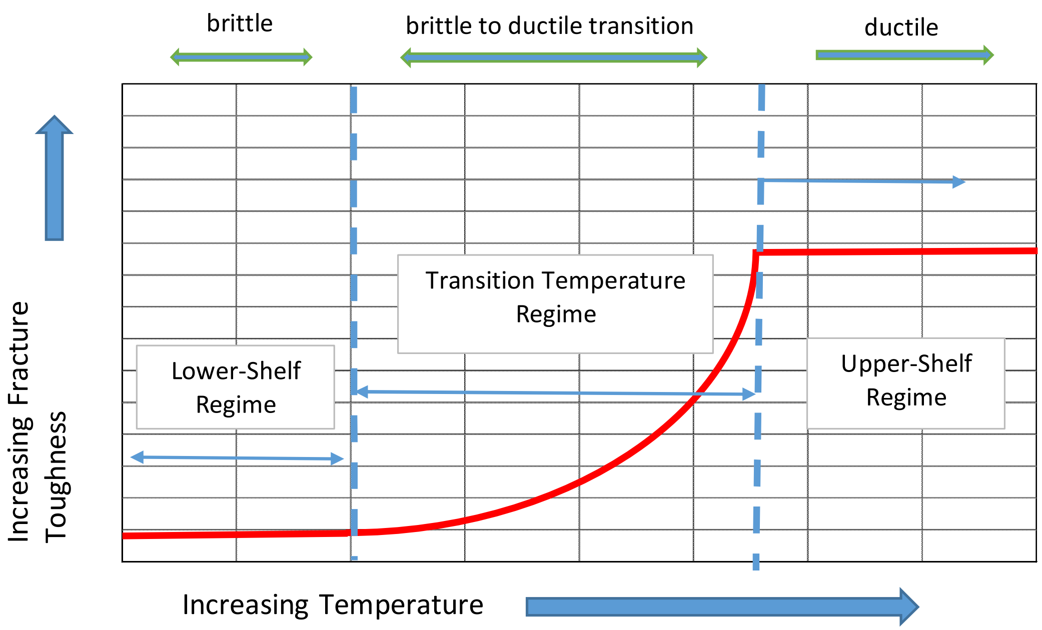
- Resistance to propagation of a through wall crack
- Measured using rising pressure burst tests
- Supplemented with small scale test specimens from removed tubes
- PTs exhibit lower-shelf, transition and upper shelf behavior



Destructive testing of rising pressure burst test specimens.
Used with permission of CANDU Owners Group.

Commission Meeting, January 21, 2021
CMD 21-M4

Fracture Toughness Behaviour



Two Fracture Toughness Models

- Upper shelf: lower bound to a multi-variable regression model
  - applicable above 250°C (normal at power operation)
  - insensitive to Heq
  - on-going verification using materials surveillance tubes
- Lower shelf and transition region: “Cohesive Zone Model” (CZM)
  - applicable from room temperature to 250°C
  - continued validation with experiments
  - revision 1 currently in use with restrictions
  - plans to issue Revision 2 in 2021

CZM Revision 1 Restrictions

- Incorporated in 2019 update to CSA N285.8
  - restricted to maximum Heq of 120ppm
  - restricted to maximum Heq of 80 ppm in “front end” of pressure tubes
    - discussed in next section
- Licensees must demonstrate that future Heq predictions do not exceed these values for reactor core evaluation periods

Fracture toughness model cannot be used beyond range of validity

CZM Revision 1 Uncertainty

- 2.5^{th} lower percentile predictions from CZM Revision 1 model used in core evaluations to bound uncertainty in model predictions
- One test result to date (BT-29) has a measured toughness below 2.5^{th} lower percentile prediction
  - additional restriction on the application of the model
  - CZM Revision 2 intended to address the restriction
  - more detail to follow

Lower bound of fracture toughness predictions used to address modelling uncertainty

Commission Meeting, January 21, 2021
CMD 21-M4

Objectives of CZM Revision 2

- Increase upper applicability limit to 160 ppm Heq
- Address front end effect to remove 80 ppm Heq restriction

Revision to fracture toughness model required to demonstrate fitness for service to end of operation of some tubes

Commission Meeting, January 21, 2021
CMD 21-M4

BT-29 TEST: FRONT END EFFECT

e-Doc 6367848 (PPTX)
e-Doc 6459353 (PDF)

Background

- A 2017 fracture toughness tests, BT-29, challenged the results of the pressure tube fracture toughness model in CSA Standard N285.8-15.
- The N285.8-15 model is the 2.5th lower bound prediction from the CZM Revision 1 model
- CNSC staff previously provided information to Commission Members during the Pickering licence renewal and in a December 2019 briefing

Information on BT-29

- Ex-service pressure tube material
- Hydrided to 103 ppm Heq
- Test temperature 225^{o}C
- Burst test specimen was extracted from the "front end" of a pressure tube
- Test result generated a fracture toughness below lower bound prediction of the CZM Revision 1 model

Commission Meeting, January 21, 2021
CMD 21-M4

Pressure Tube Front End

- Pressure tubes are mechanically extruded from ingots
- The “front end” is the end of the tube where the extrusion process was started
- Differential cooling results in differences in microstructure along the length of the tube

Safety Implications

- Front end region of pressure tube with higher Heq could have lower fracture toughness than predicted by the lower bound model
- Potential for non-conservative reactor core evaluations using fracture toughness as an input
- Significant for reactors with front end oriented at outlet end of pressure tube
  - higher [D] pick-up rates

Commission Meeting, January 21, 2021
CMD 21-M4

CNSC Staff Response

CNSC staff required that licensees

- provide information on front end orientation of tubes and Heq predictions
- evaluate the impact on current and future pressure tube evaluations
  - report any tubes predicted to exceed 80 ppm at front end prior to removal from service / end of operation
  - re-assess evaluations if required
- establish a validity limit for the fracture toughness model for the front end

Additional Testing

- 1.5 year focused R&D program
  - small specimen tests and additional burst tests of front end material
- BT-29 attributed to hydride orientation distribution due to front end microstructure
- 9 similar burst tests completed, none exhibited the same low fracture toughness
  - Heq from 69 to 101 ppm
  - test temperatures 200°C to 250°C
- Plan to accommodate front end effect in CZM Revision 2

Commission Meeting, January 21, 2021
CMD 21-M4

CSA Standard Update

Incorporate restriction on the application of the fracture toughness model to less than 80 ppm for evaluations 1.5 meters from the front end of pressure tubes.

- based on additional testing
- included in the 2019 update to the standard

Commission Meeting, January 21, 2021
CMD 21-M4

Tube Installation Review (1/2)

Station	Units	Tube Orientations	Impact on Evaluations?
Darlington	1, 4	100% front end inlet	No
	2	100% front end outlet	No
Pickering	1	50% front end outlet	No
	4-8	100% front end inlet	No
Bruce	1, 2	100% front end outlet	No
	3	50% front end outlet	Low
	4-8	100% front end inlet	No
Point Lepreau	N/A	100% front end outlet	No

No significant impact on current evaluations

Tube Installation Review (2/2)

- Darlington Unit 2, Bruce Units 1 & 2, Point Lepreau
  - operating with new tubes so current Heq will be low
  - unlikely to approach 80 ppm in front end for some time
- Bruce Unit 3
  - potential for some tubes to reach 80 ppm by end of 2020
  - burst test of Unit 3 tube provided better fracture toughness than BT-29
  - low population of flaws detected in outlet region of Bruce PTs, all minor
  - CZM Revision 2 expected early 2021

Correction to Briefing Note

- December 2019 briefing note states 58 Bruce Unit 3 PTs may exceed 80 ppm in the front end by the end of 2020
- Correction
  - there are 58 tubes that were predicted to exceed 86 ppm by end of 2020
  - there are 130 tubes that were predicted to exceed 80 ppm by end of 2020
- No impact on risk evaluation that was completed

Commission Meeting, January 21, 2021
CMD 21-M4

SUMMARY

e-Doc 6367848 (PPTX)
e-Doc 6459353 (PDF)

Commission Meeting, January 21, 2021
CMD 21-M4

Conclusions

- Compliance verification criteria establish safe operating margins
- Extensive regulatory oversight
- Understanding of aging mechanisms
- Multi-tiered evaluation approach for pressure tube fitness for service
- Regulatory focus on priority issues
  - Heq, fracture toughness, PT-CT contact
- Adequate industry response to BT-29 fracture toughness test

Appropriate safety margins and extensive regulatory oversight

Canadian Nuclear Safety Commission | Commission canadienne de sûreté nucléaire

Canada

Connect With Us

Join the conversation

nuclearsafety.gc.ca