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Written submission from Bruce Power

Mémoire écrit de Bruce Power

Update from OPG and Bruce Power on Hydrogen Equivalent Concentrations in Pressure Tubes

Mise à jour par OPG et Bruce Power sur les concentrations d’équivalent hydrogène dans les tubes de force

Commission Meeting

Réunion de la Commission

February 25 and 26, 2025

25 and 26 février 2025

Canada

BrucePower™
Innovation at work

January 24, 2025

BP-CORR-00531-05959

Dr. A. Viktorov
Director General
Directorate of Power Reactor Regulation
Canadian Nuclear Safety Commission
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Ms. C. Salmon
Commission Registrar
Legal and Commission Affairs Branch
Canadian Nuclear Safety Commission
P.O. Box 1046
280 Slater Street
Ottawa, Ontario
K1P 5S9

Dear Dr. Viktorov and Ms. Salmon:

Bruce A and B: Progress Update on Industry R&D Plan for Elevated Hydrogen Equivalent Concentrations in the Inlet Rolled Joint Region, Action Item 2023-07-27173

The purpose of this letter is to provide an update to the Commission, as directed in Reference 1, regarding Bruce Power's research and development (R&D) activities with respect to elevated hydrogen equivalent concentration ($[H]_{eq}$) in the inlet rolled joint region of pressure tube (PT).

Since the discovery of elevated $[H]_{eq}$ concentrations in the rolled joint regions of removed surveillance pressure tube B6S13 and during the Unit 3 2021 outage (A2131) in 2021, Bruce Power has undertaken several activities to confirm the understanding of elevated $[H]_{eq}$ and to demonstrate fitness-for-service and continued safe operation of Bruce PTs. Regular progress updates on these activities have been provided to the Commission and to CNSC staff in References 2, 3, 4, 5, and 6, in addition to annual industry workshop meetings on elevated [H]eq with CNSC staff since 2022. Throughout this time, Bruce Power has continued to demonstrate fitness of service and maintained the integrity of our PT's.

A progress update on industry R&D plan activities related to elevated $[H]_{eq}$ concentrations in the inlet rolled joint region of pressure tube—specifically, characterization and understanding of blip formation (the localized region of elevated $[H]_{eq}$), model development and experiments—is provided in Attachment A. R&D activities completed to date have provided Bruce Power and industry partners an improved understanding of the mechanism for blip formation. This continues to be supported by modelling work that has demonstrated good agreement with available measurements, with additional benchmarking and experimental validation in-progress. Work is progressing on the completion of the experimental programs on crack initiation and delayed hydride cracking (DHC) growth rates to validate the current material property limits including high [H]eq levels in the models that is representative of the blip and local [H]eq.

Results from these experiments to date indicate that higher $[H]_{eq}$ levels consistent with the development of blips near the PT outer diameter (OD) surface will have a limited effect on the risk of crack initiation and are therefore not expected to increase the risk of PT failure.

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The activities described in Attachment A are part of the industry's $[H]_{eq}$ roadmap process to address the elevated $[H]_{eq}$ concentrations in the inlet and outlet rolled joint regions as originally established in Reference 2. Bruce Power will continue to provide regular semi-annual updates to the CNSC staff on the status of activities with the next update planned for the end of Q1 2025.

If you require further information or have any questions regarding this submission, please contact Mr. Maury Burton, Senior Director, Regulatory Affairs, at 519-386-2394, or maury.burton@brucepower.com.

Yours truly,

Digitally signed by
Maury Burton
Date: 2025.01.24
14:15:18 -05'00'

Maury Burton
Senior Director, Regulatory Affairs
Bruce Power

cc: CNSC Bruce Site Office
Ms. Anupama Bulkan, CNSC – Ottawa

Attach.

References:

1. Minutes of the Canadian Nuclear Safety Commission (CNSC) Meeting held on May 22, 2024, e-Doc 7299560.
2. Letter, M. Burton to A. Viktorov and D. Saumure, “Bruce A and B: Update to the Commission regarding Elevated Hydrogen Equivalent Concentrations – Action Item 2022-07-23135”, July 19, 2022, e-Doc 6844485, BP-CORR-00531-02909.
3. Letter, M. Burton to M. Hornof, “Bruce A and B: Update Regarding Elevated Hydrogen Equivalent Concentrations and Response to CNSC Risk Assessment, Action Item 2022-07-26737, Closed Action Item 2022-07-23135”, March 29, 2023, BP-CORR-00531-03855.
4. Letter, M. Burton to M. Hornof, “Bruce A and B: Update Regarding Detailed Plan to Further Evaluate the Effect of Hydrogen Equivalent Concentration on Pressure Tube Fitness for Service, Action Item 2023-07-27173”, September 27, 2023, BP-CORR-00531-04393.
5. Letter, M. Burton to K. Lun, “Bruce A and B: Semi-Annual Update on Industry R&D Plan on Elevated Hydrogen Equivalent Concentrations, Action Items 2023-07-27173, 2022-07-26737”, March 25, 2024, e-Doc 7249743, BP-CORR-00531-05033.
6. Letter, M. Burton to A. Bulkan, “Bruce A and B: Semi-Annual Update on Industry R&D Plan on Elevated Hydrogen Equivalent Concentrations, Action Items 2023-07-27173 and 2022-07-26737”, September 26, 2024, BP-CORR-00531-05650.

Attachment A

Progress Update on Industry R&D Plan Activities Regarding Elevated $[H]_{eq}$ Concentrations in the Inlet Rolled Joint Region of Pressure Tubes

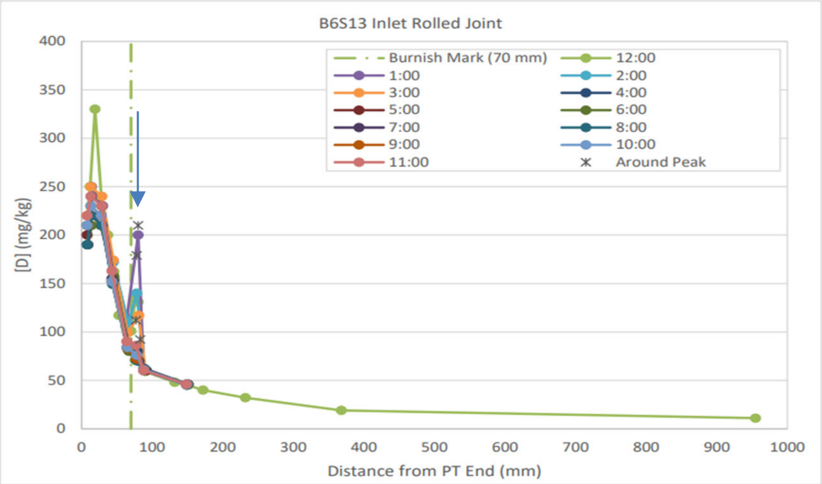
Attachment A:
Progress Update on Industry R&D Plan Activities Regarding Elevated $[H]_{eq}$ Concentrations in the Inlet Rolled Joint Region of Pressure Tubes

Table A-1 provides a progress update on activities regarding improving the characterization of the “blip” and expected evolution of the inlet region of elevated $[H]_{eq}$ with continued reactor operation as requested in Reference A1. This progress update focuses on the following activities:

- Characterization of blips in ex-service pressure tube (PT) material, including profiling their extent and the local $[H]_{eq}$ variations axially, circumferentially, and through-wall.
- Understanding the mechanism of blip formation in inlet rolled joints (RJs).
- Model development to predict blip formation and evolution.
- Experiments to support validation of the formation mechanism and support models for predicting blip formation and evolution.

These activities are part of the industry’s $[H]_{eq}$ roadmap process to address the elevated $[H]_{eq}$ concentrations in the inlet and outlet rolled joint regions as originally established in Reference A2. Ongoing status updates have been provided in semi-annual submissions to the CNSC staff (References A3, A4, A5 and A6).

Table A-1: Progress Update on Activities

R&D Activity	**Status of R&D Activities**
Improve characterization of ‘blip’ and expected evolution of the inlet region of elevated $[H]_{eq}$ with continued operation	Currently planned work has been completed. Measurement of $[H]_{eq}$ profiles for the purposes of characterizing elevated $[H]_{eq}$ concentrations has been performed in surveillance and other ex-service pressure tubes from Bruce, Pickering B, and Darlington fuel channels. For Bruce B6S13 PT, the inlet rolled joint $[H]_{eq}$ profile that shows the localized blip is provided below (Figure 1) .  **Figure 1.** Deuterium Concentration Profiles from the Inlet (Top) Rolled Joint of B6S13 (arrow indicates blip location) Hydride blips have been consistently found with an axial extent of only a few millimeters, centered at approximately 10 mm inboard of the burnish mark at varying circumferential locations within the top-half of the pressure tube. This spatial localization has been seen in all instances of removed pressure tubes where blips have been observed in the concentration

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profile. Hydride blips are also found near the outlet rolled joints with similar axial and circumferential locations and extents.

Through-wall imaging of the gradient in $[H]_{eq}$ by metallography has been performed to characterize the evolution of $[H]_{eq}$ through the wall, for comparison to modelling and identification of representative through-wall gradients for experiments. This through-wall characterization has shown that the blip is localized near the outer diameter of the pressure tube, and that the $[H]_{eq}$ closer to the inner diameter of the pressure tube is commensurate with levels adjacent to the blip that do not show elevated $[H]_{eq}$.

Routine circumferential sampling of RJ $[H]_{eq}$ and RJ metallography will continue as part of regular fuel channel R&D and surveillance program activities.
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<td>Understanding Mechanism of Blip Formation</td>
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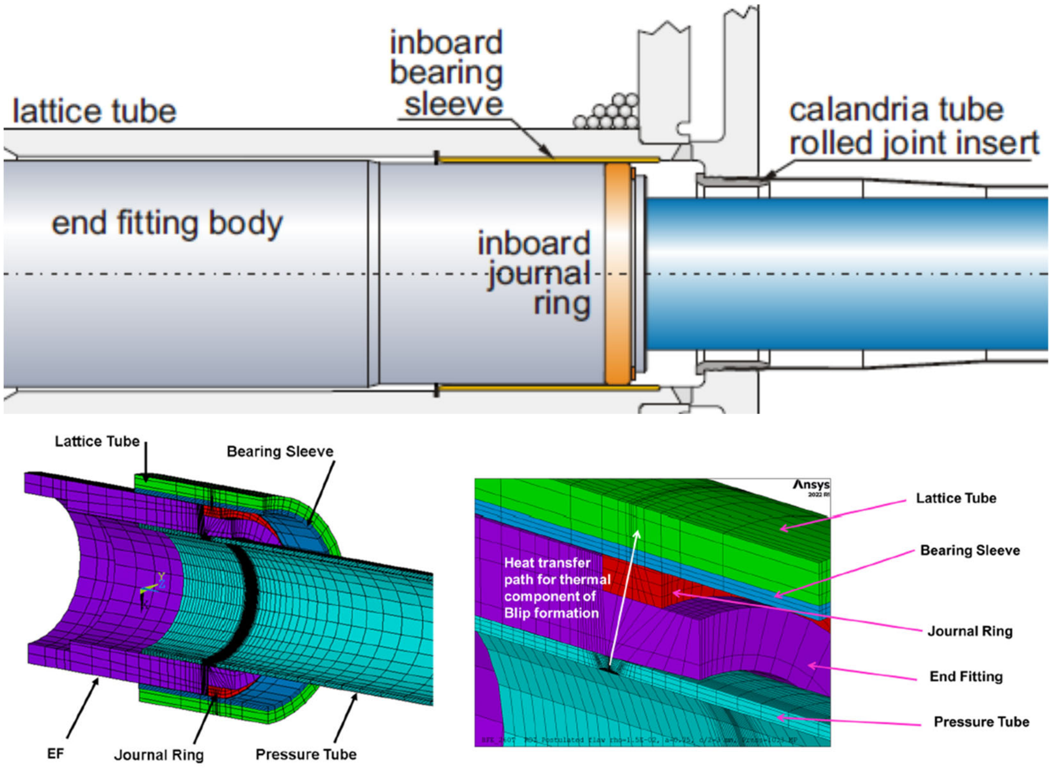
It is currently understood that blip formation results from a region of localized contact between the pressure tube outer surface and the end-fitting taper, and the resulting local decrease in pressure tube operating temperature due to heat-transfer through the inboard bearing components to the reactor end-shield. This localized decrease in pressure tube operating temperature results in the accumulation of hydrogen isotopes locally. Once the local solubility limit is exceeded, accumulated hydrogen isotopes remain as hydrides following cooldown-heat-up cycles, and subsequent reactor operation results in further accumulation of $[H]_{eq}$ at the blip.



3D Finite Element Model of Inboard Bearing and FC Assembly (Overview)

Figure 2. Illustration of Fuel Channel Bearing Components (Top) and Simulated Heat Transfer Path at Location of Bearing Contact (Bottom)
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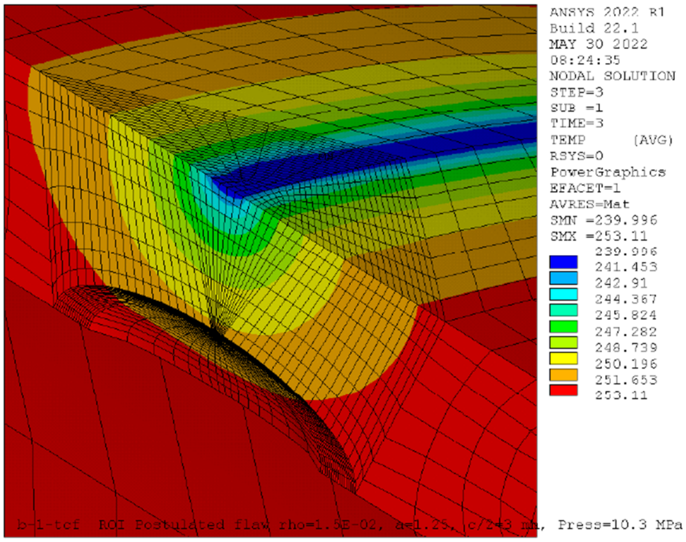
	 **Figure 3:** Thermal Gradients in PT from Local EF Taper Contact Due to Bearing Heat Conduction This localized contact region on the outer diameter of the PT and the resulting temperature profile is understood to be responsible for the size of blips and their relatively localized nature; hydride blips are expected to be constrained axially and circumferentially, as the necessary temperature gradients do not extent further inboard or outboard with operating time. Figures 2 and 3 above illustrate the heat transfer path through the bearing components and the resulting temperature gradients in the PT wall. Modelling of hydride blip formation and evolution, via thermal contact and the formation of locally colder regions, shows good agreement with observation, and also supports the temperature-driven redistribution mechanism. Physical examination of pressure tube outer diameter surfaces at locations of blip formation by surface and chemical characterization methods has been performed, supporting industry's current understanding of blip formation resulting from local temperature variation. Physical examinations of these regions support that firm contact between the components is occurring in this region; however, there is no direct evidence of metal-to-metal contact or loss of oxide that would result in localized ingress (i.e. any ingress path). Consistent indicators of localized PT to end fitting contact ~10 mm in this region have been seen in ultrasonic inspections of fuel channels where blips have been found in corresponding ex-service examinations. Localized PT to end fitting contact is understood to constrain the blip extent axially. As a result of bearing clearances, contact in the bearing occurs at specific locations that are influenced by the loads on the end fitting, resulting in colder temperatures on one side of the PT, which constrains the blip extent circumferentially.
Modelling Blip Formation and Evolution	Work is progressing. Industry has developed a finite element model (ANSYS/HFE) that simulates the loading and contact of fuel channel bearing components, resulting heat transfer in this region and the associated migration of hydrogen isotopes with operating time. This ANSYS/HFE model has been used to simulate $[H]_{eq}$ profiles of select ex-service PT rolled joints and the associated circumferential and axial variations, and shows good agreement with observations $[H]_{eq}$ measurements and metallographic examinations of ex-service pressure tubes. Additional model comparisons to observed through-wall (radial) gradients also show good agreement (see Figures 4 and 5) between the predicted and observed $[H]_{eq}$ distributions. Industry is currently performing sensitivity cases with the intent of establishing potential bounding $[H]_{eq}$ profiles and accumulations that may occur due to blip formation considering the established ranges of relevant input parameters. ANSYS/HFE code results are currently being benchmarked against other industry established tools for simulating hydrogen isotope

diffusion and accumulation, and initial outcomes show good agreement. Model refinements and sensitivity cases for understanding the evolution of blips in later-life are ongoing.

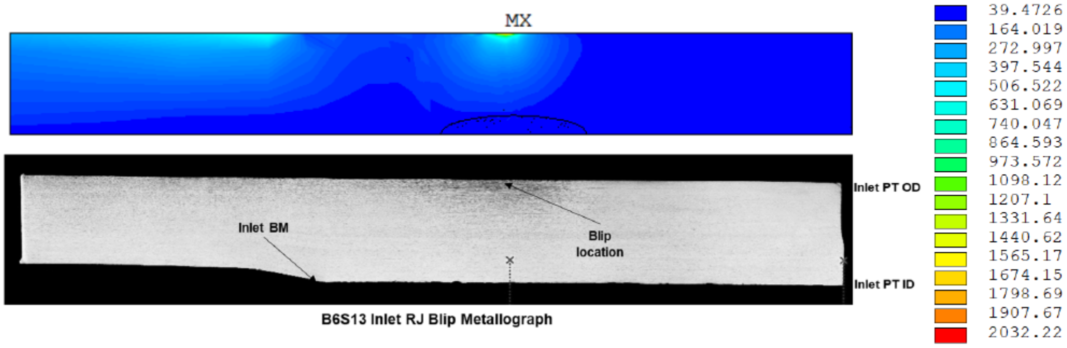


Figure 4: Comparison of [H]eq Contours from ANSYS/HFE to Metallography in the Axial-Radial Plane of the PT

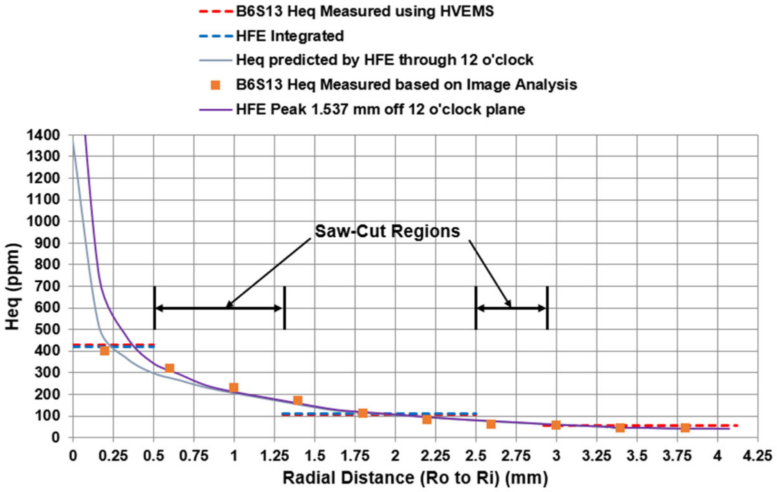
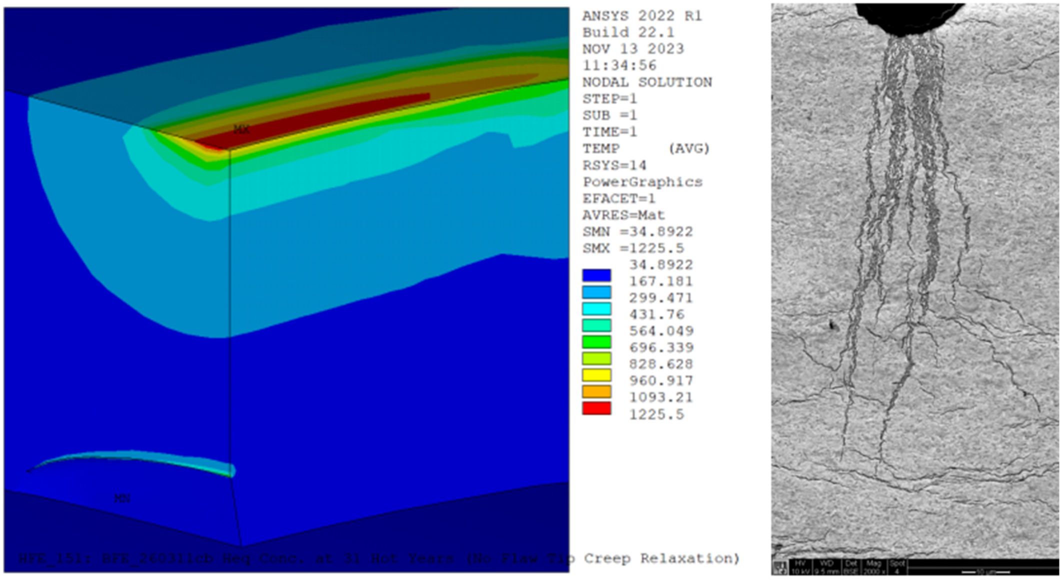


Figure 5: Comparison of ANSYS/HFE Predicted Through-Wall Concentration Profile to Measurements and Analysis of Through-Wall Metallographic Images

The ANSYS/HFE model has also been utilized for investigating the interaction between inner diameter pressure tube flaws located at the PT inner diameter coincident with locations of blip formation on the PT outer diameter (Figure 6). These investigations conclude that there is no discernable effect on the blip on [H]eq at the tip of a postulated bounding flaw (i.e., the presence of a blip does not result in higher than predicted levels of hydride accumulations at PT inner diameter surface flaws (i.e. debris frets). Additional modelling work in this area is planned as part of future sensitivity cases.

	 **Figure 6:** $[H]_{eq}$ Profiles Near a PT Outer Diameter Blip and PT Inner Diameter Flaw Showing Non-Interaction Updates to benchmarking, sensitivity case results, and other modelling work are expected as part of the Q3 2025 semi-annual update to CNSC staff.
Experiments Supporting Blip Modelling and Understanding	Experiments are ongoing to support validation of the mechanism of blip formation and to support models used to simulate blip formation and evolution_namely the occurrence of sufficient contact and heat transfer path from the PT to the end shield tube through the bearing components. The intent of these experiments is to provide experimental support for heat transfer parameters used in modelling and to confirm that thermal contact is the means of blip formation. Currently, an experimental mock-up has been constructed and testing is in-progress. The results of this work are expected to be included as part of the Q3 2025 elevated $[H]_{eq}$ submission to CNSC staff.
Material Property Testing at Elevated $[H]_{eq}$	Currently ongoing. Results are expected to be included in the Q3 2025 semi-annual update to CNSC staff. Material property tests at elevated bulk $[H]_{eq}$ are being performed to better establish the material properties at $[H]_{eq}$ levels consistent with blips, and to extend the validity of existing models to higher $[H]_{eq}$ levels in order to support evaluations of pressure tubes in inlet and outlet regions of interest. Results obtained to date show that generally there is no impact of elevated $[H]_{eq}$ on parameters relating to delayed hydride cracking (DHC) initiation and growth, with exception of a small adverse effect on threshold stress intensity for DHC initiation from a blunt flaw. There is no evidence of an adverse effect of high $[H]_{eq}$ on DHC initiation from a sharp flaw/crack, initiation from a planar surface, or DHC growth rates in the axial or radial directions. Testing for fatigue crack initiation and hydride region overload is ongoing; preliminary results for fatigue crack initiation do not indicate any adverse effects. In the case of the blip, the through-wall gradient provides that, for a surface breaking flaw at the inner diameter, the $[H]_{eq}$ at the flaw tip is significantly lower. As it has been found that the blip and inner diameter flaws do not materially interact, this provides for additional defense for any possible impact of elevated $[H]_{eq}$ on crack initiation properties. Additional experiments are planned beyond the current scope to examine the effect of large through-wall gradients in $[H]_{eq}$ on crack initiation behaviour in PTs. Results of these experiments are expected to be reported in 2026.

References:

A1. Minutes of the Canadian Nuclear Safety Commission (CNSC) Meeting held on May 22, 2024, e-Doc 7299560.

A2. Letter, M. Burton to A. Viktorov and D. Saumure, “Bruce A and B: Update to the Commission regarding Elevated Hydrogen Equivalent Concentrations – Action Item 2022-07-23135”, July 19, 2022, e-Doc 6844485, BP-CORR-00531-02909.

A3. Letter, M. Burton to M. Hornof, “Bruce A and B: Update Regarding Elevated Hydrogen Equivalent Concentrations and Response to CNSC Risk Assessment, Action Item 2022-07-26737, Closed Action Item 2022-07-23135”, March 29, 2023, BP-CORR-00531-03855.

A4. Letter, M. Burton to M. Hornof, “Bruce A and B: Update Regarding Detailed Plan to Further Evaluate the Effect of Hydrogen Equivalent Concentration on Pressure Tube Fitness for Service, Action Item 2023-07-27173”, September 27, 2023, BP-CORR-00531-04393.

A5. Letter, M. Burton to K. Lun, “Bruce A and B: Semi-Annual Update on Industry R&D Plan on Elevated Hydrogen Equivalent Concentrations, Action Items 2023-07-27173, 2022-07-26737”, March 25, 2024, e-Doc 7249743, BP-CORR-00531-05033

A6. Letter, M. Burton to A. Bulkan, “Bruce A and B: Semi-Annual Update on Industry R&D Plan on Elevated Hydrogen Equivalent Concentrations, Action Items 2023-07-27173 and 2022-07-26737”, September 26, 2024, BP-CORR-00531-05650.