Canadian Nuclear Safety Commission | Commission canadienne de sûreté nucléaire

CMD 26-M10.B

Date: 2026-03-09

Supplementary Information

Renseignements supplémentaires

Written Submission from CNSC Staff

Mémoire du personnel de la CCSN

In the matter of the

À l'égard de l'

Status of licensee research and development commitments on elevated hydrogen equivalent concentration in pressure tubes

État des engagements en matière de recherche et développement de titulaires de permis sur les concentrations élevées d'hydrogène équivalent dans les tubes de force

Commission Meeting

Réunion de la Commission

March 2026

Mars 2026

Document ID: QQQVZZNDK725-166150894-10796 (PDF)

Canada

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MEMORANDUM/MÉMORANDUM

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Fully releasable ATIP/ AIPRP entièrement communiquable :
Yes / oui

To / A — Candace Salmon
Commission Registry/ Greffe de la Commission

2026-03-09

From / De — X

Dr. Alexandre Viktorov
Director General, Directorate of Power Reacto...
Signed by: Viktorov, Alexandre

Subject / Sujet — CNSC Staff Clarifications Concerning CMD 26-M10.3
Clarifications du personnel de la CCSN concernant CMD 26-M10.3

This memorandum provides responses from CNSC staff following the submission of CMD 26-M10.3 by an intervenor. The submission posed a number of detailed comments and questions regarding the status of the research and development on elevated Heq in operating pressure tubes (see Attachment A). CNSC staff will be present at the Commission meeting to respond to any follow-up questions.

CNSC staff appreciate the input from the intervenor. Having considered the intervention, staff have concluded that the information presented in the submission has already been considered and that the topics raised do not impact the conclusions and recommendations documented in CMD 26-M10.

Ce mémorandum présente les réponses du personnel de la CCSN à la suite du dépôt du CMD 26-M10.3 par un intervenant. La soumission comportait un certain nombre de commentaires et de questions détaillés concernant l'état des activités de recherche et développement sur l'Heq élevé dans les tubes de force en exploitation (voir la pièce jointe A). Le personnel de la CCSN sera présent à la réunion de la Commission pour répondre à toute question de suivi.

Le personnel de la CCSN apprécie la contribution de l'intervenant. À la suite de l'examen de l'intervention, le personnel a conclu que l'information présentée dans la soumission avait déjà été prise en considération et que les sujets soulevés n'ont aucune incidence sur les conclusions et recommandations consignées dans le CMD 26-M10.

Acknowledgement of concurrence with Director General:
Accusé de conformité avec le directeur général :

I approve/ approuvé

2026-03-09

X

Ramzi Jammal
Executive Vice-President and CROO
Signed by: Jammal, Ramzi

I do not approve/ non approuvé

X

Ramzi Jammal
Executive Vice-President and CROO

Attachment A: CNSC staff clarifications to intervenor comments from CMD 26-M10.3
Pièce jointe A : Précisions du personnel de la CCSN concernant les commentaires de l'intervenant sur le CMD 26-M10.3

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

Attachment A – CNSC staff clarifications to intervenor comments from CMD 26-M10.3
Pièce jointe A - Précisions du personnel de la CCSN concernant les commentaires de l'intervenant sur le CMD 26 M10.3

Please note that in CNSC staff clarifications "hydrogen" is used to refer to both the protium, H, isotope and deuterium, D, isotope in combination.
Il convient de noter que, dans les précisions du personnel de la CCSN, le terme « hydrogène » est utilisé pour désigner à la fois l'isotope protium (H) et l'isotope deutérium (D).

Intervenor Comments from CMD 26-M10.3 Commentaires par un intervenant dans CMD 26-M10.3	CNSC Staff Clarifications	Précisions du personnel de la CCSN
On February 1st, 2023, under control document Ref. 2023-H-103, we have the following announcement by the CNSC: *The CNSC is to conduct a Hearing in Writing on application from Bruce Power Inc. to amend the power reactor operating licence for Bruce Nuclear Generating Stations A and B to reflect recent Commission decisions. The CNSC will conduct a hearing based on written submissions to consider an application from Bruce Power Inc. (Bruce Power) to amend the power reactor operating licence for the Bruce Nuclear Generating Stations (NGS) A and B.* *The proposed amendment is as follows: to remove licence condition 15.3, Pressure Tube Fracture Toughness, and to include all fitness-for-service requirements applicable to pressure tubes under licence condition 6.1, Fitness for Service.* The events leading up to this Hearing in Writing are as follows. On July 5, 2021, Bruce Power reported that measurements obtained from a Unit 6 pressure tube after 271,729 hot hours of operation showed Hydrogen Equivalent Concentrations ($[H_{eq}]$) above the generic predictions and exceeding the Licence Condition 15.3 $[H_{eq}]$ limit of 120 parts per million (ppm – by weight). Bruce Power reported that pressure tube B6S13 has a $[H_{eq}]$ of 211 ppm at the burnish mark and 212 ppm at the burnish mark plus 10 mm. Also, on July 8, 2021, Bruce Power reported that measurements obtained from a Unit 3 pressure tube showed $[H_{eq}]$ above the generic predictions and above the Licence Condition 15.3 $[H_{eq}]$ limit of 120 ppm.	CSA N285.4 establishes acceptance standards* or "unconditionally acceptable conditions" for the operation of pressure boundary components, including pressure tubes, inspected in accordance with the requirements of the standard. If these acceptance standards cannot be satisfied, a licensee is required to complete detailed fitness for service evaluations to demonstrate that the components are safe for continued operation. The process for addressing inspection findings is described in Appendix A of more recent editions of CSA N285.4. The objective of a fitness for service evaluation is to demonstrate that aged components can continue to meet the requirements identified in the design specification. Different approaches can be adopted to meet this objective. CSA N285.8 contains fitness for service guidelines that can be applied when the acceptance standards in N285.4 are not met. Generally, all licensees follow the standardized approaches in N285.8, but they are permitted to adopt alternate approaches that are acceptable to CNSC staff should the need arise.	La norme CSA N285.4 établit les normes d'acceptation* ou « conditions inconditionnellement acceptables » pour l'exploitation des composants de l'enveloppe sous pression, y compris les tubes de force, inspectés conformément aux exigences de la norme. S'il est impossible de satisfaire à ces normes d'acceptation, le titulaire de permis doit effectuer des évaluations détaillées de l'aptitude fonctionnelle afin de démontrer que l'exploitation prolongée des composants est sécuritaire. Le processus de gestion des constatations d'inspection est décrit à l'annexe A des versions plus récentes de la norme CSA N285.4. L'évaluation de l'aptitude fonctionnelle vise à démontrer que les composants vieillissants peuvent continuer à satisfaire aux exigences énoncées dans les spécifications nominales. À cette fin, différentes approches peuvent être adoptées. La norme CSA N285.8 énonce des lignes directrices sur l'aptitude fonctionnelle qui peuvent être appliquées lorsqu'il n'est pas possible de satisfaire aux normes d'acceptation de la norme N285.4. En général, tous les titulaires de permis suivent les approches normalisées énoncées dans la norme N285.8, mais ils sont autorisés à adopter des approches alternatives jugées acceptables par le personnel de la CCSN, le cas échéant.

Intervenor Comments from CMD 26-M10.3 Commentaires par un intervenant dans CMD 26-M10.3	CNSC Staff Clarifications	Précisions du personnel de la CCSN
For the Unit 3 pressure tube B3F16, Bruce Power indicated a preliminary measurement of 131 ppm [H_{eq}]. Additionally, on March 24th 2022, Bruce Power issued the Event Initial Report CMD 22-M16 stating: *Following the July 2021 discovery of elevated Heq near the outlet rolled joint, Bruce Power performed additional surveillance testing on the removed PT B6S13 and discovered that elevated Heq also exists near the inlet end of the PT. The reported Heq level from a through-wall punch sample was 126 ppm at approximately 10 mm in board of the burnish mark.* *Bruce Power does not have a mechanistic understanding of the phenomenon nor validated models as a result of this finding. In other words, their Heq model is invalid because the outputs of the Heq models do not align with the B6S13 measurement of 126 ppm at the inlet end of the PT. These Heq outputs are used as inputs into Fitness for Service Assessments such as leak-before-break (LBB) and fracture protection (FP) assessments. The uncertainty of the Heq inputs impact the LBB and FP assessments. CNSC staff are of the opinion that Bruce Power cannot confidently perform these assessments until the Heq phenomenon is understood and modelled.* The licence condition for Bruce A & B with respect to pressure tube fitness for service has always been based on two CSA Standards as follows:	Licence Condition 15.3 was implemented to establish conditions that needed to be met to increase the validity limits of the fracture toughness model. When the licences were amended to remove Licence Condition 15.3, industry had already obtained CNSC staff acceptance to increase the validity limits of the model up to 140 ppm. Given that some pressure tubes exceeded the earlier limits and acceptance of new limits, licence Condition 15.3 no longer served a useful purpose. New Licence condition 6.2 was added by the Commission to establish alternate compliance verification criteria for pressure tubes in extended operation with uncertain Heq levels near the burnish marks for the planned duration of the research and development program. LC 6.2 remains in the licences until the Commission amends a licence to remove it. * Note that in more recent editions of CSA N285.4 the term "acceptance criteria" has been replaced with "acceptance standards" to better differentiate between the screening criteria provided in that standard and the fitness for service criteria that ultimately determine the acceptability of the component.	La condition de permis 15.3 visait à établir les conditions à respecter afin d'élargir les limites de validité du modèle de ténacité à la rupture. Lorsque les permis ont été modifiés pour supprimer la condition de permis 15.3, l'industrie avait déjà obtenu l'acceptation du personnel de la CCSN pour augmenter les limites de validité du modèle jusqu'à 140 ppm. Comme certains tubes de force dépassaient les anciennes limites et que de nouvelles limites avaient été acceptées la condition de permis 15.3 n'était plus pertinente. La nouvelle condition de permis 6.2 a été ajoutée par la Commission afin d'établir des critères de vérification de la conformité pour les tubes de force en exploitation prolongée dont les concentrations de Heq près des marques de brunissage demeuraient incratines pendant la durée prévue du programme de recherche et développement. La CP 6.2 demeure en vigueur dans les permis jusqu'à ce que la Commission les modifies pour la retirer. *Il convient de noter que, dans les versions plus récentes de la norme CSA N285.4, le terme « critères d'acceptation » a été remplacé par « normes d'acceptation » afin de mieux distinguer les critères de sélection établis dans cette norme des critères d'aptitude fonctionnelle qui, en définitive, déterminent l'acceptabilité du composant.
CSA Standard N285.4:	These acceptance standards* are for the body of the pressure tube, not the rolled joint regions (which include the burnish mark regions). These values are not	Ces normes d'acceptation* s'appliquent au corps du tube de force, et non aux zones des joints dudgeonnés (qui comprennent les marques de brunissage). Ces

Intervenor Comments from CMD 26-M10.3 Commentaires par un intervenant dans CMD 26-M10.3	CNSC Staff Clarifications	Précisions du personnel de la CCSN
(Intervenor provide a copy of Clause 12.3.5.2 from CSA Standard N285.4 which is protected by copyright and not reproduced here.)	safety limits. They are screening criteria that would trigger a fitness for service evaluation considering the impact of higher Heq pick-up rates on future operation. When the limits specified in CSA N285.4 are exceeded, the licensee must submit a disposition to the CNSC demonstrating that the pressure tubes remain safe to operate. The acceptance standards for the rolled joint regions are provided in Clause 12.3.5.2.2 of CSA N285.4, which establish unconditional acceptance if the Heq near the inlet burnish mark is below 70 ppm and near the outlet burnish mark is below 100 ppm. Findings that do not meet those acceptance standards must be dispositioned for continued operation in accordance with Clause 12.3.5.3 of CSA N285.4 to assess the impact on pressure tube fitness for service.	valeurs ne constituent pas des limites de sûreté. Il s'agit de critères de sélection qui déclencheraient une évaluation de l'aptitude fonctionnelle, en tenant compte de l'incidence des taux plus élevés d'absorption de Heq sur l'exploitation future. En cas de dépassement des limites précisées dans la norme CSA N285.4, le titulaire de permis doit démontrer à la CCSN que l'exploitation des tubes de force demeure sûre. Les normes d'acceptation visant les zones des joints dudgeonnés sont énoncées à la clause 12.3.5.2.2 de la norme CSA N285.4, laquelle stipule une acceptation inconditionnelle si la concentration de Heq est inférieure à 70 ppm près de la marque de brunissage au point d'entrée et inférieure à 100 ppm près de la marque de brunissage au point de sortie. Les constatations qui ne satisfont pas à ces normes d'acceptation doivent être gérées de sorte à permettre l'exploitation prolongée conformément à la clause 12.3.5.3 dans CSA N285.4, afin d'évaluer l'incidence sur l'aptitude fonctionnelle des tubes de force.
CSA Standard N285.8: (Intervenor provided a copy of Table 5 from CSA Standard N285.8 which is protected by copyright and not reproduced here.)	The acceptance criteria for CSA N285.8 were established prior to 2010, before the licensees initiated the fuel channel life management plan, to assess the impact of higher Heq levels on pressure tube fitness for service to support extended operation. The values provided in this table are based on solubility limits for hydrogen at normal full power operating temperatures. If Heq levels remain below these values in the bulk of the material all hydrogen present during normal operation will be dissolved and no solid	Les critères d'acceptation de la norme CSA N285.8 ont été établis avant 2010, soit avant que les titulaires de permis ne mettent en œuvre le plan de gestion de la durée de vie des canaux de combustible, afin d'évaluer, à l'appui de l'exploitation prolongée, l'incidence de concentrations supérieures de Heq sur l'aptitude fonctionnelle des tubes de force. Les valeurs fournies dans le tableau sont fondées sur les limites de solubilité de l'hydrogène à des températures normales d'exploitation à pleine

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	zirconium hydrides will be present unless flaws exist that cause sufficient stress localization to attract hydrogen. The effect of flaws on local hydrogen accumulation is considered in the flaw evaluation procedures in CSA N285.8. More recent work has demonstrated that pressure tubes are safe to operate with higher Heq and Heq limits for analytical models have been increased to higher values than listed in Table 5 of CSA N285.8. Except near the burnish marks, measured Heq levels continue to remain below the limits in Table 5 of CSA N285.8. If a licensee estimates that they will exceed the values in this table for the rolled joint regions, they assess the impact on pressure tube fitness for service and submit the disposition to CNSC staff. The CSA technical committee for CSA N285.8 intends to update the standard to remove Table 5 and align the upper limits of Heq with the validity limits of the analytical models in the standard.	puissance. Si les concentrations de Heq demeurent inférieures à ces valeurs dans la majeure partie du matériau, tout l'hydrogène présent durant l'exploitation normale sera dissous, et aucun hydrure de zirconium à l'état solide ne sera présent, à moins qu'il existe des défauts entraînant une localisation suffisante des contraintes pour attirer l'hydrogène. L'effet des défauts sur l'accumulation locale d'hydrogène est pris en compte dans les procédures d'évaluation des défauts établies dans la norme CSA N285.8. Des travaux plus récents ont permis de constater que les tubes de force peuvent être exploités en toute sûreté même lorsqu'ils présentent une concentration accrue de Heq. Par conséquent, les limites de concentration de Heq dans les modèles analytiques sont maintenant supérieures aux valeurs indiquées au tableau 5 de la norme CSA N285.8. Sauf près des marques de brunissage, les concentrations mesurées de Heq demeurent inférieures aux limites indiquées au tableau 5. Si, d'après ses estimations, un titulaire de permis est d'avis que le Heq dans la zone des joints dudgeonnés dépassera les valeurs indiquées dans ce tableau, il doit évaluer l'incidence sur l'aptitude fonctionnelle des tubes de force et soumettre les résultats au personnel de la CCSN. Le comité technique de la norme CSA N285.8 compte mettre à jour la norme de sorte à supprimer le tableau 5 et à aligner les limites supérieures de Heq sur

<table>
<tr><th>Intervenor Comments from CMD 26-M10.3
Commentaires par un intervenant dans CMD 26-M10.3</th><th>CNSC Staff Clarifications</th><th>Précisions du personnel de la CCSN</th></tr>
<tr><td></td><td></td><td>les limites de validité des modèles analytiques figurant dans la norme.</td></tr>
<tr><td>The three fuel channel temperatures listed in Clause 12.3.5.2 of CSA N285.4, shown above, – namely, 315 °C, 305 °C, and 295 °C – correspond to the conditions for Darlington, Bruce and Pickering NGS fuel channel outlets, respectively. Thus, we see that CSA N285.4 sets the maximum allowable rate of increase in H_{eq} per 10,000 hot hours, ($\Delta H_{eq}/10^4$ HH), to be 3 ppm, 2 ppm and 1 ppm, for Darlington, Bruce and Pickering respectively.</td><td>These acceptance standards are for the body of the pressure tubes, not the burnish mark locations.

In the body of the pressure tube, the change in Heq is primarily due to general corrosion due to contact with the coolant. It is possible to observe rates higher than these values, but Heq levels in the body of the pressure tubes consistently remain below the limits of the analytical models used to assess pressure tube fitness for service, even in extended operation. Hence there is no direct safety impact arising from exceeding these pickup rates. However, higher rates may indicate the need to enhance monitoring activities.</td><td>Les normes d'acceptation s'appliquent au corps du tube de force, et non aux emplacements des marques de brunissage.

Dans le corps du tube de force, la variation de la concentration de Heq s'explique principalement par la corrosion générale due au contact avec le caloporteur. Il est possible d'observer des taux supérieurs à ces valeurs, mais les concentrations de Heq dans le corps des tubes demeurent constamment inférieures aux limites des modèles analytiques servant à évaluer l'aptitude fonctionnelle des tubes de force, même durant l'exploitation prolongée. Par conséquent, le dépassement de ces taux d'absorption n'a aucune incidence directe sur la sûreté. Toutefois, des taux accrus pourraient indiquer le besoin de renforcer les activités de surveillance.</td></tr>
<tr><td>In order to investigate if Bruce Power is in non-compliance with the CSA N285.4 Standard, I have reviewed the available data for Heq in Bruce B pressure tubes since the start of their commercial operations in the mid-1980s. The results of this review, and in particular estimates of $\Delta Heq/10^4$ HH as a function of the hot hours of exposure of the pressure tubes, are summarized in Table 1, below.</td><td>There would only be a non-compliance with N285.4 if a licensee failed to submit a disposition to CNSC staff after determining the established rate specified in the standard was exceeded.</td><td>Un titulaire de permis contreviendrait à la norme N285.4 seulement si, après avoir constaté le dépassement du taux établi dans la norme, il omet de soumettre les résultats au personnel de la CCSN.</td></tr>
<tr><td>Table 1: Average $\Delta H_{eq}/10^4$ HH (in ppm) for Bruce Units 5 - 8
<table><tr><th>Bruce B Units 5 - 8
Average Hot Hours</th><th>$\Delta H_{eq}/10^4$ HH
(ppm)</th></tr><tr><td>50,000</td><td>0.4</td></tr></table></td><td>The rate of Heq uptake near the rolled joint burnish marks has generally been higher than the body of pressure tubes because of the impact of the end fittings which act as an additional source of hydrogen due to galvanic effects between the pressure tube and end fittings. Pressure tubes also have a higher affinity for</td><td>Le taux d'absorption de Heq près des marques de brunissage des joints dudgeonnés a généralement été plus élevé que celui du corps des tubes de force compte tenu de la présence des raccords d'extrémité, qui constituent une source supplémentaire d'hydrogène en raison des effets galvaniques entre le</td></tr>
</table>

<table>
<tr><th>Intervenor Comments from CMD 26-M10.3
Commentaires par un intervenant dans CMD 26-M10.3</th><th>CNSC Staff Clarifications</th><th>Précisions du personnel de la CCSN</th></tr>
<tr><td><table><tr><td>100,000</td><td>1.0</td></tr><tr><td>150,000</td><td>2.0</td></tr><tr><td>200,000</td><td>3.4</td></tr><tr><td>250,000</td><td>4.9</td></tr><tr><td>300,000</td><td>6.5 [1]</td></tr></table>
Ref 1 = Extrapolated Value

The data in Table 1 show two important trends:
(i) After approximately 150,000 hot hours of exposure the $\Delta H_{eq}/10^4$ HH values are consistently above the Bruce B limit of 2 ppm per 10,000 hot hours
(ii) The rate of hydrogen pick up steadily increases as the hot hours of exposure increase</td><td>hydrogen than the stainless steel end fittings so hydrogen present in the end fittings can be transferred to the pressure tubes through direct contact.</td><td>tube de force et les raccords d’extrémité. Les tubes de force sont également plus susceptibles à l’hydrogène que les raccords d’extrémité en acier inoxydable, de sorte que l’hydrogène présent dans les raccords d’extrémité peut être transféré aux tubes par contact direct.</td></tr>
<tr><td>CSA Standard N285.8 was revised in 2019 to an Heq of 80 ppm at a pressure tube’s inlet and 120 ppm Heq at its outlet. Nevertheless, it is clear that the July 2021 high Heq concentrations measured at the inlet, (126 ppm), and the outlet, (212 ppm), of the B6S13 pressure tube place Bruce Power in violation of the requirements of the revised CSA Standard N285.8.</td><td>These limits were based on the validity limits of the fracture toughness model. To be clear, the 80 ppm limit applies to material within 1.5 m of the end of a pressure tube that is extruded first during the fabrication process, or the front end of a tube, not the inlet end of the tube with respect to coolant flow. The 120 ppm limit applies to the remainder of the pressure tube.

More recently, CNSC staff has accepted use of the Revision 2 fracture toughness model, which increases these limits to 100 ppm for front end material and to 140 ppm for the remainder of the pressure tube, based on additional material testing with higher Heq levels (CMD 22-M37).</td><td>Les limites étaient fondées sur les limites de validité du modèle de ténacité à la rupture. Il convient de préciser que la limite de 80 ppm s’applique aux matériaux se trouvant à moins de 1,5 m de l’extrémité du tube de force qui est extrudée en premier durant le processus de fabrication, appelée « extrémité avant », à ne pas confondre avec l’extrémité d’entrée, par laquelle le caloporteur pénètre dans le tube. La limite de 120 ppm s’applique au reste du tube de force.

Plus récemment, le personnel de la CCSN a accepté l’utilisation de la révision 2 du modèle de ténacité à la rupture, dans lequel les limites ont été augmentées à 100 ppm pour les matériaux d’extrémité avant et à 140 ppm pour le reste du tube de force, d’après des essais</td></tr>
</table>

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	These limits may be changed as further refinements of the fracture toughness model are made to incorporate information from ongoing material testing. Changes to the model limits are subject to CNSC staff review and acceptance prior to application in fitness for service evaluations. Bruce Power was forthcoming with the findings of Heq exceeding the limits of the fracture toughness model in 2021 through the issuance of event reports, which were assessed by CNSC staff and discussed at Commission proceedings.	des matériaux supplémentaires effectués en fonction de concentrations de Heq supérieures (CMD 22-M37). Ces limites pourraient augmenter davantage à mesure que d'autres améliorations sont apportées au modèle de ténacité à la rupture pour intégrer l'information provenant des essais des matériaux en cours. Les modifications aux limites du modèle doivent être examinées et acceptées par le personnel de la CCSN avant leur application aux évaluations de l'aptitude fonctionnelle. En 2021, Bruce Power a divulgué activement la découverte de concentrations de Heq supérieures aux limites du modèle de ténacité à la rupture par le biais de rapports d'événement, lesquels ont été évalués par le personnel de la CCSN et ont fait l'objet de discussions lors des séances de la Commission.
Thus, we see that Bruce Power is in non-compliance with regard to both the CSA N285.4 and the CSA N285.8 Standards. However, as noted above, the fact that the *rate* of hydrogen pickup is not only well *above* the 2 ppm per 10,000 hot hours licence limit, but is steadily *increasing*, is worrisome and needs to be explained. An important clue as to *why* $\Delta H_{eq}/10^4$ HH is increasing may be found in data on the oxidation kinetics of Bruce pressure tubes derived from a C-13 oxide dating technique I developed in the 1990s. This technique is based on SIMS (Secondary Ion Mass Spectrometry) depth-profiling, as described in the following references: 1. *The Detection and Interpretation of Carbon-13 Isotope Effects in the Oxide Scales of Irradiated Zr-2.5 wt% Nb Pressure Tubes.* OHRD Report 91-93-P, (June 1991).	The variability and potential increase in hydrogen pick-up is the primary reason why licensees are required to periodically obtain Heq measurements from in-service and ex-service pressure tubes and evaluate the potential impact of the findings on pressure tube fitness for service. Well before the findings of elevated Heq in 2021, Bruce Power had been performing more Heq measurements from in-service pressure tubes than required by CSA N285.4 to evaluate the rate of hydrogen pick-up.	La variabilité et l'augmentation potentielle de l'absorption d'hydrogène constituent la principale raison pour laquelle les titulaires de permis sont tenus de mesurer périodiquement la concentration de Heq des tubes de force en service et retirés du service ainsi que d'évaluer l'incidence possible des constatations sur l'aptitude fonctionnelle des tubes. Bien avant la découverte de concentrations élevées de Heq en 2021, Bruce Power effectuait davantage de mesures de la concentration de Heq des tubes de force en service que ce qu'exige la norme CSA N285.4 afin d'évaluer le taux d'absorption d'hydrogène.

Intervenor Comments from CMD 26-M10.3 Commentaires par un intervenant dans CMD 26-M10.3	CNSC Staff Clarifications	Précisions du personnel de la CCSN
2. *Post Irradiation Investigations of Corrosion and Deuterium Pickup by Zr-2.5 wt% Nb Alloy Pressure Tubes: Isotope Tracers in Inside Oxides.* OHT Report A-NFC-96-200-P, (December 1996). The formation of radiogenic C-13 by the O-16(n,α)C-13 nuclear reaction allows a pressure tube's oxidation rate to be determined. C-13 SIMS data are available for a number of Bruce A and Bruce B pressure tubes, as in the examples shown in Figures 1a and 1b, below: **Figure 1a: Pressure Tube B3U11** (Uncredited figure included) **Figure 1b: Pressure Tube B6G12** (Uncredited figure included) The C-13 plots in Figures 1a and 1b exhibit the following features for the B3U11 and the B6G12 pressure tubes: (i) The B3U11 tube's ID oxide is 20 µm thick, compared to only a 7 µm thick oxide for the B6G12 tube (ii) An approximate doubling of the pressure tubes oxidation rate is observed after about 13 µm of growth for the B3U11 tube, compared to a similar doubling for the B6G12 tube, but after only about 5 µm of growth These observations show that there is a great deal of variability in the oxidation rate of the inside surfaces of Bruce pressure tubes. However, these data also show that there is a tendency for the oxidation rate to increase at higher hot hours of exposure, and this occurs *regardless of the initial rate of oxide growth*. This acceleration in the rate of oxidation of pressure tubes is very significant because it has implications for the associated rate of H/D pickup by these tubes. This is because zirconium		

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alloy pressure tubes pick up deuterium during zirconium corrosion in D_2O through the following two-step processes: $Zr + 2D_2O = ZrO_2 + 2D_2$ …………………………(1) $Zr + x/2\ D_2 = ZrD_x$ …………………………..(2) It may be shown that the deuterium concentration for 100 % pickup by formation of 1 µm oxide is 14.3 ppm. However, measurements of pressure tube oxide thicknesses together with the associated deuterium concentrations generally show pickups in the range 5 - 15 % of the theoretical maximum.		
A predictive model, referred to as the *Design Equation*, for corrosion and deuterium ingress by Zr-2.5Nb pressure tubes, was first developed by AECL in the late 1990s – see for example the 1996 COG Report No. COG-95-596/RC-1551. Specifically for Bruce tubes, the *Design Equation* predicts accelerating oxidation kinetics and accelerating deuterium pick up for exposures of more than about 150,000 hot hours. Hence, it is important to note that the acceleration of H/D pickup by aging pressure tubes was predicted by the Canadian nuclear industry more than 25 years ago. And, the fact that accelerated corrosion and H/D pickup have been a constant feature of CANDU pressure tube aging is confirmed in an article published by Chalk River Nuclear Laboratories – See CNL Nuclear Review Vol 5 (1), June 2016: *Along the main body of a pressure tube the deuterium concentration increases and peaks near the outlet end. Approximately 2% - 10% of the deuterium generated by the corrosion process is absorbed. In general, the deuterium concentration in the main body of the pressure tube increases with time. At the 1.5 m axial location the increase is approximately linear with time, whereas at the 4 m and 5 m axial locations the uptake rate is increasing with time.*	CNSC staff acknowledged during the September 3rd, 2021, Commission proceedings that there was insufficient evidence at the time to confirm the validity of the statement made by industry. That was a key consideration when CNSC staff recommended to the Commission that industry should undertake a research and development program to confirm industry's hypothesis.	Lors des séances de la Commission en 2021, le personnel de la CCSN a reconnu qu'il n'y avait pas à ce moment suffisamment de données probantes pour confirmer la validité de la déclaration faite par l'industrie. Ce manque de preuves a constitué un facteur clé de la recommandation du personnel de la CCSN à l'intention de la Commission consistant à demander à l'industrie de mettre en œuvre un programme de recherche et développement visant à confirmer son hypothèse.

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My emphasis in red Nevertheless, it is of interest to see if this view of H/D pickup is currently also held by Bruce Power, especially in light of the discovery of very high Heq in some of its pressure tubes. In the months following the July 2021 reporting of high Heq concentrations in two Bruce pressure tubes, there have been several CNSC Meetings/Hearings to discuss these findings. At the Public Meeting held on September 3rd 2021, Bruce Power was asked by CNSC Commissioner Lacroix for its interpretation of the high [Heq] observed in some of its operating pressure tubes, to which Bruce Power replied: *"We're not seeing a change in the rate of hydrogen uptake. What we're seeing is a redistribution (of the hydrogen) to the cooler region at the top of the pressure tube. So, it's not an acceleration but a redistribution"*.		
Based on the data presented in the first part of this intervention, the fact that Bruce Power still believes the high Heq data reported for some of its pressure tube is *not* due to accelerated pickup, but is due to a *redistribution* of ingressed deuterium, is fraught with difficulties. And, it is important to note that Bruce Power provides no evidence or proof for its belief that there is no acceleration in H/D pickup by its pressure tubes. It is simply stated as a fact, when it is nothing more than a plausible hypothesis – *and a plausible hypothesis is not necessarily true*.	Work completed under the research and development program has demonstrated that the redistribution of hydrogen can generate results consistent with the measurements observed in the Bruce Power pressure tubes without the need for enhanced ingress. Detailed hydrogen measurements indicate significant circumferential variability in Heq levels that, when averaged over the full circumference, show total levels of hydrogen inventory consistent with ingress from the two established sources; corrosion from interaction with the coolant and from contact with the end fittings.	Les travaux réalisés dans le cadre du programme de recherche et développement ont démontré que la redistribution de l'hydrogène peut produire des résultats qui correspondent aux mesures observées dans les tubes de force de Bruce Power sans qu'une pénétration accrue d'hydrogène soit nécessaire. Les mesures détaillées de l'hydrogène montrent des concentrations de Heq très variables sur le plan circonférentiel. Ces concentrations, lorsqu'elles sont réparties sur toute la circonférence, aboutissent à un inventaire total d'hydrogène qui correspond avec une pénétration provenant des deux sources établies, soit la corrosion causée par l'interaction avec le caloporteur et par le contact avec les raccords d'extrémité.
However, there are plenty of other reasons, including real physical evidence, to accept as a well-established fact that accelerated H/D pickup	It has long been recognized that ΔHeq values near the burnish marks are higher than in the body of pressure tubes due to the interaction with the end fittings. This	On reconnaît depuis longtemps que les valeurs de ΔHeq près des marques de brunissage sont supérieures à celles dans le corps des tubes de force en raison de

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_is_ occurring in Bruce pressure tubes, and has been for some time. For example, please consider: (i) The data reported for ΔHeq previously shown in Table 1 of this intervention (ii) A major problem with Bruce Power's redistribution hypothesis may be seen by eliminating the effects of diffusion and calculating the actual amount of H/D entering the B6S13 pressure tube. Thus, using data from Table 2, found in OPG's September 3rd 2021 *Written Submission* to the CNSC, CMD 21-M37.2, we may calculate an *average* concentration of H/D at a distance *x* from a pressure tube's inlet using the H/D concentrations measured at the 6 and 12 o'clock locations as follows: $[C_{Av}(x)] = \{[C_6(x)] + [C_{12}(x)]\}/2$ Then, for B6S13, the average H/D concentration near its outlet burnish mark, $[C_{Av}(BM)]$, is equal to (211 + 59)/2 or 135 ppm, *which is significantly above the CSA N285.8 limit of 120 ppm*. From this result I conclude that the postulated redistribution of H/D is unable to explain how or why the _*average*_ circumferential [Heq] at the burnish mark of tube B6S13 is in excess of the CSA N285.8 limit.	was accounted for in pressure tube fitness for service evaluations. Using only the 12:00 and 6:00 measurements results in a significant overestimate of the average Heq. When more circumferential measurements are taken into account, the average value is lower than 135 ppm. The Heq measured over more than half of the pressure tube circumference is close to the 6:00 measurement and is only elevated for about 1/3 of the circumference. When Heq measurements from the four clock positions shown in the figure below for B6S13 are averaged, the Heq value is about 95 ppm or 40 ppm lower than the intervenor's estimate. The average value would be reduced further if additional intermediate measurements are included in the calculation. Hence the total inventory of hydrogen is lower than suggested by the intervenor's calculation. Source of plot below: Bruce Power CMD 21-M37.1	l'interaction avec les raccords d'extrémité, ce qui a été pris en compte dans l'évaluation de l'aptitude fonctionnelle des tubes de force. Le fait de n'utiliser que les mesures prises à des orientations de 12 et 6 heures entraîne une surestimation importante de la concentration de Heq moyenne. Lorsqu'on tient compte de mesures davantage réparties sur le plan circonférentiel, la valeur moyenne est inférieure à 135 ppm. La valeur de la concentration de Heq mesurée sur plus de la moitié de la circonférence du tube de force est semblable à la mesure à une orientation de 6 heures et n'est élevée que sur environ le tiers de la circonférence. Lorsque l'on fait la moyenne des mesures de la concentration de Heq prises à une orientation de 4 heures, comme le montre la figure ci-dessous, pour le tube de force B6S13, la valeur de Heq est d'environ 95 ppm, soit inférieure de 40 ppm à l'estimation de l'intervenant. La valeur moyenne serait réduite davantage si d'autres mesures intermédiaires étaient incluses dans le calcul. Par conséquent, l'inventaire total d'hydrogène est inférieur à ce que laisse entendre le calcul de l'intervenant. Source du pointage : CMD 21-M37.1 de Bruce Power

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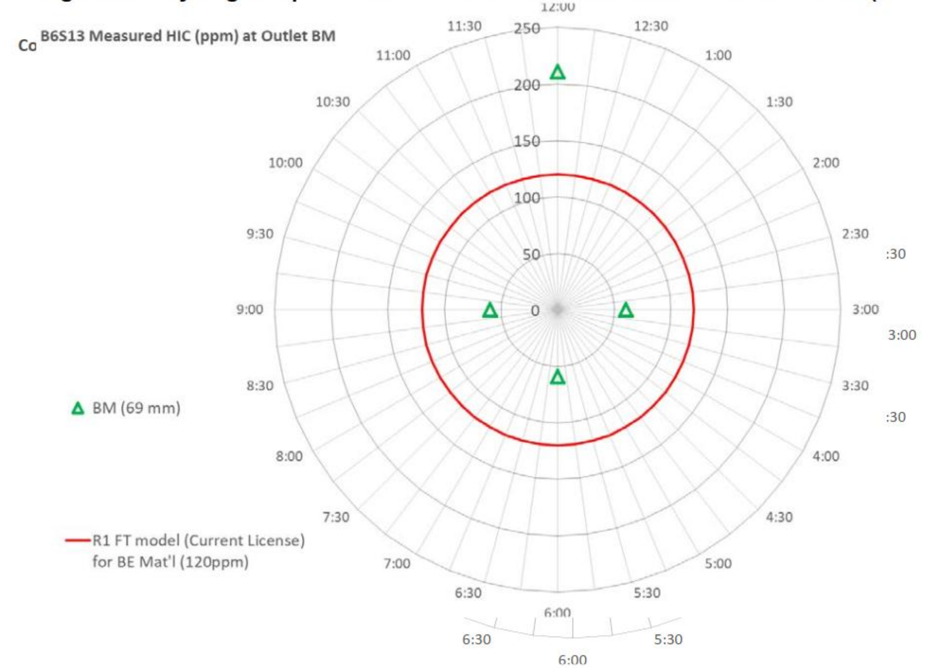
	Figure A1 – Hydrogen Equivalent Concentration of B6S13 at Outlet Burnish Mark (69 mm) 	
At this point I would say that Bruce Power *must* accept that accelerated H/D pickup is occurring for the B6S13 and B3F16 pressure tubes. However, when Bruce Power states that: "*We're not seeing a change in the rate of hydrogen uptake. What we're seeing is a redistribution (of the hydrogen) to the cooler region at the top of the pressure tube. So, it's not an acceleration but a redistribution*." One needs to ask: What is the relevance of this statement? Because it has no bearing on the fact that Bruce Power was	In response to not having met this requirement of their operating licence, Bruce Power took the required action and submitted an event report in accordance with the requirements of REGDOC-3.1.1. This triggered a detailed review of the significance of the finding by CNSC staff and the Commission.	En réponse au fait qu'elle n'avait pas satisfait à cette exigence de son permis d'exploitation, Bruce Power a pris les mesures nécessaires et a présenté un rapport d'événement conformément aux exigences du REGDOC-3.1.1, ce qui a déclenché un examen détaillé de l'importance de la découverte par le personnel de la CCSN et la Commission.

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non-compliant with CSA N285.8. following the July 5th, 2021, discovery of elevated Heq concentrations in Unit 6 pressure tubes. Indeed, in a letter from Bruce Power to the CNSC dated July 15th, 2021, – See CNSC document CMD 21-M37.1 – we read, (with my emphasis in red): Bruce B Power Reactor Operating Licence, (PROL 18.01/2028), Conditions 6.1 and 15.3, require that Bruce Power, "*…implement and maintain a fitness-for-service program*" and that "***before*** *hydrogen equivalent concentrations exceed 120 ppm,* [Bruce Power] *shall demonstrate that pressure tube fracture toughness will be sufficient for safe operation beyond 120 ppm.*" However, *nowhere* in Bruce B's current PROL, (18.01/2028), or in CSA Standard N285.8 is there a stipulation that exceedances of a Unit's 120 ppm Heq limit are permissible *if they are due to a redistribution of ingressed H/D*. So, again, I must ask why Bruce Power would believe that "*the redistribution of hydrogen*" is an acceptable excuse for a clear licence non-compliance?		
In this intervention I have presented a brief history of events and actions following the discovery of high Heq concentrations in several Bruce pressure tubes in July 2021. And I have shown that, as a consequence of these high Heq measurements, Bruce Power is in non-compliance with regard to both the CSA N285.4 and CSA N285.8 Standards. This situation is, as it should be, of great concern to the CNSC because, as noted in the Event Initial Report CMD 22-M16: *Bruce Power does not have a mechanistic understanding of the phenomenon nor validated models as a result of this finding. In other words, their Heq model is invalid because the outputs of the Heq models do not align with the B6S13 measurement of 126 ppm at the inlet end of the PT. These Heq outputs are used as inputs into Fitness for Service Assessments such as leak-before-break (LBB) and fracture protection (FP)*	The significance of the events was reviewed by CNSC staff and staff's recommendations were provided to the Commission in a series of proceedings held between September 2021 and March 2022. Since March 2022, CNSC staff has provided several updates to the Commission through public meetings. As a result of the Commission proceedings industry has undertaken a significant research and development program to understand and model the Heq phenomenon at the inlet and outlet rolled joint regions	L'importance des événements a été examinée par le personnel de la CCSN, dont les recommandations ont été présentées à la Commission à l'occasion d'une série de séances tenues entre septembre 2021 et mars 2022. Depuis mars 2022, le personnel de la CCSN a fourni plusieurs mises à jour à l'intention de la Commission dans le cadre de réunions publiques. À la suite des séances de la Commission, l'industrie a entrepris un important programme de recherche et développement pour comprendre et modéliser le phénomène lié au Heq dans les zones d'intérêt près des joints dudgeonnés aux points d'entrée et de sortie afin

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assessments. The uncertainty of the Heq inputs impact the LBB and FP assessments. CNSC staff are of the opinion that Bruce Power cannot confidently perform these assessments until the Heq phenomenon is understood and modelled.	of interest to allow for fitness for service assessments to be performed.	de permettre la réalisation d'évaluations de l'aptitude fonctionnelle.
Unfortunately, OPG and Bruce Power are, by their own admission, unable to provide a new and improved model of hydrogen pickup by Zr-2.5%Nb pressure tubes, but acknowledge that the research required to validate a new fracture toughness model of pressure tube aging is "a work in progress" that will not be completed for years to come. And when I say "a work in progress," the record shows that problems stemming from discrepancies between Heq predictions and Heq measurements may be traced back many years, as shown by the examples below. **1.** In 2013, the CNSC asked OPG to establish a fracture toughness model "of upper transition and lower shelf behavior" for Heq > 100 ppm. And in July 2014 the CNSC issued a Bid Solicitation for the provision of a "R565.1 Report" on the fracture toughness properties of Zr-2.5Nb pressure tube material with high hydrogen concentration. The contract was for $120,000 over two years and was awarded to Areva Canada in December 2014. The contract included the following description of the research project: *Determine parameters describing the fracture toughness of pressure tube material with high hydrogen concentrations. Develop a methodology or a model to predict fracture toughness of pressure tube material with elevated hydrogen concentrations (50 ppm and 120 ppm [H]eq). Validate the predictions against experimental results derived from a parallel experimental program commissioned by the CNSC.* **2.** In June 2015, OPG provided the following "update" on this issue:	With OPG's and Bruce Power's proposed plans to extend the operation of pressure tubes to permit a staggered refurbishment schedule for the reactor fleet, there were several technical challenges identified related to pressure tube aging that had to be addressed. OPG and Bruce Power initiated a fuel channel life management project to address these challenges, one of which focused on increasing the Heq validity limits of the pressure tube fracture toughness model. The work scope included testing of material with higher Heq levels and revising the fracture toughness model as necessary. The intent was to perform the work in a staged and strategic approach to increasing the Heq limits in the tested material before any operating pressure tubes reached those levels.	Compte tenu des plans proposés par OPG et Bruce Power visant à prolonger l'exploitation des tubes de force afin de permettre un calendrier échelonné de réfection des réacteurs, on a cerné en ce qui concerne le vieillissement des tubes de force plusieurs défis techniques auxquels il fallait donner suite. Pour relever ces défis, OPG et Bruce Power ont lancé un projet de gestion de la durée de vie des canaux de combustible, dont l'un visait à augmenter les limites de validité du modèle de ténacité à la rupture des tubes de force. La portée des travaux comprenait la mise à l'épreuve de matériaux en fonction de concentrations de Heq supérieures ainsi que la révision du modèle de ténacité à la rupture, au besoin. L'intention était d'effectuer les travaux selon une approche stratégique par étapes qui visait à augmenter les valeurs de Heq des matériaux mis à l'épreuve avant que des tubes de force en exploitation n'atteignent ces valeurs.

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Based on R&D work, ... a new fracture toughness model has been developed and is being integrated into the 2015 edition of CSA N285.8 Standard and will become part of the Licence Condition Handbook for Darlington. However, in Darlington's 2016 Licence Condition Handbook, we read: *CNSC staff accepted (e-Doc 4272552 and 4369355) OPG's approach (e-Doc 4250561) to fitness for service assessment, regarding the application of new fracture toughness models and probabilistic Leak-Before-Break (LBB) assessments for pressure tubes at increased hydrogen content. OPG has planned continuing research & development to further validate and improve the fracture toughness models (e-Doc 4405852).* *In the probabilistic core assessments for flaw, Leak-Before-Break and Pressure Tube to Calandria Tube contact, OPG should provide a comparison of the derived 95 % upper bound PT failure frequency with the criterion identified in "Table C.1 of CSA N285.8-15" and "Table 3 of COG-JP-4363-V078-R02". CNSC staff will compare the 95% upper bound of the calculated PT failure frequency with Table 3 of COG-JP-4363-V078 R02,* ***until such time*** *as the CSA N285.8 committee completes its review of the application of Table C. l of the CSA N285.8-15.* My emphasis in red		
3. In August 2021, we have OPG's Progress Report to the CNSC on the status of its new fracture toughness model: [Heq] MODELLING ENHANCEMENTS *[Heq] modelling enhancements including use of 3D Finite Element Analysis considering fuel channel geometries, local temperatures, location-specific [Heq], and material stress states are being pursued. Note that these*	CMD 22-M16 was presented during a Commission meeting in March 2022 addressing the elevated Heq findings detected at the inlet rolled joint of the Bruce Power pressure tube B6S13. The analysis to determine the causes of regions of elevated Heq were incorporated into the industry research and development program, which began after	Le CMD 22-M16 a été présenté lors d'une réunion de la Commission en mars 2022 portant sur la découverte de concentrations élevées de Heq près du joint dudgeonné au point d'entrée du tube de force B6S13 de Bruce Power. L'analyse visant à déterminer les causes des zones de concentration élevée de Heq a été intégrée au

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*proactive enhancements were already in progress prior to the B3 and B6S13 findings. OPG, with industry alignment, intends to submit modelling enhancements for CNSC acceptance **once fully validated**.* My emphasis in red **4.** In an email from the CNSC I received on January 10th, 2023 we read: *The External Advisory Committee (EAC) will consider all of the relevant information that has been gathered to date, including your written intervention CMD-M37.4 and other submissions. The EAC's report, and the Commission's consideration of that report, will be transparent and public, in accordance with the Commission's commitment to transparency. **We expect the EAC report to be submitted in Spring or early Summer 2023**.* High Heq concentrations, well in excess of Bruce Power's operating license limits, were first seen in Bruce Unit 6 pressure tubes in July 2021. By way of dealing with this problem the CNSC ordered Bruce Power to conduct a detailed assessment of the safe continued operability of Bruce Units 1, 2, 4, 5, 7 and 8. Bruce Power was also told, given the discrepancy between the current fracture toughness model predictions and inspection results for Units 3 and 6, to assess whether operation of these Units remains within the licensing basis. At the same time, the CNSC stressed the need for Bruce Power to carry out a **root cause analysis** to determine if the measured elevated hydrogen concentration was caused by a new phenomenon specific to these Units and their pressure tubes. At its September 3rd, 2021, meeting, the CNSC promised there would be: "*a follow-up public Commission meeting on this topic in late Winter 2021 or early Spring 2022*". However, by July 2022, one year after the discovery of high Heq in some Bruce pressure tubes, no public Commission meeting on	the findings were reported in 2021. The CNSC requested that OPG and Bruce Power submit a report summarizing activities undertaken since the fall of 2021 and a detailed plan for future work. These submissions were received in the summer of 2022 and discussed at a Commission meeting in November 2022 (CNSC staff CMD 22-M37, OPG CMD 22-M37.1 and Bruce Power CMD 22-M37.3) included a requirement for the licensees to provide semi-annual updates to CNSC staff. CNSC staff monitored the output of the research and development program and reported on the status regularly in Commission proceedings. Between September 2021 and December 2025, CNSC staff provided updates to the Commission of the status of the industry's response to elevated Heq findings in at least seven (7) hearings related to the restart of reactors following the events reports, five (5) dedicated Commission meetings, eleven (11) status reports on power reactors, two (2) memoranda and two (2) licence amendment hearings. All communication between CNSC staff and the Commission for these proceedings were available to the public through the CNSC website. Licence Condition 6.2 was added to the Pickering and Bruce A and B operating licensees by the Commission to establish alternate compliance verification criteria to assess safe operation of pressure tubes in extended operation with uncertain Heq levels near the burnish marks for the planned duration of research and development program. LC 6.2 will remain in the	programme de recherche et développement de l'industrie, qui a débuté après la déclaration de la découverte en 2021. La CCSN a demandé à OPG et à Bruce Power de présenter un rapport résumant les activités réalisées depuis l'automne 2021 ainsi qu'un plan détaillé des activités futures. Les mémoires ont été reçus à l'été 2022 et ont fait l'objet de discussions lors d'une réunion de la Commission en novembre 2022 (CMD 22-M37 du personnel de la CCSN, CMD 22-M37.1 d'OPG et CMD 22-M37.3 de Bruce Power). Les titulaires de permis ont reçu la directive de fournir des mises à jour semestrielles au personnel de la CCSN. Le personnel de la CCSN a surveillé les résultats du programme de recherche et développement et a fait régulièrement rapport sur l'état d'avancement lors de séances de la Commission. Entre septembre 2021 et décembre 2025, le personnel de la CCSN a fourni à la Commission des mises à jour sur l'état d'avancement de la réponse de l'industrie à la découverte de concentrations élevées de Heq à l'occasion d'au moins sept (7) audiences liées au redémarrage de réacteurs à la suite des rapports d'événements, de cinq (5) réunions de la Commission consacrées à la question, de onze (11) rapports d'étape sur les centrales nucléaires, de deux (2) notes de service et de deux (2) audiences visant la modification d'un permis. Toutes les communications entre le personnel de la CCSN et la Commission dans le cadre de ces séances ont été mises à la disposition du public sur le site Web de la CCSN.

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high Heq issues had taken place. In fact, the promised meeting was eventually held in early November 2022, *one year and 4 months after the high Heq problem was first recognized*. Now, this delay might be considered acceptable, if the November 2022 meeting did in fact provide a root cause analysis of the high Heq concentrations, but, regrettably, this was not the case. As noted above, the CNSC stated in a January 10th, 2023, email: "*We expect the EAC report to be submitted in Spring or early Summer 2023*"; with such a timeline, the EAC's report would be issued *a full two years on from the first observation of high Heq at Bruce*. This leads me to conclude that the CNSC is in no hurry to find a root cause of the high Heq problem, but is apparently quite content to let CANDU reactors operate with deuterium ingress rates running well above the predictions of existing [Heq] models.	licences until the Commission amends a licence to remove it.	La condition de permis 6.2 a été ajoutée par la Commission aux permis d'exploitation de Pickering et de Bruce A et B afin d'établir des critères de vérification de la conformité de rechange pour évaluer la sûreté des tubes de force en exploitation prolongée présentant une concentration de Heq incertaine près des marques de brunissage pour la durée prévue du programme de recherche et développement. La CP 6.2 demeurera dans les permis jusqu'à ce que la Commission modifie un permis afin de la retirer.
Interestingly, it appears that the Canadian nuclear industry is like-minded in this regard, which may be seen in the timeline proposed to develop a new and improved [Heq] model, as first reported at an industry workshop on elevated hydrogen equivalent ([H]eq) concentration held on March 25th, 2022. In an account of this meeting, published by Bruce Power in July 2022, we find Attachment B which provides "*a path forward with a target schedule and summary of key deliverables to improve hydrogen equivalent concentration predictions in the inlet/outlet rolled joint regions of pressure tubes*". Action Item 5G in Attachment B, described as "The Development of a Comprehensive [Heq] Model", gives the target date for the completion and issuance of a "comprehensive [Heq] Model" as **the 2nd Quarter of 2026**. This target date means that the Canadian nuclear industry would have taken ***5 years*** to develop a new and improved [Heq] model as a response to the discovery of high Heq concentrations in some Bruce tubes in July 2021. However, it is important to note that the CNSC issued a bid solicitation	The research activities required to update the Heq models and allow the licensees to return to the adoption of the traditional compliance verification criteria of Licence Condition 6.1 was completed in under 4 years (end of 2021 to end of 2025). During that time, alternate compliance verification criteria were established and the intermediate deliverables of the research and development program were monitored by CNSC staff to ensure no findings invalidated the alternate criteria. CNSC staff would have promptly notified the Commission if any of the research and development results indicated further action was required to maintain safe operation. Heq modelling and fracture toughness modelling are related in that Heq is an input to the fracture toughness model, but the models are developed independently.	Les activités de recherche nécessaires pour mettre à jour les modèles de concentration de Heq et permettre aux titulaires de permis d'adopter à nouveau les critères de vérification de la conformité traditionnels associés à la condition de permis 6.1 ont été menées à bien en moins de quatre ans (de la fin de 2021 à la fin de 2025). Au cours de cette période, des critères de vérification de la conformité de rechange ont été établis, et les livrables intermédiaires du programme de recherche et développement ont fait l'objet d'une surveillance par le personnel de la CCSN afin de s'assurer qu'aucune constatation n'invalidait les critères de rechange. Le personnel de la CCSN en aurait rapidement informé la Commission si les résultats des travaux de recherche et développement avaient laissé entendre que d'autres mesures sont nécessaires pour maintenir l'exploitation sûre.

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document, No. 87055-18-0098, in November 2018 for an independent contractor to: "*Predict the fracture toughness of pressure tubes with elevated hydrogen concentrations (40 ppm to 160 ppm [H]eq), and validate the modelling predictions against the experimental results provided by CNSC staff*". And what is most significant about this *Request for Proposal* document is that the CNSC stipulated that the requested work must be completed within ***fifteen months*** of the awarding of the contract, with a final report issued by March 2020.	Bid solicitation 87055-18-0098 was cancelled because a qualified bidder was not identified. It is not uncommon for CNSC staff to initiate parallel research activities to obtain independent insights to support regulatory reviews of licensee activities. The deadline associated with the project was not related to a specific safety issue. It was driven by two factors: 1) to obtain information prior to receiving substantial updates from industry of their progress to update the fracture toughness model; and 2) the budget cycle for CNSC research activities.	La modélisation du Heq et la modélisation de la ténacité à la rupture sont liées, puisque la valeur de Heq constitue un paramètre d'entrée du modèle de ténacité à la rupture. Toutefois, les modèles sont élaborés de manière indépendante. La demande de soumission 87055-18-0098 a été annulé à la suite du processus de demande d'offres, étant donné qu'aucun offrant qualifié n'a été trouvé. Il n'est pas rare que le personnel de la CCSN entreprenne des activités de recherche parallèles pour obtenir des renseignements indépendants à l'appui des examens réglementaires visant les activités des titulaires de permis. L'échéance associée au projet n'était pas liée à un problème particulier sur le plan de la sûreté, mais était plutôt motivée par deux facteurs, soit 1) l'obtention de renseignements avant de recevoir de l'industrie des mises à jour importantes sur les progrès réalisés en vue d'actualiser le modèle de ténacité à la rupture, et 2) le cycle budgétaire associé aux activités de recherche de la CCSN.
5. The real situation with regard to the quest for a new and improved fracture toughness model for CANDU pressure tubes is well illustrated by the current status of one of the Standards on which the model is based – namely CSA N285.8. Thus, as described in clause C.5 of the latest update of CSA N285.8, we read, (with my emphasis in red italics): (Intervenor reproduced Clause C.5 from CSA Standard N285.8 which is protected by copyright and not reproduced here.)	While methodologies for evaluating the impact of findings have not been incorporated into the standard, the Canadian industry has developed approaches for doing so. There are different and equally valid statistical evaluation methods to assess the goodness of fit of data to models. The methods employed by industry have been used on multiple occasions to assess the need to redefine the statistical bounds for evaluation models as more data has become available. When it is determined that model bounds require adjustment,	Bien qu'aucune méthode d'évaluation de l'incidence des constatations n'ait été intégrée à la norme, l'industrie canadienne a élaboré des approches à cet égard. Il existe différentes méthodes d'évaluation statistique tout aussi valides pour évaluer la pertinence des données par rapport aux modèles. Les méthodes employées par l'industrie ont été utilisées à plusieurs reprises afin d'évaluer la nécessité de redéfinir les limites statistiques des modèles d'évaluation à mesure que de nouvelles données devenaient disponibles.

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Clearly, these five clauses show that the key determinants of CSA Standard N285.8 are all "under development," and evidence already presented in this intervention suggests that this uncertainty in one of the key Standards governing the fitness for service of pressure tubes will remain unresolved for years to come.	licensees evaluate the impact on pressure tube fitness for service evaluations and submit those assessments for CNSC staff review.	Lorsqu'il est nécessaire d'ajuster les limites du modèle, les titulaires de permis analysent l'incidence sur l'évaluation de l'aptitude fonctionnelle des tubes de force et soumettent ces analyses au personnel de la CCSN aux fins d'examen.
Nevertheless, the CNSC claims that it provides "*Comprehensive and Effective Regulatory Oversight of pressure tube degradation mechanisms*." And, according to a CNSC presentation from a January 2018 Commission Meeting, this is achieved by setting goals and guidelines for reactor operators which include: (i) Clear and well-documented expectations and Licence Compliance Plans through REGDOC-2.6.3 and CSA Standard N285.8 (ii) Effective Compliance Verification Criteria as presented in the Licence Condition Handbooks for a particular NGS (iii) Licensees must have an in-depth understanding of pressure tube degradation phenomena The Compliance Verification Criteria for Bruce Units may be found in Section 15.3 of Licence Conditions Handbook, LCH-PR-18.01/2028-R002. Through this license condition, Bruce Power is required to submit to the CNSC a fracture toughness model for review and acceptance and no Bruce Unit is authorized to operate above the 120 ppm [Heq] limit set in Clause 8.2 of CSA Standard N285.8. In addition, through a fracture toughness model, Bruce Power must verify that measured Heq changes between inspection periods are bounded by Heq concentrations predicted by an acceptable model. But what constitutes an acceptable model? This question has been addressed by the CNSC, as shown by the overhead presented below taken from a January 2018 Commission Meeting:	To assess the impact of future Heq levels on pressure tube fracture toughness and allow the models to be verified and validated prior to use, the licensees add hydrogen to ex-service pressure tube material to perform laboratory testing. Because of the time and effort involved in preparing these specimens the test program strategy focused on increasing the Heq levels in a manner that would allow a systematic evaluation of results. The program schedule was aimed at the expected hydrogen levels in pressure tubes and did not account for the local redistribution of hydrogen discovered near the burnish marks. Aging management and inspection programs incorporate provisions to monitor the condition of pressure tubes to detect aging related changes. The results are used to validate assumptions and, if necessary, implement corrective actions before the safe operation is impacted. While the Heq models existing in 2021 did not accurately predict the redistribution of hydrogen in the rolled joint regions, the fitness for service program was successful from the perspective that the issue was identified before there was an impact on safe operation.	Afin de déterminer l'incidence des futures concentrations de Heq sur la ténacité à la rupture des tubes de force et de permettre la vérification et la validation des modèles avant leur utilisation, les titulaires de permis ajoutent de l'hydrogène au matériau des tubes de force retirés du service pour effectuer des essais en laboratoire. En raison du temps et des efforts consacrés à la préparation de ces éprouvettes, la stratégie du programme d'essai consistait à accroître la concentration de Heq d'une manière qui permet l'évaluation systématique des résultats. Le calendrier du programme visait les concentrations d'hydrogène prévues dans les tubes de force et ne tenait pas compte de la redistribution locale de l'hydrogène découvert près des marques de brunissage. Les programmes de gestion du vieillissement et d'inspection intègrent des dispositions visant à surveiller l'état des tubes de force afin de détecter tout changement lié au vieillissement. Les résultats servent à valider les hypothèses et, au besoin, à mettre en œuvre des mesures correctives avant que l'exploitation sûre ne soit affectée. Bien que les modèles de concentration de Heq existants en 2021 n'aient pas prédit avec précision la redistribution de l'hydrogène dans les zones des joints dudgeonnés, le programme

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Commission Meeting, January 23 2018 CMD 18-M4 APPENDIX **Attributes of an Acceptable Model** 1. The model should (preferably) be founded on a mechanistic understanding of the phenomenon, and/or based on experimental evidence 2. The model must be verified and its predictions validated prior to use 3. Model inputs and assumptions must be identified and justified 4. Model uncertainties must be quantified 5. To focus improvements to the model, a sensitivity analysis is invaluable 6. Forward-looking models must be periodically re-validated Of the six attributes listed above, No. 2 – "The model must be verified and its predictions validated prior to use" – is perhaps the most important, but is also the most problematic. This is because the required predictive modeling involves making estimates of future pressure tube performance parameters, such as hydrogen pickup rates and fracture toughness values; however, because we are dealing with future expectations, it follows that appropriate experimental data are obviously not yet available from real-world pressure tubes. And since it is not possible to verify or validate a model without the requisite experimental data, one has to ask how any fracture toughness model could ever be "verified and validated prior to use".		d'aptitude fonctionnelle a été concluant, en ce sens que le problème a été cerné avant qu'il ait une incidence sur la sûreté de l'exploitation.
An issue that further complicates the validation of fracture toughness models is the fact that the fracture toughness of a pressure tube depends on many factors, including the [Heq], temperature, neutron fluence, trace impurities, etc., of the tube in question This leads to a large variability in measured values of fracture toughness parameters such as a pressure tube's crack growth resistance, dJ/da, as shown in the Figure below: (Uncredited figure provided)	The variability in pressure tube fracture toughness is recognized by both CNSC staff and industry and provisions have been established for the use of the fracture toughness model predictions to address the potential impact on assessment results. It is also worth noting that many materials exhibit variability in fracture toughness test results and this is not unique to pressure tubes.	Le personnel de la CCSN et l'industrie reconnaissent la variabilité sur le plan de la ténacité à la rupture des tubes de force, et des dispositions ont été établies à l'égard de l'utilisation des prédictions du modèle de ténacité à la rupture pour donner suite à l'incidence potentielle sur les résultats d'évaluation. Il convient également de noter que de nombreux matériaux présentent des résultats d'essais de ténacité à la rupture variables. En effet, la situation n'est pas propre aux tubes de force.

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This extreme variability in a tube's fracture toughness – a variability that is also seen in many other pressure tube properties such as H/D pickup rates – means that predictive models themselves are inherently uncertain and can only offer upper bounds, for H/D pickups, or lower bounds, for fracture toughness parameters.	It is correct that pressure tube fracture toughness depends upon multiple parameters and not just Heq. Plotting fracture toughness versus any one of the variables as shown in the figure provided by the intervenor can exaggerate the variability as each data point is likely to represent a different combination of influential parameters. To assess the effect of fluence versus fracture toughness in a plot, all other test parameters must be held constant for each data point. To address the effects of variability that remain in model predictions even after accounting for different parameter interactions, special considerations are applied to the use of the model in fitness for service evaluations. For instance, in deterministic calculations, lower bound estimates generated by the toughness model are used. In probabilistic evaluations, restrictions are placed on the fracture toughness distributions per the conditions of acceptance of the Revision 2 model as discussed in CNSC staff CMD 22-M37. It is also important to note that evaluation methodologies in codes and standards recognize that there is uncertainty in any engineering assessment. In addition to selecting input parameter values that bound known data, the evaluations incorporate explicit safety margins. For example: • The accepted failure limit in CSA N285.8 for a pressure tube containing a detected flaw subject to normal operating pressures and temperatures is set at 3 times the normal operating pressure.	Il est exact que la ténacité à la rupture des tubes de force dépend de plusieurs paramètres, et non seulement de la concentration de Heq. Le pointage de la ténacité à la rupture par rapport à n'importe quelles autres variables présentées dans la figure fournie par l'intervenant peut exagérer la variabilité, car chaque point de données est susceptible de représenter une combinaison différente de paramètres influents. Pour évaluer l'effet de la fluence par rapport à la ténacité à la rupture dans un pointage, tous les autres paramètres d'essai doivent être maintenus constants pour chaque point de données. Pour tenir compte des effets de la variabilité restants dans les prédictions du modèle, même après avoir tenu compte des interactions entre différents paramètres, des considérations spéciales sont appliquées à l'utilisation du modèle dans le cadre de l'évaluation de l'aptitude fonctionnelle. Par exemple, en ce qui concerne les calculs déterministes, on utilise des estimations de la limite inférieure générées par le modèle de ténacité. Aux fins des évaluations probabilistes, des restrictions sont imposées à l'égard des distributions relatives à la ténacité à la rupture aux termes des conditions d'acceptation de la révision 2 du modèle, comme il est indiqué dans le CMD 22-M37 du personnel de la CCSN. Il convient également de noter que les méthodes d'évaluation figurant dans les codes et normes reconnaissent qu'il existe de l'incertitude dans toute

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	• For probabilistic pressure tube fracture protection evaluations, the allowable probability of failure for a pressure tube in the evaluation is set to a probability 0.0001. Sensitivity studies are also often used to assess the potential impacts of uncertainties. These margins provide confidence that pressure tubes passing evaluations are unlikely to fail even if there is uncertainty in the input assumptions and model predictions.	évaluation technique. En plus de sélectionner les valeurs des paramètres d'entrée qui délimitent les données connues, les évaluations intègrent des marges de sûreté explicites, par exemple : • la limite de défaillance acceptée aux termes de la norme CSA N285.8 pour un tube de force présentant un défaut connu et soumis à des pressions et températures normales d'exploitation est fixée à trois fois la pression d'exploitation normale • pour l'évaluation probabiliste de la protection contre la rupture des tubes de force, la probabilité admissible de défaillance d'un tube de force est établie à 0,0001 De plus, les études de sensibilité servent souvent à évaluer les effets potentiels des incertitudes. Ces marges donnent l'assurance que les tubes de force dont l'évaluation est réussie sont peu susceptibles de subir une défaillance, même s'il existe de l'incertitude sur le plan des hypothèses d'entrée et des prédictions du modèle.
However, in addition to the model predictions provided annually by a reactor operator, the operator is also obligated to obtain scrape measurements during each planned outage to determine the level of [Heq] in sampled pressure tubes. These measurements serve as a means of comparison to model predictions and allow a reactor operator to determine if the validity limits of the fracture toughness model are satisfied. It follows that the predictions need only go as far as the next scheduled inspection – a time interval that is typically about 2 to 3 years.	There is no evidence from in-service measurements from pressure tubes or the research and development program results, which included the examination of ex-service pressure tubes, that the findings from 2021 are the result of accelerated corrosion and accelerated hydrogen uptake. The results demonstrate that the 2021 measurements can be reproduced with quantities of hydrogen well within established rates of uptake.	D'après les mesures provenant des tubes de force en service ou les résultats du programme de recherche et développement, lequel comprenait l'examen de tubes de force retirés du service, rien n'indique que les constatations faites en 2021 sont le résultat d'une accélération de la corrosion et de l'absorption d'hydrogène. Les résultats démontrent que les mesures de 2021 peuvent être reproduites avec des quantités

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Until the discovery of very high Heq concentrations in several Bruce pressure tubes in July 2021, the Canadian nuclear industry, and the CNSC, stated at many Public Hearings that Canadian reactors are operating in full compliance with the fracture toughness model described in CSA Standard N285.8-2015 Update 1, Clause D.13.2.3.1.2 (a). And such a claim was made by all parties concerned in spite of the fact, as shown above, that the required validation and verification of the 2015 fracture toughness model has not been accomplished. Of course, such an approach may appear to work as long as pressure tube corrosion and H/D uptake rates remain relatively constant. But this approach is doomed to failure if a tube is subject to the rapid onset of accelerated corrosion, which appears to be the case for Bruce pressure tubes B6S13 and B3F16.		d'hydrogène bien inférieures aux taux d'absorption établis.
Before completing this intervention, I wish to address an important issue that, (I believe), has been inadequately dealt with by our nuclear operators and regulators alike – namely the link between the concentrations of H/D in a pressure tube and the tube's fracture toughness. The operational limits on a pressure tube's fracture toughness are specified in Clause 8.3 of CSA Standard N285.8-15 as shown below: (Intervenor reproduced Clause 8.3 from CSA Standard N285.8 which is protected by copyright and not reproduced here.) Here we see CSA Standard N285.8-15 imposing the license requirement that a reactor owner/operator shall establish a fracture toughness model "*on the basis of available fracture toughness data, including surveillance measurements under evaluation*." However, this apparently straightforward license requirement is actually quite complex and problematic because, as previously noted in this intervention, the fracture toughness of a pressure tube depends on a number of variables including the temperature, neutron fluence and Heq concentration, the effects of which need to be included in any meaningful evaluation.	The fracture toughness testing program for ex-service material considers a range of input parameters including elevated Heq concentrations generated by adding hydrogen to the material. Irradiation effects are also considered. Recent tests have been performed on material with Heq levels in excess of 300 mg/kg and fluence levels close to $3x10^{26}$ n/m^2 (E>1MeV).	Le programme d'essais de ténacité à la rupture visant les matériaux retirés du service tient compte d'un éventail de paramètres d'entrée, y compris les concentrations élevées de Heq générées par l'ajout d'hydrogène. Les effets de l'irradiation sont également pris en compte. Des essais récents ont été effectués sur des matériaux dont la concentration de Heq était supérieure à 300 mg/kg et dont la fluence atteignait près de 3x1026 n/m2 (E>1 MeV).

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Furthermore, in order to replicate a pressure tube's behavior as it approaches end-of-life, pressure tube data for samples with fast neutron fluences up to 2 × 10^{26} n/m^2, (E>1MeV), and Heq concentrations in excess of 100 mg/kg, are required. Unfortunately, the availability of such data for real-world pressure tube material is very limited.		
CSA Standard N285.8-15 also includes a Table 7 which stipulates that a pressure tube's fracture toughness, K_c, should be evaluated "*on a case-by-case basis*". However, Table 7 also introduces the additional parameters V_a and V_r, the DHC axial and radial crack growth rates, respectively, and Clause 8.4 of CSA Standard N285.8 stipulates that the owner/operator shall establish a statistical model based on available delayed hydride cracking growth rate data. Table 7 sets limits on V_a and V_r in the form of threshold probabilities of observing a fracture toughness value below a reference lower-bound fracture toughness. Interestingly, the methodology used to quantify DHC crack growth rates in CSA Standard N285.8 has varied considerably over time. Thus, for example, the 2005 model considers a Unit's operating temperature only, but the 2015 model also includes the neutron fluence – a parameter that depends on the axial position of a pressure tube. This means that the 2005 model assumes one DHC crack growth rate while, for the 2015 model, the DHC growth rate is different at the inlet and outlet locations. Furthermore, in the case of a probabilistic assessment, the 2005 fracture toughness model does not consider the known hydrogen concentration variations, while the 2015 fracture toughness model is segmented into different calculation regions according to the pressure tube's hydrogen content and temperature range. Thus, it is not surprising the 2005 and 2015 models give different answers to the same question.	It is not uncommon for evaluation models to change as technology changes, and new analysis methods and more data become available. The newer models can include more input parameters than the older models because there is now sufficient data available to demonstrate the statistical significance of additional parameters. The DHCR model has been updated since 2015 and the latest model provides further refinements to the growth rate estimates with the inclusion of more test data.	Il n'est pas rare que les modèles d'évaluation changent à mesure que la technologie évolue et que de nouvelles méthodes d'analyse et davantage de données deviennent disponibles. Les nouveaux modèles peuvent inclure un plus grand nombre de paramètres d'entrée que les modèles plus anciens, car is existe maintenant suffisamment de données pour démontrer la signification statistique des paramètres supplémentaires. Le modèle de taux de croissance des fissures par hydruration retardée a été actualisé depuis 2015, et le dernier modèle apporte d'autres améliorations aux estimations du taux de croissance grâce à l'inclusion de données d'essai supplémentaires.
CSA Standard N285.8 also runs into problems with regard to the methodology it recommends for a so-called Leak Before Break, (LBB), analysis. An LBB analysis is intended to evaluate the response of an annulus	There are five levels of defence described in REGDOC-2.5.2, which can be summarized as:	Le terme défense en profondeur est souvent cité dans la documentation, sans plus de précision. Le

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gas system to a leak, and specifies the required operator actions in the event of a pressure tube through-wall crack. The concept of leak-before-break, (LBB), is an operational requirement that, in the event of a pressure tube leak from a through-wall crack, there will be sufficient time for the leak to be detected and the reactor shut down *before* the crack grows to the critical size for a fast-uncontrolled rupture. Thus, if a pressure tube develops a through-wall crack, it is assumed that there will always be a "window of opportunity" for the reactor operator to detect the leak and safely shut down the Unit. This assumption is the basis for the claim that CANDU reactors safety systems provide "*defense in depth*," a notion that is often touted by the Canadian nuclear industry – but is such a claim justified?	Level 1: Prevention of failures through high quality of design, manufacturing and maintenance Level 2: Prevent deviations from normal operation to prevent escalation to accidents Level 3: Minimize the consequences of accidents Level 4: Keep radioactive releases from severe accidents as low as practicable Level 5: Mitigate the consequences of radioactive releases from accidents The aim is to have each level of defence as effective as reasonably practical. In the context of the topics discussed in this intervention, Levels 1-3 are important to consider. Aging management and periodic inspection programs support the prevention of pressure tube failures (Level 1). Heq is an input into the models used to assess the findings of pressure tube inspections and provide direct evaluations of fitness for service. Instances of cracking in CANDU pressure tubes arose in in the 1980s as a result of installation issues, issues with material selection and issues with the annulus gas system. Industry responded to those findings, implemented corrective actions and enhanced aging management practices. There have been no instances of cracking detected in CANDU reactors since.	REGDOC-2.5.2 décrit cinq niveaux de défense, qui peuvent être résumés comme suit : Niveau 1 : Prévenir les défaillances Niveau 2 : Prévenir les écarts par rapport à l'exploitation normale afin d'éviter que la situation dégénère et se transforme en accident. Niveau 3 : Réduire au minimum les conséquences d'accidents Niveau 4 : Maintenir les rejets radioactifs découlant d'accidents graves au niveau le plus bas qu'il soit raisonnablement possible d'atteindre Niveau 5 : Atténuer les conséquences des rejets radioactifs découlant d'accidents L'objectif consiste à optimiser l'efficacité de chaque niveau de défense, dans la mesure du possible. Dans le contexte des sujets abordés dans cette intervention, les niveaux 1 à 3 sont les plus pertinents. Les programmes de gestion du vieillissement et d'inspection périodique favorisent la prévention de la défaillance des tubes de force (niveau 1). La valeur de Heq constitue un paramètre d'entrée des modèles servant à analyser les résultats d'inspection des tubes de force et à fournir une évaluation directe de l'aptitude fonctionnelle. Des cas de fissuration des tubes de force CANDU sont survenus dans les années 1980 en raison de problèmes liés à l'installation, au choix des matériaux et au circuit du gaz annulaire (CGA). L'industrie a réagi aux problèmes constatés, a mis en œuvre des mesures correctives et a renforcé les

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	The annulus gas system provides a means of detecting and responding to a pressure tube leak, which represents a deviation from normal operation (Level 2). A pressure tube break or rupture is considered an accident scenario. LBB evaluations are used to achieve confidence in the effectiveness of the leak detection capabilities supporting Level 2 defence, but they are not a direct evaluation of pressure tube fitness for service since they begin with the postulation of the presence of a through-wall crack, assuming Level 1 measures have not been effective.. In the event the leak detection capabilities are not sufficient to detect a leak before a pressure tube rupture occurs, safety systems are designed to respond to the rupture and prevent escalation to a severe accident scenario (Level 3). Level 3, 4 and 5 provisions are not impacted by the condition of pressure tubes. In the history of CANDU and Indian pressurized heavy water reactors there have been instances of pressure tube failures, but none have progressed passed Level 3 response measures and most have not progressed beyond Level 2 response measures. The consequences of these events were mitigated, the fuel channels replaced and the reactors returned to operation without unacceptable impacts on people or the environment.	pratiques de gestion du vieillissement. Aucun cas de fissuration n'a été détecté dans les réacteurs CANDU depuis. Une fuite dans un tube de force représente un écart par rapport à l'exploitation normale (niveau 2). Le CGA offre un moyen de détecter une telle fuite et d'intervenir. La rupture ou le bris d'un tube de force est considéré comme un scénario d'accident. L'évaluation des FAR permet d'établir la confiance dans l'efficacité des capacités de détection des fuites à l'appui de la défense de niveau 2, mais elle ne constitue pas une évaluation directe de l'aptitude fonctionnelle des tubes de force puisqu'elle est déclenchée par l'hypothèse de la présence d'une fissure complète de la paroi, ce qui laisse supposer que les mesures du niveau 1 n'ont pas été efficaces. Lorsque les capacités de détection des fuites ne sont pas suffisantes pour déceler une fuite avant la rupture d'un tube de force, les systèmes de sûreté sont conçus pour réagir à la rupture et prévenir la dégénération en un scénario d'accident grave (niveau 3). Les dispositions des niveaux 3, 4 et 5 ne sont pas touchées par l'état des tubes de force. Dans le passé, des cas de défaillance de tubes de force des réacteurs à eau lourde sous pression canadiens (CANDU) et indiens sont survenus, mais aucun n'a nécessité de mesures d'intervention au-delà du niveau 3, et la plupart n'ont pas nécessité d'intervention au-delà du niveau 2. Les conséquences de ces événements ont été atténuées,

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		les canaux de combustible ont été remplacés, et les réacteurs ont été remis en service sans conséquences inacceptables pour les personnes ou l'environnement.
The practical implementation of LBB is described in Section C.4 of CSA Standard N285.8: *Technical requirements for in-service evaluation of zirconium alloy pressure tubes in CANDU reactors*. Clause C.4.1 of this Standard stipulates that: *LBB analysis shall demonstrate that the leak detection capability of the annulus gas system (AGS) provides the operator with sufficient warning time to shut down and depressurize the reactor in a controlled manner.* Similarly, Clause C.4.2.2.6 of the Standard states that: (Intervenor reproduced Clause C.4.2.2.6 from CSA Standard N285.8 which is protected by copyright and not reproduced here.) There are four key parameters that need to be evaluated in a LBB analysis: (i) *The initial crack length at wall penetration*, L_p. This is typically in the range 20 – 30 mm. (ii) *The location of crack initiation*. Cracks may originate anywhere in the body of a pressure tube, but are most likely to occur in the vicinity of the rolled joint between a pressure tube and its end-fitting. (iii) *The axial crack growth rate*, V_a, which is usually expressed as a velocity, in m/s, and is typically in the range 1×10^{-7} to 2×10^{-6} m/s. As previously noted in this intervention, V_a depends on the temperature, irradiation history and hydrogen equivalent concentration in the pressure tube at the crack location. (iv) *The critical crack length*, CCL. This refers to the point in the development of a crack in the *axial* direction of a pressure	This example illustrates why it can be beneficial to update the model as more data becomes available to reduce the uncertainty in growth rate estimates compared to the early model which only included temperature as an input parameter. There is a significantly larger data set available now compared to 1989 to support model refinement. When refining models, industry is requested to submit evaluations for CNSC staff review to assess the impact of the changes on existing fitness for service evaluations. CNSC staff can reject the use of models that are not adequately justified or place restrictions on the use of models subject to ongoing research.	L'exemple de l'intervenant illustre pourquoi il peut être avantageux de mettre à jour le modèle à mesure que de nouvelles données deviennent disponibles afin de réduire l'incertitude dans les estimations du taux de croissance par rapport au modèle initial, qui ne comprenait que la température comme paramètre d'entrée. Un ensemble de données beaucoup plus important est maintenant disponible qu'en 1989 pour appuyer l'amélioration du modèle. Lorsqu'elle souhaite affiner les modèles, l'industrie doit soumettre des évaluations aux fins d'examen par le personnel de la CCSN pour évaluer l'incidence des modifications sur les évaluations existantes de l'aptitude fonctionnelle. Le personnel de la CCSN peut rejeter l'utilisation de modèles qui ne sont pas assortis d'une justification suffisante ou imposer des restrictions à l'utilisation de modèles pour lesquels les études se poursuivent.

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tube at which a slowly increasing crack, (e.g. ~ 2 mm/hr), accelerates to a fast rupture (e.g. to a crack velocity > 2 mm/s). The CCL of a pressure tube is dependent on the temperature and hoop stress at the crack location but is typically in the range 30 – 80 mm. A CANDU station's operating procedures require immediate shutdown of a Unit at a confirmed D_2O leakage rate of 0.5 kg/s. It is therefore important to closely monitor D_2O leaks and it follows that a LBB analysis of a pressure tube should include an estimate of potential D_2O leak rates as a function of crack length. One approach that has been used to make such estimates is to collect data from tests on removed pressure tubes and look for a correlation between D_2O leak rate and crack length. Unfortunately, data from hot tests on removed pressure tubes show considerable scatter – for example, tubes with crack lengths in the range 18 – 30 mm exhibit D_2O leak rates in the range 0.8 to 30 kg/hr. Nevertheless, in spite of these large variabilities, the approach used at CANDU stations is to simply average the available data. Using this approach, *typical* pressure tube LBB behavior, as presented in a station's AGS Design Manual, is as follows: 1. With a reactor at full power, a crack will penetrate a pressure tube wall at a crack length of 27 mm and grow at a velocity ~ 5.3×10^{-7} m/s, equivalent to 1.94 mm/hr. 2. After 0.5 hours, the crack length would extend to 28 mm and the leak rate would be 0.6 kg/hr. 3. After 1.5 hours, the crack length would be 30 mm and the leak rate would have increased to 1.79 kg/hr. 4. The Unit's AGS leak detection capability is expected to recognize such a leak within this time window, (i.e, ~ 2 hrs).		

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However, this approach is quite different to the methodology used in CSA N285.8 which recommends the following *cubic* leak rate equation for LBB analysis: $$Q = -11.2 + 0.0014(2C)^3$$ Q = D_2O leak rate in kg/hr 2C = crack length in mm For crack growth at a velocity ~ 5×10^{-7} m/s, this equation predicts a D_2O leak rate of 4 kg/hr after 0.5 hr and 15 kg/hr after 1.5 hrs. These values are more than 6 times higher than the AGS Design Manual values noted above. Nevertheless, regardless of the precise leak rate that occurs after a crack extends through the wall of a pressure tube and starts to leak, it is expected that D_2O will enter the AGS at a rate of at least 1 kg/hr within the first hour after leak initiation. However, it is important to note that neither a station's AGS Design Manual nor the CSA Standard N285.8 have anything to say about the *methodology* to be used, or how well it should perform, for D_2O leak detection. Similarly, although Fitness for Service Guidelines for a CANDU power reactor do require the operator to establish a pressure tube leak detection capability that is active at all times during reactor operation, *no leak detection methodology is specified*. A theoretical basis for the LBB methodology as currently applied to CANDU pressure tubes is provided by the equation: *t=CCL- Lp2Va* ……………………..(i) Where: *t* is the time for a crack to propagate to a critical length for fast rupture CCL is the critical crack length L_p is the crack length when it penetrates through the pressure tube wall V_a is the axial crack velocity		

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Equation (i) has *three* unknown variables – CCL, L_p and V_a – and the assignment of meaningful values to these parameters has proven to be quite difficult because of the tremendous scatter in the available experimental data. Thus, for example, we have the values of CCL quoted by Cheadle et al. in "*Operating Performance of CANDU Pressure Tubes*", AECL Report No. AECL-9939, (April, 1989). The CCL values are for Zr-2.5% Nb exposed to 240 – 300 °C D_2O and fast neutron irradiations up to 8×10^{25} n/m^2 and span the range from 40 to 90 mm. Similarly, the same report provides values for V_a in the temperature range 150 – 280 °C. These data show that V_a is strongly dependent on the pressure tube temperature, but even for a *fixed* temperature such as 250 °C, the values of V_a span the range 1×10^{-7} to 6×10^{-7} m/s, (equal to 0.36 to 2.16 mm/hr).		
More recent research has confirmed most of these values for CCL and V_a. For example, consider the report by D. Rogers et al: "*Performance of Pressure Tubes in CANDU Reactors*," CNL Nuclear Review Vol 5, (1), pp 1 – 15, November 2015. Here we read: "*For a test temperature of 250 °C, the CCL ranges from a minimum of ≈ 41 mm to a maximum of >80 mm*". In addition, Rogers et al's 2015 publication includes a plot of a pressure tube's 95% upper bound mean, and lower bound crack growth velocity, as a function of temperature. At 250 °C the data span the range 1×10^{-7} to 4×10^{-7} m/s or 0.36 to 1.44 mm/hr which is similar to Cheadle's 1989 estimate noted above. The value of L_p, the crack length when it first penetrates the pressure tube wall and D_2O starts leaking into the annulus gas system (AGS), is also subject to great uncertainty. It was initially assumed that the upper bound on L_p would be 4W, where W is the wall thickness of a pressure tube, (which is ≈ 4 mm). However, it was subsequently realized that a pressure tube crack may tunnel so that the length of a crack at wall penetration may be considerably larger than 4W – See report by Moan et al: "*Leak Before*	CNSC staff acknowledge there is uncertainty in models and input parameters as discussed previously and many of the studies quoted by the intervenor are considered in the development of the analysis procedures to improve the confidence that adequate safety margins are maintained. It is not expected that an analysis would provide an exact result for a specific pressure tube, but is instead expected to provide a bounding evaluation for the expected performance of leak detection capabilities factoring in potential uncertainties outlined in the intervenor's discussion points. CNSC staff oversight of pressure tube fitness for service programs involves monitoring research activities and operational experience to assess potential impacts that might adversely affect evaluation methodologies.	Le personnel de la CCSN reconnaît que les modèles et paramètres d'entrée sont assortis d'incertitudes, comme il a été mentionné précédemment, et bon nombre des études citées par l'intervenant sont prises en compte dans l'élaboration des procédures d'analyse afin de renforcer la confiance quant au maintien de marges de sûreté adéquates. On ne s'attend pas à ce qu'une analyse donne un résultat exact pour un tube de force donné, mais plutôt à ce qu'elle fournisse une évaluation limitative du rendement attendu des capacités de détection des fuites en tenant compte des incertitudes potentielles décrites dans les points de discussion de l'intervenant. La surveillance par le personnel de la CCSN des programmes d'aptitude fonctionnelle des tubes de force comprend le suivi des activités de recherche et de l'expérience d'exploitation afin d'évaluer les

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Break Experience in CANDU Reactors." AECL Report No. AECL-9609, issued April 1988. Data collected from measurements of pressure tubes removed from Pickering and Bruce has shown that 27 mm is the longest initial crack opening size observed to date. For this reason, the initial crack length, L_p, for pressure tube LBB assessments is often conservatively assumed to be 27 mm. Using these bounding values for the parameters in question we then have: *t=CCL- Lp2Va* *t = (40 – 27)/(2×1.44)* hours *t* = 4.5 hours It is very telling that estimates of the time it takes for a pressure tube crack to reach its critical crack length have varied considerably since the LLB approach to CANDU pressure tube fitness for service assessments was first introduced in the 1970s. Thus a 1988 review by E.G. Price et al. entitled *Leak Before Break Experience in CANDU Reactors* asserted that "*the time available for operator response is about 100 hours*." Remarkably, just two years later, the same authors reduced this estimate to a mere 18 hours in a paper published in the International Journal of Pressure Vessels and Piping in 1990. However, by 1995, a Korean Atomic Energy Research Institute report entitled "*Safety Margin Improvement Against Failure of Zr-2.5Nb Pressure Tubes*", stated that the time for operator action in the event of a DHC-induced pressure tube rupture is 11.7 hours. But ten years later, a 2005 report from the same Korean Institute concluded: "*The time for the operator to take action against a LOCA is 1.7 hours*. More details on the problems associated with the LBB methodology described in CSA Standard CSA N285.8 may be found in the journal		répercussions potentielles qui pourraient avoir des effets négatifs sur les méthodes d'évaluation.

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article: *CANDU Pressure Tube Leak Detection by Annulus Gas Dew Point Measurement: A Critical Review*. Kerntechnik Volume 82, pages 1 -15, (2017).		
Summary of Bruce Power's Position on High [Heq] Issues: **1.** On July 5, 2021, Bruce Power reported that measurements obtained from a Unit 6 pressure tube after 271,729 hot hours of operation showed Hydrogen Equivalent Concentrations ([H_{eq}]) above the generic predictions and exceeding the Licence Condition 15.3 [H_{eq}] limit of 120 parts per million (ppm – by weight). Bruce Power reported that pressure tube B6S13 has a [H_{eq}] of 211 ppm at the burnish mark and 212 ppm at the burnish mark plus 10mm. Also, on July 8, 2021, Bruce Power reported that measurements obtained from a Unit 3 pressure tube showed [H_{eq}] above the generic predictions and above the Licence Condition 15.3 [H_{eq}] limit of 120 ppm. For the Unit 3 pressure tube B3F16, Bruce Power indicated a preliminary measurement of 131 ppm [H_{eq}]. **2.** On September 10th, 2021 CNSC held a Public Hearing where Bruce Power made the following three comments with reference to the high [Heq] data reported in July 2021: **MR. NEWMAN:** *For the record, Gary Newman. Chief Engineer and Senior Vice President of Engineering at Bruce Power:* **(i)**. *High hydrogen concentrations alone do not impact pressure tube integrity. This is why we evaluate, the combination of both hydrogen concentration and flaws. There are no flaws in the region of interest where the elevated hydrogen concentrations are observed on any Bruce unit. This means there is no driver for crack initiation. The higher hydrogen concentrations at the top of the tube is caused by hydrogen redistribution due to a temperature gradient at outlet ends. This is not an overall increase in the amount of hydrogen in the pressure tube, but rather a redistribution to the region of interest*	Deuterium pick-up rates in the rolled joint regions of pressure tubes cannot be evaluated from single measurement locations because of the axial and circumferential and redistribution effects. More accurate estimates of the mass of hydrogen present and ingress rates are obtained from averaging measurements from different axial and circumferential locations from ex-service pressure tubes. The measurements reproduced in the table are from scrape samples within the region outboard of the burnish where the pressure tube contacts the end fitting. Not only are the measurements impacted by circumferential redistribution due to temperature gradients, they can be influenced by local contact conditions between the pressure tube and end fitting. Using scrape sampling of in-service pressure tubes it is only possible to obtain samples from the top half of a tube and experience has shown that estimating the mass of hydrogen present from those measurements is generally conservative. Using this information, the Heq modelling process tends to overestimate the total mass of hydrogen that is available for diffusion. Prior to the 2021 events, the Heq diffusion models only modelled the diffusion in the axial direction. In doing so the modelling generally bounded the total inventory of hydrogen present at specific axial locations of the tubes	Les taux d'absorption du deutérium dans les zones des joints dudgeonnés des tubes de force ne peuvent pas être évalués à partir d'un seul emplacement de mesure en raison des effets liés à la distribution axiale et circonférentielle ainsi qu'à la redistribution. Des estimations plus précises de la masse d'hydrogène présente et des taux de pénétration sont obtenues en faisant la moyenne de mesures prises à différents emplacements, sur le plan axial et circonférentiel, des tubes de force retirés du service. Les mesures reproduites dans le tableau proviennent d'échantillons prélevés par grattage dans la zone s'étendant vers l'extérieur à partir de la marque de brunissage, où le tube de force entre en contact avec le raccord d'extrémité. Non seulement les mesures sont affectées par la redistribution circonférentielle en raison des gradients de température, mais elles peuvent également être influencées par des contacts localisés entre le tube de force et le raccord d'extrémité. Lors de l'échantillonnage par grattage des tubes de force en service, il est seulement possible d'obtenir des échantillons provenant de la moitié supérieure du tube. D'après l'expérience acquise, l'estimation de la masse d'hydrogène présente à partir de ces mesures est généralement prudente. Lorsqu'il est fondé sur cette estimation, le processus de modélisation de la

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(ii). *We do not see an incremental change in the rate of deuterium pick-up, and that's reflected in the modelling and bounding nature of the deuterium predictions we're doing in the largest part of the pressure tube. What we are seeing, though, where that model doesn't work and we've had to go to, now, a new model and a two-dimensional treatment is that we're getting a redistribution of H/D. But it's not a change in the corrosion rate or the pick-up rate; it's actually just -- it's just a redistribution of the hydrogen that's already there.* **3.** In March 2022 Bruce Power submitted an Initial Event Report, CMD 22-M16, which informed the CNSC that *inlet rolled joint*, (IRJ), punch samples from pressure tube B6S13 showed an elevated [Heq] concentration of 126 ppm localized at ~ 10 mm inboard of the burnish mark (BM). Metallographic examinations on these IRJ punch samples showed a significant radial gradient in hydride concentration decreasing from the pressure tube outer diameter (OD) to inner diameter (ID). The radial gradient was confirmed by direct [H] and [D] measurement of radial sections of B6S13 IRJ. Bruce Power acknowledged that the root cause and impact of this discovery on the fitness for service of Bruce pressure tubes remains undetermined. 1. On October 11th, 2022 Bruce Power applied for an Amendment to its Power Reactor Operating Licence. In its application, Bruce Power is seeking to remove licence condition 15.3, which states that "Before hydrogen equivalent concentrations ([Heq]) exceed 120 ppm, the licensee shall demonstrate that pressure tube fracture toughness will be sufficient for safe operation beyond 120 ppm." Bruce Power is, instead, proposing a Licence Amendment that all fitness-for-service requirements related to pressure tubes be incorporated into the existing Licence condition 6.1, which	when averaged over the full circumference. What the models failed to do was reproduce the circumferential redistribution leading to differences at different clock orientations as reported by Bruce Power in 2021. This is significant because the local Heq concentration near a flaw will have a more significant effect on fitness for service evaluations than the circumferential average. Therefore, it is important that the Heq models be able to estimate Heq values at known/possible flaw locations.	concentration de Heq a donc tendance à surestimer la masse totale d'hydrogène disponible aux fins de diffusion. Avant les événements de 2021, les modèles de diffusion du Heq ne permettaient que la modélisation sur le plan axial. Ainsi, lorsque l'inventaire total d'hydrogène présent à certains emplacements précis des tubes sur le plan axial était réparti sur toute la circonférence, il respectait généralement les limites de la modélisation. Ce que les modèles n'ont pas réussi à faire, c'est reproduire la redistribution circonférentielle menant à des différences selon diverses orientations (à l'image des heures sur une horloge), comme l'a signalé Bruce Power en 2021. Cela est important, car la concentration localisée de Heq à proximité d'un défaut aura une incidence accrue par rapport à la moyenne circonférentielle lors de l'évaluation de l'aptitude fonctionnelle. Par conséquent, il est important que les modèles de concentration de Heq puissent estimer les valeurs de Heq à l'emplacement de défaut connus/possibles.

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states simply that “The licensee shall implement and maintain a fitness for service program.” **Discussion:** In July 2021, very high $[H_{eq}]$ levels were measured in pressure tube samples removed from Bruce Units 3 and 6. At a CNSC Public Meeting held on September 3rd, 2021, to discuss this finding, Bruce Power was asked by Commissioner Lacroix for its interpretation of this observation, to which Bruce Power Chief Engineer, Gary Newman, replied: “*We're not seeing a change in the rate of hydrogen uptake. What we're seeing is a redistribution (of the hydrogen) to the cooler region at the top of the pressure tube. So, it’s not an acceleration but a redistribution*”. Here we see Bruce Power proposing that the very high $[H_{eq}]$ levels measured in a number of pressure tubes from Bruce Units 3 and 6 are simply due to a *redistribution* of ingressed H/D and that this ingress does not represent *acceleration* in the H/D pickup rate. However, in order to validate the assertion that there is no accelerated H/D ingress occurring in Bruce pressure tubes, we need to look for evidence of this in the available data. With this in mind, I have collected recent data reported for Bruce Unit 3 pressure tubes near the 12 o’clock location as shown in Table 5, below. The Table includes values for the initial hydrogen in the pressure tube ingot, $[H_{Init}]$, which is needed to make a small correction to the hydrogen pickup data used in calculating the ratio $\{[H]_{Cor} /0.5[D]\}$, where: $[H]_{Cor} = [H] - [H_{Init}]$		

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Table 5: Hydrogen and Deuterium Concentrations Near the Outlet Rolled Joints in Selected Pressure Tubes from Bruce Unit 3

Pressure Tube ID (~10 mm from ORJ [Ref 1])	[D] (mg/kg)	[H] (mg/kg)	$[H_{Init}]$ (mg/kg)	Ratio $\{[H]_{Cor} / 0.5[D]\}$
F16	1340	111	12.6	0.147
L11	790	60	9.3	0.128
G15	853	103	11.3	0.181
K10	1016	74	7.4	0.156
Q16	853	96	10.9	0.233
H06	730	66	15.0	0.329
X09	475	73	14.9	0.245
O20	921	96	12.3	0.182
Q12	850	99	10.2	0.209
N04	337	58	14.7	0.257
O15	303	56	8.7	0.312
O17	122	28	9.0	0.311
O13	443	72	12.5	0.269
P14	191	34	9.0	0.262
Q13	582	87	11.7	0.259
L12	156	27	6.7	0.260
F05	75	25	11.7	0.355
L22	42	24	9.3	–
R10	199	26	5.5	0.206
S13	314	38	6.0	0.204

Ref 1: ORJ = Outlet Rolled Joint

Inspection of the data in Table 5 shows that there is a great deal of variability in the deuterium concentrations in these samples: from a high of

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1340 mg/kg for sample F16, to a low of 42 mg/kg in sample L22. In a few cases, such as sample X09, the pressure tube outlet temperatures are known to be somewhat lower, (~ 290 °C), than the temperatures for samples from high power channels such as L12, (~ 297 °C); however, the D pickups for these samples are the reverse of what might be expected based in these temperatures alone; thus, the D-pickup is 475 mg/kg for X09, but only 156 mg/kg for L12.		
As noted above, Table 5 includes values of the $[H]_{Cor}/\{0.5\times[D]\}$ ratio, where $[H]_{Cor}$ represents the *corrected* hydrogen concentration, derived by subtracting $[H_{Init}]$ from the measured [H], and the factor of 0.5 in the denominator is needed to convert the ratios to *atom ratios*. What is noteworthy about these values is that the atom ratios are relatively constant, averaging 0.24 ± 0.08, even though the tube-to-tube values of $[H_{eq}]$ vary by a factor of more than 20. The most important question concerning the data in Table 5 relates to the notion of “redistribution” of ingressed H/D. This phenomenon has been proposed by Bruce Power to explain the high H/D levels observed in some B3 and B6 tubes analyzed in July 2021. However, the suggestion that ingressed H/D could *redistribute* within the wall of a pressure tube is not new. Thus, in a COG Report issued in 1998, we read in an Appendix C entitled: “*Influence of Temperature & Concentration Gradients on the Redistribution of Hydrogen Isotopes*”: *Based on a thermal hydraulic simulation, temperature differences between the 6 and 12 o'clock locations in a tube with 2% diametral creep have been calculated to be 20 °C. Modeling results, assuming a 20 °C temperature difference, show that the deuterium concentration may be up to ~ 17% higher at the top compared to the bottom of the pressure tube.* The modeling calculation referred to in this COG Report is for a pressure tube after about 12 EFPY of operation which was the longest exposure of	The Arrhenius-type equation only applies to the concentration of hydrogen that is in solution and free to diffuse in the material. After the concentration exceeds solubility limits, some of the hydrogen becomes permanently locked in the form of solid zirconium hydrides and is no longer free to diffuse. During cooldown cycles, the solubility limits drop and more hydrogen becomes trapped in solid form and does not fully dissolve during heat up to full power operation. This is a process that is referred to as hydride ratcheting. This process will lead to higher local Heq due to circumferential temperature gradients that cannot be explained by the Arrhenius-type equation alone. This was previously discussed by CNSC staff in CMD 23-M3. In CMD 22-M37.5 another intervenor made a similar assertion that the circumferential gradient was not sufficient based on the Arrhenius-type diffusion equation, but retracted the assertion in CMD 23-M27.11 with an acknowledgement that consideration of solubility limits and ratcheting effects were omitted from his earlier assessment.	L'équation d'Arrhenius ne s'applique qu'à la concentration d'hydrogène sous forme de solution qui peut se diffuser librement dans le matériau. Lorsque la concentration dépasse les limites de solubilité, une partie de l'hydrogène est piégé de façon permanente sous forme d'hydrure de zirconium à l'état solide et ne peut plus se diffuser librement. Au cours des cycles de refroidissement, les limites de solubilité diminuent, et une plus grande quantité d'hydrogène est emprisonnée sous forme solide et ne se dissout pas complètement durant le réchauffement en vue de l'exploitation à pleine puissance. Il s'agit d'un processus qu'on appelle le rochetage d'hydrure. Ce processus aboutira à une augmentation localisée de la concentration de Heq en raison de gradients circonférentiels de température qui ne peuvent être expliqués uniquement par l'équation d'Arrhenius. Le personnel de la CCSN a déjà abordé la question dans le CMD 23-M3. Dans le CMD 22-M37.5, un autre intervenant a fait une affirmation semblable, selon laquelle le gradient circonférentiel n'était pas adéquatement fondé sur l'équation d'Arrhenius, mais il a retiré son affirmation dans le CMD 23-M27.11. Il a reconnu que la prise en

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pressure tubes in Canadian reactors at that time (1998). If we extrapolate this calculation to currently operating Units, we would expect the diametral creep to have increased from ~ 2% to ~ 6%. The resulting diffusional redistribution of H/D may then be estimated using the following formalism: Assuming that the diffusion of hydrogen isotopes in zirconium alloys is a thermally activated process, an Arrhenius-type temperature dependence is expected which may be modelled by the following equation: $\ln\{[D_{12}]/[D_6]\} = (Q/R) \times \Delta T/(T_6 \times T_{12})$ where, $[D_{12}]$ is the deuterium concentration near the pressure tube outlet at 12 o'clock $[D_6]$ is the deuterium concentration near the pressure tube outlet at 6 o'clock Q is the activation energy for deuterium diffusion in Zr-2.5Nb = 22.7 kJ $mol^{-1}K^{-1}$ R is the gas constant = 8.314 J $mol^{-1}K^{-1}$ T_6 is the temperature at the bottom, 6 o'clock, position at the outlet of the pressure tube T_{12} is the temperature at the top, 12 o'clock, position at the outlet of the pressure tube ΔT is the temperature difference between the 6 o'clock and 12 o'clock locations Figure10, below, is a graphical representation of this equation plotted for ΔT values up to 40 °C, which may be considered as the highest value of ΔT achievable in mature pressure tubes.	While Heq remains below solubility limits at normal operating temperatures the $[D_{12}]/[D_6]$ ratios should remain nominally the same since the difference from the top to bottom is dominated by the temperature gradient. As the solubility limit is exceeded in the top of a tube, more of the hydrogen isotopes become locked in the form of solid hydrides in the top portion of a tube and the $[D_{12}]/[D_6]$ would be expected to increase.	compte des limites de solubilité et des effets de rochetage avait été omise dans son évaluation antérieure. Bien que le Heq demeure sous les limites de solubilité à des températures normales d'exploitation, les rapports $[D_{12}]/[D_6]$ devraient en principe demeurer les mêmes puisque la différence entre les parties supérieure et inférieure est dominée par le gradient de température. À mesure que la limite de solubilité est dépassée dans la partie supérieure d'un tube, un plus grand nombre d'isotopes de l'hydrogène sont piégés sous forme d'hydrures solides dans la partie supérieure du tube, et on s'attend à ce que les rapports $[D_{12}]/[D_6]$ augmentent.

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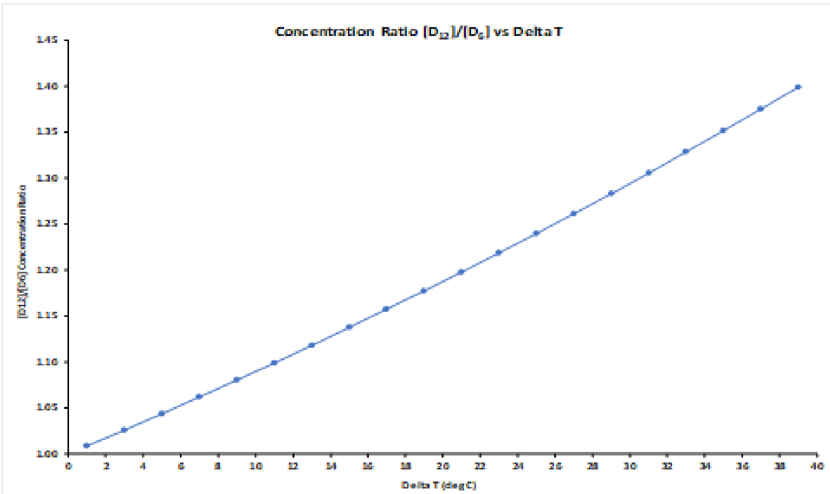
Figure 10: Deuterium Concentration Ratio $[D_{12}]/[D_6]$ vs. $\Delta T = (T_6 - T_{12})$  This formalism was previously used to analyze [H] and [D] concentration data in the P3LSFCR sample set at different clock positions and locations approximately 150 mm from the pressure tube outlets – see for example, OHRD 1994 Report A-NFC-94-115-K. For this particular case the observed [D12]/[D6] ratios were in the range 1.18 ± 0.06 corresponding to a ΔT of 20 °C which is in good agreement with predictions of ΔT for a CANDU reactor after 12 EFPY of Unit operation. Similar H/D data for a Darlington pressure tube, (D3S13), after 25 EFPY was recently reported by OPG – See the July 2021 OPG Memo: NK38-CORR-31100-0934854. For this pressure tube, data are reported at distances between 8- and 120-mm inboard of the outlet rolled joint and at several different circumferential (clock) positions. The observed [D12]/[D6] ratios for these samples are in the range 1.25 ± 0.05 corresponding to a ΔT of about 25 °C. Once again, these values are in good agreement with predictions of ΔT for a CANDU reactor after 25 EFPY of Unit operation.		

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Turning now to [H/D] data for a Bruce pressure tube, namely B6S13, (See OPG Memo: NK38-CORR-31100-0934854), we find the observed [D12]/[D6] ratio is about 3 which gives a physically unrealistically high value > 60 °C for the corresponding ΔT. This indicates that an additional, (non-thermally activated), process is involved in the H/D ingress into the B6S13 pressure tube. This conclusion is supported by the behavior of H (light hydrogen) in the B6S13 sample which is quite different to the behavior of H in the D3S13 sample, as shown in Figure 11, below. This, once again, is a good indication of an additional source of H/D for the B6S13 sample.		

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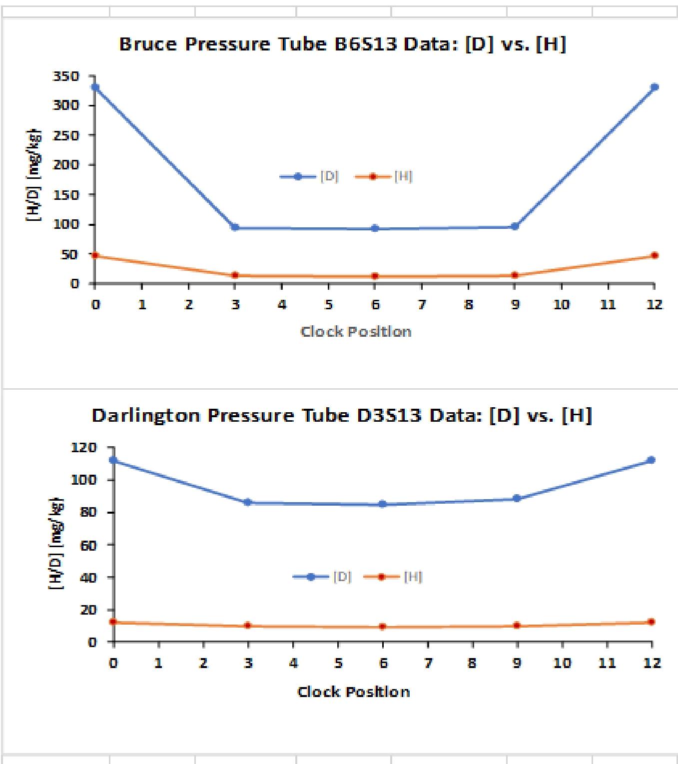
Figure 11: [D] and [H] for Pressure Tubes at Different Clock Positions: **Data for Bruce and Darlington near the Outlet Rolled Joints**  The data in Figure 11 are taken from measurements using hot vacuum extraction spectrometry reported in March 2021 by B. Payne at the Canadian Nuclear Laboratories – See Report # COG-19-1034. These results are also discussed in a CNL memo, (ID No: RCC-21-018), dated September 17th 2021, entitled: *Concentrating Hydrogen Isotopes at the Top of Tube at the Outlet rolled Joint Region*, where we read:	Protium is subject to diffusion and redistribution in the same way as deuterium. Hence, the total mass of protium cannot be inferred from spot measurements. It stands that regions with elevated deuterium concentrations from redistribution would also have elevated protium. If the protium measurements were averaged over a larger volume of material over the full circumference the average mass would be much lower than the measurements in Table 6 indicate. When the hydrogen concentration exceeds the solubility limits protium becomes locked in place as solid hydrides which will lead to local increases in concentration. The KAPS scenarios were attributed to use of CO_2 annulus gas containing an unlisted impurity (ethylene) that lead to the breakdown of the protective oxide layer on the outside surface of the pressure tubes and visible external pitting corrosion of the tube [1]. The Canadian utilities use food grade CO_2 (i.e. CO_2 that would be used to carbonate beverages). Hence the ethylene impurity is not present in Canadian reactor AGS systems. Additionally, a small amount of oxygen is added to the annulus gas system to ensure that the oxide layer is maintained during operation. Visual examination of ex-service pressure tubes removed from the Canadian reactors have exhibited no external surface corrosion pitting in pressure tubes that have been in service longer than the KAPS tubes.	Le protium est sujet à la diffusion et à la redistribution de la même manière que le deuterium. Par conséquent, la masse totale de protium ne peut pas être inférée à partir de mesures ponctuelles. Il va de soi que les zones présentant une concentration élevée de deutérium à la suite de la redistribution présenteraient aussi une concentration élevée de protium. Si les mesures du protium étaient réparties sur un plus grand volume de matériaux couvrant toute la circonférence, la masse moyenne serait bien inférieure aux mesures indiquées au tableau 6. Lorsque la concentration d'hydrogène dépasse les limites de solubilité, le protium est emprisonné sous forme d'hydrures solides, ce qui donne lieu à une hausse localisée de la concentration. Les scénarios associés à la centrale nucléaire KAPS ont été attribués à l'utilisation d'un gaz annulaire de CO_2 contenant une impureté non répertoriée (éthylène), ce qui a mené à la dégradation de la couche protectrice d'oxyde et à une corrosion par piqûres visible sur la surface extérieure des tubes de force [1]. Les installations canadiennes utilisent du CO_2 de qualité alimentaire (c.-à-d., le CO_2 qui sert à gazéifier les boissons). Par conséquent, cette impureté (l'éthylène) n'est pas présente dans le circuit du gaz annulaire (CGA) des réacteurs canadiens. De plus, une petite quantité d'oxygène est ajoutée au CGA pour s'assurer que la couche d'oxyde est maintenue en cours d'exploitation. Un examen visuel n'a révélé aucune corrosion par piqûres sur la surface extérieure de tubes de force retirés du service, qui avaient été enlevés de réacteurs canadiens et qui étaient en service depuis

Intervenor Comments from CMD 26-M10.3 Commentaires par un intervenant dans CMD 26-M10.3	CNSC Staff Clarifications	Précisions du personnel de la CCSN
Hydrogen isotopes in the rolled joint region of the pressure tube originate from three sources: hydrogen initially present in the tube from fabrication, deuterium (including minor amounts of hydrogen) entering the tube during operation from corrosion reactions between the tube and coolant, and deuterium (including minor amounts of hydrogen) entering the tube from the stainless-steel end fitting during operation from corrosion reactions between the end fitting and coolant. The operational sources are evaluated during surveillance examinations and ingress through the end fitting has been observed to be the greater contributor to hydrogen isotope concentrations in this region. For the case of B6S13, the ingress through the inside surface of the pressure tube is in line with other surveillance tubes and scrape campaigns, while the ingress through the rolled joint is marginally greater but well within prior experience projected forward. There is no need, or obvious evidence, for an additional and unknown source of hydrogen to account for the current observations. There are two statements that I would question in this CNL assessment of the root cause of the high [H_{eq}] observed in pressure tube B6S13: (i) The statement that there are only ***three*** sources of the hydrogen observed in the vicinity of the outlet rolled joint region of a pressure tube (ii) The statement that "*there is no need, or obvious evidence, for an additional and unknown source of hydrogen*" Both of these statements ignore the existence of H/D entry into a pressure tube from the ***annulus gas system***. Certainly, the three operational sources of H/D identified in this CNL memo are generally considered to be the *major* sources of H/D in CANDU pressure tubes; however, H/D entry from the AGS cannot be ruled out *a priori*. Indeed, there are ***two*** recent examples of pressure tube failures from high H/D pickup – namely, KAPS-2 on July 1, 2015 and KAPS-1 on March 11, 2016 – that were attributed to H/D entry from the AGS of these Units. Specifically, for item (i) above, it is		plus longtemps que les tubes de force de la centrale nucléaire KAPS.

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important to consider potential H/D pickup contributions of *light hydrogen*, H – as opposed to heavy hydrogen, D – to the total hydrogen pickups observed in Bruce pressure tubes. The CNL memo identifies two such sources: • Hydrogen initially present in the tube from fabrication • Hydrogen present in the primary heat transport water Table 5 of this report includes values for the initial hydrogen, H_{Init}, for twenty Bruce Unit 3 pressure tubes, from which an average value for [H_{Init}] of 10 ± 5 mg/kg may be calculated. If we conservatively take an upper limit of 15 mg/kg for [H_{init}], this represents the *minimum* value for [H] after in-reactor exposure of these tubes. It follows that any [H] value *greater* than 15 mg/kg is due to entry from external sources of hydrogen such as the heat transport water. However, as previously noted, heat transport D_2O is specified to have an isotopic purity of at least 99.3 % deuterium, so that the light hydrogen content is only 0.7%. Using these data, it is possible to estimate a *theoretical hydrogen pickup*, [H_{calc}] for each of the twenty measured deuterium pickups referred to above. Thus, starting with the initial hydrogen contents, [H_{Init}], noted in Table 5, we add a contribution from hydrogen that is assumed to have entered the pressure tube as a fixed, (small), percentage of the measured ingressed deuterium. To allow for kinetic isotope effects in the corrosion reactions leading to such hydrogen ingress, (which depends on the square root of the ratio of the atomic mass of deuterium to the atomic mass of hydrogen), this percentage hydrogen ingress is assumed to be equal to √2 × 0.7%, or 1.0% of [D]. Table 6, below, shows the observed [D] and [H] data for twenty Bruce 3 pressure tubes, as well as the calculated hydrogen concentrations, [H_{calc}], expressed as a percentage of the observed [H].		

Table 6: Hydrogen and Deuterium Concentrations Near Bruce Unit 3 Outlet Rolled Joints: Comparison of Data at Three Locations Including [H] Predictions as a % of Observations

Bruce Unit 3	Data for Samples taken at 10 mm			Data for Samples taken at 55 mm			Data for Samples taken at 112 mm		
Pressure Tube ID	[D] (mg/kg)	[H] (mg/kg)	$[H]_{calc}$ as % of Obs	[D] (mg/kg)	[H] (mg/kg)	$[H]_{calc}$ as % of Obs	[D] (mg/kg)	[H] (mg/kg)	$[H]_{calc}$ as % of Obs
F16	1340	111	23.4	670	67	28.8	241	31	48.4
L11	790	60	28.7	350	29	44.1	99	12	85.8
G15	1016	103	20.8	531	63	26.4	178	30	43.6
K10	853	74	21.5	330	35	30.6	120	26	33.1
Q16	730	96	19.0	314	51	27.5	130	32	38.1
H06	310	66	27.4	171	42	39.8	104	41	39.1
X09	475	73	26.9	186	40	41.9	107	24	66.5
O20	921	96	22.4	451	53	31.7	218	35	41.4
Q12	850	99	18.9	400	52	27.3	142	29	40.1
N04	337	58	31.2	87	22	70.8	100	28	56.1
O15	303	56	20.9	151	31	32.9	94	24	40.2
O17	122	28	36.5	103	26	38.6	89	20	49.5
O13	443	72	23.5	216	50	29.3	108	26	52.2
P14	191	34	32.1	125	24	42.7	86	22	44.8
Q13	582	87	20.1	341	61	24.8	139	29	45.1
L12	156	27	30.6	99	23	33.4	83	19	39.6
F05	75	25	49.8	82	23	54.4	69	27	45.9
L22	42	24	40.5	42	21	46.3	43	18	54.1
R10	199	26	28.2	122	20	33.6	93	16	40.2
S13	314	38	24.1	133	19	38.6	98	17	41.1
Averages	–	–	27.4	–	–	37.2	–	–	47.2

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Table 6 shows that for these B3 pressure tubes, the observed light hydrogen concentrations are significantly *higher* than the predicted concentrations. In particular, and taking *average* values, the measured light hydrogen concentrations, [H], are 3.7, 2.7 and 2.2 times higher than the calculated values at the 10 mm, 55 mm and 112 mm locations, respectively. First, however, it is important to note that the theoretical [H] values in Table 8 are calculated based on the following assumptions: (i) The heat transport D_2O is the sole source of both hydrogen and deuterium pickup. (ii) The heat transport D_2O in Bruce Unit 3 contains ~ 1% H_2O (iii) The calculated [H] values are corrected for contributions from the initial hydrogen in the Zr-2.5Nb ingot used to fabricate the pressure tube. The fact that the observed concentrations are up to three times *higher* than the calculated concentrations is clear evidence that B3 pressure tube hydrogen isotope pickups near their outlet rolled joints do not conform with the proposal that H/D entry into these pressure tubes comes solely from heat transport D_2O. Furthermore, this excess light hydrogen needs to be explained because it contradicts the claim, made in the CNL memo, (ID No: RCC-21-018), dated September 17th 2021, that "*there is no need, or obvious evidence, for an additional and unknown source of hydrogen*."		
However, it is acknowledged that there are examples of pressure tubes in other CANDU reactors that *are* consistent with H/D entry solely from the heat transport system. Thus, consider the H/D data reported in the July 2021 OPG Memo: NK38-CORR-31100-0934853 for the Darlington pressure tube D3S13, as shown in Table 7, below. The calculated [H] values in the Table are derived assuming an average [H_{Init}] of 10.5 mg/kg for the three samples of interest.	The Heq for the measurement locations is below the solubility limit of the material, so the measurements are not impacted by the ratcheting phenomenon and all hydrogen present is free to diffuse at full power operating temperatures. Therefore, these measurements are less impacted by circumferential temperature gradients than the B6 tube measurements	La concentration de Heq aux emplacements des mesures est inférieure à la limite de solubilité du matériau, de sorte que les mesures ne sont pas affectées par le phénomène de rochetage et que tout l'hydrogène présent peut se diffuser librement aux températures d'exploitation à pleine puissance. Par conséquent, ces mesures sont moins affectées par les

<table>
<tr><th>Intervenor Comments from CMD 26-M10.3
Commentaires par un intervenant dans CMD 26-M10.3</th><th>CNSC Staff Clarifications</th><th>Précisions du personnel de la CCSN</th></tr>
<tr><td>
Table 7: H and D Concentration Data Near a Darlington Unit 3 Outlet Rolled Joint: Comparison of Data at Three Locations Including [H] Predictions as a % of Observations
<table>
<tr><th rowspan="2">Darlington Unit 3 Pressure Tube ID</th><th colspan="3">Data for Samples taken at 8 mm</th><th colspan="3">Data for Samples taken at 64 mm</th><th colspan="3">Data for Samples taken at 79 mm</th></tr>
<tr><th>[D] (mg/kg)</th><th>[H] (mg/kg)</th><th>$[H]_{calc}$ as % of Obs</th><th>[D] (mg/kg)</th><th>[H] (mg/kg)</th><th>$[H]_{calc}$ as % of Obs</th><th>[D] (mg/kg)</th><th>[H] (mg/kg)</th><th>$[H]_{calc}$ as % of Obs</th></tr>
<tr><td>D3S13</td><td>109</td><td>12</td><td>96.6</td><td>112</td><td>12</td><td>96.8</td><td>122</td><td>12</td><td>97.7</td></tr>
</table>
In contrast to the corresponding data for Bruce Unit 3, (See Table 6, above), these Darlington Unit 3 samples show calculated [H] values that are within a few percent of the observed [H] values. Thus, in the case of the D3S13 pressure tube at least, the observed H/D entry at the outlet rolled joint is consistent with the heat transport D2O being the sole source of ingressed hydrogen.
</td><td>shown in Table 6 where hydrogen concentrations exceed solubility limits at the measurement locations by significant margins.</td><td>gradients circonférentiels de température que les mesures associées au tube B6 présentées au tableau 6, selon lesquelles les concentrations d'hydrogène dépassent largement les limites de solubilité aux emplacements de mesure.</td></tr>
<tr><td>As previously noted, a number of Canadian nuclear industry experts have suggested that the root cause of the high [Heq] observed near the outlets of some Bruce Unit 3 & 6 pressure tubes is the redistribution of ingressed [Heq] induced by diffusion of H/D in the temperature gradient at this location; with the top of the pressure tube being cooler than the bottom by about 25 °C, so that ingressed hydrogen migrates to, and accumulates at the cooler top of the tube.

However, if this is in fact true, evidence for H/D thermal diffusion in a circumferential temperature gradient should be observed at the outlets of all mature CANDU pressure tubes, which is certainly not the case for the D3S13 example noted above. Furthermore, proponents of the diffusional redistribution of H/D as the sole cause of the high [Heq] observed at the 12 o'clock position near a pressure tube outlet, should explain how at least</td><td>Not all pressure tubes pick-up hydrogen at the same rate. There are operational factors including differences in operating temperature, plus there are random variables that can influence pickup rates between the pressure tube and end-fitting connections that affect pick-up rates. For instance, if the oxide layer on the OD surface is scraped off when the pressure tube is inserted into the end fitting, bare metal to metal contact can enhance hydrogen uptake locally compared to locations where the oxide layer is not damaged. It is not possible for the Heq modelling process to address such tube-to-tube variabilities. The focus of Heq model development is to take a larger sample of data from multiple tubes and provide bounding predictions.</td><td>Les tubes de force n'absorbent pas tous l'hydrogène à la même vitesse. Il existe des facteurs opérationnels, notamment les différences de température d'exploitation, ainsi que des variables aléatoires qui peuvent influer sur les taux d'absorption entre les tubes de force et les raccords d'extrémité. Par exemple, si la couche d'oxyde sur la surface extérieure est éraflée lorsque le tube de force est inséré dans le raccord d'extrémité, un contact entre deux pièces de métal nu peut accroître l'absorption locale d'hydrogène, par comparaison avec les emplacements où la couche d'oxyde est intacte. Le processus de modélisation du Heq ne peut tout simplement pas tenir compte des variabilités d'un tube à l'autre. La mise au</td></tr>
</table>

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five Bruce Unit 3 pressure tubes could pick up close to 100 mg/kg of light hydrogen at this location.	The new Heq models incorporating circumferential redistribution of hydrogen will not be able to estimate exact Heq values for specific tubes. Instead modelling focused on providing bounding estimates for the population of the tubes in a reactor core. In doing so, this will likely overestimate Heq levels for many pressure tubes, but this will be a conservative input into fitness for service evaluations.	point du modèle de concentration de Heq vise principalement à incorporer un échantillon élargi de données provenant de multiples tubes et à fournir des prédictions limitatives. Les nouveaux modèles de concentration de Heq intégrant la redistribution circonférentielle de l'hydrogène ne seront pas en mesure d'estimer la valeur de Heq exacte associée à un tube donné. La modélisation vise plutôt à fournir des estimations limitatives pour la population de tubes dans le cœur d'un réacteur. Ainsi, les concentrations de Heq pour de nombreux tubes de force seront probablement surestimées, mais il s'agira d'un paramètre d'entrée prudent pour l'évaluation de l'aptitude fonctionnelle.
The corresponding heavy hydrogen pickups were approximately 1000 mg/kg, (See Table 5). This implies a H/D *atom ratio* of about 0.2. And one has to ask: What is the *source* of this light hydrogen? Surely the answer must be: the light hydrogen is coming from the AGS of these Units. So, we need to consider evidence for the presence of light hydrogen in operating AGS. Unfortunately, there are only a few published data on light hydrogen concentrations, (H_2 or H_2O), in CANDU AGS; however, as shown below, what little data there is, shows three significant trends: (i) Measured H/D atom ratios are typically in the range 0.1 to 0.25 (ii) H/D ratios are highest immediately after an AGS purge and decrease over time (iii) H/D ratios tend to be higher in the AGS of older Units	CNSC staff acknowledge that in the 1980s and 1990s the AGS was a contributor to early operation issues with CANDU pressure tubes, which led to higher hydrogen pick-up rates. However, since the AGS gas has been changed to CO_2 with oxygen addition there have been decades of operation without a repeat of the early life incidents. If the AGS remained a significant source of protium pickup, higher protium concentrations would be expected along the entire length of the pressure tube exposed to the AGS gas. Measurements have shown otherwise. In the body of the pressure tube away from the rolled joint regions the protium concentrations are generally close to initial hydrogen measurements from samples of the pressure tubes that are retained prior to pressure tube installation.	Le personnel de la CCSN reconnaît que, dans les années 1980 et 1990, le circuit du gaz annulaire (CGA) a été mis en cause dans le contexte des problèmes précoces d'exploitation des tubes de force CANDU, ce qui a donné lieu à des taux accrus d'absorption d'hydrogène. Cependant, depuis le remplacement du gaz annulaire par un mélange de CO_2 enrichi d'oxygène, le CGA a été exploité durant des décennies sans que de tels incidents surviennent de nouveau. Si le CGA demeurait une source importante d'absorption de protium, on s'attendrait à déceler une concentration supérieure de protium sur toute la longueur du tube de force exposé au gaz du CGA. Les mesures ont démontré le contraire. Dans le corps du tube de force, loin des zones du joint dudgeonné, les concentrations de protium sont généralement

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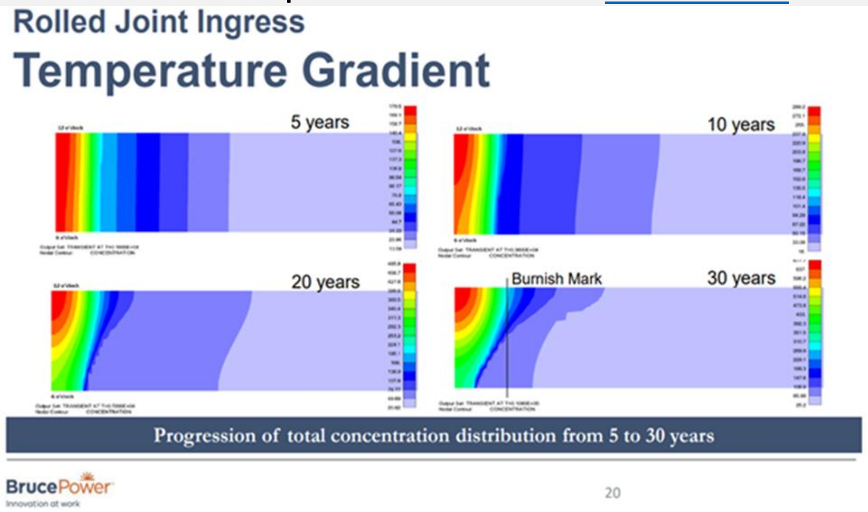
Available evidence suggests that the largest contributor to light water in an AGS is the CO_2 gas supply itself. This is because, at its specified dewpoint of – 45 °C, CO_2 that is deemed to be "dry", nevertheless contains about 70 vpm H_2O. Studies caried out by myself in the period 1990 to 1998 have shown that light hydrogen, in the form of absorbed water, (H_2O), is always present on the pipework of an AGS and is only *partially desorbed* after system exposures of over 3 hours to dry CO_2, as in a typical AGS purge. (See OHRD Report A-NFC-96-114-P and COG Report COG-96-308). Such incomplete purges leave significant amounts of light water, H_2O, in the system; and this becomes the initial condition of an AGS at the start of its inter-purge period which usually lasts between 5 and 15 days depending on the Unit. During this time period, water – now mostly as D_2O – builds up in the system via the reverse water gas shift reaction, ($D_2 + CO_2 \rightarrow D_2O$ + CO), which is in line with trend (ii) noted above.		semblables aux mesures initiales d'hydrogène prises à partir d'échantillons prélevés sur les tubes de force avant leur installation.
Issues of Concern: 1. For my first issue I wish to address some of the material presented by Bruce Power on September 10th, 2021, at CNSC Public Hearing CMD 21-H11.2A. Specifically, I am especially interested in Slide No. 20 from this Hearing – as shown below:	The information provided in CMD 21-H11.2A was not developed from a fully validated model and was an early attempt at explaining the observations from tube B6S13. At the time it was presented, CNSC staff expressed similar comments to the Commission noting that a significant research effort would be required to verify and validate such a model. The industry research and development program deliverables addressed verification, validation and sensitivity studies. The reports documenting this information are proprietary to the licensees so specific details are not shared by CNSC staff in CMD 26-M10. However, some of the work has been published in the public domain CMD 21-H11.2A.	Les renseignements fournis dans le CMD 21-H11.2A n'ont pas été produits à partir d'un modèle entièrement validé et constituaient une première tentative en vue d'expliquer les observations associées au tube B6S13. Lorsque ces renseignements ont été présentés, le personnel de la CCSN a formulé des commentaires semblables à l'intention de la Commission, soulignant qu'un effort de recherche important serait nécessaire pour vérifier et valider un tel modèle. Les livrables du programme de recherche et développement de l'industrie portant sur la vérification, la validation et les études de sensibilité. Les rapports documentant ces renseignements sont la

Intervenor Comments from CMD 26-M10.3 Commentaires par un intervenant dans CMD 26-M10.3	CNSC Staff Clarifications	Précisions du personnel de la CCSN
 Slide No. 20 is entitled: "*Temperature Gradient*" – suggesting it could provide some insight into the alleged hydrogen redistribution phenomenon; but most remarkably, *no temperature gradient data whatsoever are provided by Slide 20*. Instead, we are presented with hydrogen concentration profiles calculated for a generic pressure tube outlet rolled joint after 5, 10, 20 and 30-years of Unit operation, *with no indication as to how these concentration profiles were determined*. Worse yet, *the magnitude of the alleged temperature gradient is not even mentioned in Slide 20*, and neither is any information provided as to the values of the diffusion coefficients and H/D ingress rates that must have been used to calculate these concentration profiles. However, regardless of the paucity of useful information provided by Slide 20, we know that Bruce Power's so-called "predictive model" for [Heq] in operating pressure tubes has been *seriously in error* for many years. By way of acknowledging this problem, Bruce Power agreed back in July 2021 to undertake the "*development of a predictive model accounting for elevated [Heq] and*		propriété exclusive des titulaires de permis. Par conséquent, le personnel de la CCSN n'a pas inclus de renseignements précis dans le CMD 26-M10. Toutefois, certains des travaux ont été publiés dans le domaine public CMD 21-H11.2A.

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circumferential variation of [Heq] observed in the outlet rolled joint region. – See Bruce Power's letter to the CNSC File No. BP-CORR-00531-01884. Now, I assume that Slide 20 represents [Heq] values derived from Bruce Power's promised new and improved "predictive model" for [Heq] in its operating pressure tubes. But, for such a model to be scientifically valid, and not merely a curve fitting exercise, it should clearly identify its starting assumptions, input parameters and computational methodology – which is something that has never been provided by Bruce Power. From this observation I believe that Bruce Power's current attempt to predict H/D pickup at pressure tube rolled joints – as exemplified by Slide 20 – is totally unacceptable because it is entirely lacking in scientific rigor, and adds nothing to our understanding of this high H/D pickup phenomenon. But I have to ask if the CNSC would agree with this assessment, or please show me where I am in error.		
2. My second issue concerns statements made by CNSC staff member Blaire Carroll at the CNSC Public Meeting held on September 3rd, 2021, (See, CMD 21-M39/21-M37/21-M37.A), as follows, (with my emphasis in red): **MR. CARROLL:** *For the record, my name is Blaire Carroll. I'm a technical specialist with the Operational Engineering Assessment Division at the CNSC. Dr. Viktorov has provided overall a very good answer from the CNSC staff perspective. We do understand--or we don't understand the root cause at this point. And with regards to some of the modelling that Bruce Power has provided in its presentation, that has not been formally submitted to CNSC staff yet, so we have not completed a technical review of that. In theory, it would be the thermal gradients that would move the hydrogen to the top of the pressure tube because that's where the tube is coldest, and the hydrogen tends to migrate to the colder temperature locations in the tube. That would explain*	CNSC staff was not satisfied with the explanation when first presented in 2021 because it was not supported by an appropriate technical justification. Following staff recommendations, Bruce Power and OPG were requested to submit: *a detailed plan to improve hydrogen equivalent concentration predictions near the rolled joints and evaluate the effect of increased hydrogen equivalent concentrations on pressure tube fitness for service evaluations*. The plans were submitted in CMD 22-M37.1 and CMD 22-M37.3. CMD 26-M10 summarizes CNSC staff's conclusions regarding the deliverables of the multi-year industry research and development program. CNSC staff has concluded that the theory proposed by industry in 2021 is now supported by an adequate technical justification.	Le personnel de la CCSN n'était pas satisfait de l'explication lorsqu'elle a été présentée pour la première fois en 2021, car elle n'était pas appuyée par des documents justificatifs techniques appropriés. À la suite des recommandations du personnel, Bruce Power et OPG ont été invitées à soumettre un plan détaillé visant à améliorer les prédictions relatives à la concentration de Heq près des joints dudgeonnés et à évaluer l'effet d'une concentration accrue de Heq sur l'évaluation de l'aptitude fonctionnelle des tubes de force. Les plans ont été soumis dans le CMD 22-M37.1 et le CMD 22-M37.3. Le CMD 26-M10 résume les conclusions du personnel de la CCSN à l'égard des livrables du programme pluriannuel de recherche et développement de

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why the concentration is highest at the top. But it doesn't explain the magnitude of the concentration that's been seen, and that's an area where CNSC staff is expecting licensees to do more work to try to determine the cause of the elevated values. This statement by CNSC Staff Member Carroll suggests that the CNSC is not satisfied with Bruce Power's hydrogen diffusion explanation of the high [Heq] observed in some of its pressure tubes. I therefore have to ask, one year on from this statement by a CNSC staff member, if Bruce Power has "*done more work*" and provided the CNSC with an acceptable and experimentally verified root cause of these elevated [Heq] values?		l'industrie. Le personnel de la CCSN a conclu que l'hypothèse proposée par l'industrie en 2021 est maintenant appuyée par une justification technique adéquate.
Issue 3: I believe one of the most important issues concerning Heq pick up is the need for a *root cause* of the high [Heq] first reported in July 2021 for several pressure tubes operating in Bruce Units 3 & 6. Indeed, it is very troubling that it is now over three years since this problem with Bruce pressure tubes was first discovered and, remarkably, the Canadian nuclear industry, and its paid supporters in academia, have only offered a very sketchy qualitative, not quantitative, theory as to the cause of Bruce Units 3 & 6 high [Heq}that is totally lacking in supporting evidence. The basis of the nuclear industry's current theory is twofold: (i) Deuterium, produced by zirconium corrosion in the PHTS, enters a pressure tube at the highest rate at the hottest region of a tube which is at, or near to, the lower (6 o'clock) outlet rolled joint (ii) The ingressed deuterium subsequently migrates to the cooler regions of the pressure tube located at the top (12 o'clock position) of the tube	The results provided in Figure 4, based on a relatively simple assessment considering thermal power and diametral expansion of the pressure tubes, generated circumferential temperature differences in the outlet end of the pressure tubes ranging from about 12°C to 18°C, which is close to the approximately 20°C difference that was suggested by industry based on more detailed thermo-hydraulic modelling. As previously discussed, the assumption that a temperature difference greater than 50°C is required to generate the observed Heq profiles at the outlet rolled joint region omits the effect of the solubility limit which will lead to increased accumulation due to hydride ratcheting effects.	Les résultats fournis à la figure 4, fondés sur une évaluation relativement simple tenant compte de la puissance thermique et de la dilatation diamétrale des tubes de force, ont généré du côté de l'extrémité de sortie des tubes de force des différences de température sur le plan circonférentiel qui variaient entre 12 °C et 18 °C, ce qui se rapproche de la différence d'environ 20 °C suggérée par l'industrie à partir d'une modélisation thermohydraulique plus détaillée. Comme il a été mentionné précédemment, l'hypothèse selon laquelle une différence de température supérieure à 50 °C est nécessaire pour générer les profils de Heq observés dans la zone du joint dudgeonné au point de sortie omet de tenir compte de la limite de solubilité, qui entraînera une accumulation accrue en raison des effets de rochetage d'hydrure.

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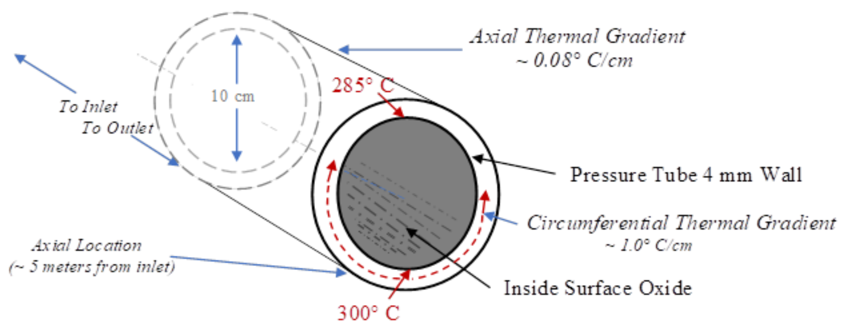
At power, pressure tubes exhibit *two* types of thermal gradients: axial and circumferential, as shown in Figure 1 below. The axial gradient stems from the difference in the inlet and outlet temperatures of the D_2O coolant and equals approximately 0.08 °C/cm along the length of a pressure tube. The circumferential thermal gradient is caused by the off-axis location of the fuel bundles within a fuel channel, especially when the pressure tube wall is subject to neutron-induced diametral creep. As discussed below, the temperature gradient around the circumference of a pressure tube near its outlet end is usually assumed to be about 1.0 °C/cm. **Figure 1: Schematic Illustration of a Pressure Tube near its Outlet End**  Thus, for example, D. Rogers et al. at CNL published a plot of the calculated temperature profiles at the 6 o'clock and 12 o'clock circumferential locations for a typical mature pressure tube as shown in Figure 2, below, (See CNL Nuclear Review Vol 5, Number 1, June 2016). **Figure 2: CNL Calculated Temperature Profiles for a Mature Pressure Tube**		

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Commentaires par un intervenant dans CMD 26-M10.3</th><th>CNSC Staff Clarifications</th><th>Précisions du personnel de la CCSN</th></tr>
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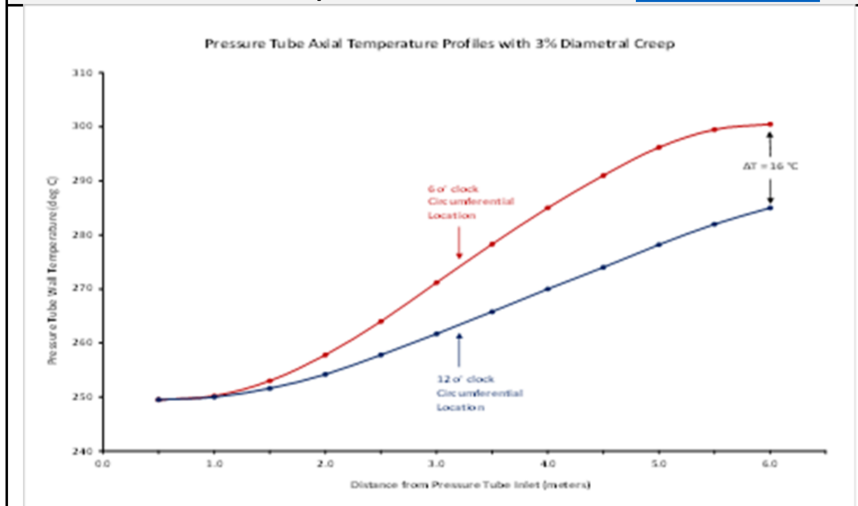

These plots predict a ΔT – defined as the temperature difference between the bottom and the top of a pressure tube at its outlet end – of about 16 °C. Unfortunately, the methodology used by the CNL to determine these temperature profiles is not provided by the CNL report noted above, from which Figure 2 is derived. Nevertheless, it is possible to predict the basic features of these profiles based on the fact that there are two main contributing factors that determine ΔT:

(i) A contribution, ΔT_6, from *the localized heating of a pressure tube* in the vicinity of the 6 o'clock location, caused by the direct physical contact of fuel bundles with the pressure tube wall at the bottom of a tube

(ii) A contribution, ΔT_{12}, from *the localized cooling of a pressure tube* in the vicinity of its 12 o'clock location, caused by coolant flow bypass due to pressure tube diametral expansion from neutron induced creep

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It is assumed that: $$\Delta T(x) = \Delta T_6(x) + \Delta T_{12}(x)$$ Where x is the axial distance (in meters) from the pressure tube inlet, (x = 0), to outlet, (x = 6). **Determination of ΔT_6:** ΔT_6 depends on the bundle power, usually expressed in kW, at a given axial location. I have used bundle power data from a Bruce B Safety Report for a high power, (7.5 MW), channel to derive a dimensionless axial power profile, P(x), over the full 6-meter reactor core, with the data points normalized to the maximum channel power of 1035 kW at the 3-meter axial location. It is assumed that ΔT_6 may be approximated by the simple relationship: $$\Delta T_6(x) = C_1 \times P(x)$$ Where C_1 is a proportionality constant, (in units of °C), between the excess pressure tube wall temperature and the local fuel bundle output power – a conversion factor to be determined. Using published data derived from CANDU reactor thermal hydraulic codes such as ASSERT-PV, C_1 is estimated to be 10 °C. 1. **Determination of ΔT_{12}:** ΔT_{12} depends on the amount of pressure tube diametral expansion induced by neutron induced creep. CNL has published plots of the amount of diametral expansion, D(x), along the axial length of a pressure tube, (See R. B. Adamson et al. in Journal of Nuclear Materials Vol. 521, 167 – 244, (2019). It is assumed that ΔT_{12} may be approximated by the simple relationship: $$\Delta T_{12}(x) = C_2 \times D(x)$$		

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Where C_2 is a proportionality constant, (in units of °C), between the amount of pressure tube wall temperature cooling and the neutron-induced pressure tube diametral expansion normalized to its maximum value which is well in-board of the mid-core, 3-meter location. For this intervention I have used a value of 8 °C for C_2. Combining these parameter values with axial power profile and the diametral expansion data noted above we are able to calculate ΔT(x) for a set of axial locations from x = 0 to x = 6.0 meters, as shown in Table 1, below, together with ΔT values taken from CNL's 2016 report.		

Table 1: Calculated ΔTs at Different Axial Locations vs. CNL's Published Data

Axial Location, x (meters)	ΔT_6 (Deg C)	ΔT_{12} (Deg C)	$\Delta T_6 + \Delta T_{12}$ (Deg C)	CNL ΔT (Deg C)
0.0	0.0	0.0	0.0	0.0
0.5	0.6	0.0	0.6	0.0
1.0	2.4	1.5	4.0	0.2
1.5	4.4	2.9	7.3	1.4
2.0	6.4	4.2	10.6	3.6
2.5	8.0	5.4	13.4	6.2
3.0	9.5	6.6	16.0	9.5
3.5	10.0	7.5	17.5	12.5
4.0	9.5	8.0	17.5	15.0
4.5	8.0	7.8	15.7	17.0
5.0	6.4	6.7	13.1	18.0
5.5	4.5	4.2	8.7	17.5
6.0	2.4	0.0	2.4	15.5

It is instructive to plot the data in columns 4 and 5 of Table 1 to directly compare the ΔT values determined by the methodology described above, with the results reported by CNL, as shown in Figure 3 below.

Figure 3: Calculated vs. CNL Reported Values for a Pressure Tube 6 to 12 o'clock ΔT

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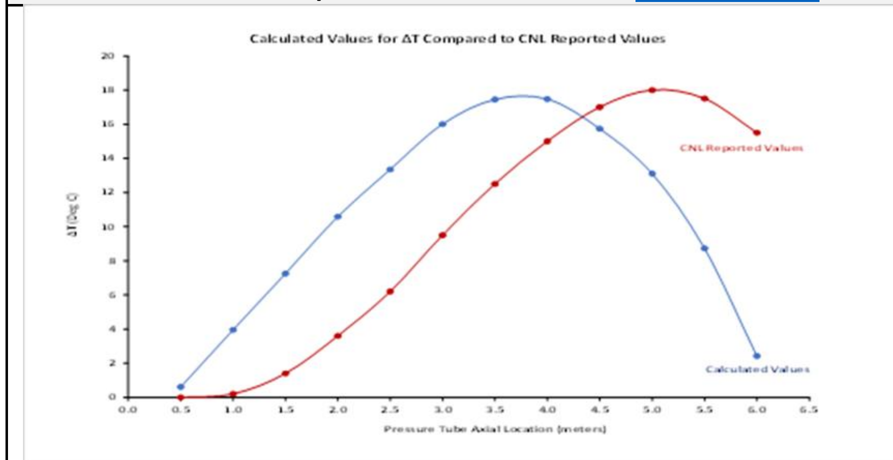 The most striking feature of my calculated values of ΔT compared to CNL's values, as seen in Figure 3, is the large divergence between the data sets at the pressure tube outlet region near the 5-to-6-meter axial location. In this outlet region of the reactor core the neutron flux drops off rapidly with increasing x, as the bundle power declines by about 200 kW/meter from its mid-core output of about 1000 kW. Because diametral creep is a function of the fast neutron fluence, the pressure tube diametral expansion also falls to a minimum value of about 15% of its peak value at the 6-meter location. This trend is clearly seen in my calculated ΔTs, but is barely evident in CNL's calculated values, which is difficult to explain. I believe that my calculated ΔTs are much closer to reality than CNL's and as a consequence it appears that the ΔTs for the Bruce Unit 3 and 6 pressure tubes with elevated [Heq] near their respective outlet rolled joints are most probably less than 5 °C – a value that is incompatible with the observed [D12]/[D6] ratio of about 3, which requires a physically unrealistic value > 50 °C for the corresponding ΔT, (See Figure 10 of this intervention).		

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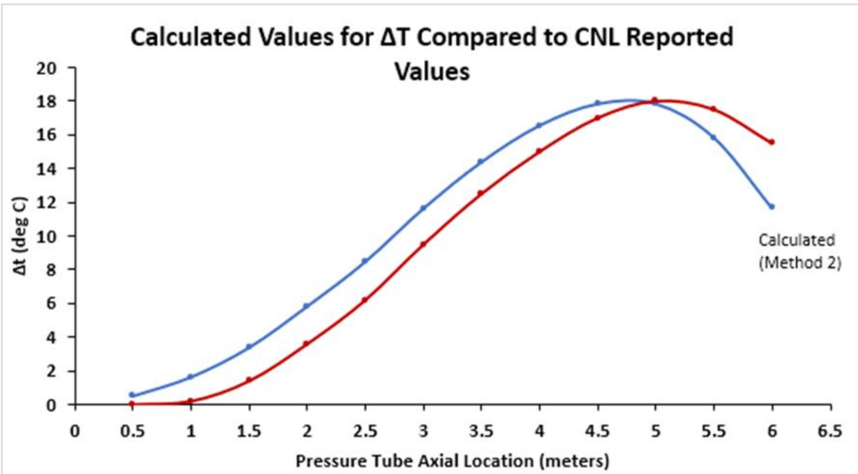
I have recently re-calculated EoL pressure tube ΔTs using a different formalism of the effects of pressure tube diametral expansion from neutron induced creep. In this alternative approach the pressure tube expansion is calculated from the change in the cross-sectional area of the tube to more accurately quantify the flow bypass. The resulting values of ΔT are plotted as compared to the CNL calculated values in Figure 4. **Figure 4: Calculated vs. CNL Reported Values for a Pressure Tube 6 to 12 o'clock ΔT** **Alternative Calculation Method**  Figure 4 shows better agreement with the CNL values but still shows lower, and more realistic ΔTs near the pressure tube outlet than the CNL values.		
A plot of the predicted maximum diametral expansion data for Bruce Unit 7 pressure tubes shows that this Unit will have already exceeded the 108.6 mm diameter limit at 300,000 EFPH. One therefore has to ask if Bruce	Pressure tube diametral expansion is measured during inspection campaigns and predictive models are refined based on inspection results. Fitness for service	La dilatation diamétrale des tubes de force est mesurée durant les campagnes d'inspection, et les modèles de prévision sont affinés en fonction des résultats

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Power can guarantee that Bruce Unit 7 will not be subject to fuel sheath dry-out if operated beyond 300,000 EFPH?	compliance verification criteria establish the limits for diametral expansion and no tubes are permitted to operate if the diameters are predicted to exceed the limits that would lead to fuel sheath dry-out. CNSC staff would not recommend continued operation of pressure tubes if diametral expansion limits were likely to be exceeded.	d'inspection. Les critères de vérification de la conformité visant l'aptitude fonctionnelle établissent les limites de la dilatation diamétrale, et l'exploitation d'un tube est interdite si, selon les prédictions, le diamètre dépasse les limites au-delà desquelles la gaine de combustible s'assècherait. Le personnel de la CCSN ne recommanderait pas l'exploitation prolongée des tubes de force si les limites de dilatation diamétrale étaient susceptibles d'être dépassées.

References/ Références:

1. IAEA NEWS, "Leak from primary coolant system at Kakrapar Atomic Station-1", November 19, 2018 (NEWS).