Canadian Nuclear Safety Commission | Commission canadienne de sûreté nucléaire

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CMD: 22-M37

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Technical briefing

Exposé technique

CNSC staff update on elevated hydrogen equivalent concentration discovery events in the pressure tubes of reactors in extended operation

Mise à jour du personnel de la CCSN sur les événements liés aux découvertes de concentrations élevées d'hydrogène équivalent dans les tubes de forces de réacteurs en exploitation prolongée

All nuclear power plant licensees

Tous les titulaires de permis de centrales nucléaires

Public meeting

Réunion publique

Scheduled for:

3 November 2022

Prévue pour :

3 novembre 2022

Submitted by:

CNSC staff

Soumis par :

Le personnel de la CCSN

e-Doc 6809551 (WORD)
e-Doc 6848197 (PDF)

Summary

- The purpose of this Commission member document (CMD) is to provide an update to the Commission on events related to the discovery of elevated hydrogen equivalent concentration (Heq) in pressure tubes covering the following areas:
  - CNSC staff's assessment of industry's Heq research and development plan, including discussion of preliminary results
  - CNSC staff's assessment of licensees' most recent submissions regarding the discovery of elevated Heq and, in particular, at the inlet rolled joint of pressure tubes, and its impact on fitness-for-service assessments
  - Results from CNSC staff's risk informed decision making assessment

There are no actions requested of the Commission. This CMD is for information only.

Résumé

- Le but de ce document à l'intention des commissaires (CMD) est de fournir une mise à jour à la Commission sur les événements liés à la découverte de concentrations élevées d'hydrogène équivalent (Heq), plus particulièrement :
  - l'évaluation, par le personnel de la CCSN, du plan de recherche et développement relatif au Heq préparé par l'industrie, y compris une analyse des résultats préliminaires
  - l'évaluation, par le personnel de la CCSN, des plus récents documents soumis par les titulaires de permis concernant la découverte de concentrations élevées de Heq, en particulier au niveau du joint dudgeonné du point d'entrée des tubes de force, et son incidence sur les évaluations de l'aptitude fonctionnelle
  - les résultats de l'évaluation du personnel de la CCSN sur la prise de décisions tenant compte du risque

Aucune mesure n'est requise de la Commission. Ce CMD est fourni à titre d'information seulement.

Signed/Signé le

August 22, 2022/22 août 2022

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EXECUTIVE SUMMARY

Commission meetings were held in September 2021 and March 2022 to discuss the discovery findings related to elevated hydrogen equivalent concentration (Heq) in the Bruce Power pressure tubes that are in extended operation (i.e., beyond 210,000 equivalent full power hours). The findings were discovered near the outlet rolled joint burnish mark as well as the inlet rolled joint burnish mark of the pressure tubes. The Heq values measured in the Bruce Power 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. The findings were presented in Commission Member Document (CMD) 21-M39, CMD 21-M37 and CMD 22-M16, and have an impact on the operation of Bruce A and B Units 3, 4, 5, 7 and 8, Pickering B Units 5 to 8 and Darlington Unit 4.

During those two Commission meetings, CNSC staff presented their conclusion that these findings posed a low risk for nuclear safety for the affected units; there was no impact on the ability of process and safety systems to mitigate the consequences of a pressure tube rupture because of these findings. Pressure tube failure is a design-basis event for CANDU reactors, which have built-in mitigating capabilities that would ensure that the dose to the public would be within the prescribed dose limits should this event occur. In addition, pressure tube failure is accounted for in the probabilistic safety assessment, and the results for Darlington, Bruce, and Pickering stations show that the safety goals are met with enough margin.

The discovery findings did put into question the full efficacy of Level 1 and Level 2 defence in depth with respect to the operation of the affected units. CNSC staff were unable to confirm that the fitness for service compliance verification criteria for potentially affected pressure tubes are satisfied. In July 2021, in response to the outlet rolled joint elevated Heq event, CNSC Designated Officer (DO) orders were issued to OPG and Bruce Power requiring the licensees to obtain authorization from the Commission prior to the restart of their units following any outage that result in cooldown of the heat transport system (HTS).

To address CNSC staff’s concerns, the industry has undertaken additional surveillance and monitoring activities such as investigating the root cause of the locally elevated Heq near the inlet and outlet rolled joints, introduced operational changes and additional training to minimize the possibility of cold overpressure transients, and produced plans for research and development (R&D) to update predictive model capabilities and analytical tools for the rolled joint region of pressure tubes.

The Commission was satisfied with the preliminary information provided at the two Commission meetings and the actions taken by the licensees. Based on CNSC staff’s recommendations in CMD 21-H112, CMD 21-H114 and CMD 22-H100, the Commission authorized OPG and Bruce Power to restart their units following any outages that result in cooldown of the HTS and concluded that the terms of the DO orders have been satisfied. As a follow-up, the Commission has requested licensees and CNSC staff to provide an update in fall 2022.

The purpose of this CMD is to address the Commission’s follow-up request by providing updates on:

1. CNSC staff’s assessment of industry’s inlet rolled joint and outlet rolled joint Heq R&D plan, including discussion of preliminary results
2. CNSC staff’s assessment of licensees’ most recent submissions regarding the discovery of elevated Heq, and in particular at the inlet rolled joint of pressure tubes, and its impact on fitness for service assessments
3. CNSC staff’s risk informed decision making risk assessment results related to the IRJ-BM finding

SOMMAIRE

La Commission a tenu des réunions en septembre 2021 et en mars 2022 pour discuter des constatations relatives à la découverte de concentrations élevées d'hydrogène équivalent (Heq) dans les tubes de force de Bruce Power qui sont en exploitation prolongée (c.-à-d. au-delà de 210 000 heures équivalentes pleine puissance) près de la marque de brunissage du joint dudgeonné du point de sortie et de la marque de brunissage du joint dudgeonné du point d'entrée des tubes de force. Les valeurs de Heq mesurées dans les tubes de force de Bruce Power dépassaient la limite de 120 parties par million (ppm) par poids établie pour le modèle de résistance à la rupture des tubes de force en vigueur au moment de la découverte. Les constatations ont été présentées dans les documents à l'intention des commissaires (CMD) 21-M39, 21-M37 et 22-M16, et ont une incidence sur les tranches 3, 4, 5, 7 et 8 de Bruce A et B, les tranches 5 à 8 de Pickering-B et la tranche 4 de Darlington.

Au cours de ces deux réunions de la Commission, le personnel de la CCSN a présenté sa conclusion selon laquelle ces constatations présentaient un faible risque pour la sûreté nucléaire des tranches touchées. Elle a aussi indiqué que ces constatations n'avaient pas d'incidence sur la capacité des systèmes fonctionnels et de sûreté d'atténuer les conséquences d'une rupture d'un tube de force. La défaillance d'un tube de force est un événement de dimensionnement pour les réacteurs CANDU, qui sont dotés de capacités d'atténuation intégrées garantissant que la dose reçue par le public serait inférieure aux limites de dose prescrites si cet événement se produisait. De plus, la défaillance des tubes de force est prise en compte dans l'étude probabiliste de sûreté, et les résultats pour les centrales de Darlington, de Bruce et de Pickering montrent que les objectifs de sûreté sont atteints avec une marge suffisante.

Ces constatations ont remis en question la pleine efficacité de la défense en profondeur de niveau 1et de niveau 2 en ce qui concerne l'exploitation des tranches touchées. Le personnel de la CCSN n'a pas été en mesure de confirmer que les critères de vérification de la conformité à l'aptitude fonctionnelle des tubes de force susceptibles d'être touchés étaient respectés. Pour donner suite à la découverte de concentrations élevées de Heq au niveau du joint dudgeonné du point de sortie, des ordres ont été délivrés par des fonctionnaires désignés (FD) de la CCSN à OPG et à Bruce Power en juillet 2021, exigeant que ces derniers obtiennent l'autorisation de la Commission avant de redémarrer leurs tranches à la suite de tout arrêt entraînant le refroidissement du circuit caloporteur.

Afin de répondre aux préoccupations du personnel de la CCSN, l'industrie a entrepris des activités de surveillance supplémentaires. Elle a notamment réalisé des enquêtes sur la cause profonde des concentrations élevées de Heq au niveau des joints dudgeonnés des points d'entrée et de sortie, mis en œuvre des changements opérationnels et offert de la formation supplémentaire dans le but de réduire au minimum la possibilité que surviennent des transitoires de surpression à froid. L'industrie a également élaboré des plans de recherche et développement visant à renforcer la capacité prédictive des modèles et à mettre à jour les outils analytiques pour la zone des joints dudgeonnés des tubes de force.

La Commission a été satisfaite des renseignements préliminaires présentés lors des deux réunions de la Commission, ainsi que des mesures prises par les titulaires de permis. De plus, selon les recommandations du personnel de la CCSN dans les CMD 21-H112, 21-H114 et 22-H100, la Commission a autorisé OPG et Bruce Power à redémarrer leurs tranches à la suite de tout arrêt entraînant le refroidissement du circuit caloporteur, et elle a conclu que les modalités des ordres des FD avaient été respectées. La Commission a aussi demandé aux titulaires de permis et au personnel de la CCSN de lui présenter une mise à jour à l'automne 2022.

Pour donner suite à la demande de la Commission, le présent CMD vise à lui fournir des mises à jour sur les points suivants :

1. L'évaluation, par le personnel de la CCSN, du plan de recherche et développement de l'industrie sur la concentration de Heq au niveau des joints dudgeonnés du point d'entrée et du point de sortie, de même qu'une analyse des résultats préliminaires.
2. L'évaluation, par le personnel de la CCSN, des plus récents documents soumis par les titulaires de permis concernant la découverte de concentrations élevées de Heq, en particulier au niveau du joint dudgeonné du point d'entrée des tubes de force, et son incidence sur les évaluations de l'aptitude fonctionnelle.
3. Les résultats de l'évaluation du personnel de la CCSN de la prise de décisions tenant compte du risque relativement aux constatations liées à la marque de brunissage du joint dudgeonné du point d'entrée.

1 BACKGROUND

Through physical inspections, it has been found that pressure tubes in CANDU reactors have surface flaws (on the inner surface) caused by the interactions of fuel bundles, inspection tools and foreign material. These flaws, under certain conditions, can result in initiation of a pressure tube crack that could grow through-wall and lead to a pressure tube rupture. High hydrogen equivalent concentration (Heq) reduces the fracture toughness (resistance to fracture) of pressure tubes at lower-than-normal operating temperatures (i.e., during unit heat up/cooldown), which could increase the likelihood of a pressure tube failure should a crack be initiated. While in-service cracking has been observed in older installed pressure tubes in the 1980's and 1990's, the contributing factors have been identified and the impacted tubes were replaced. In-service cracking has not been observed in the current population of pressure tubes to date.

The fitness for service compliance verification criteria (CVC) for pressure tubes can only be established for pressure tubes with Heq below the applicable limits of the evaluation models, most notably the fracture toughness model. The upper Heq limit of the fracture toughness model in CSA Standard N285.8, *Technical requirements for in-service evaluation of zirconium alloy pressure tubes in CANDU reactors*[1] at the time of the Bruce Power and Pickering licence renewals in 2018 was 120 ppm, and that the end-of-life Heq values for some pressure tubes in extended operation (i.e., beyond 210,000 equivalent full power hours (EFPH)) was expected to exceed the 120 ppm limit.

As a result, a specific Licence Condition (LC) was placed on the Bruce Power and Pickering Power Reactor Operating Licences (PROLs) at the time of licence renewal in 2018, which required the licensees to seek approval from the Commission to operate pressure tubes beyond Heq levels of 120 ppm. To address this concern, the industry has committed to undertake a program to increase the Heq limit for the fracture toughness model. Note that this 120 ppm limit does not refer to threshold effect in material behaviour; rather it is based upon the maximum Heq levels in material used for fracture toughness testing up to the time of the Bruce and Pickering licence renewal.

The specific LC related to the Heq limit was implemented for the Bruce Power and OPG Pickering PROLs, but was not implemented for NB Power and OPG Darlington. For Pt. Lepreau, the unit was recently refurbished so its pressure tubes are not expected to exceed Heq levels of 120 ppm prior to the revision of the fracture toughness model. The OPG Darlington PROL was issued in 2015 and did not include this condition. However, CNSC staff hold OPG Darlington to the same standard as the Bruce and Pickering stations through the adoption of CSA N285.8 as CVC in the Licence Conditions Handbook associated with the Darlington PROL.

<u>Discovery Events</u>

In September 2021, CNSC staff submitted to the Commission an Event Initial Report (EIR), under Commission Member Document (CMD) 21-M39 [1], regarding findings of

[1] The Revision 1 model was included in the 2015 edition of CSA Standard N285.8. Update No. 1 to the 2015 edition was issued in 2019 and included an additional Heq limit of 80 ppm with 1.5 m of the front end of a pressure tube. Further information on the fracture toughness model is provided in Section 3.3 of this CMD.

elevated Heq in the Bruce Power pressure tubes near the outlet rolled joint burnish mark (ORJ-BM) -- see **Figure 1** for a schematic diagram of the relevant portion of a pressure tube. The findings were observed in a Bruce Unit 6 pressure tube that was removed for material surveillance during the major component replacement outage (tube B6S13) and in several in-service scrapes obtained from Bruce Unit 3 pressure tubes during a physical inspection.

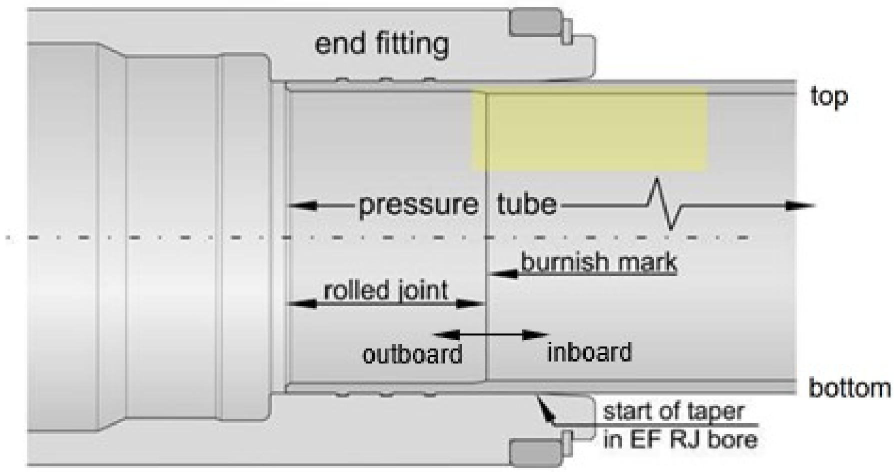


Figure 1: Schematic diagram of a pressure tube at the end fitting

The Heq values measured in these pressure tubes, which was restricted to a small region near the top of the pressure tubes (as highlighted in yellow in **Figure 1**), exceeded the limit of 120 ppm established for the accepted pressure tube fracture toughness model. In the unlikely event that there is a sufficiently large pressure transient combined with the presence of a flaw in the high Heq area of the pressure tube, the lower fracture toughness could lead to a pressure tube rupture. As such, the findings from the pressure tube examinations raised questions regarding conclusions of the pressure tube fitness for service evaluations performed with the accepted model.

Following further testing on the same Bruce Unit 6 B6S13 surveillance tube, Bruce Power also discovered elevated Heq near the inlet rolled joint burnish mark (IRJ-BM) in December 2021.

Commission Meetings were held in September 2021 [2] and March 2022 [3] to discuss the potential effect of elevated Heq on units in extended operation (i.e., reactors operating beyond 210,000 EFPH). The following CNSC staff's conclusions were presented to the Commission during those meetings for near-term operation:

- continued operation of reactors currently at power does not pose unreasonable risk to nuclear safety
- existing safety analysis remains valid and indicate minimal radiological consequences to workers in case of pressure tube rupture

However, the discovery findings did put into question the full efficacy of Level 1[2] and Level 2[3] defence in depth (DiD) with respect to the operation of the affected units. CNSC staff were unable to confirm that the fitness for service CVC for potentially affected pressure tubes are satisfied. In response to the outlet rolled joint elevated Heq event, CNSC Designated Officer (DO) orders were issued to OPG and Bruce Power in July 2021 requiring the licensees to obtain authorization from the Commission prior to the restart of their units following any outage that resulted in cooldown of the heat transport system (HTS).

To address CNSC staff's concerns, the industry has undertaken surveillance and monitoring activities such as investigating the root cause of the locally elevated Heq near the inlet and outlet rolled joints, introducing operational changes and additional training to minimize the possibility of cold overpressure transients, and producing plans for research and development (R&D) to update predictive model capabilities and analytical tools for the rolled joint region of pressure tubes.

The Commission was satisfied with the preliminary information provided at the two Commission meetings. Based on CNSC staff's recommendations in CMD 21-H112, CMD 21-H114 and CMD 22-H100[4], the Commission authorized OPG and Bruce Power to restart their units following any outages that result in cooldown of the HTS and concluded that the terms of the DO orders have been satisfied. As a follow-up, the Commission has requested licensees and CNSC staff to provide an update in fall 2022.

For further technical background related to elevated Heq at the ORJ-BM and IRJ-BM, please refer to Appendix A of this CMD.

2 PURPOSE

This CMD is to address the Commission's follow-up request by providing an update on the status of the industry's activities to address the events related to elevated Heq detected near the inlet and outlet rolled joints of pressure tubes in extended operation. To assess the impact of the uncertainties associated with pressure tube fitness for service due to elevated Heq near the inlet rolled joint on nuclear safety, CNSC staff conducted an internal Risk Informed Decision Making (RIDM) review in July 2022; this update includes the results of CNSC staff's evaluation of the risk associated with pressure tube fitness for service.

3 UPDATES SINCE MARCH 2022

This section of the CMD provides the following updates reflecting developments since the last Commission Meeting:

[2] Level 1 DiD is achieved through processes and activities to prevent failures including evaluations of aged pressure tubes to confirm they meet the intent of the design standard.
[3] Level 2 DiD is achieved through equipment and processes that allow early detection of, and response to, pressure tube leaks.
[4] Note: In the CMDs, alternate compliance verification criteria were proposed and adopted to assess the fitness for service of pressure tubes in the near term in response to the ORJ-BM elevated Heq event

- Assessment of Heq modeling activities, including Industry's R&D Plan (Section 3.1)
- Assessment of licensees' most recent submissions regarding the discovery of elevated Heq and its impact on fitness for service assessments, specifically the licensees' submissions on:
    - crack initiation testing (Section 3.2)
    - adoption of Revision 2 of the pressure tube fracture toughness model (Section 3.3)
- CNSC RIDM assessment results related to the IRJ-BM finding (Section 3.4)

3.1 CNSC Staff's Assessment of Heq Modelling Activities and R&D plan

In July 2021, as a result of the discovery findings, CNSC issued a formal request for information to OPG and Bruce Power, pursuant to subsection 12(2) of the *General Nuclear Safety and Control Regulations* (GNSCR), relating to the concern that the models used by the licensees under-predicted the maximum Heq in pressure tubes and the impact on the fitness for service evaluations. The request included placing the following actions on the licensees:

- Analyze the impact of the findings on the demonstration of pressure tube fitness for service
- Conduct necessary tests and analysis to verify that operation of reactors remains within their licensing basis
- Inform CNSC of any other measures taken in response to the findings
- Assess this information on the planned restart of any units following their outages
- Analyze the hydrogen uptake model validity reflecting the results of the findings

In January 2022, OPG and Bruce Power responded [4], [5] to the CNSC's request related to the analysis of the hydrogen uptake model validity. The submissions also provided a high-level overview of the industry's planned work to improve outlet rolled joint Heq predictive capability. This was followed by an industry-CNSC staff meeting in March 2022 with the industry providing an update on the R&D plan being carried out under a joint project by CANDU's Owner Group (COG). This section of the CMD is focused on the industry's Heq modelling activities and R&D plan.

To address the inlet rolled joint finding, the industry expanded the scope of the Heq modeling activities and subsequently shifted its focus on the Heq near the IRJ-BM finding in the near term. The shift in focus was appropriate given that, for the ORJ-BM region of the pressure tube, fitness for service could be demonstrated. This was because there was sufficient inspection data to confirm with high degree of certainty that no flaws were present in the region of interest (ROI)[5] at risk of initiating cracking and that corrective actions would be implemented for pressure tubes containing flaws.

For the Pickering pressure tubes in extended operation, CNSC staff determined that fitness for service can be demonstrated for the IRJ-BM region in a manner that is consistent with the restart criteria (see Appendix A1 for the restart criteria) used for the ORJ-BM region, as the mechanisms for the formation of flaws that lead to crack initiation are not active within a 20 mm axial distance from the IRJ-BM.

This approach could not be applied to pressure tubes with elevated Heq near the IRJ-BM in the Bruce and Darlington reactors in extended operation since flaws are known to exist near the IRJ-BM. As such, further work is needed to demonstrate that the presence of elevated Heq near the IRJ-BM does not lead to a significant increase in the potential for crack initiation from flaws. The work includes simulating the formation and evolution of the IRJ-BM "blip"[6] and assessing its impact.

In June 2022, Bruce Power provided the results of preliminary modelling of hydrogen ingress and diffusion near the IRJ-BM to demonstrate that it was possible to simulate the formation and evolution of the IRJ-BM "blip" in the B6S13 pressure tube due to contact between the pressure tube and end fitting. Bruce Power asserted that localized contact between the pressure tube and the end fitting would result in localized lower temperature. This would cause the hydrogen to migrate to that location and thus could generate an Heq "blip" similar to that observed in pressure tube B6S13 and several Darlington pressure tubes.

To assess the potential impact of the observed phenomenon leading to the locally elevated Heq on the outer surface of the pressure tubes, the preliminary study compared Heq predictions from simulations with and without inner surface flaws at the same axial and circumferential orientations as the Heq "blips". The simulated flaws were deeper than any flaws detected in service to date at that axial position in the pressure tubes. The preliminary results suggested that Heq levels at the flaw tip could increase by up to 15% compared to modelling results without the localized contact between the pressure tube and end fitting taper after about 31 hot years of operation, which equates to the end of the operating life of the B6S13 tube. The significance of this increase on pressure tube fitness for service has not been fully evaluated by CNSC staff at this time.

<u>CNSC staff's review conclusion</u>

For the Pickering units the mechanisms to generate flaws that would lead to crack initiation are not active within a 20 mm axial distance from the IRJ-BM. Therefore, fitness for service can be demonstrated in the manner that was consistent with the restart criteria established to address the ORJ-BM elevated Heq findings.

For the outlet rolled joint regions of Bruce Power and Darlington pressure tubes in extended operation there are no flaws, and no mechanisms for the formation of flaws that are at risk for crack initiation within the regions of the pressure tubes where elevated

[5] Refer to Appendix A for a description of the region of interest

[6] The localized region of elevated Heq is referred to as a "blip" by the industry, which is based on the shape of the Heq profile.

levels of Heq have been observed in the Bruce Power pressure tubes. However, the preliminary results of industry's modelling cannot be used to directly confirm the pressure tube fitness for service with inner diameter surface flaws near the inlet burnish mark; further model development is required. The industry will need to perform further validation work to address CNSC staff's concern that the models used are under-predicting the maximum Heq in pressure tubes, and the potential impact on the fitness for service evaluations.

Industry is also expected to support the preliminary results through ongoing model development activities to confirm industry's assertions that the presence of IRJ-BM "blips" does not lead to a significant increase in the potential for crack initiation from flaws, which would validate the use of current crack initiation models for inlet rolled joint region flaws.

CNSC staff concluded that the evaluation of fitness for service of the pressure tubes subject to the IRJ-BM Heq "blips" could not be confirmed at this time for Bruce Power and OPG Darlington reactors with pressure tubes in extended operation. However, CNSC staff determined that, through the risk informed decision making process (see Section 3.4 of this CMD), the near-term increase in risk to nuclear safety remains low. CNSC staff will continue to monitor the industry's model development work and expect to receive further updates on this work from the industry in early 2023.

3.1.1 CNSC Staff's Assessment of Industrywide outlet rolled joint and inlet rolled joint evaluation plans

In addition to the Heq modelling activities and R&D plan, Bruce Power, OPG and New Brunswick Power provided reports [6], [7], [8] reports in July 2022 summarizing all activities undertaken since the fall of 2021. This section of the CMD is focused on CNSC staff's assessment of industrywide outlet and inlet rolled joint evaluation plans provided in those reports. The reports included the results of surveillance tests of pressure tubes, model development and assessments of pressure tube fitness for service, and detailed research plans to improve Heq predictions near the rolled joint burnish mark.

The OPG and Bruce Power submissions also included a roadmap that highlighted the surveillance and modelling actions. The surveillance actions included:

- R&D activities related to ex-service material surveillance
- Additional IRJ punch sampling and metallography to investigate "blips" at the IRJ burnish mark
- Scrapes at additional clock positions and axial locations in future campaigns
- Continued flaw monitoring in inlet and outlet region of interest during future volumetric and dimensional inspections

Regarding the modelling actions, the work included developing an interim Heq model by Q4 2023 and developing and validating a comprehensive model by Q2 2026. This work included sub-actions such as:

- Developing models to simulate inlet and outlet end rolled joint Heq evolution

- Enhancing fuel channel deformation/heat transfer model
- Performing hydrogen diffusion analysis
- Confirming validity of existing crack initiation models

CNSC staff's review conclusion

Based on the review of the modelling activities and evaluation plans, CNSC staff concluded that industry has adequately targeted the key issues raised by CNSC staff regarding pressure tube fitness for service evaluations and that industry has established both experimental and modelling activities with adequate scope and deliverables throughout the plan.

It is CNSC staff's view that the industry's plans are appropriate to address key issues related to Heq modelling. The industry is committed to provide semi-annual updates to CNSC staff on the overall status, with the first submission to be provided by end of Q1 2023. CNSC staff intend to actively engage with industry during the execution of the plans.

3.2 CNSC Staff's Assessment of Crack Initiation Testing

The crack initiation testing was originally undertaken to demonstrate that the introduction of scrape marks in regions of elevated Heq in the Bruce Unit 3 pressure tubes did not pose a risk of initiating cracking in these pressure tubes. Three models are used by the industry to evaluate the potential for crack initiation from flaws in pressure tubes related to:

- Delayed hydride cracking (DHC)
- Fatigue
- Hydrided Region Overload (HROL)

Heq has a direct impact on DHC and HROL since these mechanisms have the potential to generate cracks due to the formation of hydrides at the tip of a flaw. The formation of cracks by fatigue may be indirectly impacted by Heq due to potential changes in material properties with increasing Heq. Currently, the crack initiation models have only been confirmed to be appropriate for use with material with Heq levels up to 120 ppm, although the industry has suggested that the models will not be significantly impacted by higher Heq values.

The models assume that the potential for crack initiation is impacted primarily by the amount of hydrogen isotope in solution in the material that is available to diffuse to the location of a flaw. The amount of hydrogen in solution is a function of the solubility limit and at normal operating temperatures. The solubility limit is less than 120 ppm. In theory, as the total Heq increases, the amount of soluble hydrogen will remain limited. The industry has committed to a crack initiation testing program for higher Heq material to confirm the current assumptions.

The outlet rolled joint ROI, it has a low likelihood of flaws with geometries which would lead to crack initiation. Scrape sampling have introduced some flaws into the region. Such flaws have benign geometries that resulted in very low stresses, so they are unlikely to accumulate sufficient hydrogen to lead to crack initiation. However, as the crack initiation models were never evaluated for levels of Heq shown to exist in some of the Bruce pressure tubes, it was prudent for the industry to develop a research program to verify these assumptions.

The crack initiation testing program includes testing to evaluate all three crack initiation mechanisms. Initial testing was carried out on unirradiated material with elevated Heq to compare to results on similar material with lower Heq values. This will be followed by further testing on irradiated material. Although the crack initiation program was developed and commenced prior to the IRJ-BM finding, the results could be beneficial to support fitness for service evaluations of flaws near the inlet rolled joint as well.

The first series of tests related to DHC on unirradiated material have been completed and the results have been provided for CNSC staff review. The DHC model uses the following two input parameters derived from testing directly:

- K_{IH} – the threshold stress intensity for DHC initiation from a crack
- p_c – the threshold stress for DHC from a smooth surface

Tests were completed to evaluate three material parameters relevant to DHC using material with Heq values of nominally 240 ppm to compare against results for material with Heq of nominally 60 ppm. The maximum value was selected to bound the measurements from the ORJ-BM ROI of the Bruce Power pressure tubes, which could be compared to results from the same material that was previously tested with Heq of 60 ppm. If the industry can show that there were no changes in the crack initiation behaviour at the different Heq levels, it would indicate there was no impact of elevated Heq on crack initiation.

Early test results showed no changes between K_{IH} and p_c for material with Heq of 60 ppm or 240 ppm. These results suggest that the current model could demonstrate that there is no reduction in crack initiation behaviour for pressure tubes with elevated Heq. Additional tests have been completed for a specimen with a specific flaw geometry (See **Figure 2**).

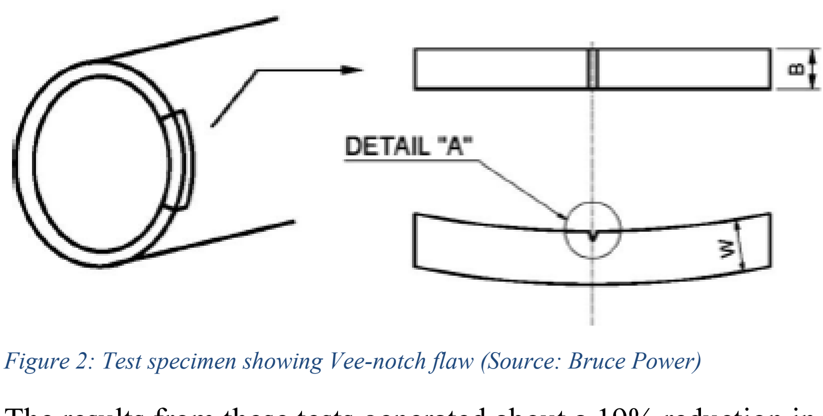


Figure 2: Test specimen showing Vee-notch flaw (Source: Bruce Power)

The results from these tests generated about a 19% reduction in the crack initiation threshold for the 240 ppm tests compared to the 60 ppm tests. The current industry theory is that the finding is the result of an interaction between hydrides forming at the flaw tip and larger bulk hydrides present in the 240 ppm material that are not present in the 60 ppm material. Therefore, it may be necessary to modify the DHC model to account for this finding, specifically for material with elevated Heq.

CNSC staff's review conclusion

CNSC staff concluded that these results do not indicate an immediate concern for the Heq scrape measurement flaws that have been introduced to the ORJ-BM ROI in Bruce Unit 3 pressure tubes. Bruce Power provided a detailed stress analysis for the scrape flaws and demonstrated that the stresses arising from scrape flaw geometry are well below the stresses that would be required to initiate cracking. The flaw geometry used in the testing generates more significant stresses when compared to scrape mark geometries and even if the 19% reduction in the crack initiation threshold observed in those was applied to the scrape flaws, the stresses would not be high enough to initiate cracking.

Although it has been demonstrated that flaws generated from scrapes would not initiate cracking, the results illustrate the importance of continuing with testing programs to ensure the full impact of elevated Heq on pressure tube integrity is evaluated. These findings could impact the industry's evaluations of inlet rolled joint region flaws going forward.

CNSC staff will continue to monitor the industry's testing program, as well as updates to the DHC model. The testing program for all three crack initiation mechanisms is expected to be completed by the end of 2024, which aligns with the evaluated operating period in the CNSC RIDM assessment (see Section 3.4 of this CMD).

3.3 Adoption of the Revision 2 Fracture Toughness Model

In 2018, as part of the Bruce Power and OPG Pickering licence renewal hearings, CNSC staff recommended that a LC 15.3 be placed on their respective PROLs as the industry could only demonstrate that the fracture toughness model is valid up to the Heq limit of 120 ppm. The LC stipulates: "*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.*"

This value of the Heq in this LC was based on the upper validity limit for the Revision 1 fracture toughness model for operating temperatures below 250°C incorporated in CSA Standard N285.8, *Technical requirements for in-service evaluation of zirconium alloy pressure tubes in CANDU reactors*. Fracture toughness models are used to assess risk of pressure tube failure from postulated flaws in uninspected pressure tubes.

At the time of licence renewal, Bruce Power estimated that the Heq for some pressure tubes could reach as high as 150 ppm for operation up to 300,000 EFPH. For the Pickering and Darlington pressure tubes, the Heq levels prior to refurbishment were estimated to be lower, but could still exceed 120 ppm prior to refurbishment or permanent shutdown. The Commission accepted CNSC staff's recommendation for placing LC 15.3, and agreed that Commission approval would be required for Bruce Power and OPG Pickering to operate with pressure tubes in excess of 120 ppm of Heq.

To address CNSC staff's concerns, the industry provided plans to extend the validity limit of the existing fracture toughness model to 160 ppm to support operation to the planned end-of-life of the pressure tubes in extended operation. The intent of revising the fracture toughness model (Revision 2) was that it would permit fitness for service evaluations at higher Heq values and satisfy the LC requirement. This new model will need to be supported by results from burst tests.

During testing to increase the model validity limits, one in a series of burst test (BT) (referred to as test BT-29) that was conducted in 2018 challenged the upper validity limit of the Revision 1 model. The BT-29 sample had an Heq value of approximately 100 ppm and exhibited a fracture toughness that was much lower than expected. After further investigation by the industry, the result was attributed to differences in the pressure tube material along the length of a pressure tube. The BT-29 specimen was taken from the front end of the pressure tube, which is the end that is first formed when the tube is extruded during the manufacturing process. The finding led to a second limit being placed on the Revision 1 model in CSA Standard N285.8, which requires a licensee to provide a technical justification to use the model for evaluations when Heq levels exceed 80 ppm within 1.5 m from the front end of a tube. Additional information on this subject was provided to the Commission in CMD 21-M4 [9].

The technical basis for the Revision 2 model was submitted for CNSC staff review in the Spring of 2022. The industry requested acceptance for the use of the Revision 2 model for Heq values up to a maximum of 140 ppm, with a 100 ppm restriction for material within 1.5 m of the front end of the pressure tube. While the industry originally targeted an upper limited of 160 ppm for the Revision 2 model, the original testing schedule had to be modified in response to the BT-29 test result. Prior to the high Heq events in Bruce Units 3 and 6, it was expected that these revised limits would be sufficient to cover pressure tube operation until additional testing could be completed to achieve the 160 ppm target. These Revision 2 limits bound the IRJ-BM punch measurements obtained from the Darlington ex-service tubes, but do not bound the peak values near the outer diameter (OD) surface of the tubes nor the Heq measurements near the outlet or inlet rolled joints of Bruce Units 3 and 6. Additional R&D is also required to justify the application of the current fracture models for material with large through thickness Heq gradients because current models are based on the assumption that Heq is uniform through the wall thickness.

Based on the information submitted by the licensees, CNSC staff conditionally accepted the use of the Revision 2 model [10], [11]. Specifically, the condition stipulated that the model can be applied to material with Heq up to a maximum of 140 ppm, with a 100 ppm restriction for material within 1.5 m of the front end of the pressure tube, with restrictions for use in probabilistic pressure tube evaluations. For deterministic fracture protection and leak-before-break evaluations, the lower bound estimates of fracture toughness are considered acceptable to support pressure tube operation up to the new specified Heq limits. However, for probabilistic evaluations, the model generates a very large prediction range with a lack of evidence that the range is appropriate for all pressure tubes. Further testing will be required in order to remove those conditions.

Additionally, the Revision 2 model applicability has not been demonstrated for the material with Heq greater than 100 ppm with 1.5m of the front end of the pressure tubes and 140 ppm for the remainder of the pressure tubes. It will be necessary to continue testing and model development to include more tube samples and a larger temperature range in order to confirm that the model can be applied to material with higher Heq values.

CNSC staff's review conclusion

Although the Revision 2 engineering fracture toughness model is an improvement from the first revision, there is more work required (such as expanding the tests to include different tube samples and selecting a larger temperature range) to remove the restrictions for probabilistic evaluations, as well as to further increase the Heq limits. CNSC staff will continue to monitor the work associated with the Revision 2 model.

Since the industry is now able to extend this validity limit beyond 120 ppm, it is CNSC staff's view that LC 15.3 is no longer applicable and requires an amendment. In March 2022, Bruce Power submitted its notice of intent [12] to seek the Commission's approval to amend the PROL in Q3/4 of 2022; CNSC staff will make a recommendation to the Commission based on licensees' amendment requests once they're submitted.

3.4 CNSC staff's Risk Informed Decision Making process to Address High Heq at Inlet Rolled Joints

In July 2022, a CNSC team was set up to apply the CNSC Risk Informed Decision Making (RIDM) process to provide recommendations to CNSC management, from a risk perspective, with respect to assessing the impact of the uncertainties associated with pressure tube fitness for service due to elevated Heq on nuclear safety.

More specifically, the purpose of RIDM was to identify and assess risks resulting from the discovery of elevated Heq near the IRJ-BM and continued operation of NPPs with pressure tubes affected by the discovery. Elevated Heq near the ORJ-BM is less risk significant since the mechanisms for the formation of flaws likely to initiate cracks are not present in that region of pressure tubes.

The team followed the principles established in the CNSC Policy document on the *Use of a Risk-Informed Approach for Regulatory Oversight of Nuclear Activities and Facilities* [13] and adhered to the RIDM process as outlined in CSA N290.19, *Risk Informed Decision Making for Nuclear Power Plants*. The RIDM process is based on an evaluation methodology which uses a risk tolerability scale (Risk Significance Levels (RSLs)[7]) from 1 to 4 (1 being a matter of concern that brings no additional risk or a negligible one, whereas 4 being that the risk has been evaluated to be not acceptable).

The outcome was a Risk Assessment Report (RAR) [14] that, while the industry continues to conduct further analysis to understand the Heq phenomenon and evaluates the impact on pressure tube fitness for service, allowed CNSC staff to inform the Commission and stakeholders of the incremental risks arising from the extended operation of reactors. The conclusions and recommendations are applicable to the Bruce and Darlington reactors in extended operation beyond 210,000 EFPH. Pickering A and B are not part of the scope of this RIDM process since the mechanisms for the formation of

[7] RSL is defined in CSA N290.19

flaws that lead to crack initiation are not active within a 20 mm axial distance from the IRJ-BM where the Heq "blip" was detected (as discussed in Section 3.1 of this CMD).

As discussed earlier, based on the information submitted by the industry to date, CNSC staff cannot confirm whether Levels 1 or 2 DiD effectiveness can be fully demonstrated. This is because the discovery of elevated Heq near the IRJ-BM put into question the applicability of the models used for demonstration of fitness for service of pressure tubes. However, CNSC staff's risk assessment determined that, even with elevated Heq at either the inlet or outlet region of the pressure tube:

- Level 3[8] DiD is not affected by the type of pressure tube failure (PTF) that could potentially result from reduced fracture toughness. In other words, special safety systems will perform their intended functions to ensure that prescribed dose limits will not be exceeded in the event of a single PTF. This is because protection against single PTF is part of the design basis for all CANDU reactors.
- The increase in Severe Core Damage Frequency (SCDF) and Large Release Frequency (LRF)[9] due to postulated increases in pressure tube failure frequency is negligible for up to three years of continued operation. This conclusion is based on CNSC staff's review of Bruce Power's sensitivity analysis of the Probabilistic Safety Assessment (PSA) results, as well as CNSC staff's own independent PSA sensitivity analysis.

CNSC staff also determined the RSL for the various risk scenarios that have been evaluated are all are within the tolerable region (RSL equal to 1) for the evaluated operating period; that is, the findings identified are "… *a matter of concern [that] brings no additional risk or a negligible one*". The evaluated operating period for Bruce A is two years, Bruce B is three years and Darlington is three years.

To ensure that Levels 1 and 2 DiD have not been compromised, the industry have committed to perform additional work to confirm the mechanisms responsible for elevated Heq at the inlet end of pressure tubes, and to update their fitness for service assessments (which includes updates to the current models) as summarized in Sections 3.1 to 3.3 above.

<u>CNSC staff's review conclusion</u>

Based on CNSC staff's risk assessment of elevated Heq at the inlet end of pressure tubes at reactors in extended operation at Bruce A and B and Darlington, CNSC staff concluded that the risk due to the issue of elevated Heq at the inlet rolled joint of pressure tubes is negligible for up to 2-3 years of continued operation (depending on the station); as such, no immediate action is required. As previously discussed, the industry has committed to completing additional R&D in this timeframe to address the effects of elevated Heq on pressure tube fitness for service.

The RAR included the following Recommendations:

[8] Level 3 DiD is achieved through the provision of inherent safety features to minimize the consequences of pressure tube failures and maintain at least one barrier to prevent radioactive releases.
[9] SCDF: Less than 1 occurrence in 10,000 years, LRF: Less than 1 occurrence in 100,000 years

1. Industry to provide an Heq R&D plan with timelines that are acceptable to CNSC staff. The plan should include but should not be limited to:
   a) Determination of root causes/mechanisms for elevated Heq at outlet rolled joint and inlet rolled joint regions of pressure tubes including actual testing
   b) Heq model updates based on item a) above
   c) Updated Heq analyses
   d) Updated fitness for service Assessments based on item c) above

2. Licensees to undertake material surveillance activities by removing and testing pressure tubes during upcoming refurbishments/major component replacements, and to provide a statistically significant sample size in order to validate updated Heq models in the outlet rolled joint and inlet rolled joint regions.

Bruce Power and OPG Darlington are carrying out the actions under Recommendations #1 and #2, which will help inform the quantification of the probability of pressure tube rupture used to determine the risk, and provide assurance that prescribed dose limits will not be exceeded in the event of a single PTF. Given the 2-3 year timeframe that will be required to implement Recommendations #1 and #2, it is CNSC staff's view that the short-term corrective action should be on the following Risk Control Measure:

> *Licensees to ensure there are adequate procedures, surveillance programs, as well as training in place to monitor the dominant contributors' failure probabilities to pressure tube failure and pressure tube leak event*[10] *sequences leading to core damage.*

Bruce Power has introduced some operational changes and additional training to address this Risk Control Measure. At the time of writing this CMD, the RIDM report has just been finalized. Therefore, CNSC staff are in the process of determining whether additional compensatory measures need to be taken to further reduce the risk.

4 OVERALL CONCLUSIONS

Overall, CNSC staff concluded that the evaluation of fitness for service of the pressure tubes subject to the inlet rolled joint Heq "blips" could not be conclusively confirmed at this time. However, CNSC staff determined that, through the risk informed decision making process, the increase in risk is negligible for continued operation up to 3 years, which provides industry time to complete additional R&D. The industry has adequately targeted the key issues raised by CNSC staff regarding pressure tube fitness for service evaluations and has established both experimental and modelling activities with adequate scope and deliverables throughout the plan. It is CNSC staff's view that the industry's R&D plans are in the right direction to address key issues related to Heq modelling.

[10] Pressure tube failure event is a failure resulting in an initial discharge rate in excess of 1 kg/s, while pressure tube leak is a failure resulting in an initial discharge rate of less than 1 kg/s

On the subject of Heq modeling activities and R&D Plan, including assessment of the industrywide outlet and inlet rolled joint evaluation plans, CNSC staff concluded that:

- For the Pickering units, there are no active mechanisms for the formation of flaws that are at risk for crack initiation within the regions of the pressure tubes where elevated levels of Heq have been observed in Bruce Power and Darlington pressure tubes in extended operation. Therefore, fitness for service can be demonstrated for Pickering units as OPG will continue to ensure that sufficient inspection data will be available, and that corrective actions will be implemented if flaws are ever detected in these regions.
- For the outlet rolled joint regions of Bruce Power and Darlington pressure tubes in extended operation there are no flaws, and no mechanisms for the formation of flaws that are at risk for crack initiation within the regions of the pressure tubes where elevated levels of Heq have been observed in the Bruce Power pressure tubes. Therefore, fitness for service can be demonstrated for these units as the licensees will continue to ensure that sufficient inspection data will be available, and that corrective actions will be implemented if flaws are ever detected in these regions.
- For the Bruce and Darlington units, the preliminary modelling results of hydrogen ingress and diffusion near the inlet rolled joint cannot be used to directly confirm the fitness for service of pressure tubes with ID surface flaws near the inlet burnish mark of pressure tubes without further model development.
    - The licensees are expected to support the preliminary results through ongoing model development activities to confirm industry's assertions that the presence of inlet rolled joint Heq "blips" does not lead to a significant increase in the potential for crack initiation from flaws, which in turn would validate the use of current crack initiation models for inlet rolled joint region flaws.
- Based on the review of the modelling activities and evaluation plans, CNSC staff concluded that industry has targeted the key issues raised by CNSC staff regarding pressure tube fitness for service evaluations. CNSC staff will continue to monitor the licensees' Heq experimental and modelling activities, and intend to actively engage with industry during the execution of the plan.

Regarding crack initiation testing, CNSC staff concluded that:

- The crack initiation testing results do not present an immediate concern for the Heq scrape measurement flaws that have been introduced near the outlet rolled joint burnish mark of pressure tubes.
- Although it has been demonstrated that flaws generated from scrapes would not initiate cracking, the results illustrate the importance of continuing with testing programs to ensure the full impact of elevated Heq on pressure tube integrity is evaluated.

- CNSC staff will continue to monitor further testing results, as well as updates to crack initiation models, to ensure that the full impact of elevated Heq on pressure tube integrity is evaluated.

Regarding the adoption of Revision 2 of the pressure tube fracture toughness model, CNSC staff concluded that:

- The Revision 2 model is conditionally acceptable, and that it can be applied to material with Heq up to a maximum of 140 ppm, with a 100 ppm restriction for material within 1.5 m of the front end of the pressure tube.
- Although Revision 2 engineering fracture toughness model is an improvement from the first revision, there is more work required (such as expanding the tests to include different tube samples and selecting a larger temperature range) to remove the restrictions for probabilistic evaluations, as well as to further increase the Heq limits.
- It is CNSC staff's view that LC 15.3 is no longer applicable and requires an amendment. CNSC staff will make a recommendation to the Commission based on licensees' amendment requests once they are submitted.

Regarding the RIDM assessment results related to the IRJ-BM finding, CNSC staff concluded that:

- At this time, CNSC staff cannot confirm that whether the efficacy of Levels 1 or 2 DiD for Darlington and Bruce reactors in extended operation (i.e., beyond 210,000 EFPH).
- Level 3 DiD is not affected by the type of pressure tube failure (PTF) that could potentially result from reduced fracture toughness. In other words, special safety systems will perform their intended functions to ensure that prescribed dose limits will not be exceeded in the event of a single PTF.
- The risk due to the issue of elevated Heq at the inlet rolled joint of pressure tubes is negligible for up to 2-3 years of continued operation (depending on the station); no immediate action is required.
- To address the risk:
    - In the longer term, the actions undertaken by the licensees are consistent with CNSC staff's Recommendations #1 (Heq R&D plan) and #2 (material surveillance activities). The licensees have submitted a schedule for address the recommendations.
    - In the short term, the industry is ensuring there are adequate procedures, surveillance programs, as well as training in place to monitor the dominant contributors' failure probabilities to PTF and PTL event sequences leading to core damage.
- Further assessment is needed to determine if additional compensatory measures are required for the short term.

REFERENCES

[1] CMD 21-M39, “Event Initial Report – Bruce A Unit 3 and Bruce B Unit 6 Hydrogen Equivalent Concentration in Pressure Tube Licence Limit Exceedance”, September 29, 2021, eDocs # 6608088.

[2] CMD 21-M37, “Presentation – Impact on NPPs of Bruce Units 3 and 6 Licence Limit Exceedance of Hydrogen Equivalent Concentration in Pressure Tubes”, September 3, 2021, eDocs # 6626961.

[3] CMD 22-M16, “Event Initial Report – Elevated Hydrogen equivalent concentration (Heq) in the inlet rolled joint of a Bruce pressure tube removed from service”, March 24, 2022, eDocs # 6754276.

[4] OPG Letter, M. Knutson to D. Saumure and A. Viktorov, “OPG Response to Request Pursuant to Subsection 12(2) of the General Nuclear Safety and Control Regulations: Follow Up Response to Item 5 Related to Hydrogen Concentration in Pressure Tubes”, February 8, 2022, eDocs # 6733825.

[5] Bruce Power Letter, M. Burton to D. Saumure and A. Viktorov, “Bruce A and B: Supplemental Information to Subsection 12(2) of the General Nuclear Safety and Control Regulations: Measurement of Hydrogen Equivalent Concentration in Pressure Tubes – Item 5”, January 31, 2022, eDocs # 6728960.

[6] OPG Letter, M. Knutson to A. Viktorov and D. Saumure, “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, eDocs # 6840208.

[7] Bruce Power Letter, M. Burton to A. Viktorov and D. Saumure, “Bruce A and B: Update to the Commission regarding Elevated Hydrogen Equivalent Concentrations – Action Item 2022-07-23135”, July 19, 2022, eDocs # 6844485.

[8] NB Power Letter, M. Power to A. Viktorov and D. Saumure, “Point Lepreau NGS: Request for an Update to the Commission on Activities Related to the Discover of Elevated Hydrogen Equivalent Concentration (Heq) – New Action Item 221204-23135”, July 20, 2022, eDocs # 6844356.

[9] CMD 21-M4, “Status Update: Condition of Pressure Tubes in Operating CANDU Reactors in Canada”, January 21, 2021, eDocs # 6459353.

[10] CNSC Letter, J. Burta and R. Richardson to M. Knutson, “Darlington and Pickering NGS – CNSC staff review of the Revision 2 Engineering Fracture Toughness Model for Pressure Tubes”, June 2, 2022, eDocs # 6795279.

[11] CNSC Letter, L. Sigouin to M. Burton, “Bruce A and B: CNSC Review of the Revision 2 Engineering Fracture Toughness Model for Pressure Tubes”, May 12, eDocs # 6795110.

[12] Bruce Power Letter, M. Burton to D. Saumure and L. Sigouin, “Notice of Intent to Seek Amendment of the Power Reactor Operating Licence, PROL 18.02/2028”, March 21, 2022, BP-CORR-00531-01841, e-Docs # 6760529.

[13] CNSC Internal Policy Document, “Policy on the use of a risk-informed approach for regulatory oversight of nuclear activities and facilities”, November 6, 2017, e-Docs # 5185215.

[14] CNSC Risk Assessment Report, “Risk Informed Considerations Related to Elevated Heq levels at the Inlet Rolled Joint Region of Pressure Tubes”, July 2022, eDocs # 6788784.

GLOSSARY

Abbreviations used in this CMD are listed below:

BM	burnish mark
BT	burst test
CANDU	Canadian Deuterium Uranium
CMD	Commission Member Document
CNSC	Canadian Nuclear Safety Commission
COG	CANDU Owner’s Group
COPT	cold overpressure transient
CSA	Canadian Standards Association
CVC	compliance verification criteria
DBA	design basis accident
DHC	delayed hydride cracking
DiD	defence in depth
DO	Designated officer
EFPH	equivalent full power hours
EIR	event initial report
GNSCR	*General Nuclear Safety and Control Regulations*
Heq	hydrogen equivalent concentration
HROL	hydrided region overload
HTS	heat transport system
IRJ-BM	inlet rolled joint burnish mark
K_{IH}	the threshold stress intensity for DHC initiation from a crack
LC	licence condition
LRF	large release frequency
NGS	nuclear generating station
NPP	nuclear power plant
OPG	Ontario Power Generation
ORJ-BM	outlet rolled joint burnish mark
p_c	the threshold stress for DHC from a smooth surface
ppm	parts per million by weight
PROL	Power Reactor Operating Licence
PSA	probabilistic safety assessment
PHTS	primary heat transport system
PTF	pressure tube failure
PTL	pressure tube leak
R&D	research and development
RAR	risk assessment report
RCM	risk control measure
RIDM	risk informed decision making
ROI	region of interest
RSL	risk significance level
SCDF	severe core damage frequency

A. APPENDIX - Technical background on elevated Heq

Appendix A provides a summary of the discovery issues related to pressure tubes with elevated Heq that have an impact on fitness for service evaluation; Appendix A.1 provides the technical background related to the outlet rolled joint while Appendix A.2 provides the technical background related to the inlet rolled joint.

For an overall summary of factors that can impact pressure tube fitness for service, please refer to CMD 21-M4 [A1].

Heq discovery event correspondence timeline

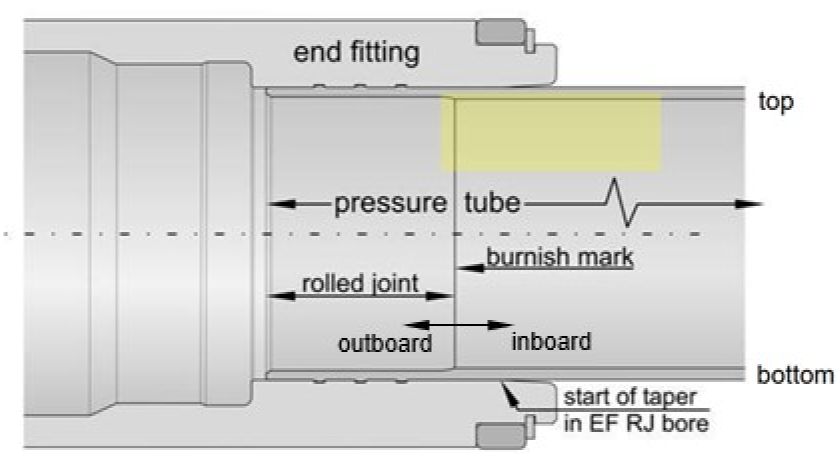
The following table provides a timeline of the correspondence associated with the pressure tube Heq discovery events:

Date	Description
21JAN2021	CNSC staff presentation (21-M4) on condition of pressure tubes in operating CANDU reactors in Canada. The presentation provided detailed description of factors that can impact pressure tube fitness for service
05JUL2021	REGDOC-3.1.1 report on U6 pressure tube with high Heq (outlet rolled joint)
08JUL2021	REGDOC-3.1.1 report on U3 pressure tube with high Heq (outlet rolled joint)
08/09JUL2021	CNSC sent letters requesting for licensees' additional information on the two REGDOC-3.1.1 reports
13JUL2021	GNSCR subsection 12(2) requests to all NPP licensees
26/27JUL2021	CNSC Designated Officer (DO) Orders to OPG and Bruce Power requiring the licensees to obtain authorization from Commission prior to restart of their units following any outage that result in cooldown of the heat transport system
30JUL2021	Licensees responded to GNSCR subsection 12(2) requests
03SEP2021	CNSC staff presentation (CMD 21-M37) on impact on NPPs of Bruce Unit 3 and 6 Licence Limit Exceedance of Hydrogen Equivalent Concentration in pressure tubes, which provided details related to CMD 21-M39
29SEP2021	CNSC staff Event Initial Report (CMD 21-M39) on measurements obtained from pressures tube in the outlet rolled joint with Heq above prediction and exceeding Licence Condition 15.3 limit of 120 ppm.
12OCT2021	Commission issued summary decision (via email) that Pickering Unit 5 has satisfied terms of DO order and that unit is no longer subject to DO order
10NOV2021	Commission Record of Decision DEC 21-H110 allowing Bruce Power to restart Unit 3 following its planned outage, concluding that Bruce Power has demonstrated that no service-induced flaws are present in the ROI, and that pressure tube fracture toughness is sufficient

12NOV2021	Commission issued summary decision (via email) that Bruce Units 4, 5, 7 and 8 have satisfied terms of DO order and those units are no longer subject to DO order
22DEC2021	Commission Record of Decision DEC 21-H112 allowing Pickering to restart Units 6-8 following any planned outages, and that terms of DO order have been satisfied (DO order closed)
04FEB2022	Commission Record of Decision DEC 21-H114 allowing Darlington to restart Units 1-4 following any planned outages, and that terms of DO order have been satisfied (DO order closed)
09MAR2022	Commission Record of Decision DEC 22-H100 allowing Bruce Power to restart Unit 3 following any planned outages, and that terms of DO order have been satisfied (DO order closed)
24MAR2022	CNSC staff Event Initial Report (CMD 21-M16) on measurements obtained from pressures tube in the inlet rolled joint from Bruce Unit 6 (previously discoveries were related to outlet rolled joint).

A.1 Elevated Heq at the outlet rolled joint

In early July 2021, Bruce Power made a discovery related to pressure tubes in Bruce Nuclear Generating Station (NGS) Units 3 and 6 [A2], [A3]. Namely, the measured Heq near the ORJ-BM of some pressure tubes exceeded the Bruce Power Reactor Operating Licence (PROL 18.02/2028) Condition 15.3 limit of 120 ppm. Bruce Power reported that material surveillance testing of pressure tube B6S13 had an Heq measurement of 211 ppm at the burnish mark (BM) and 212 ppm at the BM plus 10 mm inboard. The Heq value predicted by the model at the BM was 103 ppm. Similar elevated Heq values were later reported from in-service scrape measurements in Bruce Unit 3 pressure tubes. The approximate area of the pressure tube impacted by the measurements from the perspective of pressure tube fitness for service is illustrated in **Appendix Figure 1**.



Appendix Figure 1: pressure tube at end fitting (the yellow shaded region represents the region of where elevated Heq was measured, called "Region of Interest")

It is worth noting that the measurements from the Unit 6 pressure tube and the Unit 3 pressure tubes were obtained by different means. The Unit 6 tube was removed from the reactor at the start of the Unit 6 refurbishment outage and sent to a laboratory for testing. Detailed measurements could be obtained from this pressure tube at several axial and circumferential positions to bound the region of elevated Heq. 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. Due to pressure tube geometry and tool limitations fewer samples were obtained from these Unit 3 pressure tubes. More specifically, scrapes could not be obtained directly from or close to the burnish mark. Data from scrape samples obtained from both sides of the burnish mark were used to interpolate the Heq values at the burnish mark. According to traditional scraping procedures based on industry best practice, the first scrape location inboard of the burnish mark is about 60 to 70 mm away. Due to tooling improvements Bruce Power was able to obtain scrapes from some pressure tubes slightly closer to the burnish mark.

<u>Fitness for Service Evaluations</u>

For pressure tube fitness for service evaluations required in accordance with CSA standards, elevated Heq is only a concern in the tensile region that is between the inlet and outlet burnish marks on the opposite ends of the pressure tube. This is region of the tube where the stresses are tensile because of the primary heat transport system (PHTS) operating pressure.

Based on observations from past scraping campaigns, CNSC staff are unable to confirm if there are other pressure tubes that have Heq values in excess of 120 ppm because those campaigns have not acquired samples from the same locations that were sampled in the Bruce Unit 3 and Unit 6 tubes. As an interim measure, CNSC staff recommended that all pressure tubes in extended operation beyond 210,000 EFPH be treated as if regions of elevated Heq could exist near the ORJ-BM.

<u>CNSC request for information and Designated Officer Order</u>

In response to the discovery issues, CNSC staff requested that all Canadian NPP licensees evaluate the impact of the finding on their pressure tubes under *General Nuclear Safety and Control Regulations* (GNSCR) 12(2) [A4],[A5],[A6]. Upon review of the responses, CNSC staff concluded that the finding had the potential to impact all units in extended operation beyond 210,000 EFPH. While the phenomenon had not yet been observed in Darlington and Pickering pressure tubes, it could not be ruled out because:

- No tubes in the Darlington or Pickering reactors that were in operation as long as the Unit 6 tube had been subject to detailed Heq examination.
- The root cause could not be confirmed and there was no means of predicting which pressure tubes would be affected.

Subsequently, Designated Officer (DO) Orders were issued to Bruce Power and OPG [A7],[A8],[A9] requiring the licensees to seek Commission authorization to restart reactors following any outage that resulted in cooldown of the PHTS. Reactor start-up from an outage was considered the most likely scenario for a pressure tube rupture given the potential to pressurize a tube at a low enough temperature where the fracture toughness would be insufficient to resist failure if a crack-like flaw was present. These DO Orders led to a series of Commission Hearings to obtain the necessary restart authorizations for the following reactor units[11]:

Bruce:	Units 3, 4, 5, 7, 8
Pickering:	Units 1, 4, 5, 6, 7, 8
Darlington:	Units 1 and 4

The estimation of the fracture toughness used for pressure tube fitness for service evaluations was called into question for the region of pressure tubes in extended operation near the outlet burnish mark for the following reasons:

- Uncertainty associated with the model predictability for Heq uptake
- The high Heq measurements discovered at Bruce A U3 and Bruce B U6 exceed the validity range of the current fracture toughness model
- The absence of measurements in the same areas in the pressure tubes of units that operating beyond 210,000 EFPH.

The industry has proposed a "Region of Interest" for elevated Heq limited to the top 120º of the pressure tubes. However, CNSC staff recommended expanding the ROI to encompass the full circumference of the pressure tube until such time as industry was able to verify their assumptions related to the cause and evolution of the ROI with continued operation, and this recommendation was accepted by the Commission [A10]. For Pickering and Darlington pressure tubes, the axial extent of the ROI was defined as 60 mm inboard of the burnish mark and for Bruce Power the axial extent is 75 mm. The axial extents were established based on the typical location of the first inboard scrape measurements in the licensee's pressure tube periodic inspection programs. Industry has not yet provided new information that would change CNSC staff's current recommendation for the size of the region of interest.

[11] Note that Bruce NGS Units 1 and 2, Darlington NGS Unit 2 and Point Lepreau NGS were recently refurbished, which involved pressure tube replacement, so the pressure tubes in those reactors had not accumulated sufficient operating time to be affected by the phenomenon. Bruce Unit 6 and Darlington Unit 3 are currently in refurbishment outages and will have the pressure tubes replaced before return to service. Finally, Pickering Units 2 and 3 and Gentilly-2 are permanently shut down.

To achieve a recommendation to support restart from CNSC staff, industry was provided [A11],[A12],[A13] with two options that would satisfy the intent of LC 15.3 of the Bruce Power and Pickering operating licenses[12], which were referred to as Restart Criteria (a) and (b):

Restart Criteria Option (a)

1. Licensee shall demonstrate an understanding of the mechanism leading to high Hydrogen equivalent (Heq) concentration in the region of interest, and are able to conservatively model Heq concentration in this region.

or

Restart Criteria Option (b)

1. Sufficient inspection data shall be available for the reactor unit to justify, with a high degree of certainty, that no flaws are present in the region of interest greater than 0.15 mm in depth.
2. Corrective actions shall be implemented for tubes containing flaws greater than the specified depth.

Authorization for continued operation for all of the in-scope units was based on analyses demonstrating compliance with Restart Criteria Option (b), with the exception of Pickering Units 1 and 4. Upon further review, CNSC staff concluded that the pressure tubes in those two units had not accumulated sufficient operating time to be impacted by the phenomenon. The pressure tubes in these units had been replaced in the late 1990's and early 2000's and the current population of pressure tubes in those reactors will not exceed 210,000 EFPH prior to the planned permanent shutdown dates.

In addition to demonstrating that there was a low risk of flaws that would lead to crack initiation in the ROI, the licensees also committed to undergoing R&D to confirm the root cause of the elevated Heq and confirm that crack initiation models will continue to remain valid for elevated Heq in the ROI. The scrape campaigns to measure Heq in the ROI will introduce blunt flaws on the inner surface of pressure tubes. These Heq scrape flaws have benign geometries and are not expected to initiate cracking, but prior to these events crack initiation tests were never conducted in material with Heq in the range measured in the Bruce Unit 3 and Unit 6 pressure tubes because Heq models never predicted values as high as was observed in these tubes.

Industry is currently attributing the cause of the elevated Heq to a thermal gradient around the pressure tube circumference due to coolant bypassing the top of the fuel bundles at the outlet end of the pressure tubes. The pressure tubes increase in diameter as they age due to an irradiation induced creep mechanism. This increases the gap between the top of the fuel bundles and the top of the pressure tube is assumed to result in a lower

[12] While the Darlington licence does not contain LC 15.3, CNSC staff consistently applied the relevant compliance verification associated with this condition to the pressure tube fitness for service evaluations for the Darlington units.

temperature the top of the pressure tube compared to the bottom. Hydrogen isotopes will migrate to regions of lower temperature, which would result in an increase in the Heq at the top of the pressure tube.

Some preliminary modelling has been completed by industry to demonstrate the concept, but further work is required to confirm the theory and improve predictive models to support continued operation of pressure tubes.

CNSC staff's review conclusion

The industry was able to justify restart and continued operation of the units with pressure tubes in extended operation with potentially elevated Heq near the outlet rolled joint burnish mark. This is done by demonstrating that the likelihood of crack initiation was low in the defined ROI. Hence, Heq in excess of 120 ppm in this region of the pressure tubes would not impact fitness for service. These evaluations satisfy the intent of LC 15.3 in the Bruce Power and Pickering operating licences.

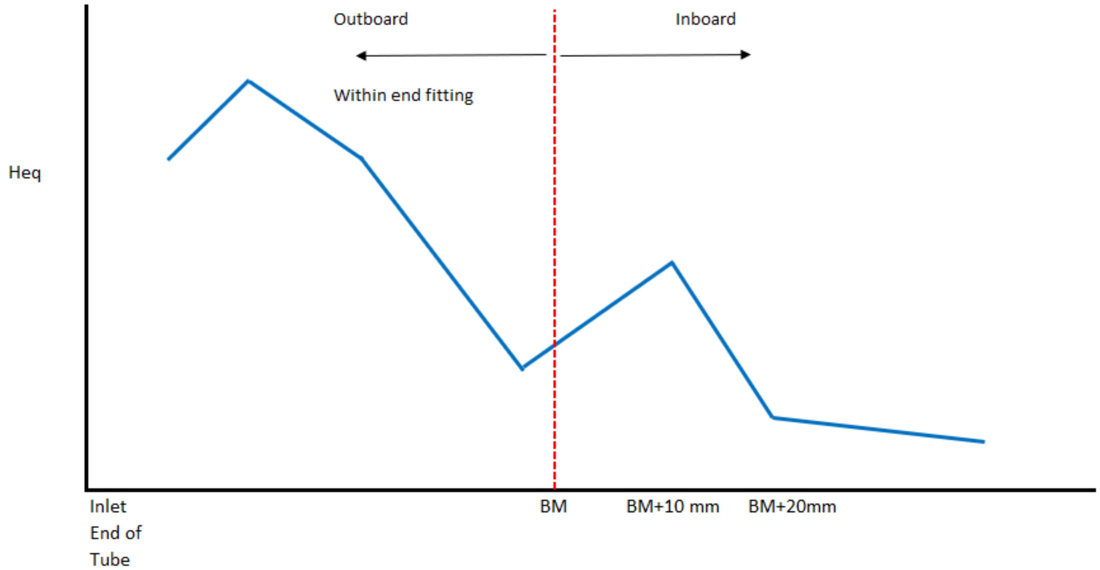
From a deterministic safety analysis perspective, CNSC staff concluded that the potential of elevated Heq concentration in the region of interest do not impact the currently assumed accident sequence, the key analysis parameters (sub-criticality margin and fuel temperatures), nor the ability of the Structures, Systems and Components (SSCs) from performing fundamental safety functions or the accident consequences (dose). Further, a simultaneous pressure tube and calandria tube rupture is explicitly analyzed as a DBA in the safety analysis for all NPPs. These safety analyses demonstrate that the plant is capable of performing the fundamental safety functions of control, cool and contain.

CNSC staff also concluded that the licensees demonstrated that the Heq concentration findings at NPPs do not impact the likelihood of a pressure tube failure or pressure tube leak and do not change the Probabilistic Safety Assessment (PSA) estimations. Therefore, the plant risk does not change and all the conclusions from the PSA remain valid.

A.2 Elevated Heq at the inlet rolled joint

In December 2021, after further testing on the same Bruce B Unit 6 B6S13 surveillance tube, Bruce Power discovered elevated Heq exceeding 120 ppm near the inlet rolled joint burnish mark near the 1 o'clock orientation, which was measured using punch samples [A14]. CNSC staff presented an EIR to inform the Commission of this new finding on March 23, 2022 under CMD 22-M16 [A15].

The region of elevated Heq in this case was more localized in axial extent than was observed near the outlet rolled joint burnish mark and is referred to as a "blip" because of the appearance of the Heq profiles. **Appendix Figure 2** provides a schematic diagram of a "blip" in the axial direction from the inlet end of a pressure tube.



Appendix Figure 2: Diagram of IRJ-BM Heq "blips" (Note: This diagram is not to scale)

In addition to the smaller observed extent of the region of the blip at the inlet end of the B6S13 pressure tube compared to the outlet end finding, there are other important factors that should be considered:

- The Heq measured from the punch sample was only marginally above the 120 ppm licensing limit.
- Flaws that have the potential for crack initiation can exist near the inlet rolled joint burnish mark in many reactors. For example, debris can become trapped between the pressure tube and the fuel bundle and causing fretting flaws with irregular geometries.
- Diametral expansion due to irradiation induced creep is not an issue at the inlet end of pressure tubes so the blips cannot be attributed to the same mechanism that was attributed to the outlet rolled joint burnish mark findings.

For pressure tubes that are installed in the front end inlet orientation, the actual Heq limit for the Revision 1 pressure tube fracture toughness model established by CSA N285.8 for tubes installed in this manner is 80 ppm. This limit was established in response to burst test findings that indicate front end material (material extruded first during tube manufacturing) may exhibit reduced fracture resistance compared to the remainder of the pressure tube. The current fracture toughness model in the CSA standard does not address front end effects for material with Heq above 80 ppm. This subject was discussed in CMD 21-M4 [A16].

Further examination of the B6S13 tube material containing the blip also revealed that there was a significant through thickness gradient of Heq. The punch sample provides the average value of Heq in the volume of the sample, but when the through thickness profile of Heq was evaluated it was determined that near the outer diameter (OD) surface of the tube the Heq reached a value of over 400 ppm, while at the inner diameter (ID) surface the Heq was below 50 ppm.

In 2020 and 2021, OPG reported blips at the inlet rolled joint of several ex-service pressure tubes, including D1U09 (reported in 2020), D2N15 (reported in 2021), D2O03 (reported in 2021), and D3S13 (reported in 2021). However, in these cases the punch sample Heq values were below the 120 ppm licensing limit and only slightly above the 80 ppm fitness for service limit of CSA N285.8 for two of these tubes. These findings were being investigated by industry and monitored by CNSC staff, noting that these results were nominally in-line with the end-of-life Heq estimates for the pressure tubes. All of these findings were on pressure tubes that had been removed from reactors during refurbishment outages. The findings led to industry expanding the punch measurement samples near rolled joint burnish marks in surveillance programs, which ultimately led to the Bruce Unit 6 outlet and inlet elevated Heq findings.

After the discovery of the through thickness gradient in the Bruce Unit 6 inlet rolled joint burnish mark blip region, OPG re-assessed the Darlington pressure tube data and confirmed the presence a through-thickness gradient in those tubes. For instance, the punch measurement Heq in the D1U09 tube was 89 ppm, but Heq near the OD surface was over 250 ppm and near the ID surface it was below 50 ppm [A17].

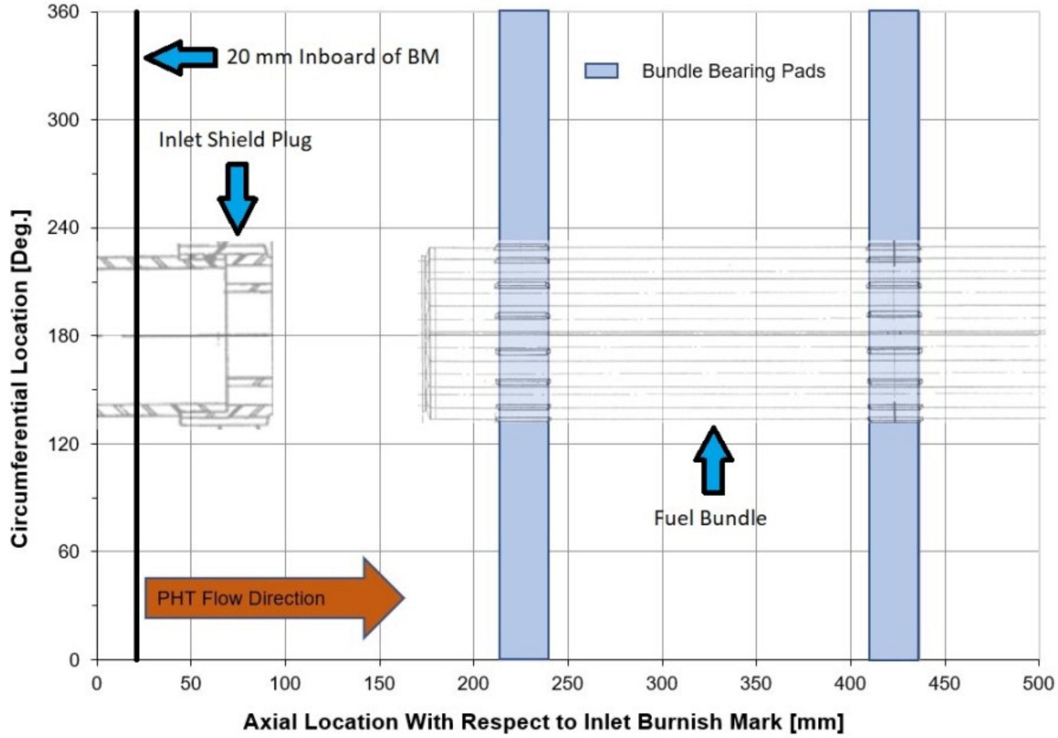
These observations led to the development of a different theory for the formation of inlet rolled joint blips compared to the outlet rolled joint elevated Heq. The weight of the pressure tube will cause the tube to sag between the end fitting and the first spacer. As the pressure tubes elongate in service due to the irradiation induced creep, the amount of bending increases leading a small region of localized contact with the tapered section of the end fitting (see Figure 1), which creates a local cold spot that can attract hydrogen in the tube material.

Due to the through thickness gradient, it is not possible to identify affected tubes from in-service scrapes, which are obtained from the ID surface of the pressure tubes where the Heq values are lower.

In response to the finding, Bruce Power and OPG submitted evaluations of pressure tube fitness for service considering the presence of flaws near the IRJ-BM. CNSC staff's findings regarding these submissions is summarized in the following paragraphs.

<u>CNSC staff's review of findings</u>

For the Pickering reactors, there are no driving mechanisms for the formation of flaws that are at risk for crack initiation since the fuel bundles do not reside at the inlet rolled joint burnish mark during operation and the shield plug extends almost 100 mm past the burnish mark as illustrated in **Appendix Figure 3**. Therefore, for the Pickering pressure tubes in extended operation, fitness for service can be demonstrated in a manner that is consistent with Restart Criteria Option (b) that was used for the outlet rolled joint elevated Heq issue.



Appendix Figure 3: Inlet end fuel bundle and shield plug configuration in Pickering reactors

For the Bruce and Darlington reactors, fuel bundles reside in the inlet rolled joint burnish mark region during operation and flaws have been detected at this axial location. The licensees indicated that the majority of the flaws at the inlet end of pressure tubes are located in the bottom half of the pressure tube, while the blips have been observed in the top half suggesting that it is unlikely that a flaw would be coincident with an Heq blip.

However, CNSC staff do not fully accept the industry assertion that the ROI for blip formation is restricted to the top half at this time because the cause of the blip has not been confirmed. In addition, a blip has been observed at the 3 o'clock orientation of one Darlington pressure tube and flaws have also been detected at that orientation in some pressure tubes. While the maximum blip Heq was observed at a single clock position, the Heq is higher over clock positions on either side of the clock position with the maximum value, compared to measurements taken and diametrically opposite orientations. A comparison of results amongst the Darlington and Bruce surveillance tubes completed by CNSC staff suggested there was a trend between the circumferential extent of the region of elevated Heq and the operating life at the time the tube was removed from service. Hence, there is evidence that the region of higher Heq increases circumferentially with time, but the maximum possible extent is not known at this time.

Fitness for Service Assessments

The licensees also provided submissions containing flaw assessments and fracture protection evaluations suggesting that the blips would not impact pressure tube fitness for service. However, these evaluations relied on assumptions related to hydrogen diffusion, crack initiation behaviour and fracture toughness that were not yet fully verified at the time of the submissions in the Spring of 2022. Hence, CNSC staff could not conclude that fitness for service compliance verification criteria were met for pressure tubes subject to the inlet rolled joint Heq blips. For instance, it was assumed that current crack initiation and fracture toughness models could be applied for the Heq values observed in the measurements even though the models were not developed for material with through thickness Heq gradients and not validated for the peak Heq values observed near the OD surface. Furthermore, it was assumed that the blip will not affect redistribution of hydrogen at the flaw. While hydrogen will diffuse to regions of lower temperature, it will also diffuse to regions of higher stress. The most recent developments related to these issues are discussed in the update provided in Section 2 of this CMD.

CNSC staff's conclusion

CNSC staff have concluded that the analysis of fitness for service of the pressure tubes subject to the inlet rolled joint Heq blips could not be adequately assessed and that a risk informed assessment would be required to determine whether the incremental risk from continued operation of these units would be acceptably low. A CNSC team was set up to apply the CNSC RIDM Process to provide recommendations to CNSC management, from a risk perspective, to identify and assess any significant risks which may be impacted by the discovery of elevated Heq near the IRJ-BM and continued operation of Canadian NPP reactors with pressure tubes affected by the discovery. Details regarding the RAR [A18], which includes CNSC staff's conclusions from their risk assessment of elevated Heq at the inlet end of pressure tubes at reactors in extended operation at Bruce and Darlington, is discussed in Section 3.4 of this CMD.

APPENDIX A REFERENCES

[A1] CMD 21-M4, "Status Update: Condition of Pressure Tubes in Operating CANDU Reactors in Canada", January 21, 2021, eDocs # 6459353.

[A2] REGDOC-3.1.1 Report B-2021-93819 DR, "A2131 Outage Scrape Campaign Hydrogen Equivalent Concentration Measurements", June 15, 2021, eDocs # 6597908.

[A3] REGDOC-3.1.1 Report B-2021-98077 DR, "Pressure Tube Surveillance Hydrogen Equivalent Concentration Measurements on Unit Shutdown for Major Component Replacement", June 30, 2021, eDocs # 6601668.

[A4] CNSC Letter, A. Viktorov to S. Gregoris and J. Franke, "Darlington and Pickering NGS: Request pursuant to Subsection 12(2) of the General Nuclear Safety and Control Regulations: Issues Relating to Measurement of Hydrogen Concentration in Pressure Tubes", July 13, 2021, eDocs # 6603931.

[A5] CNSC Letter, A. Viktorov to M. Power, "PLNGS: Request pursuant to Subsection 12(2) of the General Nuclear Safety and Control Regulations: Issues Relating to Measurement of Hydrogen Equivalent Concentration in Pressure Tubes", July 13, 2021, eDocs # 6604246.

[A6] CNSC Letter, A. Viktorov to M. Burton, "Bruce A and B: Request pursuant to Subsection 12(2) of the General Nuclear Safety and Control Regulations: Issues Relating to Measurement of Hydrogen Equivalent Concentration in Pressure Tubes", July 13, 2021, eDocs # 6603948.

[A7] CNSC DO order to Bruce Power, July 26, 2021, eDocs # 6612405.

[A8] CNSC DO order to OPG Pickering, July 26, 2021, eDocs # 6612567.

[A9] CNSC DO order to OPG Darlington, July 26, 2021, eDocs # 6612592.

[A10] CNSC Commission Record of Decision DEC 21-H111, "Request for Authorization to Restart Pickering Nuclear Generating Station B Unit 5 follow a forced outage", December 6, 2021, eDocs # 6695848.

[A11] CNSC Letter, L. Sigouin to M. Burton, "Bruce A and B: CNSC Staff Assessment Criteria for Restart Requirements, August 12, 2021, eDocs 6621711.

[A12] CNSC Letter, A. Viktorov to J. Franke, "Pickering NGS - CNSC Staff Assessment Criteria for Restart Requirements", August 12, 2021, eDocs 6621914.

[A13] CNSC Letter, A. Viktorov to S. Gregoris, "Darlington NGS, Units 1 and 4 - CNSC Staff Assessment Criteria for Restart Requirements", August 12, 2021, eDocs # 6621921.

[A14] REGDOC-3.1.1 Report B-2021-135624, "Industry Pressure Tube (PT) Surveillance Program – Inlet, Hydrogen Equivalent Concentration Measurements on PT from Unit Shutdown for Major Component Replacement", November 19, 2021, eDocs # 6699742.

[A15] CMD 22-M16, "Event Initial Report – Elevated Hydrogen equivalent concentration (Heq) in the inlet rolled joint of a Bruce pressure tube removed from service", March 24, 2022, eDocs # 6754276.

[A16] CMD 21-M4, "Status Update: Condition of Pressure Tubes in Operating CANDU Reactors in Canada", January 21, 2021, eDocs # 6459353.

[A17] OPG Letter, S. Gregoris to J. Burta, "Darlington NGS – Resubmission of Unit 1 Pressure Tube D1U09 Material Surveillance Hydrogen Equivalent Measurement Results and Submission of the Research & Development Finding", April 29, 2021, eDocs # 6288748.

[A18] CNSC Risk Assessment Report, "Risk Informed Considerations Related to Elevated Heq levels at the Inlet Rolled Joint Region of Pressure Tubes", July 2022, eDocs # 6788784.