Canadian Nuclear Safety Commission | Commission canadienne de sûreté nucléaire

CMD 25-M27

Date: 2025-05-06

Written Submission from CNSC Staff

Mémoire écrit du personnel de la CCSN

In the matter of the

À l'égard du

Update on an item from a previous Commission proceeding

Mise à jour sur un sujet découlant d'une séance précédente de la Commission

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Response to Provide a Technical Update on Elevated Hydrogen Equivalent Concentration Research and Development Activities

Réponse visant à fournir une mise à jour technique sur les activités de recherche et développement liées à une concentration équivalente en hydrogène élevée

Commission Meeting

Réunion de la Commission

June 3, 2025

Le 3 juin 2025

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MEMORANDUM

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Yes

To / A: Candace Salmon
Commission Registry

From / De: X

DR Alexandre Viktorov
Director General, Directorate of Power Reacto...

Subject: CNSC Staff Response to the Direction from the Commission to Provide a Technical Update on Elevated Heq R&D Activities

Purpose

During a Commission meeting held on January 29, 2025, Commission Member Dr. Lacroix requested the following from CNSC staff [1]:

> *"What I would very much appreciate in the next few months, at least in the near future, is it possible to provide the Commission with a technical progress report along the lines of a CMD 23-M3 that you provided us two years ago in January 2023. And that would provide a general view of the technical progress. And I insist on this on the technical progress concerning the crack initiation model, the fracture toughness model, and the crack growth rate model."*

CNSC staff have prepared this memorandum in response to the request to provide an update on findings generated from the elevated hydrogen equivalent concentration (Heq) research and development (R&D) program [2, 3] that were communicated from Bruce Power and OPG to CNSC staff in four semi-annual updates and two in-person industry workshops.

Background

Appendix A of CMD 23-M3 [4] provided an overview of the potential impact of localized regions of elevated Heq near the rolled joints of pressure tubes, focusing on:

- Updates to Heq models
- Verification of delayed hydride cracking initiation models
- Potential impact on pressure tube fracture toughness model

Figure 1 illustrates the role of these models in pressure tube flaw evaluations.

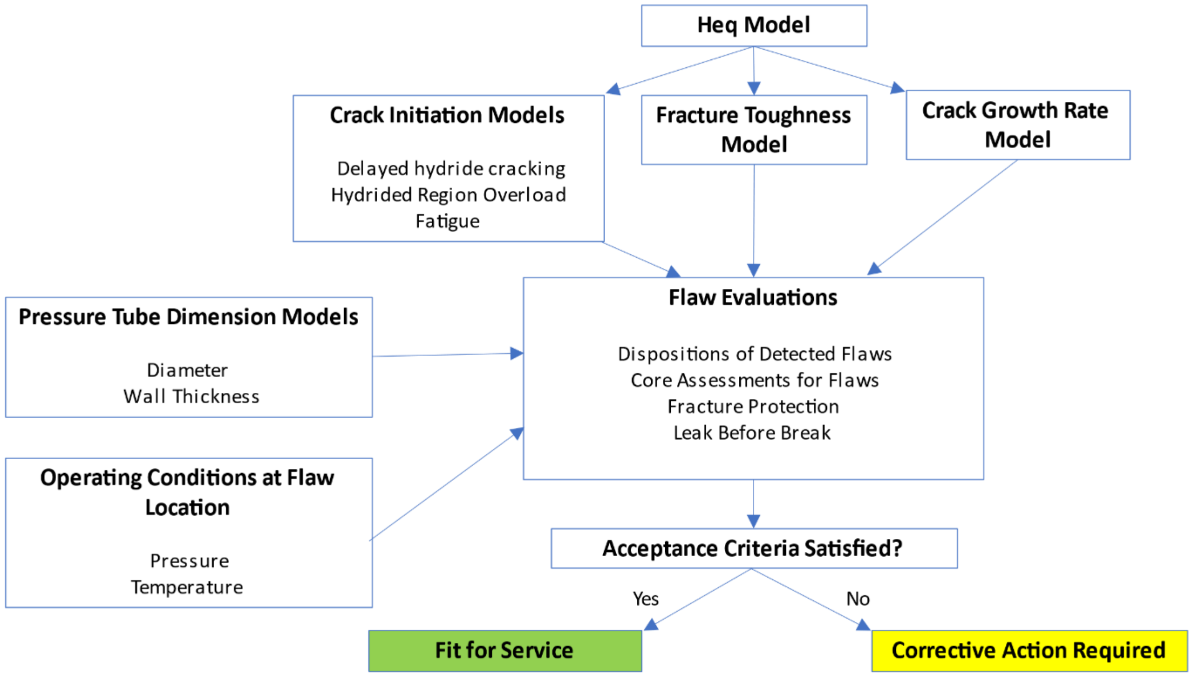

Figure 1: Overview of fitness for service evaluations for flaws in pressure tubes

Updates to the Heq Models

Industry has proceeded with the development of two three-dimensional hydrogen isotope ingress and diffusion models to refine Heq predictions near the rolled joint burnish marks for conditions associated with the extended operation of pressure tubes beyond 210,000 equivalent full power hours (EFPH).

<u>Outlet Rolled Joint (ORJ) Region</u>

- Thermalhydraulics modelling of aged fuel channel configurations has indicated that an approximately 20°C temperature difference between the top and bottom of a pressure tube can exist near the outlet rolled joint after a pressure tube has been subject to diametral expansion because of thermal and irradiation induced creep.
- The diametral expansion increases the gap between the top of the fuel bundles and the top of the pressure tube allowing for more coolant to bypass the bundles increasing local cooling effects compared to the bottom of a pressure tube when the fuel bundle bearing pads rest on the inner diameter (ID) surface of the tube (see Figure 2).
- While the maximum diametral expansion of the pressure tube occurs a few fuel bundle lengths upstream of the burnish mark, the cooling effects are still observed near the rolled joint.

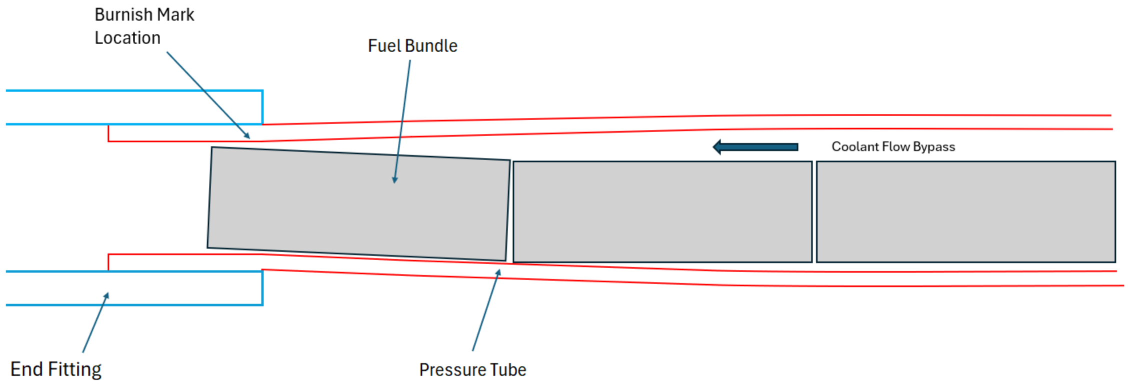

Figure 2: Illustration of coolant flow bypass at the outlet end of a pressure tube generating a circumferential temperature gradient (not to scale)

- Hydrogen in pressure tubes will diffuse to colder locations, hence the temperature gradient can result in more hydrogen accumulating in the top of the pressure tube.
- The three-dimensional modelling completed to date has illustrated that the inclusion of circumferential temperature gradients arising from the flow conditions at the outlet end of the pressure tubes can generate regions of elevated Heq consistent with the results that were observed in 2021 in the Bruce Unit 3 and Bruce Unit 6 pressure tubes.

Inlet Rolled Joint (IRJ) Region

- The mechanism that is attributed to the formation of a region of elevated Heq near the outlet rolled joint of pressure tubes cannot be the cause of the region of elevated Heq near the inlet rolled joint since there is no flow bypass as coolant enters the inlet end of the pressure tubes.
- Metallurgical examination of pressure tube material from the inlet region of affected pressure tubes indicated a region of high Heq concentrated near the outer diameter (OD) surface of the pressure tube (often called a "blip"), with much lower Heq near the ID surface (see Figure 3). This was also illustrated in a figure provided in the updates from licensees in CMD 25-M19 [6] and CMD 25-M19.1 [7].
- Industry has proposed that blips form as a result of pressure tube material coming into contact with a tapered section of the end fitting due to localized bending that occurs as the pressure tube elongates due to thermal and irradiation induced creep over the life of the reactor (See Figures 4 and 5). Since the end fitting is cooler than the coolant passing through the pressure tube, this establishes a local cold spot that attracts hydrogen to the OD surface region.

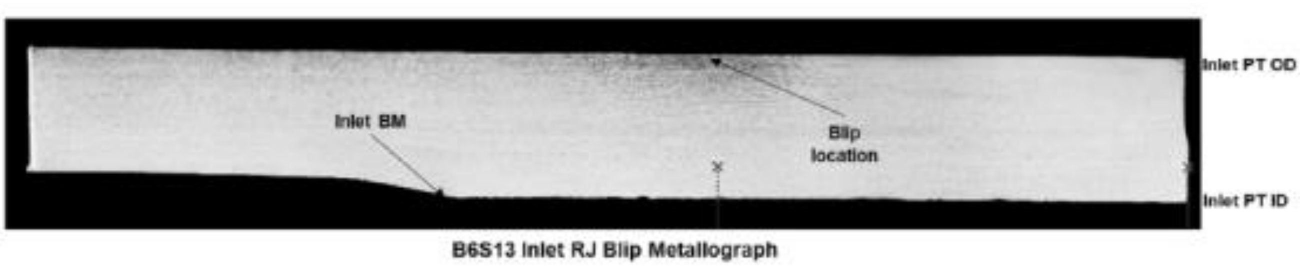

Figure 3: Illustration of an inlet rolled joint region elevated Heq blip [6, 7] (the dark region near the OD surface indicates a region of dense zirconium hydride indicating a high Heq)

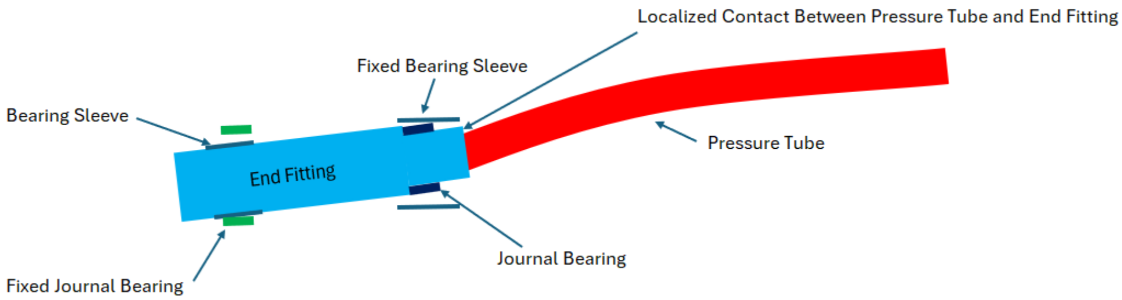

Figure 4: Illustration of the deformation scenario (exaggerated) that could lead to Heq blip formation (not to scale)

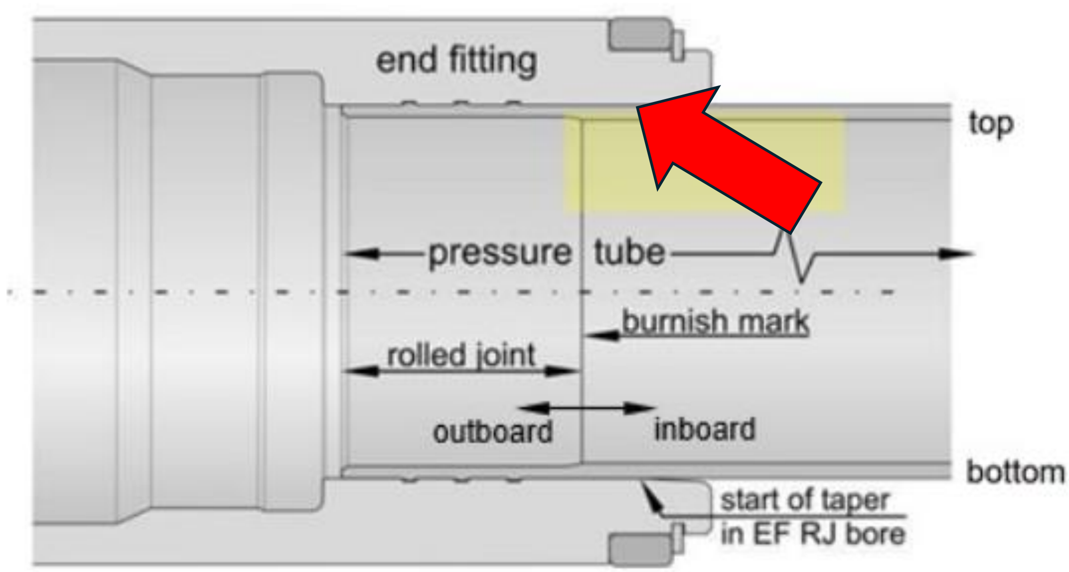

Figure 5: Illustration of rolled joint region of a pressure tube – under normal circumstances no contact at Heq blip location (red arrow) because of taper in end fitting bore. The deformation scenario shown in Figure 4 can lead to contact according to deformation modelling.

- Industry has conducted finite element analysis to demonstrate the fuel channel deformation scenario that would lead to localized contact and through-wall temperature gradients near the inlet rolled joint burnish mark. Using this information, hydrogen isotope ingress and diffusion modelling was completed and was able to reproduce Heq blips in the inlet region.

Current Status

- Further investigation into the phenomenon has indicated that blip formation may be possible at the outlet end of pressure tubes and add to the elevated Heq effects due to circumferential temperature gradients at the outlet ends of tubes.
- Work is underway to further validate model predictions, confirm the most influential input parameters and the sensitivity of model predictions to the influential parameters.

Expected Outcome

- It is expected that by the end of 2025 the licensees will be capable of modelling the maximum circumferential and axial extents of the regions of elevated Heq expected by the end of planned operation and determine if these regions can interact with locations where pressure tube flaws have been known to exist.
- If there will be no interaction between known flaws and the regions of elevated Heq by the planned end of operation of reactors, there will be no impact on a licensee's ability to demonstrate that safe operating margins are maintained.

Crack Initiation Testing

There are three crack initiation mechanisms that are considered for pressure tube flaw evaluations:

- Delayed Hydride crack (DHC) – brittle zirconium hydrides can accumulate at a flaw under a constant applied load (internal pressure) because of the stress concentration effect of the flaw geometry and grow to a size where the resulting stress can cause the hydrides to crack.
- Hydrided Region Overload (HROL) – hydrides can accumulate at the root of a flaw under a constant applied load but may not grow to a size that the hydrides crack. However, if the load (internal pressure) is increased, the increase in stress can cause the hydrides to crack.
- Fatigue – fluctuations in applied load (i.e. internal pressure) can cause a fatigue crack to initiate due to the stress concentration effect of the flaw geometry. This crack initiation mechanism is not directly influenced by Heq, but if the Heq is high enough to cause large zirconium hydrides to exist in the material, the presence of the hydrides could change the fatigue resistance of the material.

Delayed Hydride Cracking

- A discussion of the role of Heq on the delayed hydride cracking (DHC) mechanism is provided in CMD 23-M3 [4].
- Three types of tests, using similar specimens, are performed by industry to assess the pressure tube material resistance to DHC (see Figures 6-8):
    - Test to determine the threshold stress intensity for DHC initiation from a blunt flaw, K_{TH}
    - Test to determine the threshold stress intensity for DHC initiation from the tip of a crack, K_{IH}
    - Test to determine the threshold stress for DHC initiation from material with no flaw present, p_c
- K_{TH} is not used directly in the crack initiation model but can be used to verify the model predictions. K_{TH} is determined for a flaw with a specific geometry and can be used to assess any changes to the crack initiation threshold for that geometry given changes to material (i.e. different Heq values) or test conditions (i.e. test temperature, etc.).
- K_{IH} and p_c are parameters that are used in the DHC model to estimate the potential for crack initiation from a random flaw.
    - Service induced flaws, particularly those caused by debris trapped between a fuel bundle and the pressure tube wall, can generate random flaw geometries and different stress concentrations.

Therefore, it is not possible to directly test the crack initiation threshold for all possible flaw geometries.

- The DHC model uses the two extreme scenarios of a crack being present (K_{IH}) or no flaw being present (p_c) and stress conditions associated with specific flaw geometries to estimate the potential for crack initiation for specific flaws.

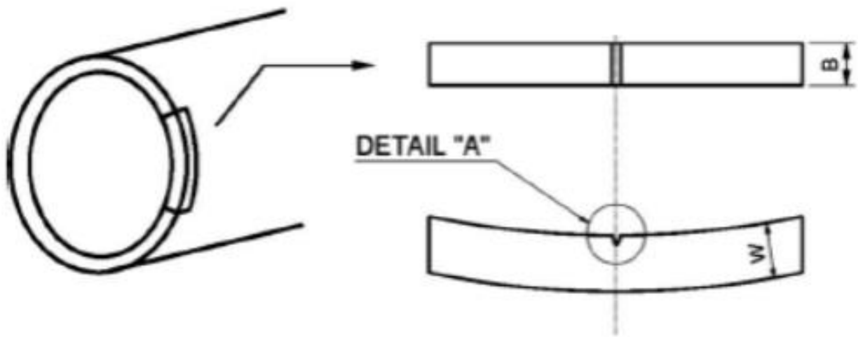

Figure 6: Illustration of DHC testing sample with blunt notch used for K_{TH} tests (source Bruce Power)

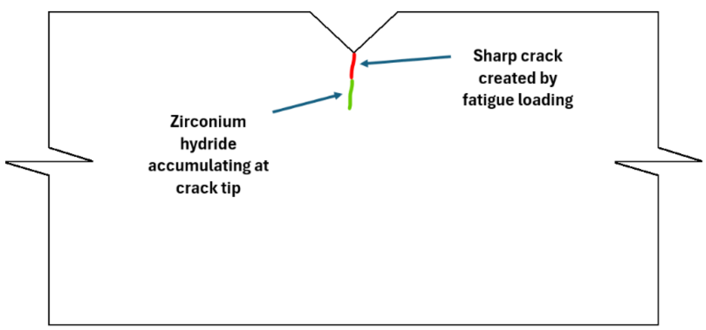

Figure 7: DHC test specimen for K_{IH} testing (a fatigue crack is formed at the notch root before testing)

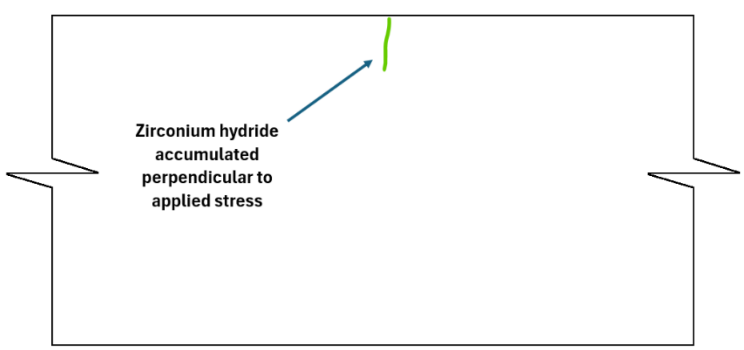

Figure 8: Specimen for p_c testing - with sufficient stress applied to allow hydrides to orient perpendicular to the ID surface without a flaw present

- The objective of the DHC initiation testing under the elevated Heq R&D program [2,3] is to compare the results of tests performed on material with a Heq of nominally 60 ppm, to material with Heq of over 200 ppm to determine if there is an observed change to the initiation threshold for the specific test conditions.
- As of the last formal update received from industry on the status of DHC initiation testing in September 2024, the following work had been completed:
    - Planned K_{IH} tests have been completed with no reduction in the threshold value observed.
    - Planned p_c tests were underway with no reduction in the threshold value observed in tests completed up to that time.
    - K_{TH} tests were continuing. Early test results indicated an approximately 20% reduction in the threshold value for the high Heq material compared to material with lower Heq. It is postulated that this could be the result of an interaction between larger hydrides in the bulk of the high Heq material and the stress field at the root of the notch.
    - Since there were no changes to threshold values for K_{IH} and p_c, but an observed change in K_{TH}, the DHC initiation model may need to be updated for material with elevated Heq to adjust the relationship between the two extreme scenarios (crack and no flaw) and a flaw of arbitrary geometry.
    - The finding does not have an immediate safety impact. The material is still resistant to crack initiation with elevated Heq and current Heq modelling indicates that the regions of elevated Heq are unlikely to expand such that they will interact with locations that flaws exist in pressure tubes. This will need to be confirmed following the sensitivity studies for the Heq models.

<u>HROL</u>

- HROL tests use specimens similar to the K_{TH} specimen. Hydrides are formed at the notch tip at a specific applied stress and the stress is then increased to determine the resistance of the specimen to crack initiation.
- As of the last formal update from industry on the elevated Heq R&D program in September 2024, HROL testing was underway.

<u>Fatigue</u>

- Fatigue crack tests use specimens similar to standard flat tensile test specimens but contain a notch like the K_{TH} specimen (Figure 9). Instead of allowing hydrides to form at the flaw tip under a constant applied load, the applied stress is cycled to assess the potential for fatigue crack initiation at the root of the notch.
- As of the last formal update from industry on the elevated Heq R&D program in September 2024, it was reported that fatigue testing was underway, with results obtained to that point indicating no change to the fatigue crack initiation threshold.

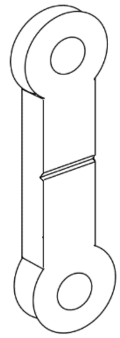

Figure 9: Illustration of a Fatigue Crack Initiation Test Specimen

DHC Crack Growth Rate Testing

- If a crack initiates from a flaw, the crack may continue to grow as a result of the DHC mechanism. Hydrides will continue to accumulate at the crack tip and subsequently propagate the crack. It is important to characterize the rate of growth to be able to predict the time to reach a critical crack size that would result in a pressure tube failure.
- DHC crack growth rate tests use specimens that are pre-cracked by fatigue to monitor crack extension with time because of hydride accumulation at the crack tip when subjected to a sustained load.
- As of the last formal update from industry on the elevated Heq R&D program in September 2024, it was reported that DHC growth rate tests had been completed and there was no impact of elevated Heq on crack growth rates.

Fracture Toughness

- CMD 23-M3 [4] provided a discussion of pressure tube fracture toughness behaviour and the potential impact of Heq on fracture toughness. As a reminder:
  - Figure 10 provides an illustration of the behaviour and a description of the different regimes of fracture behaviour with temperature.
  - Figure 11 illustrates the impact of increasing Heq on fracture toughness.
- As reported to the Commission in CMD 22-M37 [5], CNSC staff has accepted use of the Revision 2 fracture toughness models for use for fitness for service evaluations for:
  - Heq up to 100 ppm for front end of pressure tubes.
  - Heq up to 140 ppm for the remainder of pressure tube.

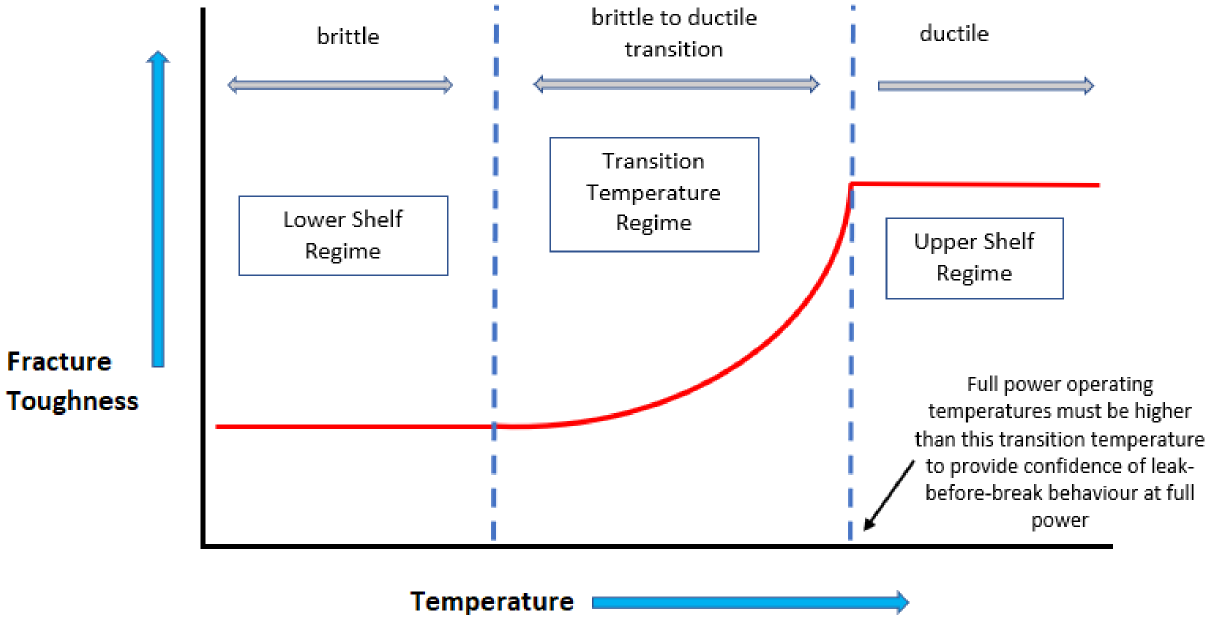

Figure 10: Fracture Toughness Behaviour for Pressure Tube Material for a given Heq Value

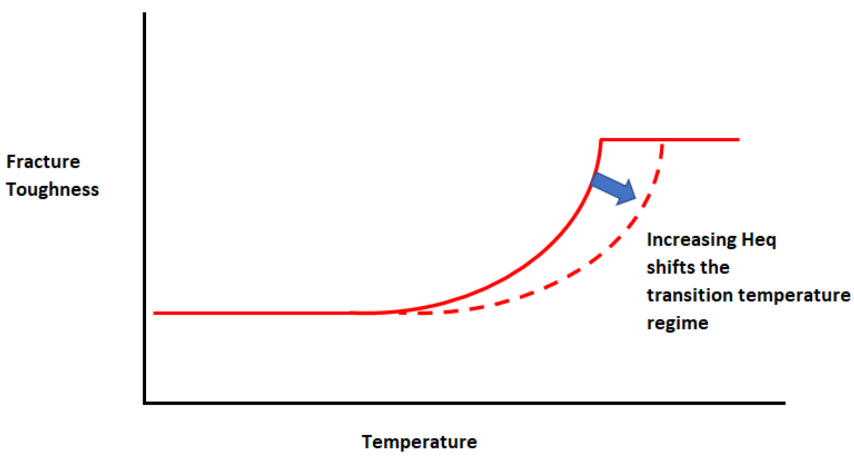

Figure 11: Effect of Increasing Heq on Fracture Toughness

- As presented to the Commission in CMD 21-M4 [8], the front end of a pressure tube is the end that is formed first when producing a tube. Because of differences in cooling rates following the extrusion process, the microstructure in the front end can be different from the remainder of the tube and result in lower fracture toughness.
- There have been eight burst tests completed on pressure tube specimens with Heq in excess of 200 ppm.
    - Front end and non-front end material.
    - Heq up to 368 ppm.

  - Covering a range of test temperatures from 65°C to 250°C.

- CNSC staff has received results for seven of the tests at the time of preparation of this memorandum and those results fell within the prediction range of the Revision 2 fracture toughness model predictions.
- In December 2024, Bruce Power and OPG reported to CNSC staff that the latest burst test completed with a Heq value above 200 ppm (designated test BT-49) generated a test result that was not bounded by the Revision 2 model. Specific details have not yet been provided to CNSC staff; however, the following has been provided:
  - Front end material was tested at 250°C.
  - The material did not exhibit upper shelf regime behaviour at the test temperature.
- The implications of this result:
  - Front end material with elevated Heq may not achieve upper shelf behaviour during normal operation, so leak-before-break behaviour would not be assured for a crack that initiates during normal full-power operation.
  - The Revision 2 model will require further modification for application to elevated Heq material.
- Currently, this test result does not impact the conditions for safe operation:
  - The only region of the front end of pressure tubes that remain in operation where Heq is expected to exceed the current 100 ppm limit of the Revision 2 model is within an IRJ blip.
  - For Pickering pressure tubes, the blip region is covered by a shield plug, so flaws that would lead to crack initiation are not expected near a blip.
  - The finding has no impact on the assumptions of the Risk Informed Decision Making (RIDM) evaluation established for Bruce Power operation until the end of 2025.
  - As noted previously, elevated Heq modelling for the IRJ region currently indicates that the blip would not impact crack initiation for an ID surface flaw coincident with a blip.
- The implications of this finding will need to be fully addressed to support operation of Bruce B reactors to planned refurbishment dates after the expiration of the RIDM evaluation.

Summary

- Findings from the R&D activities completed to date do not affect previous CNSC staff conclusions regarding safety of reactors in extended operation.
- Based on the progress to date, CNSC staff expect that licensees will complete the tasks listed in the R&D plans [2,3] and that the overall project deliverable is on track to be completed by the end of 2025.
- As the R&D activities are still in progress, CNSC staff will continue to review new information and engage with the licensees concerning CNSC staff's review findings, as well as inform the Commission of progress through the Status Report on Power Reactors.

Acknowledgement of concurrence with Director General decision:

I approve

X SJ Eaton

Ramzi Jammal

Executive Vice-President and CROO

I do not approve

X

Ramzi Jammal

Executive Vice-President and CROO

Attachment: CMD Routing Slip - Memo Technical Update on Heq R&D - March 2025, e-Doc 7486326

c.c.: R. Jammal, D. Haslip, M. Rickard, A. Bulkan, R. Richardson, V. Tavasoli, B. Carroll, D. Carrière

References

1. Transcript of the January 29, 2025, Public Commission Meeting, e-Doc 7469355.
2. Commission Member Document, “Bruce A and B: Update to the Commission regarding Elevated Hydrogen Equivalent Concentrations -Action Item 2022-07-23135”, July 19, 2022, CMD 22-M37.3, e-Doc 6858728.
3. Commission Member Document, “OPG Response – Darlington and Pickering NGS – Request for an Update to the Commission on Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration (Heq) – New Action Item 2022-OPG-23135”, July 19, 2022, CMD 22-M37.1, e-Doc6858724.
4. Commission Member Document, “Responses to the questions from the External Advisory Committee regarding the update on the discovery of elevated hydrogen equivalent concentrations in the pressure tubes of reactors in extended operation”, January 25, 2023, CMD 23-M3, e-Doc 6951418.
5. Commission Member Document, “CNSC staff update on elevated hydrogen equivalent concentration discovery events in the pressure tubes of reactors in extended operation”, November 3, 2022, CMD 22-M37, e-Doc 6848197.
6. Commission Member Document, “Written submission from Bruce Power – Update from OPG and Bruce Power on Hydrogen Equivalent Concentration in Pressure Tubes”, January 24, 2025, CMD 25-M19, e-Doc 7464423.
7. Commission Member Document, “Written submission from Ontario Power Generation Inc. – Update from OPG and Bruce Power on Hydrogen Equivalent Concentrations in Pressure Tubes”, January 27, 2025, CMD 25-M19.1, e-Doc 7464414.
8. Commission Member Document, “Status Update: Condition of Pressure Tubes in Operating CANDU Reactors in Canada”, January 21, 2021, CMD 21-M4, e-Doc 6459353.