Canadian Nuclear Safety Commission | Commission canadienne de sûreté nucléaire

CMD 22-M37.3

Date: 2022-08-25
File / dossier : 6.02.04
Edocs pdf : 6858728

Written submission from Bruce Power

Mémoire de Bruce Power

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

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

---

Responses from Bruce Power to the request from the Commission for an update

Réponses de Bruce Power à la demande de la Commission pour une mise à jour

Commission Meeting

Réunion de la Commission

November 3, 2022

Le 3 novembre 2022

Canada

July 19, 2022

BP-CORR-00531-02909

Dr. A. Viktorov
Director General
Directorate of Power Reactor Regulation
Canadian Nuclear Safety Commission
P.O. Box 1046
280 Slater Street
Ottawa, Ontario
K1P 5S9

Mr. D. Saumure
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 Mr. Saumure:

Bruce A and B: Update to the Commission regarding
Elevated Hydrogen Equivalent Concentrations – Action Item 2022-07-23135

The purpose of this letter is to provide the following, as requested in Reference 1:

a) a report summarizing the activities undertaken since the fall of 2021 and covering the results of surveillance tests of pressure tubes, models development, and assessments of the pressure tube (PT) fitness for service (FFS); and

b) 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.

Since the discovery of elevated hydrogen equivalent concentrations in the rolled joint regions of surveillance pressure tube B6S13 and during the Unit 3 2021 outage (A2131), Bruce Power has expanded outage inspection activities in the 2021 Units 3 and 7 and 2022 Unit 5 outages by modifying the Circumferential Wet Scrape Tool (CWEST) to acquire inlet and outlet rolled joint measurements at various clock positions and axial positions. An industry workshop on elevated hydrogen equivalent ($[H]_{eq}$) concentration was held on March 25, 2022, to present the status on the work completed to-date to improve the mechanistic understanding of this behavior and predictive modelling capabilities and to solicit CNSC feedback on future work.

Since the time they were noted in July 2021, Bruce Power has provided regular updates to the CNSC on the elevated $[H]_{eq}$ concentration observations through various correspondences and meetings. As requested by CNSC staff in Reference 1, a report summarizing the activities undertaken since September 2021 is provided as Attachment A, which includes a summary of the results of surveillance tests of pressure tubes, models development, and completed pressure tube fitness-for-service assessments:

1) Pressure tube surveillance and in-service monitoring activities have demonstrated consistent behaviour with respect to elevated $[H]_{eq}$ findings.

2) Model development activities have demonstrated the capability to explain the elevated $[H]_{eq}$ observations.

Maury Burton, Senior Director, Regulatory Affairs
P.O. Box 1540 B10 2nd Floor E, Tiverton ON N0G 2T0
Telephone 519-361-5291
maury.burton@brucepower.com

Dr. A. Viktorov
Mr. D. Saumure July 19, 2022

3) Validity of the existing crack initiation models and the current fracture toughness model to elevated $[H]_{eq}$ has been confirmed.

4) Pressure tube fitness-for-service assessments have been completed to support the evaluation of potential elevated $[H]_{eq}$ impacts on PT FFS and confirmation of $[H]_{eq}$ model validity.

Attachment B 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, established through the industry's $[H]_{eq}$ roadmap process. Bruce Power commits to provide a semi-annual update to CNSC staff on the status of actions identified in Attachment B, with the first submission to be provided by end of Q1 2023.

Bruce Power has demonstrated that the pressure tubes installed in Bruce Units 3 to 8 remain fit-for-service and safe for operation with elevated $[H]_{eq}$ in the inlet region of interest through the completion of activities, summarized in Attachment A, and similarly for the outlet region of interest, consistent with the conclusion in the Commissions Reasons for Decision in References 2 and 3. Bruce Power will continue working with the industry to update fitness for service assessments to incorporate the results of the activities identified in Attachment B as they become available and as per established processes.

With the submission of the requested information, Bruce Power requests closure of Action Item 2022-07-23135. Note that Action Item 2022-07-24426, raised in Reference 4, remains open.

If you require further information or have any questions regarding this submission, please contact [redacted]

Yours truly,

Maury Burton
Bruce Power
2022.07.19 11:07:54
-04'00'

Maury Burton
Senior Director, Regulatory Affairs
Bruce Power

cc: CNSC Bruce Site Office
Mr. L. Sigouin, CNSC - Ottawa

Attach.

Dr. A. Viktorov
Mr. D. Saumure

July 19, 2022

References:

1. Letter, L. Sigouin to M. Burton, “Bruce A and B: Request for an Update to the Commission on Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration (Heq) – AI 2022-07-23135”, April 28, 2022, e-Doc 6761165, BP-CORR-00531-02753.
2. “Record of Decision DEC 21-H110 Request for Authorization to Restart Bruce Nuclear Generating Station A Unit 3 following its current planned outage”, October 5, 2021, BP-CORR-00531-02250.
3. “Record of Decision – Bruce Power Restart Unit 3 – CMD-22-H100 PDF”, March 9, 2022, BP-CORR-00531-02630.
4. Letter, L. Sigouin to M. Burton, “Bruce A and B: CNSC Review of REGDOC-3.1.1 Event Report B-2021-135624 on Industry Pressure Tube (PT) Surveillance Program – Inlet, Hydrogen Equivalent Concentration Measurements on PT from Unit Shutdown for Major Component Replacement – New Action Item 2021-07-24426”, December 14, 2021, BP-CORR-00531-02364.

Attachment A

Summary of Work Activities Related to Elevated Hydrogen Equivalent Concentrations in Rolled Joint Regions of Pressure Tubes

Attachment A – Summary of Work Activities Related to Elevated Hydrogen Equivalent Concentrations Rolled Joint Regions of Pressure Tubes

1.0 INTRODUCTION

In Reference A1, Bruce Power was requested to submit to the CNSC registry, a report summarizing the activities undertaken since the Fall of 2021 and covering the results of surveillance tests of pressure tubes, models development and assessments of the pressure tube fitness for service in extended operation, as may be applicable.

Since the discovery of elevated hydrogen equivalent ($[H]_{eq}$) concentrations in the rolled joint regions of surveillance pressure tube (PT) B6S13 and during the Unit 3 2021 outage (A2131), Bruce Power has provided regular updates to the CNSC on this subject through various correspondences and meetings.

The purpose of Attachment A is to provide the information requested in Reference A1.

2.0 BACKGROUND

In July 2021, Bruce Power reported elevated hydrogen equivalent observations in the outlet rolled joint region of surveillance pressure tube B6S13 and during the Unit 3 2021 (A2131) scrape campaign (References A2 and A3). A review of the A2131 scrape results identified some pressure tubes with a small, localized region in the upper half of the pressure tube in the outlet region of interest with a large circumferential variation of $[H]_{eq}$. Additional scrape samples were added to the A2131 Circumferential Wet Scrape Tool (CWEST) scope as part of the investigation into elevated $[H]_{eq}$ observations. These samples included outlet rolled joint (RJ) measurements at various clock positions and axial positions relative to the inlet/outlet burnish mark.

In November 2021, Bruce Power reported additional observations of elevated hydrogen equivalent concentrations in the inlet rolled region of B6S13 (Reference A4).

3.0 SUMMARY OF WORK ACTIVITIES UNDERTAKEN

Tables A-1, A-2, and A-3 summarize all activities undertaken since Fall 2021 in response to the characterization of elevated $[H]_{eq}$ concentrations. Under each activity, tasks have been identified and completed along with a summary of the findings and/or conclusions with the corresponding Bruce Power submission(s) and path forward. As the activities are intended to address a variety of pertinent aspects, they have been organized into, and are presented in, the following categories specific to the requests made in Reference A1:

- Summary and Status of PT Surveillance/In-Service Monitoring Activities (Table A-1),
- Summary and Status of Model Development Activities (Table A-2),
- Summary and Status of PT Fitness-for Service Assessments (Table A-3).

Table A-1:
Summary & Status of PT Surveillance/In-Service Monitoring Activities

Item	Activity	Scope	Findings/Conclusions	Relevant Submission(s) /Documentation	Remarks
A.1	Perform Surveillance Activities in removed PTs.	Perform material surveillance (including Body of Tube (BOT) inlet and outlet rolled joint (IRJ and ORJ) sampling at various axial and circumferential locations), focusing on characterization of spatial variation of $[H]_{eq}$ in PTs B6S13 and P8P10.	B6S13: • IRJ punch samples showed elevated $[H]_{eq}$ concentrations localized at ~ 10 mm inboard of the burnish mark (BM) Metallographic examinations on the B6S13 IRJ punch samples showed a significant radial gradient in hydride concentration decreasing from PT outer diameter (OD) to inner diameter (ID). The radial gradient was confirmed by direct [H] and [D] measurement of radial sections of B6S13 IRJ. • ORJ punch samples showed evidence of elevated $[H]_{eq}$ OPG P8P10: • IRJ punch samples showed evidence of possible incipient 'blip' formation at ~10 mm inboard of the BM; however, $[H]_{eq}$ at this location was found to be only ~45 ppm $[H]_{eq}$ • ORJ punch samples showed evidence of elevated $[H]_{eq}$ in the compressive region, although to a lesser extent than PT B6S13	B6S13: BP-CORR-00531-02033 COG-JP-4680-001 P8P10: COG-JP-4682-V001	Additional PT research and development (R&D) activities related to ex-service material surveillance are planned via the Industry roadmap process. Additional results from material surveillance activities are planned for documentation in a future CANDU Owner's Group (COG) work program (WP) 10369 report. See Attachment B.
A.2	Perform $[H]_{eq}$ activities in ORJ and IRJ of removed Bruce PTs.	Perform $[H]_{eq}$ sampling in Bruce PTs B6N07 and B3K20 with punches obtained at various clock positions and axial positions in the ORJ and IRJ regions.	• B6N07 and B3K20 support the definition of the outlet region of interest which is confined to the top 120°.	B6N07: BP-CORR-00531-02033 B3K20: BP-CORR-00531-02334/ BP-CORR-00531-02407/ BP-CORR-00531-02450	Additional IRJ punch sampling and metallography of B6N07 and B3K20 are planned to investigate a possible 'blip' in the IRJ via the Industry roadmap process. See Attachment B.

Item	Activity	Scope	Findings/Conclusions	Relevant Submission(s) /Documentation	Remarks
A.3	Perform In-Service PT $[H]_{eq}$ Measurements.	1. Perform modifications to the CWEST tool to acquire inlet and outlet RJ measurements at various clock positions and axial positions.	• For the outlet RJ, the CWEST scope for the A2131, B2171 and B2251 outages was adjusted to include additional scrape locations at axial locations close to the BM, i.e., BM-10, BM+20 mm and at various clock positions. • For the inlet RJ, the CWEST scope for B2171 and B2251 outages was adjusted to include additional inlet RJ scrape measurements at specific clock positions (10 o'clock, 12 o'clock and 2 o'clock) and axial locations close to the BM (BM-10, BM+8 and BM+20 mm).	BP-CORR-00531-01938 BP-CORR-00531-02398	Information communicated in response to CNSC staff requests for additional information on Bruce Power's plans to address the elevated $[H]_{eq}$ findings from B6S13 in: BP-CORR-00531-01930, e-Doc 6611665 (ORJ region) BP-CORR-00531-02364, e-Doc 6701538 (IRJ region) Scrapes at additional clock positions and axial locations will be performed as required in future PT scrape campaigns.
		2. Perform CWEST inspection campaigns as follows: A2131: • Initial CWEST scope consisted of perform BOT and RJ scrape sampling in 8 channels. A total of 44 PTs was sampled in three inspection windows, i.e., 10 PTs for the inlet RJ, 42 PTs for the outlet RJ. B2171: • Perform BOT scrape sampling in 15 channels, and RJ scrape sampling in 17 channels B2251: • Perform BOT scrape sampling in 17 channels and RJ scrape sampling in 21 channels	A2131: • Higher than expected $[H]_{eq}$ levels were observed outboard and just inboard of the burnish marks of several outlet RJs. • A large circumferential variation and steep axial profiles were observed, with the highest levels towards the outboard end and the top of the tube. • The higher than expected $[H]_{eq}$ levels in the tensile region were observed to be confined to a small region of the tube known as the outlet Region of Interest (ROI) (the top 120° of the outlet RJ within 75 mm inboard of the outlet BM)	A2131: BP-CORR-00531-02004/ BP-CORR-00531-02033 B2171: BP-CORR-00531-02398 B2251: Formal submission pending	Scrapes at additional clock positions and axial locations will be included (as required) in future PT scrape campaigns as part of Bruce Power's fuel channel life cycle management plans.

Item	Activity	Scope	Findings/Conclusions	Relevant Submission(s) /Documentation	Remarks
			B2171/B2251 ORJ: • ORJ scrape measurements support the definition of the outlet ROI established during A2131. B2171/B2251 IRJ: • No indication of a blip was observed in the B2171 and B2251 IRJ scrape measurements.		
A.4	Perform In-Service PT Flaw Monitoring.	Perform PT volumetric inspections during the A2131, B2171, B2251 outages for the presence of flaws identified within the ROI.	A2131/B2171/B2251: • Based on volumetric inspections performed, no dispositionable flaws of significance were identified within the ROI, with exception of the circumferential scrape sampling tool witness marks.	A2131: BP-CORR-00531-01638 B2171: BP-CORR-00531-02400 B2251: BP-CORR-00531-02622	Continued flaw monitoring in inlet and outlet ROIs is planned during future volumetric and dimensional (V&D) inspections .

Table A-2:
Summary & Status of Model Development Activities

Item	Activity	Scope	Findings/Conclusions	Relevant Submission(s) /Documentation	Remarks
B.1	Develop Finite Element Model to Simulate Outlet End RJ $[H]_{eq}$ Evolution.	1. Develop a preliminary 2-D finite element (FE) diffusion model using the H3DMAP code to study the temperature gradient/distribution (from coolant flow bypass) along the PT circumferential direction on the $[H]_{eq}$ prediction in the ORJ.	The preliminary 2-D FE model with the temperature gradient effect explains the trend of elevated $[H]_{eq}$ outlet measurements. • Higher $[H]_{eq}$ concentration at top of the tube and lower concentrations at the bottom. • The net RJ ingress is consistent with current ingress rate model.	Via e-mail, BP-CORR-00531-02407.	CNSC comments on BP-CORR-00531-02407 were received in BP-CORR-00531-02112, e-Doc 6643726. CNSC comments addressed in BP-CORR-00531-02192. A technical presentation was provided at the Industry Workshop on Elevated $[H]_{eq}$ on March 25, 2022. Bruce Power plans to perform a parametric study as noted in Table B-2 of Attachment B.
		2. Perform review of the PT coolant temperature circumferential distributions obtained experimentally in CHF tests in support of the H3DMAP ORJ modelling activities.	The review on the experimental Stern Labs CHF tests shows that there exists a top-to-bottom temperature asymmetry, with lower coolant temperature in the top of the tube compared to the bottom.	Via e-mail, BP-CORR-00531-02407 (Reference A5).	CNSC comments on BP-CORR-00531-02407 were received in BP-CORR-00531-02112, e-Doc 6643726. CNSC comments addressed in BP-CORR-00531-02192.
		3. Perform sub-channel coolant temperature simulations with ASSERT-PV for B3F16 and B6S13 in support of H3DMAP ORJ modelling activities.	The ASSERT simulations for B3F16 and B6S13 demonstrate that a top-to-bottom temperature asymmetry under nominal high-power conditions would exist.	Via e-mail, BP-CORR-00531-02407	CNSC comments on BP-CORR-00531-02407 were received in BP-CORR-00531-02112. Bruce Power addressed CNSC comments in BP-CORR-00531-02192.
		4. Simulate outlet RJ $[H]_{eq}$ evolution accounting for ANSYS predicted conditions and ASSERT-PV temperature distributions associated with coolant flow bypass using Hydrogen Finite Element (HFE).	Preliminary HFE $[H]_{eq}$ simulations accounting for ANSYS deformation and heat transfer predictions in addition to ASSERT axial-circumferential temperature variations support redistribution of	Preliminary findings shared at the Elevated $[H]_{eq}$ Workshop on March 25, 2022.	Additional activities planned to support the Industry roadmap process in Attachment B.

Item	Activity	Scope	Findings/Conclusions	Relevant Submission(s) /Documentation	Remarks
			$[H]_{eq}$ from the bottom to the top of PT at the outlet end. **Note:** To date, the primary focus of HFE modelling has been the simulation of inlet end $[H]_{eq}$ evolution (including 'blip' formation)		
B.2	Enhance ANSYS Fuel Channel (FC) Deformation/Heat Transfer Model to Provide More Detailed Information about PT Boundary Conditions Applicable to $[H]_{eq}$ modelling.	Simulate FC deformation/heat transfer including PT to end fitting (EF) rolling, inboard bearing contact orientation evolution, PT to EF contact interface pressure, and steady state heat transfer.	FC deformation simulations predict: • Non-uniform spatial distributions of residual stress in the RJ compressive region (relaxed with operating time). • Evolution of bearing contact orientation from nominally PT Bottom Dead Centre (BDC) at Beginning of Life (BOL) to PT Top Dead Centre (TDC) at End-of Life (EOL) • PT to EF contact interface variation with localization at the axial location of EF taper blended radius • Non-uniform heat transfer from the PT to the end shield through the inboard bearing assembly	Submission prepared by OPG with BP/Industry Involvement. Preliminary findings shared at the Elevated $[H]_{eq}$ workshop on March 25, 2022.	ANSYS FC deformation modelling remains ongoing with additional work planned to support the Industry roadmap process in Attachment B.
B.3	Develop Finite Element Model to Simulate <u>Inlet</u> End Rolled Joint (RJ) $[H]_{eq}$ Evolution.	Simulate $[H]_{eq}$ evolution accounting for potential PT OD ingress at the axial location of the PT to EF taper, predicted PT stress distributions, and predicted PT temperature distributions using HFE code.	Preliminary inlet RJ HFE $[H]_{eq}$ simulations have been performed accounting for OD ingress in addition to predicted temperature and stress distributions. These simulations demonstrate the preliminary capability to model inlet 'blip' formation consistent with observations in all PT planes at the 'blip' location.	Preliminary findings shared at the Elevated $[H]_{eq}$ workshop on March 25, 2022.	Activities to be incorporated into the Industry roadmap process in Attachment B.
B.4	Perform evaluation of the potential impact of the ROI	Perform diffusion analysis using HFE and ANSYS to simulate a through-wall $[H]_{eq}$	The simulations show that the finite element predictions of the through-	BP-CORR-00531-02820	Additional sensitivities on HFE $[H]_{eq}$ modelling remains

Item	Activity	Scope	Findings/Conclusions	Relevant Submission(s) /Documentation	Remarks
	with high levels of $[H]_{eq}$ on the hydride region at a flaw tip in the IRJ using FEA.	distribution at the blip of the inlet ROI in B6S13 IRJ (or any blip similar to B6S13) and to investigate any effect of the elevated $[H]_{eq}$ at the blip on the hydrided region at a postulated flaw tip.	wall $[H]_{eq}$ gradient at 10 mm inboard of the Burnish Mark (BM) are representative, or slightly conservative, relative to the punch measurements, radial sections and image analysis taken from the B6S13 inlet rolled joint. Benchmark FE predictions of hydrogen diffusion and accumulated areas of the notch-tip hydrided regions in laboratory test specimens are shown to be in reasonable agreement with measurements. For a postulated flaw with a very conservative depth of 1.25 mm that is centered at the same axial and circumferential position as the 'blip' in the IRJ region, FE predictions of hydrogen diffusion and accumulated areas of the flaw-tip hydrided regions show that the effect of the 'blip' on the hydrided region at the postulated flaw tip is not significant.		ongoing with further work planned via Industry roadmap process.
B.5	Confirm Validity of Existing Crack Initiation Models:	1. Provide a technical justification on the review of the basis of the process-zone model for predicting delayed hydride cracking (DHC) initiation at flaws and the material properties used as inputs into the DHC initiation models.	• The technical justification concluded that the DHC properties are not affected by elevated levels of $[H]_{eq}$. • A test plan on DHC, overload and fatigue crack initiation tests at elevated $[H]_{eq}$ concentrations is planned to further confirm there is no effect on elevated $[H]_{eq}$ on crack initiation due to DHC, hydride region overload and fatigue is planned.	Technical justification and test plan submitted in BP-CORR-00531-02033	Tests will be performed as part of COG R&D longer term activities. Updates on the results of the crack initiation tests at elevated $[H]_{eq}$ will be provided in the semi-annual update on elevated $[H]_{eq}$ activities.
		2. Perform short-term DHC initiation tests at elevated $[H]_{eq}$ concentrations to support the validity of existing crack	• Results from short term crack initiation tests at high $[H]_{eq}$ indicate that the threshold stress	Results from short term tests were communicated in BP-CORR-00531-	Updates on the results of the crack initiation tests at elevated $[H]_{eq}$ will be provided

Item	Activity	Scope	Findings/Conclusions	Relevant Submission(s) /Documentation	Remarks
		initiation models.	intensity factor for DHC initiation from a crack, K_{IH}, and the threshold stress for DHC initiation from a planar surface, p_c, are not affected by high $[H]_{eq}$. It is therefore considered that there is a low likelihood that the model for DHC initiation under constant loading would not be applicable to detected service-induced flaws since lower-bound values of K_{IH} and p_c are utilized in these assessments.	02326/BP-CORR-00531-02589	in the semi-annual update on elevated $[H]_{eq}$ activities.
B.6	Confirm Validity of the Revision 2 of the Engineering Fracture Toughness (FT) Model	Justification to extend validity limit of the Rev. 2 FT model to higher $[H]_{eq}$ for the front end of the PT.	Subsequent burst tests (BT) on ex-service pressure tube (PT) sections hydrided to very high $[H]_{eq}$ were completed (i.e., BT-50, BT-51, and BT-40). The burst test results are bounded by predictions of the Rev. 2 FT model and support the technical justification to extend the limit of the Rev. 2 FT model to 120 ppm [H]eq for the front end of the PT.	BP-CORR-00531-02589	CNSC restrictions on the use of the Rev. 2 FT model were communicated in BP-CORR-00531-02808, e-Doc 6795110. Discussions between Industry and CNSC on potential alternate approaches on the use of the Rev. 2 FT model at high $[H]_{eq}$ are ongoing. Additional burst tests with elevated $[H]_{eq}$ is planned and will be communicated to CNSC via regular updates on the burst test program.

Table A-3:
Summary & Status of PT Fitness-for Service Assessments

Item	Activity	Scope	Findings/Conclusions	Relevant Submission(s) /Documentation	Remarks
C.1	Perform engineering evaluation to demonstrate continued operation of Bruce Pressure Tubes (PTs) with higher-than-expected inlet $[H]_{eq}$	Perform engineering evaluation to demonstrate the continued operation of PTs in Bruce Units 3, 4, 5, 7 and 8 with elevated $[H]_{eq}$ in the inlet ROI where localized $[H]_{eq}$ concentrations could exceed 120 ppm.	The engineering evaluation demonstrates operability for Bruce Units 3, 4, 5, 7 and 8 PTs based on supporting evidence that: • $[H]_{eq}$ concentrations at the PT inner diameter (ID) below the inlet ROI are lower than the through-wall average $[H]_{eq}$ concentrations determined from B6S13 punch sample analysis and, • the very low likelihood of having a flaw with a sufficient depth at the PT ID to interfere with the inlet ROI. Fracture protection, resistance to crack initiation and low-incidence of PT flaws in the inlet ROI of PT have been demonstrated and existing PT fitness-for-service assessments are not impacted.	BP-CORR-00531-02398	The engineering evaluation to demonstrate continued operation of Bruce PTs with higher-than-expected outlet $[H]_{eq}$ was submitted in BP-CORR-00531-01853 in response to BP-CORR-00531-01849, e-Doc 6600766 and Event Report B-2021-98077 DR.
C.2	Investigation of trends in deuterium concentration in the ORJ.	Perform a detailed review of the A2131 scrape data to investigate trends in deuterium concentration in the ORJ.	Potential variables were identified which could be correlated to high deuterium levels in the ORJ (i.e., channel power, inner zone/outer zone (IZ/OZ), Fe content, front end outlet/front end inlet (FEO/FEI) orientation, etc.). The results of this investigation were considered in the scope selection for B2171 outage.	BP-CORR-00531-02192	This addresses the CNSC request in BP-CORR-00531-02112, e-Doc 6643726. The results of this investigative work will be considered in future CWEST scope selection campaigns.
C.3	Body of Tube (BOT) and Rolled Joint (RJ) $[H]_{eq}$ Assessments	Confirm continued validity of BOT and RJ $[H]_{eq}$ predictive models after each scrape campaign.	• Current BOT Deuterium (D)-uptake models remain valid. • Excluding the outlet ROI, the outlet RJ generic deterministic $[H]_{eq}$ predictions continue to be acceptable for use. For within	A2131: BP-CORR-00531-02360 B2171: BP-CORR-00531-02621	Bruce Power is planning an update to the D-Uptake Model for Units 5-7, in order to capture the observed trend and improve model prediction capability.

Item	Activity	Scope	Findings/Conclusions	Relevant Submission(s) /Documentation	Remarks
			the ROI, enhanced modelling is required to account for the observed circumferential variation in the outlet end region and recent observations of elevated $[H]_{eq}$ for surveillance tube B6S13 in a small inlet region ('blip') and on the PT OD. • For Units 5 and 7, a revision to the inlet RJ deterministic generic $[H]_{eq}$ predictions is required outside ROI.	B2251: Formal submission pending	Activities to enhance RJ modelling to account for the observed $[H]_{eq}$ circumferential variation in the inlet and outlet end regions are being addressed via the Industry road map in Attachment B.
C.4	Evaluation of in-service flaws	Bruce Power performs in-service volumetric inspections for flaws in the ROI.	There have been no detected flaws of significance within any ROI, where the dimensions of the ROI are as defined in BP-CORR-00531-02071for the OROI and BP-CORR-00531-2398 for the IROI. This is based on volumetric inspections of 564 unique tubes in the OROI and 798 unique tubes in the IROI.	BP-CORR-00531-01638 (A2131) BP-CORR-00531-02400 (B2171) BP-CORR-00531-02622 (B2251)	CNSC acceptance of the B2251 PT flaw component disposition is pending submission of the diffusion analysis results in Item B.4.
C.5	Perform evaluation of the acceptability of CWEST scrape witness marks	1. Perform an evaluation of the acceptability of CWEST scrape witness marks inboard of the ORJ BM taken during the A2131 and B2171 outages to determine the margins against crack initiation using the DHC initiation material properties and crack initiation models in the CSA Standard N285.8.	The results of the evaluation showed substantial margins against crack initiation in terms of addressing the uncertainty in crack initiation material properties at high levels of $[H]_{eq}$ in the region of interest.	BP-CORR-00531-02033/ BP-CORR-00531-02326	Scrape witness marks are benign.
		2. Perform a sensitivity evaluation of key parameters related to DHC initiation for CWEST scrape witness marks using 3-D FEA stress analysis and process zone model for DHC initiation to evaluate the risk of crack initiation with elevated $[H]_{eq}$ concentration.	The results of the sensitivity evaluation concluded that DHC initiation will not occur at the scrape flaws for a range of postulated levels of K_{IH} and p_c at high levels of $[H]_{eq}$.	BP-CORR-00531-02326	No further action required.

Item	Activity	Scope	Findings/Conclusions	Relevant Submission(s) /Documentation	Remarks
C.6	Defense-in-Depth Approach: Risk-Informed Deterministic Fracture Protection	1. Perform a risk-informed deterministic evaluation of fracture protection for the outlet ROI based on postulated axial through wall flaw and postulated elevated $[H]_{eq}$ in Bruce Unit 3 front end outlets.	The results of the fracture protection evaluation show that flaw stability can still be demonstrated in the event of the unanticipated existence of an axial through-wall flaw in the outlet ROI.	BP-CORR-00531-02033	
		2. Perform a risk-informed fracture protection assessment to evaluate the risk of fast fracture from a postulated through-wall flaw in inlet ROI at various levels of $[H]_{eq}$ and that covers all Level A, B, C and D Service Loadings for Bruce Units 3 and 4 IRJs and Bruce Units 5, 7 and 8 in the IRJs and ORJs.	It was demonstrated that the safety factors on internal pressure are greater than the required safety factors of 1.30 for fracture protection during a reactor heat up or cooldown, 1.0 during a Service Level C overpressure excursion.	BP-CORR-00531-02495	In BP-CORR-00531-02769, e-Doc 6789710, CNSC staff provided a position in response to the defense-in-depth approach in BP-CORR-00531-02495. Discussions are underway to provide a response.
		3. Perform additional sensitivity assessments at $[H]_{eq}$ up to 200 ppm in support of the risk-informed argument for flaws in the inlet ROI.	The results of the sensitivities show that for the inlet ROI, the safety factor for each service level loading is at least 1.0.	BP-CORR-00531-02495	
C.7	Defense-in-Depth Approach: Estimate the probability of existence of a reportable/dispositionable flaw in the ROI	1. Perform an evaluation to address the probability of encountering flaws of significance in the ROI of PTs for the population of channels which were not yet inspected full length.	The results of the probabilistic evaluation is that the probability for having at least one dispositionable flaw in the ROI is < 0.5% for Unit 3 (and all Bruce Power units) and therefore, the risk of having a significant flaw in the ROI, which could challenge pressure tubes fitness for service is also low.	BP-CORR-00531-02033	
		2. Update the probabilistic evaluation of the existence of dispositionable flaws using the full 360 deg circumference of the ROI.	The evaluation results demonstrated that the probability of encountering flaws increases with increasing size of the ROI (i.e., more incidence of reportable flaws than dispositionable flaws). However, ANDE inspections carried out during the A2131 outage did not reveal the presence of flaws in the ROI for the top 180° which is consistent with the probability estimates in the evaluation.	BP-CORR-00531-02077/ BP-CORR-00531-02090	This is in response to CNSC request in BP-CORR-00531-02071, e-Doc 6646070.

Item	Activity	Scope	Findings/Conclusions	Relevant Submission(s) /Documentation	Remarks
C.8	Defense-in-Depth Approach: Probabilistic Safety Analysis (PSA) Evaluation on Impact of PT Leak and Rupture on Overall Severe Core Damage and Large Release Frequency	Confirm the existing PSA considers the unlikely event of PT leaks and failures and provides an indication of the robustness of the defense in depth of plant design and operation.	The existing PSA results have confirmed that it is highly unlikely that a spontaneous PT leak will progress to Severe Core Damage (SCD) or to a Large Release (LR) since the low Conditional Core Damage Probability (CCDP) and Conditional Large Release Probability (CLRP) are in the range of 6.50E-05 to 1.30E-07.	BP-CORR-05031-02589	
C.9	Probabilistic core assessments for flaws to evaluate the impact of elevated $[H]_{eq}$ in the outlet ROI	Investigate the impact of elevated $[H]_{eq}$ in the ORJ regions on the PCA using a very conservative treatment to account for elevated ORJ $[H]_{eq}$.	The assessment concluded the following: • Elevated $[H]_{eq}$ in the ORJ region resulted in a small increase in the number of crack initiations, PT leaks and PT ruptures for both Units 3 and 8. • The predicted annual frequencies of failure and conditional probabilities of break-before-leak (BBL) were well below their respective acceptance criteria for all impact cases considered, up to the end of evaluation time for bounding Bruce A and B Units 3 and 8.	BP-CORR-00531-02830	This addresses CNSC Request #11 from BP-CORR-00531-01930, e-Doc 6611665.

4.0 CONCLUSIONS

Bruce Power has undertaken various activities to address the elevated $[H]_{eq}$ concentrations observed in the inlet/outlet rolled joint regions of surveillance pressure tube B6S13 and during the Unit 3 2021 outage (A2131). Bruce Power has provided regular updates to the CNSC on this subject through various correspondences and meetings. The findings from these activities are provided below:

1) PT surveillance and in-service monitoring activities have demonstrated consistent behaviour with respect to elevated $[H]_{eq}$ findings:

    - Bruce Power's definition of the outlet ROI is limited to the upper half of the pressure tube i.e., top 120° circumferentially and axially 75 mm inboard of the BM based on all available information from surveillance PT B6S13, removed PTs (B6N07 and B3K20) and the scrape results collected to-date from Bruce Units 3, 5 and 7 outages.

    - Bruce Power's definition of the inlet ROI is limited to the upper half of the pressure tube i.e., top 180° circumferentially, axially 20 mm inboard of the BM and radially from the PT outer diameter (OD) to within 1.5 mm of the PT inner diameter (ID) based on surveillance examinations from B6S13 and other removed PTs. No elevated $[H]_{eq}$ concentrations were observed in the inlet RJ from Units 5 and 7 CWEST campaigns in which scrapes were obtained from the ID of the PT.

    - In-service PT volumetric inspections confirmed no dispositionable flaws of significance in the ROI.

2) Model development activities have demonstrated the capability to explain the elevated $[H]_{eq}$ observations:

    - A preliminary 2-D FE model with the circumferential temperature gradient effect explains the trend observed in the $[H]_{eq}$ measurements in the outlet RJ, i.e., higher $[H]_{eq}$ concentration at the top of the PT and lower concentrations at the bottom.

    - Preliminary inlet rolled joint hydrogen finite element (HFE) $[H]_{eq}$ simulations have been performed accounting for OD ingress in addition to predicted temperature and stress distributions. These simulations demonstrate the preliminary capability to model inlet 'blip' formation consistent with observations in all PT planes at the 'blip' location.

    - Finite-element diffusion analysis have been performed to simulate a through-wall $[H]_{eq}$ distribution at the blip of the inlet region of interest in B6S13 and to investigate any effect of the elevated $[H]_{eq}$ at the blip on the hydride region at a postulated flaw tip. The analysis confirms that the blip observed in B6S13 has no effect on PT fitness-for-service in the context of the propensity for crack initiation at the flaw.

    - Industry collaboration is ongoing for enhancing the mechanistic understanding and predictive modelling of $[H]_{eq}$ in the inlet and outlet rolled joint regions through extensive R&D activities. A roadmap process has been established to integrate industry efforts related to inlet and outlet RJ $[H]_{eq}$ modelling and establish a unified path forward.

3) Validity of the existing crack initiation models and the current fracture toughness model to elevated $[H]_{eq}$ has been confirmed by:

- Results from the short-term DHC tests with elevated $[H]_{eq}$ which supports the validity of the current DHC initiation model for elevated $[H]_{eq}$ and the risk of crack initiation due to a flaw in the inlet RJ where $[H]_{eq}$ is elevated, is low.

- The burst test results on ex-service PT sections hydrided to very high $[H]_{eq}$ are bounded by predictions of the Rev. 2 FT model and support the technical justification to extend the limit of the Rev. 2 FT model to 120 ppm $[H]_{eq}$ for the front end of the PT.

4) Pressure tube fitness-for-service assessments have been completed to support the evaluation of potential elevated $[H]_{eq}$ impacts on PT FFS and confirmation of $[H]_{eq}$ model validity:

- Engineering Evaluations have demonstrated the continued operation for Units 3, 4, 5, 7 and 8 PTs and that existing PT-fitness-for-service assessments are not impacted by the elevated $[H]_{eq}$ concentrations in the region of interest.

- Results from ex-service pressure tube monitoring and in-service PT scrape sampling continue to support the validity of existing BOT and RJ $[H]_{eq}$ predictive models outside the ROI in deterministic fitness-for-service assessments.

- The results of the evaluation on CWEST scrape witness marks showed substantial margins against crack initiation in terms of addressing the uncertainty in crack initiation material properties at high levels of $[H]_{eq}$ in the region of interest.

- A defense-in-depth approach comprised of the risk-informed fracture protection evaluation of a postulated through-wall flaw in the inlet/outlet regions of interest with elevated $[H]_{eq}$ and existing PSA concludes that the risk of PT rupture due to elevated $[H]_{eq}$ and a significant flaw in the region of interest is low. The required safety factors for all service level transients as per CSA N285.8 were met for $[H]_{eq}$ up to 120 ppm. A sensitivity assessment was performed to demonstrate that the safety factors are at least 1.0 for all service level transients for $[H]_{eq}$ up to 200 ppm.

All of the activities summarized in this document support Bruce Power's position that the PTs installed in Bruce Units 3 to 8 remain safe for operation with elevated $[H]_{eq}$ in the inlet and outlet regions of interest.

5.0 REFERENCES

A1. Letter, L. Sigouin to M. Burton, "Bruce A and B: Request for an Update to the Commission on Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration (Heq) – AI 2022-07-23135", April 28, 2022, e-Doc 6761165, BP-CORR-00531-02753.

A2. CNSC Event Report B-2021-93819 DR, "A2131 Outage Scrape Campaign Hydrogen Equivalent Concentration Measurements", June 29, 2021.

A3. CNSC Event Report B-2021-98077 DR, "Pressure Tube Surveillance Hydrogen Equivalent Concentration Measurements on Unit Shutdown for Major Component Replacement", July 5, 2021.

A4. CNSC Event Report B-2021-135624, "Industry Pressure Tube (PT) Surveillance Program – Inlet, Hydrogen Equivalent Concentration Measurements on PT from Unit Shutdown for Major Component Replacement", December 10, 2021.

A5. Email, A. Glover to A. Robert, "Additional Information in Support of the Region of Interest", September 22, 2021, BP-CORR-00531-02407.

Attachment B

Path Forward - Schedule of Key Deliverables

Attachment B – Path Forward – Schedule of Key Deliverables

The purpose of Attachment B is to provide a detailed plan with a schedule of key deliverables to improve hydrogen equivalent ($[H]_{eq}$) concentration predictions near the rolled joints as requested by CNSC in Reference B1.

In Reference B2, Bruce Power provided a Level 1 Response Plan for "Outlet Rolled Joint $[H]_{eq}$ Concentration Results". In addition, Bruce Power and industry partners developed a preliminary industry road map that outlined high-level activities to improve $[H]_{eq}$ predictions. This preliminary industry roadmap along with a status update on the work described in Reference B2 was provided during the Industry Workshop on Elevated $[H]_{eq}$ on March 25, 2022. Since then, an oversight committee comprising of industry members was created to oversee the activities of the first phase of the roadmap. In addition, task teams were created to identify gaps in areas such as model development, user requirements and experiments and data.

As recommended through the industry roadmap process (Figure B-1), Bruce Power, with industry collaboration, has identified various experimental and modelling path forward actions. For CANDU Owner's Group (COG) Work Plan (WP) items, schedule targets reflect the overall report due date. Preliminary results will be shared for information as they become available. As noted, Bruce Power will continue working with industry to update fitness for service assessments to incorporate the results of the activities identified in Attachment B as they become available and as per established processes.

The following monitoring/experimental activities are planned to support $[H]_{eq}$ technical basis validation and identification of key input parameters for modelling and assessment. For each planned experimental activity listed in Table B-1, below, scope and schedule requirements are summarized. In Table B-2 on planned modelling activities to support projection of PT condition evolution, a summary of the scope and schedule requirements are provided. Note that all schedule targets in Tables B-1 and B-2 are subject to revision/refinement as the roadmap process progresses.

The planned activities specified in Tables B-1 and B-2 establish a path forward as shown in Figure B-1 and Figure B-2 below.

References

B1. Letter, L. Sigouin to M. Burton, "Bruce A and B: Request for an Update to the Commission on Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration (H_{eq}) – AI 2022-07-23135", April 28, 2022, e-Doc 6761165, BP-CORR-00531-02753.

B2. Letter, M. Burton to L. Sigouin, "Bruce A and B: Supplemental Information to Subsection 12(2) of the General Nuclear Safety and Control Regulations: Measurement of Hydrogen Equivalent Concentration in Pressure Tubes – Item 5", January 31, 2022, BP-CORR-00531-02450.

Table B-1:
Planned Monitoring/Experimental Activities

Item	Task	Activity	Scope	Schedule Target
	Testing to Establish [Heq] Technical Basis (Industry Co-Funded)			
4A	Improve Characterization of 'Blip' Existing Condition and Expected Evolution	COG WP 10369: Circumferential Gradients in Hydrogen Isotope Concentration in Rolled Joints	• Perform further 'blip' characterization using a combination of HVEMS, metallography, and surface analysis during 2022/2023 and expand WP 10369 into 2023/2024	• Document results of additional hydrogen/deuterium (H/D) sampling, metallography, and/or surface analysis in Rolled Joint (RJ) regions (Q1 2024)
4B		COG WP 10384: Determination of Deuterium Concentration in Regions of Through-Wall Gradients from Rolled Joint Blips and Denuded Zones	• Determine through-wall deuterium concentration in regions of Blips to provide additional empirical data of through-wall concentration gradients.	• Document results of additional H/D sampling and with a focus on through wall gradients and 'blip' characterization (Q2 2024)
4C	Confirm the Cause of 'blip' Formation Differentiating the Potential Roles of Ingress and Redistribution	COG WP 10379: Measurements of Hydrogen and Deuterium Concentrations in ex-service pressure tube material to assess circumferential gradients and axial distribution	• If visible, perform HIC sampling/analysis in garter spring (GS) residence mark in B6S13 to understand the potential impact of localization thermal gradients on $[H]_{eq}$ evolution.	• Document Results of targeted H/D sampling (Q3 2023)
4D		Evaluate the Viability of RJ Mock-up Temperature Measurements	• Perform a feasibility study to determine if RJ temperature measurements could be obtained via mock-up assembly to help inform thermal inputs to RJ $[H]_{eq}$ models.	• Document conclusions of feasibility study (Q2 2023, testing to be performed after this date if viability confirmed)
4E	Improve Characterization of TSS Hysteresis	COG WP 10383: Assess the Effect of Hold Time on Hydrogen Solubility Limit Hysteresis and Hydride Redistribution in a Temperature Gradient	• Investigate potential Terminal Solid Solubility for Dissolution (TSSD)/Terminal Solid Solubility Precipitation(TSSP) hysteresis reduction associated with sustained holds at temperature in ex-service PT material. • Investigate the effect of applied thermal gradients on $[H]_{eq}$ evolution.	• Document results of hysteresis and thermal testing (Q1 2024)

Table B-2: Planned Model Development Activities

	Task	Activity	Scope	Schedule Target
	Actions to Enhance [Heq] Predictability (Industry Co-Funded)			
5A	Develop PT Temperature Model Enhancements – (ASSERT-PV Updates)	COG WP 10630 Development of a Pressure Tube Heat Transfer Model for ASSERT-PV.	• Model the PT thermal interaction in ASSERT as part of the ASSERT-PV Heat Transfer Model to help inform thermal inputs to $[H]_{eq}$ models by providing direct coolant to PT heat transfer predictions (supports modelling of $[H]_{eq}$ evolution in the presence of coolant thermal gradients).	• Document model development and simulation results (Q3 2023)
5B	Define Interim Temperature, Stress, Ingress, and TSS Inputs for $[H]_{eq}$ Models (Validate and/or Revise Existing Inputs as Required)		• Document interim inputs to $[H]_{eq}$ models to account for temperature, stress, ingress (including H-ingress as applicable), and hydrogen isotope solubility impacts on $[H]_{eq}$ evolution. This item identifies temporary inputs based on current technical basis understanding, to be validated as experimental roadmap work progresses.	• Document interim $[H]_{eq}$ model inputs (Q3 2023)
5C	Develop Interim $[H]_{eq}$ Model •		• Develop means to approximate elevated $[H]_{eq}$ effects and issue an interim $[H]_{eq}$ predictive model. This model will incorporate current technical basis understanding for the purpose of short to medium term $[H]_{eq}$ projection.	• Document and issue Interim $[H]_{eq}$ model (Q4 2023)
5D	Confirm Interim $[H]_{eq}$ Model Continued Validity as the Roadmap Actions Progresses		• Based on information/understanding gained via this roadmap process and interfacing programs, review the interim model for ongoing acceptability and either reaffirm or revise the model accordingly	• Document review(s) of interim model validity (Q4 2024, Q4 2025)
5E	Define Final Temperature, Stress, Ingress, and TSS (Terminal Solid Solubility) Inputs for $[H]_{eq}$ Models (Validate and/or Revise Interim Inputs as Required)		• Document final inputs to $[H]_{eq}$ models to account for temperature, stress, ingress (including H-ingress as applicable), and hydrogen isotope solubility impacts on $[H]_{eq}$ evolution. This item identifies final inputs after all experimental roadmap work has been completed.	• Document final $[H]_{eq}$ model inputs (Q3 2025)

5F	Define the Relative Importance of Variables Influential to $[H]_{eq}$ Evolution	• Perform a parametric study using both interim and enhanced RJ models to establish which variables are most influential to $[H]_{eq}$ evolution and which can be simplified/excluded. • Note that completion of this item will require parametric study performed. This work is targeted to begin in Q2 2024 as part of the modelling process, noting for clarity that a final comprehensive model will not be available as of Q2 2024.	• Document influential variables that most significantly impact $[H]_{eq}$ evolution (Q4 2025)
5G	Develop Comprehensive $[H]_{eq}$ Model	• Develop and issue a comprehensive $[H]_{eq}$ predictive model. This model will incorporate enhanced technical basis understanding from the roadmap for the purpose of long term $[H]_{eq}$ projection.	• Document comprehensive $[H]_{eq}$ Model (Q1 2026) • Issue comprehesnsive $[H]_{eq}$ Model (Q2 2026)

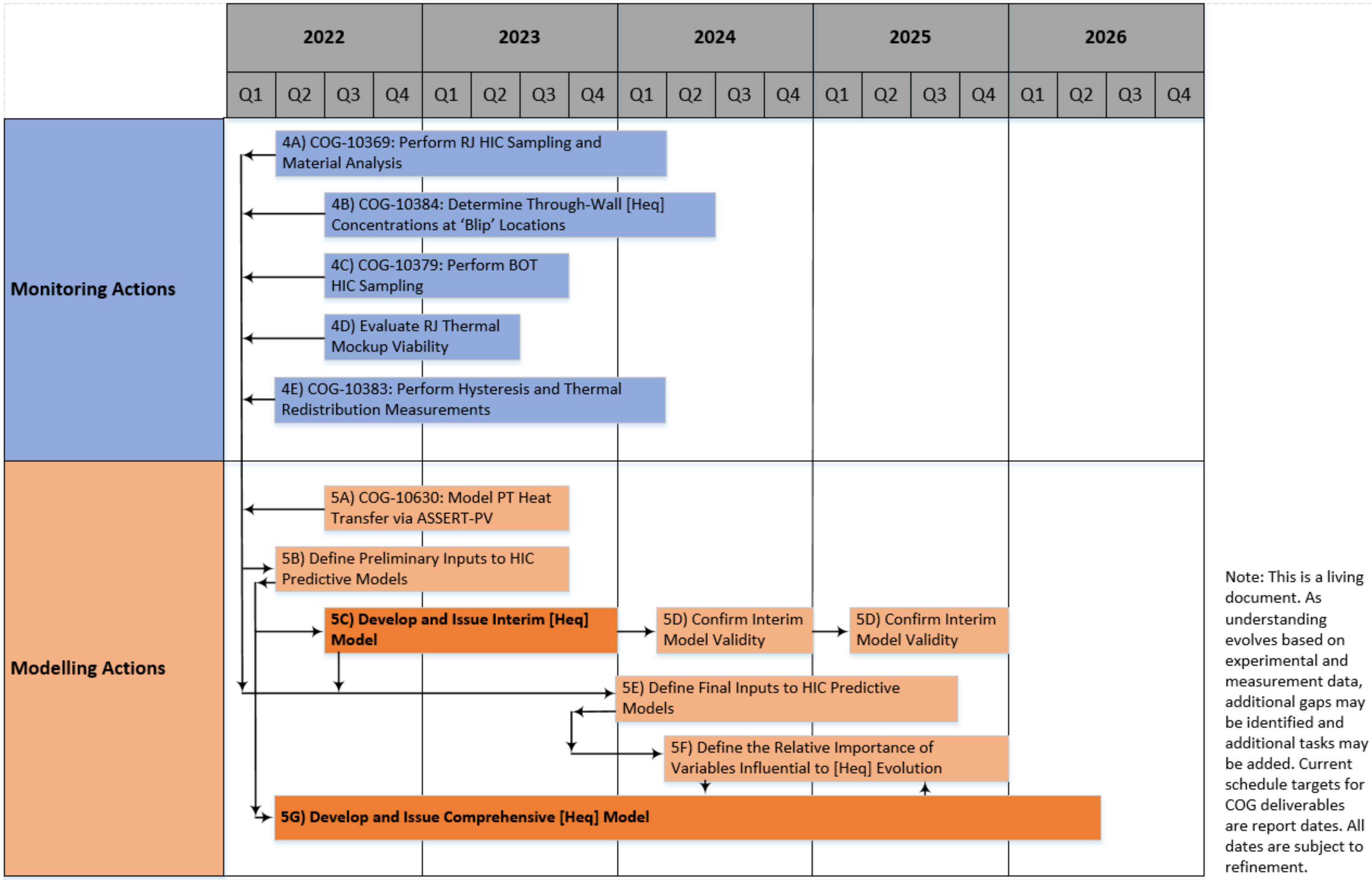

Figure B-1: Industry Roadmap on Improvement – Improve $[H]_{eq}$ Predictive Capabilities

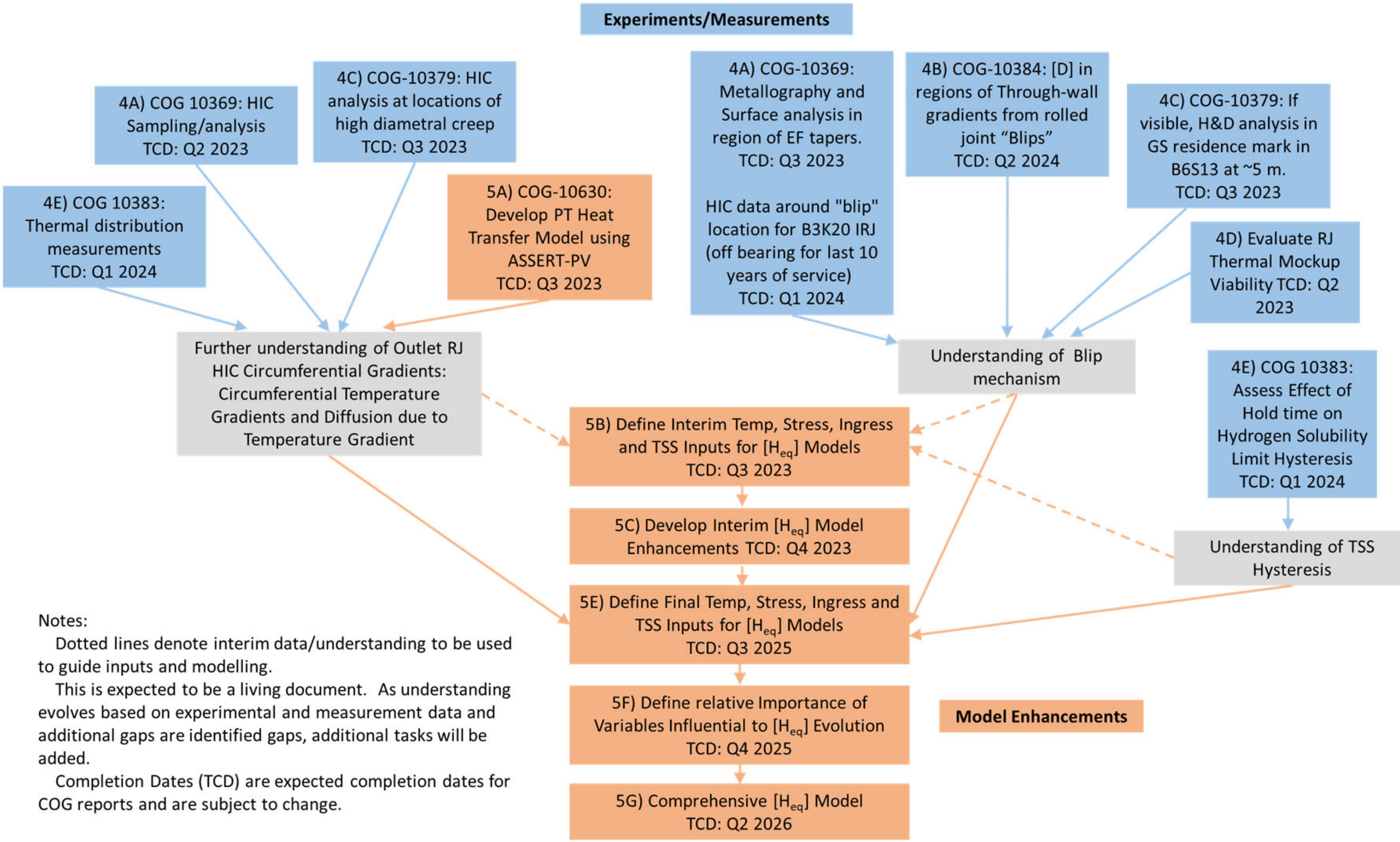

Figure B-2: Industry Roadmap to Improve [H]$_{eq}$ Predictive Capabilities