CMD 26-M10 - CNSC Staff Submission

CNSC staff update on the status of licensee R&D program for elevated hydrogen equivalent concentration in the pressure tubes of reactors in extended operation

Classification	UNCLASSIFIED
Type of CMD	Original
CMD Number	26-M10
Reference CMD(s)	CMD 21-M39, CMD 22-M16, CMD 22-M37, CMD 22-M37.4, CMD 22-M37.5, CMD 22-M37.1, CMD22-M37.3, CMD 23-M27.11, CMD 25-M27, DEC 21-H111, DEC 21-H112, DEC 21-H113, DEC 22-H100, DEC 23-H103, DEC 24-H5
Type of report	Information
Public meeting date	Week of March 23, 2026
Word SharePoint	3779UC3NXORX-1883431929-427 – EN 3779UC3NXORX-1883431929-600 – FR
PDF SharePoint	3779UC3NXORX-1883431929-597 – EN 3779UC3NXORX-1883431929-601 – FR
Summary	This CMD provides the Commission with CNSC staff's conclusions on the hydrogen equivalent concentration research and development program activities completed to date. Ontario Power Generation and Bruce Power have sufficiently achieved the results necessary to return to compliance under Licence Condition 6.1 - *The licensee shall implement and maintain a fitness for service program*.
Actions required	There are no actions requested of the Commission. This CMD is for information only.

CMD 26-M10 - Mémoire du personnel de la CCSN

Mise à jour du personnel de la CCSN sur l'état du programme de R-D des titulaires de permis à l'égard de la concentration élevée d'hydrogène équivalent dans les tubes de force des réacteurs en exploitation prolongée

Classification	NON CLASSIFIÉ
Type de CMD	Original
Numéro de CMD	26-M10
CMD(s) de référence	CMD 21-M39, CMD 22-M16, CMD 22-M37, CMD 22-M37.4, CMD 22-M37.5, CMD 22-M37.1, CMD22-M37.3, CMD 23-M27.11, CMD 25-M27, DEC 21-H111, DEC 21-H112, DEC 21-H113, DEC 22-H100, DEC 23-H103, DEC 24-H5
Type de rapport	Information
Date de la réunion publique	Semaine du 23 mars 2026
Word SharePoint	3779UC3NXORX-1883431929-427 – EN 3779UC3NXORX-1883431929-600 – FR
PDF SharePoint	3779UC3NXORX-1883431929-597 – EN 3779UC3NXORX-1883431929-601 – FR
Résumé	Le présent CMD fournit à la Commission les conclusions du personnel de la CCSN concernant les activités du programme de recherche et développement sur la concentration d'hydrogène équivalent réalisées à ce jour. Ontario Power Generation et Bruce Power ont atteint des résultats suffisant pour rétablir leur conformité à la condition de permis 6.1 : *Le titulaire de permis doit mettre en œuvre et tenir à jour un programme d'aptitude fonctionnelle.*
Mesures requises	Aucune mesure n'est requise de la Commission. Ce CMD est fourni à titre d'information seulement.

CMD 26-M10

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CNSC staff update on the status of licensee R&D program for elevated hydrogen equivalent concentration in the pressure tubes of reactors in extended operation

Canadian Nuclear Safety Commission

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Land acknowledgement

The Canadian Nuclear Safety Commission acknowledges that this update on the status of OPG's and Bruce Power's R&D commitments for elevated hydrogen equivalent concentration in the pressure tubes of reactors in extended operation pertains to activities being performed on the Traditional and Treaty territory of Indigenous Nations and Communities. Bruce Power's activities are located in the Traditional and Treaty Territory of the Saugeen Ojibway Nation (SON), and the traditional harvesting territories of the Métis Nation of Ontario (MNO) Region 7 and the Historic Saugeen Métis (HSM) peoples. OPG's activities are located in the traditional lands and waters of the Michi Saagiig Anishinaabeg, which is covered by the Gunshot Treaty (1787-88), the Williams Treaties (1923), and the Williams Treaties Settlement Agreement (2018).

Plain language summary

This update informs the Commission about the progress made by Ontario Power Generation (OPG) and Bruce Power on research and development (R&D) commitments related to elevated hydrogen equivalent concentration (Heq) in reactor pressure tubes in extended operation. Elevated Heq was first discovered in 2021 near rolled joint areas of pressure tubes, exceeding the previous limit of 120 parts per million (ppm) and raising concerns about fracture toughness and safe operation beyond 210,000 equivalent full power hours (EFPH). New licence conditions were introduced while the licensees (OPG and Bruce Power) carried out an extensive R&D program to validate models to ensure continued safe operation.

Canadian Nuclear Safety Commission (CNSC) staff confirm that all R&D activities scheduled for completion by the end of 2025 have been completed. The licensees have demonstrated that they now have the analytical tools needed to assess pressure tube fitness for service under licence condition (LC) 6.1. Bounding analyses show that regions of elevated Heq will not interact with flaws that could lead to crack initiation before the fuel channels reach end-of-life in the Pickering and Bruce units.

The compliance verification criteria for LC 6.2 will be updated to revise requirements for enhanced monitoring and continued R&D. Further R&D will focus on refining Heq modelling and addressing excessive conservatism in analytical tools. Going forward, CNSC staff will continue to actively monitor results and perform detailed reviews of licensee's fitness for service submissions.

Referenced documents in this CMD are available to the public upon request, subject to confidentiality considerations.

1 Overview

1.1 Background

In 2021, Bruce Power discovered elevated hydrogen equivalent concentration (Heq) in the pressure tubes that are in extended operation beyond 210,000 equivalent full power hours (EFPH). The elevated concentrations were discovered near the outlet rolled joint (ORJ) burnish mark (CMD 21-M39) as well as the inlet rolled joint (IRJ) burnish mark (CMD 22-M16) of the pressure tubes (see Figure A4 for an illustration of the rolled joint region of a pressure tube). Bruce Power reported that material surveillance testing of a Bruce Unit 6 pressure tube (B6S13) had an elevated Heq measurement near the outlet burnish mark and similar elevated Heq values were later reported from in-service scrape measurements in Bruce Unit 3 pressure tubes. The Heq measurements from the Unit 3 tubes were obtained from scrape samples removed from the inner diameter surface of Unit 3 pressure tubes during the maintenance outage. After further testing on the same Bruce Unit 6 B6S13 surveillance tube, Bruce Power discovered elevated Heq near the inlet rolled joint burnish mark near the 1 o'clock orientation, which was measured using punch samples. Further examination of the B6S13 punch samples near the inlet also revealed that there was a significant through thickness gradient of Heq with much higher values on the outer diameter surface than the inner diameter surface. The Heq values measured in the Bruce A and B pressure tubes exceeded the limit of 120 parts per million by weight (ppm) established for the accepted pressure tube fracture toughness model at the time of the events. CNSC staff concluded that the findings had the potential to impact all units in extended operation, including Ontario Power Generation (OPG) units. The licensees could not confirm that then-current models and evaluation processes used to assess pressure tube fitness for service in accordance with the compliance verification criteria (CVC) established for Licence Condition (LC) 6.1 were valid for the elevated levels of Heq. See Appendix A for more information regarding the mechanisms causing elevated Heq at the rolled joints.

Following several Commission proceedings held between October 2021 and February 2022, the Commission concluded that, for both OPG and Bruce Power units in extended operation, pressure tube fracture toughness in the ORJ region was sufficient for safe operation beyond 120 ppm based on the low likelihood of flaws that would lead to crack initiation existing in that region (DEC 21-H111, DEC 21-H112, DEC 21-H113, DEC 22-H100).

CNSC staff made the same conclusions for Pickering units at the IRJ region of elevated Heq where there are no active mechanisms for the formation of flaws at risk for crack initiation. However, for Bruce and Darlington units the Heq findings at the inlet region put into question the applicability of approaches used to evaluate pressure tube flaws in that region. In CMD 22-M37, CNSC staff provided the results of its risk assessment of elevated Heq at the IRJ region of

pressure tubes and determined the risk was negligible for up to 3 years of continued operation, or up to December 31st, 2025. The risk informed decision making (RIDM) conclusion established a timeframe to undertake a research and development (R&D) program to investigate the cause and impact of the localized regions of elevated Heq on pressure tube fitness for service. By the end of 2023, all Darlington units were either already refurbished or were undergoing refurbishment and were no longer implicated by the elevated Heq discoveries.

The discovery of regions with elevated Heq necessitated amendments of pertinent licence conditions. To support licence renewal in 2018, LC 15.3 (*Before hydrogen equivalent concentrations exceed 120 ppm, the licensee shall demonstrate that pressure tube fracture toughness will be sufficient for safe operation beyond 120 ppm)* was included in the Pickering NGS and Bruce NGS A and B Power Reactor Operating Licences (PROLs). LC 15.3 and the associated CVC established the regulatory requirements and expectations for the extension of the Heq validity limits for the fracture toughness model and reporting of measured Heq levels. At the time, the pressure tube fracture toughness model was developed using empirical data from material with Heq levels up to 120 ppm, while the fuel channel end-of-life (EOL) Heq levels were expected to reach up to 160 ppm. An active industry program was underway to collect additional data to extend the validity limit to higher Heq levels. Based on the Bruce Power elevated Heq events in 2021, Bruce Power concluded that some pressure tubes were operating with Heq levels exceeding 120 ppm in the inlet and outlet regions and that the fuel channel EOL Heq levels would exceed 160 ppm. Following two Commission hearings held in March 2023 and February 2024, the Commission concluded that the basis for operating pressure tubes beyond 210,000 EFPH had evolved and that LC 15.3 no longer served its intended purpose. Therefore, the Commission approved the removal of LC 15.3 from the PROLs and replaced it with a new LC 6.2 (DEC 23-H103, DEC 24-H5). LC 6.2 of the OPG and Bruce Power PROLs require the licensees to implement and maintain an enhanced fitness for service program to support safe operation of pressure tubes in extended operation and require the licensees to report on the status of the R&D activities.

1.2 Highlights

1.2.1 Status of the Heq R&D activities

- CNSC staff have confirmed that licensees successfully completed the R&D program tasks planned for the end of 2025.
- Questions and comments raised by CNSC staff and intervenors (CMD 22-M37.4 and CMD 22-M37.5) have been addressed by licensees.

1.2.2 Assessing pressure tube fitness for service using CVC for LC 6.1

- CNSC staff have evaluated the licensees' understanding of the factors that led to the formation of the regions of elevated Heq, and confirmed that:
  - The elevated Heq in the outlet region of the pressure tube can be explained by the circumferential temperature variation due to flow bypass.
  - The inlet region of elevated Heq in inlet region of the pressure tube can be explained by a localized contact with the end fitting and a thermal conductance pathway to the calandria lattice tube.
- Bounding assessments indicate that the outlet region of elevated Heq will not extend axially and circumferentially such that they could interact with service induced flaws that are at risk of crack initiation.
- Bounding assessments indicate that the inlet region of elevated Heq will be constrained axially, circumferentially and radially resulting in no interaction with inner diameter surface flaws.
- Based on the progress of the R&D program to date, CNSC staff conclude that the licensees will be able to use the CVC in LC 6.1 for pressure tube fitness for service evaluations with modifications made to the analytical tools, as follows:
  - A modification to the model for delayed hydride cracking initiation to assess flaws in material with Heq values exceeding 120 ppm.
  - A modification to the fracture toughness model for front end material (the end that is extruded first during the fabrication process) with Heq values exceeding 100 ppm.

1.2.3 Future work

- Although bounding analyses show that regions of elevated Heq will not interact with flaws that could lead to crack initiation before fuel channel EOL in Pickering and Bruce units, licensees will continue R&D activities to further refine Heq diffusion modelling processes and the fracture toughness model for front-end material for Heq greater than 100 ppm.
- CNSC staff will continue their oversight of R&D activities related to Heq modelling and the results of in-service inspection.
- CNSC staff expect licensees to collect material surveillance data to confirm that findings and recommendations remain valid until EOL of all pressure tubes in extended operation.

2 Heq R&D Activities

2.1 CNSC staff actions

In March 2023, CNSC staff raised action items for OPG and Bruce Power to track the completion of the Heq R&D work and to provide updates to CNSC staff. The following closure criteria were established for the action items:

- Submission of reports for completion of all activities described in the R&D plans (CMD 22-M37.1, 22-M37.3), including:
  - Activities related to crack initiation model validation
  - Activities related to fracture toughness model validation
- Disposition of comments from public interventions (CMD 22-M37.4 and CMD 22-M37.5)
- Submission of progress reports on a semi-annual frequency
- Responses to all comments arising from CNSC staff review of the R&D activities.

2.2 Status of Heq R&D activities

CNSC staff have reviewed R&D deliverables included in six semi-annual updates from OPG (1; 2; 3; 4; 5; 6) and Bruce Power (7; 8; 9; 10; 11; 12), as well as their responses to all CNSC staff's review comments, to confirm whether the licensees have completed the activities per the plan.

CNSC staff confirm that the licensees submitted all updates on time and that all R&D activities with target completion dates by the end of 2025 have been completed, including reports for crack initiation and fracture toughness model validation. The updated status of each activity is summarized in Appendix B.

There remains only one activity that is ongoing, per the licensees' R&D plans (CMD 22-M37.1, 22-M37.3): develop a comprehensive Heq predictive model by the Spring of 2026. Therefore, the action items that were raised to track the completion of the R&D plan will remain open until the results of the final R&D activity have been submitted and reviewed by CNSC staff. This deliverable continues to be on track for completion and does not affect the licensees' ability to apply the LC 6.1 CVC for fitness for service evaluations.

2.3 Disposition of comments from public interventions

In November 2022, CNSC staff (CMD 22-M37) and the licensees (CMDs 22-M37.1 and 22-M37.3) provided the Commission with an update on the status of industry's activities to address the discoveries related to elevated Heq. The update included comments from two intervenors (CMDs 22-M37.4 and 22-M37.5), which the Commission considered to be useful additions to the discussion on elevated Heq. In light of this, CNSC staff included the licensees' disposition of the intervenor comments as one of the closure criteria for the R&D plan action items.

CNSC staff acknowledge that the intervenor comments raised in CMD 22-M37.5 were retracted by the author as a result of their own follow-up analysis submitted in CMD 23-M27.11. CNSC staff's review of the follow-up analysis concluded that the licensees were no longer required to respond to the comments raised by that intervenor.

In the semi-annual update #2 (2; 8), the licensees provided responses to each of the comments included in CMD 22-M37.4. CNSC staff concluded that the dispositions were acceptable and that no further action was needed by the licensees (see Appendix C for CNSC staff's review comments).

3 Assessing pressure tube fitness for service using CVC for LC 6.1

3.1 Overview of fitness for service evaluations for flaws

CSA N285.8 (*Technical requirements for in-service evaluation of zirconium alloy pressure tubes in CANDU reactors*) is used to assess pressure tube fitness for service. Many of the models and the evaluation processes in this standard were not validated for levels of Heq that were measured near the rolled joint burnish marks in some Bruce A and B pressure tubes in extended operation in 2021. Heq is a key parameter for the models used to assess crack initiation, crack growth, fracture toughness and fracture initiation toughness. CMD 25-M27 provided CNSC staff's most recent technical update on crack initiation testing, delayed hydride cracking (DHC) crack growth rate testing and fracture toughness. The role of the Heq modelling in the process used by licensees to assess pressure tube fitness for service is depicted in Figure 1.

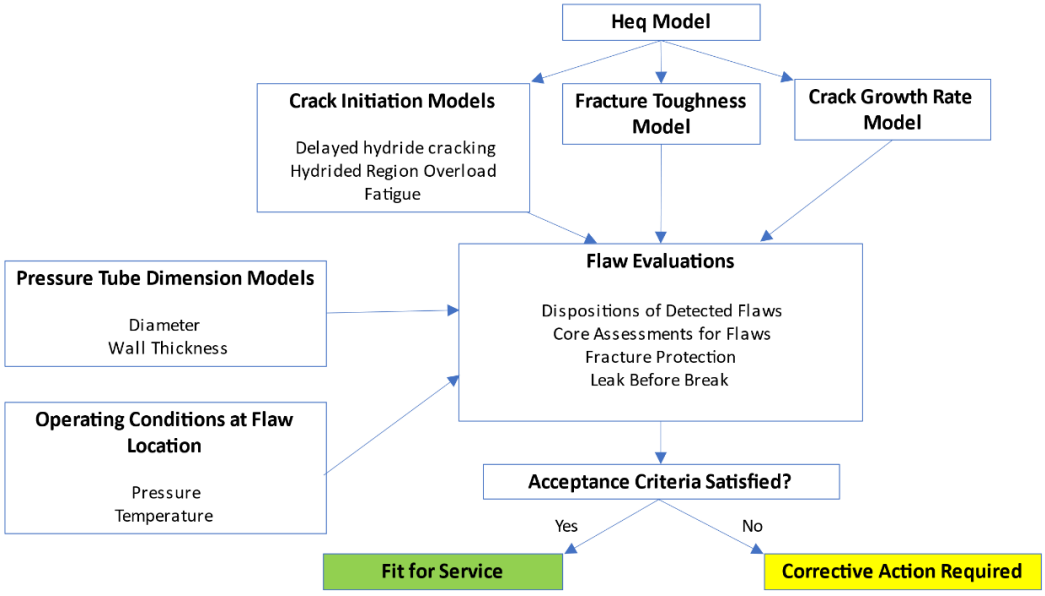


Figure 1: Overview of Fitness for Service Evaluations for Flaws in Pressure Tubes

At the time of the elevated Heq discoveries, the uncertainty in the output from the models that predict and rely on the Heq in the pressure tube prevented definitive conclusions from being made regarding satisfying the acceptance criteria. Alternate approaches were adopted on a temporary basis to assess the impact of pressure tube flaws near the burnish marks on safe operation, in accordance with the CVC under LC 6.2.

3.2 Heq modelling at the rolled joints

The Heq model uses information related to the ingress of hydrogen as well as temperature and stress gradients to predict the movement of hydrogen in the material. Soluble hydrogen in zirconium alloy diffuses to the cooler material which could increase the amount of hydrogen at the cooler spot relative to higher temperature regions.

In reviewing the licensees' R&D reports related to Heq modelling, CNSC staff considered the following questions:

- Did the modelling reproduce the Heq gradients that were measured in the in-service pressure tubes with regions elevated of Heq?
- Can the Heq gradients be explained by temperature, concentration and stress gradients alone or is there an indication that alternate sources of hydrogen ingress into the material are required?
- Do the regions of elevated Heq continue to expand axially, circumferentially and, in the case of the IRJ radially, and if so, by how much?

- Can the model explain why only some tubes appear to be affected?

CNSC staff's review of the licensees' R&D program results related to modelling confirms the following:

- The region of elevated Heq near the outlet rolled joint can be explained by the circumferential temperature variation due to flow bypass.
- The region of elevated Heq near the inlet rolled joint can be explained by a localized contact with the end fitting and a thermal conductive pathway to the lattice tube.
- There is sufficient hydrogen inventory available to produce the regions of elevated Heq near the burnish marks from the established ingress sources (end fitting to pressure tube connection and inner surface corrosion mechanisms).
    - There is no evidence that enhanced ingress from the annulus gas system (AGS) has contributed to the phenomena.
- The licensees are currently unable to identify specific tubes that are impacted by these phenomena nor accurately estimate the actual Heq values likely to be achieved at the EOL of specific pressure tubes[1]. However, bounding assessments indicate that the regions of elevated Heq will not extend far enough axially, circumferentially or radially such that they could interact with service induced flaws that are at risk of crack initiation.

3.3 Crack initiation models

Crack initiation and crack growth models have been validated, based on the recent R&D information, for material with Heq values up to nominally[2] 240 ppm from the previous limit of nominally 120 ppm. Adjustments are required to the model for the delayed hydride cracking initiation for material with Heq above 120 ppm, but no adjustments are required for the hydrided region overload and fatigue crack initiation of delayed hydride cracking growth rate models.

3.4 Fracture toughness model

The pressure tube fracture toughness model remains valid for material between 1.5 m from the front end of a pressure tube and the back end of a pressure tube for Heq values exceeding 240

[1] Using the information obtained from the R&D program, it is possible to identify tubes which are most likely to be impacted by the phenomena leading to the regions of elevated Heq, but it is not possible to confirm which tubes are impacted without Heq measurements.
[2] The target value for material testing was 240 ppm, with some tests conducted in material with higher Heq levels.

ppm. However, the current model does not capture the observed fracture behaviour of material with Heq exceeding 100 ppm within 1.5 m of the front end of a pressure tube. The current fracture toughness model was based on testing that suggested that all material achieved upper-shelf (maximum) toughness at temperatures of 250°C. This implied that the material would always exhibit upper-shelf toughness during normal full power operating temperatures. More recent testing of lower toughness front end material with Heq values exceeding 100 ppm indicated that the transition to upper-shelf behaviour can exceed 250°C.

CMD 25-M27 provided CNSC staff's most recent technical update on the pressure tube fracture toughness model. 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 as test BT-49) generated a test result that was not bounded by the Revision 2 model. Since the preparation of that CMD, one additional fracture toughness test has been completed for front end material and results were similar to the BT-49 test result, indicating that the material did not achieve upper-shelf behaviour at 250°C.

The only region in the front end of a pressure tube where Heq is expected to exceed 100 ppm is the highly localized inlet region of elevated Heq associated with a blip which the modelling indicates will not extend beyond 15 mm from a burnish mark. CNSC staff acknowledge that the licensees have presented a procedure to address the observed reduction in front end toughness in pressure tube evaluations.

3.5 Compliance verification for pressure tube fitness for service for LC 6.1

Following the review of the R&D program, CNSC staff confirm that the CVC for LC 6.1 can be used by OPG and Bruce Power to assess pressure tube fitness for service. This is supported by the following conclusions:

- For Pickering units 5-8 pressure tubes, the bounding analysis indicated that both the outlet and inlet regions of elevated Heq will not extend to locations where flaws potentially at risk of crack initiation may exist before the units are shutdown by the end of 2026. The shield plugs at each end of the pressure tubes will cover potential regions of elevated Heq and protect the pressure tubes from in-service flaw formation mechanisms.
- For the Bruce A and B pressure tubes in extended operation, the bounding analysis demonstrates that the outlet region of elevated Heq will not extend to locations where flaws potentially at risk of crack initiation may exist. The position of the fuel bundles in the outlet region eliminates the interactions between the bundles and the pressure tube which would lead to flaw formation in regions where Heq could be elevated.

- For the inlet region of elevated Heq of the Bruce A and B pressure tubes, it is possible for flaws and elevated Heq blips (see Appendix A for a description of a blip) to exist within the same axial extent of the pressure tube. However, CNSC staff's review of the R&D progress to date confirms the following:
    - The presence of an outer diameter (OD) surface blip has been demonstrated to have no adverse effect on hydride accumulation at an inner diameter (ID) surface flaw.
    - The crack initiation and growth models can be applied to material with bulk Heq values up to 240 ppm and it is unlikely that flaws would be located in material with higher Heq values by EOL of the fuel channels.
- While the current fracture toughness model is not applicable to front end material with Heq above 100 ppm, the impact of an upper-shelf transition temperature shift can be addressed in the required pressure tube evaluations. Since it is not possible to identify specific tubes which are impacted by the phenomenon which generates the regions of elevated Heq near the burnish marks, fitness for service evaluations must assume that the regions exist in all pressure tubes in extended operation.

CNSC staff conclude that the licensees have demonstrated that an appropriate analytical toolset is available to perform the required evaluations per LC 6.1. CNSC staff are not providing conclusions at this time concerning the fitness for service of pressure tubes in specific OPG and Bruce Power reactors, but can confirm the following:

- CNSC staff does not foresee the need for OPG to update current fitness for service evaluations for the Pickering NGS Units 5-8 prior to the end of operation in 2026.
- There is no immediate need for Bruce Power to update their fitness for service evaluations to support operation prior to the next planned outage for any given unit.

CNSC staff will continue to review licensees' fitness for service submissions in accordance with established practices.

3.6 Continued R&D and updated CVC for LC 6.2

CNSC staff expect that both licensees will continue research and development activities to further refine Heq models, high Heq cracking initiation testing, and fracture toughness testing. Many of these activities are likely to focus on reducing excess conservatism in the analytical toolset developed under the current R&D program. However, CNSC staff will evaluate the results of these activities and licensees are required to submit event reports should any findings ever present challenges to the conclusions regarding pressure tube fitness for service. If such an event report is received, CNSC staff will update the Commission through any means as deemed appropriate (i.e. status report on power reactors, event initial report, etc.).

Enhanced fitness for service requirements for fuel channels in extended operation remain beneficial, but the focus of the CVC will be changed from pressure tube integrity assessment to enhanced Heq monitoring activities. Although, CNSC staff conclude that the licensees are now able to perform the required fitness for service evaluations per LC 6.1, the minimum Heq measurement requirements of CSA standard N285.4 are not sufficiently detailed to capture and characterize regions of elevated Heq near the burnish marks and LC 6.2 can clarify regulatory expectations in this regard. For any reactors that are operated beyond 210,000 EFPH, an enhanced Heq monitoring program is expected for in-service Heq scrape sampling and ex-service surveillance tube Heq sampling that is sufficient to characterize the axial, circumferential and radial extents of inlet and outlet rolled joint regions of elevated Heq that may arise due to circumferential and/or localized temperature gradients. The licensees should work to expand the inlet region Heq modelling activities to include a larger sample of data obtained from ex-service pressure tubes, as this could lead to further refinements of the modelling process. The licensees should continue with material surveillance activities through both planned inspection program surveillance tubes as well as opportunities for additional material removal during refurbishment outages.

LC 6.2 will remain in the respective PROLs until the licensees submit an application to the Commission requesting amendments to the applicable licences. If a licensee chooses to request an amendment to their licence, CNSC staff will review the application and provide their recommendation to the Commission. A revised draft of Section 6.2 for Pickering NGS and Bruce NGS A and B Licence Conditions Handbooks (LCHs) is included in Appendix D.

4 Indigenous Engagement

The common-law duty to consult with Indigenous Nations and communities applies when the Crown contemplates actions that may adversely affect potential or established Indigenous and/or treaty rights. The CNSC ensures that all of its licence decisions under the NSCA uphold the honour of the Crown and uphold Indigenous peoples' potential or established Indigenous and/or treaty rights pursuant to section 35 of the *Constitution Act, 1982*. CNSC staff's considerations include, but are not limited to, Indigenous Nations and communities established or potential rights pertaining to lands and waters in relation to the facility and the expected and/or potential impacts of the activities conducted on the site in accordance with a CNSC issued licence.

REGDOC-3.2.2, Indigenous Engagement, sets out requirements and guidance for licensees whose proposed projects may raise the Crown's duty to consult. While the CNSC cannot delegate its obligation, it can delegate procedural aspects of the consultation process to licensees, where appropriate. The information collected and measures proposed by licensees to avoid, mitigate, or offset potential adverse impacts from the proposed licence renewal may be used by CNSC staff in meeting its consultation obligations.

As this CMD is for information only in order to provide the Commission with an update on the discovery of elevated Heq in pressure tubes in extended operation, CNSC staff have determined that this update to the Commission does not raise the CNSC's Duty to Consult and where appropriate accommodate obligations towards Indigenous Nations and communities. However, CNSC staff have and will continue to provide updates to interested Indigenous Nations and communities on the elevated Heq discovery, as well as information in relation to the Commission meeting and the information provided within this CMD.

In the Commission's Record of Decision (DEC 23-H103, paragraph 81) for Bruce Power's application to amend the PROL replacing LC 15.3 with LC 6.2, the Commission expected that CNSC staff fulfill its commitment to continue engaging with the SON, as well as other Indigenous Nations and communities and interested parties about elevated Heq in pressure tubes and other licensing related topics. CNSC offered to discuss elevated Heq in pressure tubes in regular meetings under Terms of Reference (TOR) for long-term engagement arrangements with SON, as well as MNO Region 7. CNSC staff provided a presentation and discussion regarding the elevated Heq, and the R&D requirements to SON environment office staff on October 28th, 2025, relating to all upcoming regulatory activities at the Bruce NGS relating to pressure tubes and the R&D commitments. CNSC staff also provided updates relating to this process, as well as concurrent applications submitted by Bruce Power relating to the Bruce NGS during regularly scheduled meetings as per the TOR, and the yearly workplan developed between SON and CNSC staff.

CNSC staff met with MNO Region 7 at the semi-annual meeting on Nov 5th, 2025, and discussed the elevated Heq findings as well as the Pressure Tube life extension activities more generally. This semi-annual meeting was held in accordance with the schedule laid out in the TOR.

CNSC staff provided information and participated in a discussion relating to elevated Heq during the semi-annual HSM-CNSC meeting on November 6th, 2025 as per the TOR.

5 Conclusions

CNSC staff conclude that:

- Licensees have completed all R&D activities scheduled for completion by the end of 2025.
- One R&D activity for developing a comprehensive Heq predictive model is due to be completed, as scheduled, in Spring 2026:
    - This does not impact the licensees' ability to apply LC 6.1 CVC for pressure tube fitness for service evaluations.
- Licensees have demonstrated that an appropriate analytical toolset is available to perform the evaluations required per LC 6.1.

- Further R&D on a variety of elevated Heq subjects will continue and CNSC staff will evaluate the results of these activities and their impact on the pressure tube fitness for service assessments.
- An enhanced Heq monitoring program for in-service Heq scrape sampling and ex-service surveillance tube Heq sampling that is sufficient to characterize the axial, circumferential and radial extents of inlet and outlet rolled joint regions of elevated Heq that may arise due to circumferential and/or localized temperature gradients is expected to be established by the licensees and submitted to CNSC staff for review.
- The CVC in the LCHs for LC 6.2 will be revised to reflect the updated requirements for an enhanced fitness for service program for fuel channels in extended operation.

6 References

1. **OPG Letter, M. Knutson to A. Mathai and R. Richardson.** *Darlington and Pickering NGS – Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration Semi-Annual Update #1 (Quarter 1 2023).* March 27, 2022. e-Doc 7019997.
2. **OPG Letter, M. Knutson to A. Mathai and R. Richardson.** *Darlington and Pickering NGS - Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration Semi-Annual Update #2 (Quarter 3 2023).* September 29, 2023. e-Doc 7137721.
3. **OPG Letter, M. Knutson to A. Mathai and R. Richardson.** *Darlington and Pickering NGS - Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration Semi-Annual Update #3 (Quarter 1 2024).* March 28, 2024. e-Doc 7252312.
4. **OPG Letter, M. Knutson to A. Mathai and R. Richardson.** *Darlington and Pickering NGS - Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration Semi-Annual Update #4 (Quarter 3 2024).* September 27, 2024. e-Doc 7372336.
5. **OPG Letter, M. Knutson to A. Mathai and R. Richardson.** *Darlington and Pickering NGS - Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration Semi-Annual Update #5 (Quarter 1 2025).* March 31, 2025. e-Doc 7492194.
6. **OPG Letter, M. Knutson to K. Lun and R. Richardson.** *Darlington and Pickering NGS - Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration Semi-Annual Update #6 (Quarter 3 2025).* September 30, 2025. e-Doc 7583218.
7. **Bruce Power Letter, M. Burton to M. Hornof.** *Bruce A and B: Update Regarding Elevated Hydrogen Equivalent Concentration and Response to CNSC Risk Assessment, Action Item 2022-07-26737, Closed Action Item 2022-07-23135.* March 29, 2023. e-Doc 7010601.

8. —. *Bruce A and B: Update Regarding Detailed Plan to Further Evaluate the Effect of Hydrogen Equivalent Concentration on Pressure Tube Fitness for Service, Action Item 2023-07-27173.* September 27, 2023. e-Doc 7135588.

9. **Bruce Power Letter, M. Burton to K. Lun.** *Bruce A and B: Semi-Annual Update on Industry R&D Plan on Elevated Hydrogen Equivalent Concentration, Action Items 2023-07-27173, 2022-07-26737.* March 25, 2024. e-Doc 7249743.

10. **Bruce Power Letter, M. Burton to A. Bulkan.** *Bruce A and B: Semi-Annual Update on Industry R&D Plan on Elevated Hydrogen Equivalent [H]eq Concentrations, Action Item 2023-07-27173 and 2022-07-26737.* September 26, 2024. e-Doc 7171763.

11. **Bruce Power, M. Burton to A. Bulkan.** *Bruce A and B: Semi-Annual Update on Industry R&D Plan on Elevated Hydrogen Equivalent [H]eq Concentrations, Action Item 2023-07-27173 and 2022-07-26737.* March 20, 2025. e-Doc 7486066.

12. **Bruce Power Letter, M. Burton to A. Bulkan.** *Bruce A and B: Semi-Annual update on industry R&D Plan on Elevated Hydrogen Conentrations, Action Items 2023-07-27173 and 2022-07-26737.* September 24, 2025. e-Doc 7581421.

7 Glossary

For definitions of terms used in this document, see REGDOC-3.6, *Glossary of CNSC Terminology*, which includes terms and definitions used in the *Nuclear Safety and Control Act* and the Regulations made under it, and in CNSC regulatory documents and other publications.

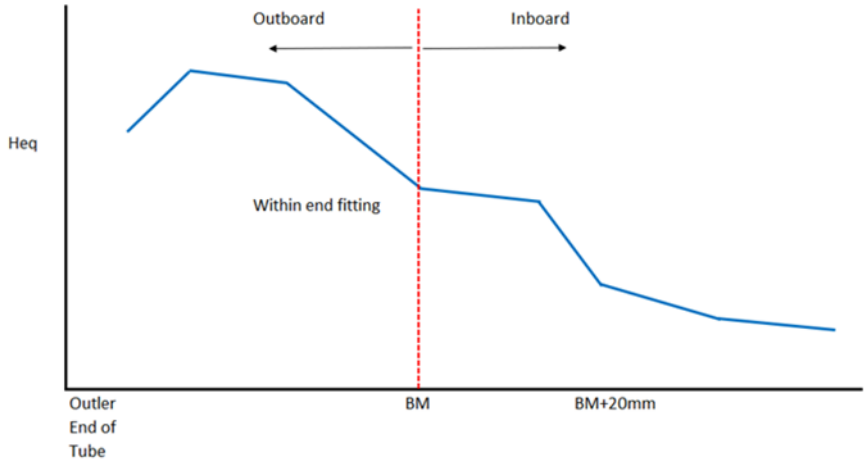
Additional terms and acronyms used in this CMD are listed below:

AGS	annulus gas system
CMD	Commission Member Document
CNSC	Canadian Nuclear Safety Commission
CSA	Canadian Standards Association
CVC	compliance verification criteria
EFPH	equivalent full power hours
EOL	end-of-life
Heq	hydrogen equivalent concentration
ID	inner diameter
IRJ	inlet rolled joint
LC	licence condition
LCH	licence conditions handbook
NGS	nuclear generating stations
ORJ	outlet rolled joint

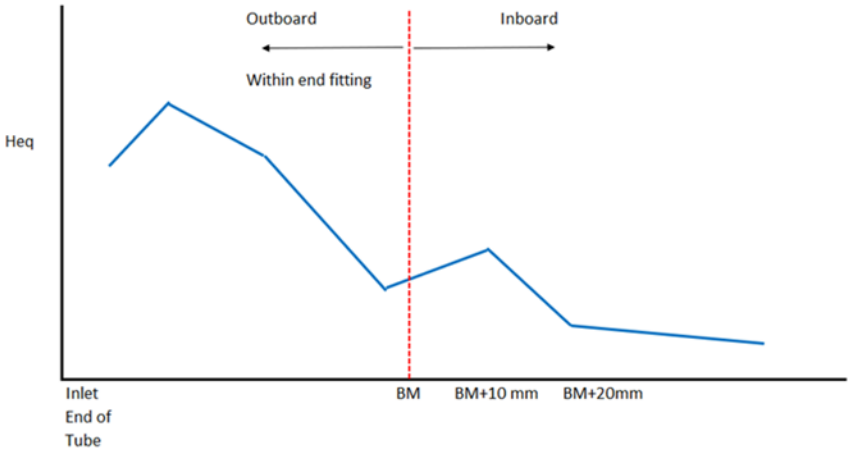
OD	outer diameter
ppm	parts per million
PROL	Power Reactor Operating Licence
R&D	research and development
RIDM	risk informed decision making

Appendix A: Elevated Heq near the rolled joints

Figure A1 provides illustrations of the axial profiles of the regions of elevated Heq near the inlet and outlet burnish marks of pressure tubes in 2021 at the circumferential orientation of the maximum Heq measurement. The local peak about 10 mm inboard of the burnish mark at the inlet region is often referred to as a “blip”.



Outlet Burnish Mark



Inlet Burnish Mark

Figure A1: Comparison of Axial Heq profiles at the outlet and inlet burnish marks (schematic illustrations, not to scale)

A1 Outlet Rolled Joint Region

- Thermalhydraulics modelling of aged fuel channel configurations indicates that a greater than 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 A2).
- 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.

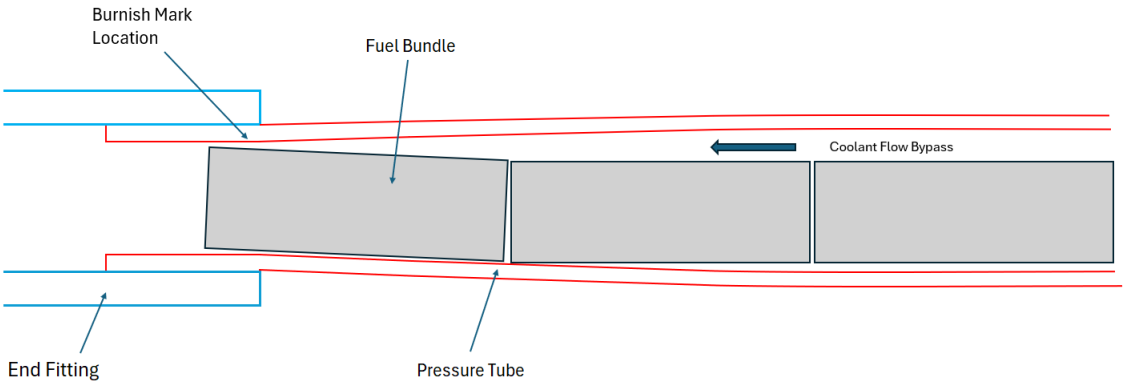


Figure A2: Illustration of coolant flow bypass at the outlet end of a pressure tube generating a circumferential temperature gradient (not to scale)

- 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.

A2 Inlet Rolled Joint 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 indicates 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.
- It has been demonstrated that blips can 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 A3 and A4). This creates a localized cooler region at the OD surface of the pressure tube due to a thermal conductance pathway from the pressure tube to the calandria end shield lattice tube.

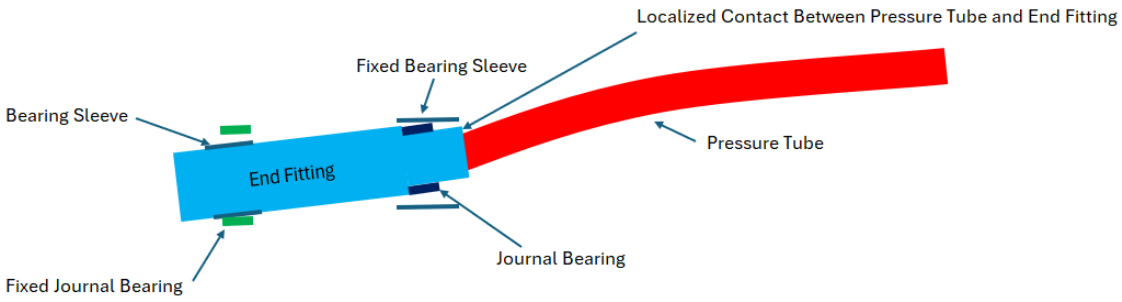


Figure A3: Illustration of the deformation scenario (exaggerated) that could lead to Heq blip formation (not to scale)

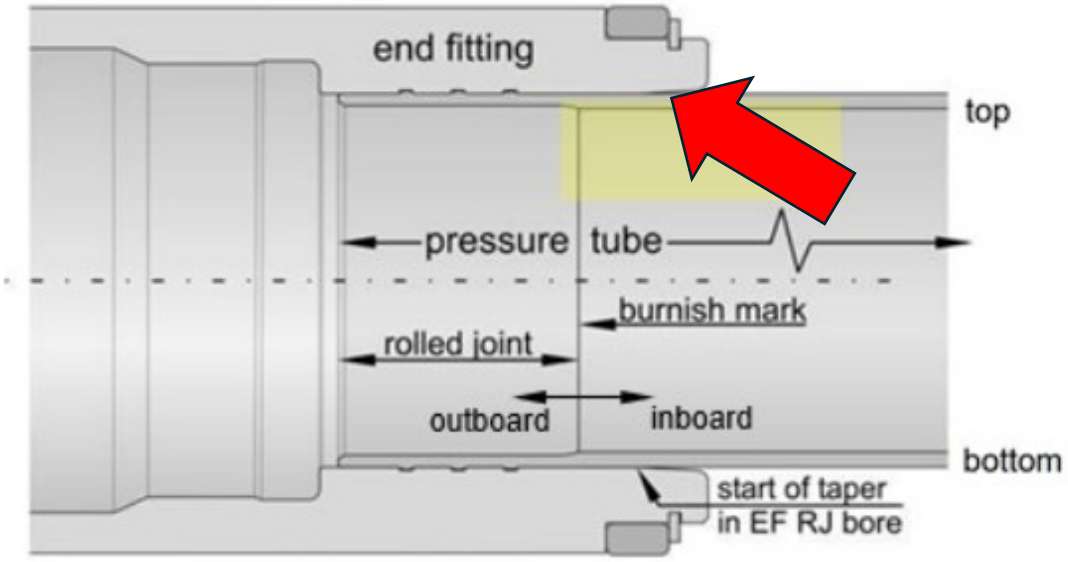


Figure A4: Illustration of rolled joint region of a pressure tube – under normal circumstances no contact at Heq blip location (red arrow) because of taper in end fitting bore. The deformation scenario shown in Figure A2 can lead to contact according to deformation modelling.

Appendix B: Status of Heq R&D activities

R&D Activity	Planned Completion Date (from CMD 22-M37.1 and 22-M37.3)	Updated Status of R&D Activities
Update finite element software to simulate outlet rolled joint Heq evolution	Fall 2023	Work has been completed
Develop finite element software to simulate inlet rolled joint Heq evolution	Fall 2023	Work has been completed
Perform evaluation to assess the potential impact of the high levels of Heq on flaws at the inside surface of pressure tubes near the inlet region of interest	Fall 2023	Work has been completed
Improve characterization of 'blip' and expected evolution of the inlet region of elevated Heq with continued operation	Spring 2024	Work has been completed
Confirm the potential roles of hydrogen isotope ingress and redistribution on the development of the inlet regions of elevated Heq	Summer 2023	Work has been completed
Improve characterization of solubility behaviour of hydrogen isotopes in tubes with elevated Heq	Winter 2024	Work has been completed
Enhance modeling of temperature distributions near the outlet rolled joint region of pressure tubes	Summer 2023	Work has been completed

R&D Activity	Planned Completion Date (from CMD 22-M37.1 and 22-M37.3)	Updated Status of R&D Activities
Define input parameters required for interim updates to the Heq model	Summer 2023	Work has been completed
Develop interim Heq model	Fall 2024	Work has been completed
Validation activities for the interim Heq model to support development of final comprehensive model	Fall 2025	Work has been completed
Define input parameters required for the final comprehensive Heq model	Summer 2025	Work has been completed
Define the relative importance of variables influential to Heq evolution	Fall 2025	Work has been completed
Develop the final comprehensive Heq model	Spring 2026	Progressing as planned
Complete hydride related crack initiation experiments for unirradiated material at Heq of 220 ppm or higher	Fall 2024	Work has been completed
Complete fatigue crack initiation experiments for unirradiated material at Heq of 220 ppm or higher	Fall 2024	Work has been completed
Complete crack initiation experiments for irradiated material with elevated Heq without flaws present	Fall 2024	Work has been completed
Complete crack initiation and crack growth experiments for irradiated material with elevated Heq with flaws present	Fall 2024	Work has been completed

Appendix C: CNSC Staff review comments regarding licensees' disposition of intervenor comments

CNSC staff concluded that the licensee dispositions of intervenor comments were acceptable, but suggested that data from AGS chemistry or ex-service surveillance tubes could further enhance the response to comments raised in CMD 22-M37.4. The licensees reported that this information was not available or not practical to obtain. No further action was recommended based on the following:

- With the exception of the regions of elevated Heq, uptake models have generally provided bounding estimates of Heq measured in pressure tubes through both punches and scrapes without considering the AGS as an ingress source.
- Modelling conducted under the R&D program has been able to nominally reproduce regions of elevated Heq consistent with the findings from pressure tubes, without incorporating an additional ingress source from the AGS. In fact, modelling suggests that the mass inventory is likely already overestimated in the outlet region of the pressure tubes when only considering current body-of-tube ingress from ID corrosion and rolled joint region ingress. The measurement data used to estimate the mass volume has traditionally been collected from in-service scrapes or ex-service punch samples from near the 12:00 orientation where higher concentrations exist due to circumferential redistribution.
- The AGS operational issues discussed in CMD 22-M37.4 have not re-occurred over several decades since the adoption of CO_2 with O_2 addition for the annulus gas. This indicates that the chemical processes identified by the intervenor are no longer active, at least not to the extent that caused the historical issues with pressure tube operation.

Appendix D: Draft of Revised Section 6.2 of LCHs

Licence Condition 6.2:

The licensee shall implement and maintain an enhanced fitness for service program for fuel channels in extended operation.

Preamble:

The fitness for service program requirements in Section 6.1 have been demonstrated to be effective for operation of pressure tubes for the original target operating life of 210,000 EFPH. However, many of the model and evaluation processes used to assess pressure tube fitness for service in CSA Standard N285.8 required further development for levels of hydrogen equivalent concentration (Heq) that may be experienced when extending the operation of pressure tubes beyond 210,000 EFPH, particularly near the inlet and outlet rolled joint burnish marks.

Heq is a key input parameter to the models used to assess crack initiation, crack growth, fracture toughness and fracture initiation toughness. Enhanced monitoring of Heq is required during extended operation of pressure tubes. Furthermore, flaw evaluation models have been updated for application to regions of elevated Heq near the inlet and outlet rolled joint burnish marks for Heq levels exceeding the limits currently specified in CSA N285.8.

Compliance Verification Criteria:

Pressure Tube Flaw Evaluations

As documented in the September 30, 2025, letter from OPG (7583218), pressure tube flaw evaluations shall be performed in accordance with the processes documented in COG-25-1021 or COG-25-1023 for the following regions of pressure tubes in extended operation beyond 210,000 EFPH:

- The region encompassing the full circumference of a pressure tube extending 20 mm axially inboard of the inlet rolled joint burnish mark.

- The region encompassing the full circumference of a pressure tube extending 60 mm axially inboard of the outlet rolled joint burnish mark.

For flaws located within an axial distance of 20 mm inboard of the inlet burnish mark, the bulk Heq shall be assumed to be in the range of 120 ppm and 240 ppm when applying the process documented in COG-25-1023.

Following inspections of the regions of the pressure tubes within an axial distance of 60 mm inboard of the outlet rolled joint burnish mark and 20 mm inboard of the inlet rolled joint burnish mark, OPG shall identify any detected flaws exceeding 0.15 mm in depth in the inspection reports submitted in accordance with Clause 12.2.6 of CSA Standard N285.4-19.

Heq Measurement Program

For reactors that are operated beyond 210,000 EFPH, an enhanced Heq monitoring program shall be established for in-service Heq scrape sampling and ex-service surveillance tube Heq sampling that is sufficient to characterize the axial, circumferential and radial extents of inlet and outlet rolled joint regions of elevated Heq that may arise due to circumferential and/or localized temperature gradients. The scope of the program shall be submitted to CNSC staff.

Guidance:

OPG should work with industry partners to expand the inlet region Heq modelling activities to include a larger sample of data obtained from ex-service pressure tube, as this could lead to further refinements of the modelling process.

OPG should continue with material surveillance activities through both planned inspection program surveillance tubes as well as opportunities for additional material removal during refurbishment outages.