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Commission canadienne de sûreté nucléaire

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Written submission from Ontario Power Generation Inc.

Mémoire écrit de Ontario Power Generation Inc.

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

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OPG Proprietary

January 27, 2025

CD# N-CORR-00531-24390 P

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Dr. Viktorov and Ms. Salmon

Darlington and Pickering NGS – Progress Update on Industry R&D Plan for Elevated Hydrogen Equivalent Concentrations in the Inlet Rolled Joint Region, Action Item 2023-OPG-27200

The purpose of this letter is to provide an update to the Commission, as directed in Reference 1, regarding OPG's progress on the research and development (R&D) activities regarding elevated hydrogen equivalent concentrations ([Heq]) in the inlet rolled joint region of the pressure tube (PT) due to blip formation.

Since the discovery of elevated [Heq] concentrations in the inlet rolled joint region of surveillance pressure tubes, OPG has undertaken several activities to confirm the understanding of elevated [Heq] and to demonstrate fitness-for-service and continued safe operation of OPG fuel channel PTs. Regular progress updates on these activities have been provided to the Commission and to CNSC staff in References 2-6, in addition to annual industry workshop meetings on elevated [Heq] with CNSC staff since 2022.

A progress update on industry R&D plan activities related to elevated [Heq] concentrations in the inlet rolled joint region of the pressure tube, including activities relating to characterization and understanding of blip formation, model development, and relevant experiments is provided in Attachment 1. Additional information is provided on programs for testing crack initiation parameters at elevated [Heq] levels expected to be representative of the blip and local [Heq]. Results from these experiments to date indicate that higher [Heq] levels commensurate with the development of blips near the PT outer diameter surface will have a very limited

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effect on the risk of crack initiation and are therefore not expected to increase the risk of PT failure.

The activities described in Attachment 1 are part of the industry's [Heq] roadmap process to address the elevated [Heq] concentrations in the inlet rolled joint regions. An overall update on roadmap activities was provided to CNSC staff most recently in Reference 2. OPG 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.

Should you require further information, please contact Mr. Alec MacDonald, Senior Manager, Major Components Engineering Department at (905) 767-2027.

Sincerely,

Mark R. Knutson, P. Eng.
Chief Enterprise Engineer and Chief Nuclear Engineer
Ontario Power Generation Inc.

Attach

cc:	N. Kline	- CNSC (Ottawa)
	B. Carr	- CNSC (Ottawa)
	V. Tavasoli	- CNSC (Ottawa)
	C. Chan	- CNSC Site Office (Darlington)
	C. Krasnaj	- CNSC Site Office (Pickering)

References:

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

2. OPG Letter, M. Knutson to A. Mathai and R. Richardson, "Darlington and Pickering NGS – Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration Semi-Annual Update #4 (Quarter 3 2024)", OPG CD# N-CORR-00531-23913, September 27, 2024.

3. OPG Letter, M. Knutson to A. Mathai and R. Richardson, "Darlington and Pickering NGS – Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration Semi-Annual Update #3 (Quarter 1 2024)", OPG CD# N-CORR-00531-23960, March 28, 2024.

4. OPG Letter, M. Knutson to A. Mathai and R. Richardson, "Darlington and Pickering NGS – Activities Related to the

Discovery of Elevated Hydrogen Equivalent Concentration Semi-Annual Update #2 (Quarter 3 2023)", OPG CD# N-CORR-00531-23799, September 29, 2023.

5. OPG Letter, M. Knutson to A. Mathai and R. Richardson, "Darlington and Pickering NGS – Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration Semi-Annual Update #1 (Quarter 1 2023)", OPG CD# N-CORR-00531-23603, March 27, 2023.

6. OPG Letter, M. Knutson to D. Saumure and A. Viktorov, "OPG Response – Darlington and Pickering NGS – Request for an Update to the Commission on Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration (Heq) – New Action Item 2022-OPG-23135", OPG CD# N-CORR-00531-08536, July 19, 2022.

ATTACHMENT 1

OPG letter, Mark R. Knutson to A. Viktorov and C. Salmon, "Darlington and Pickering NGS – Progress Update on Industry R&D Plan for Elevated Hydrogen Equivalent Concentrations in the Inlet Rolled Joint Region, Action Item 2023-OPG-27200"

CD# N-CORR-00531-24390 P

Update on Progress Made to Improve Characterization and Understanding of Blips in Hydrogen Equivalent Concentration Profiles in Rolled Joints

Prepared By: **M. Poloni**

Checked By: **J. Lam**

ATTACHMENT 1

UPDATE ON PROGRESS MADE TO IMPROVE CHARACTERIZATION AND UNDERSTANDING OF BLIPS IN HYDROGEN EQUIVALENT CONCENTRATION PROFILES IN ROLLED JOINTS

Table A-1 outlines updates on activities related to understanding the evolution of Hydrogen Equivalent Concentration ([Heq]) near inlet rolled joint burnish marks where localized regions of high [Heq] toward the pressure tube outer diameter (OD), termed “blips”, may be found. These activities relate to:

- Characterization of blips in ex-service pressure tube (PT) material, including profiling their extent and the local [Heq] variations axially, circumferentially, and through-wall.
- Understanding the mechanism of blip formation in rolled joints.
- 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.

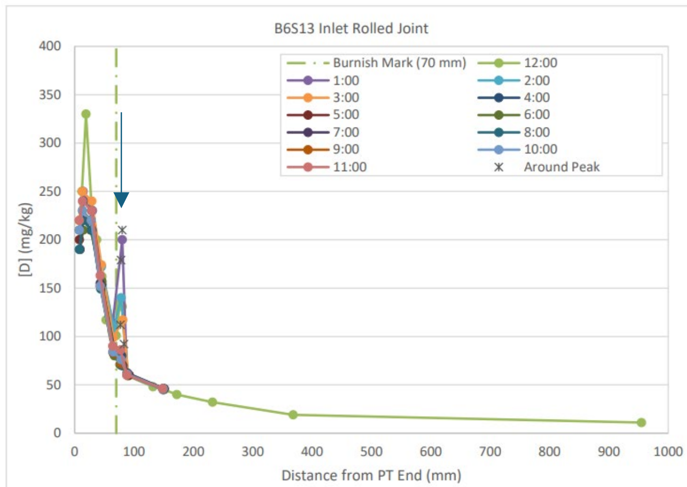
Industry has developed an understanding of the mechanism of blip formation and is developing projections of blip evolution in order to establish expected [Heq] levels from blips that may be present toward end-of-life for operating reactors, where blip formation is applicable. The models used in these projections have been compared to available measurements and show good agreement, with additional benchmarking and experimental validation in-progress.

Industry is also undertaking an extensive R&D program to extend the validity limits of material property models to high [Heq] levels expected to be representative of the blip and the local [Heq].

To date, OPG has provided CNSC staff with several routine updates on activities related to elevated [Heq] in rolled joint regions, which include activities related to blips, References [A-1][A-2][A-3][A-4]. These activities constitute the larger industry response to elevated [Heq] phenomena, termed the “Elevated [Heq] Roadmap”, which contains explicit activities related to characterizing the blip, its expected evolution, and model development.

OPG maintains that pressure tubes (PTs) remain fit-for-service with blip formation and evolution; experiments indicate that higher [Heq] levels commensurate with the development of blips near the PT Outer Diameter (OD) surface will have a limited effect on the risk of crack initiation from flaws on the PT Inner Diameter (ID) and are therefore not believed to meaningfully increase the risk of PT failure.

Table A-1: Status Update of R&D Activities

R&D Activity	Status Update of Activities
Characterizing Blips in Ex-Service Pressure Tube Material	Currently planned work for characterization of blips has been completed. To date, measurement of [Heq] profiles for the purposes of characterizing elevated [Heq] has been performed in ex-service pressure tubes from Pickering B, Darlington, and Bruce fuel channels, with a subset of rolled joints containing blips. For Bruce B6S13 PT, the inlet rolled joint [Heq] profile that shows the localized blip is provided below in Figure 1.  *Figure 1. Deuterium Concentration Profiles from the Inlet Rolled Joint of B6S13 (Arrow indicates blip location)* 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 PTs where blips have been observed in the concentration profile. Blips are also found near the outlet rolled joints with similar axial and circumferential locations and extents. Metallography at blip locations has been performed to characterize the distribution of [Heq] through the PT wall for comparison to modelling predictions and identification of representative through-wall gradients for experiments. This through-wall characterization has shown that blips are localized near the OD of the PT, and that [Heq] closer to the ID of the PT is consistent with levels in adjacent regions of the rolled joint that do not show elevated [Heq]. 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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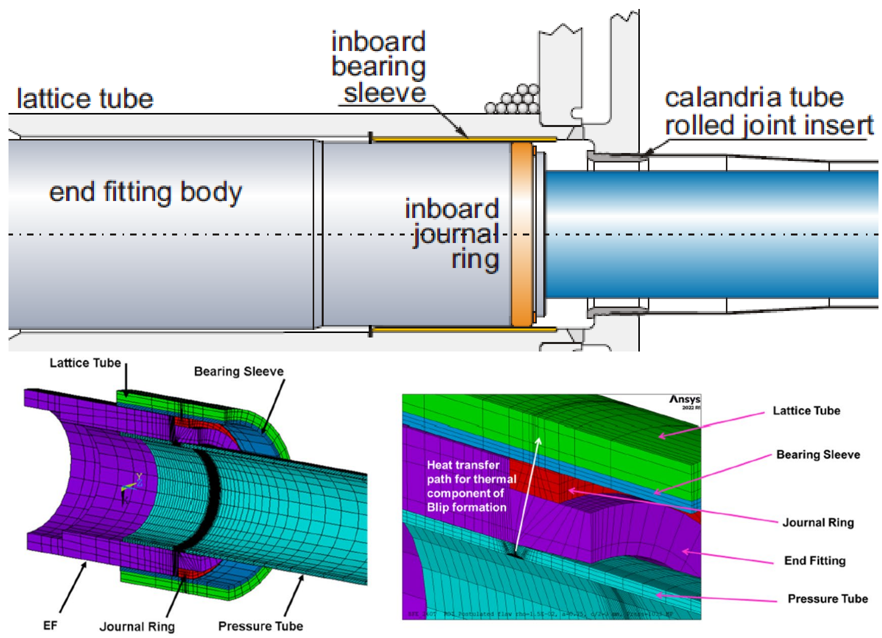
It is currently understood that blip formation results from a region of localized contact between the PT outer surface and the end-fitting taper, and a resulting local decrease in PT operating temperature at this location due to heat-transfer through the inboard bearing components to the reactor end-shield. This localized decrease in PT operating temperature results in the accumulation of hydrogen isotopes locally. Once the local solubility limit is exceeded, accumulated hydrogen isotopes remain as hydrides and subsequent reactor operation results in further accumulation of [Heq] at the blip location. This localized contact region on the OD of the PT and the resulting temperature profile is understood to be responsible for the size of blips and their relatively localized nature; blips are expected to be constrained axially and circumferentially, as the necessary temperature gradients do not extend further inboard or outboard with operating time. Figure 2 below illustrates the heat transfer path through the bearing components and Figure 3 illustrates the resulting temperature gradients in the PT wall.



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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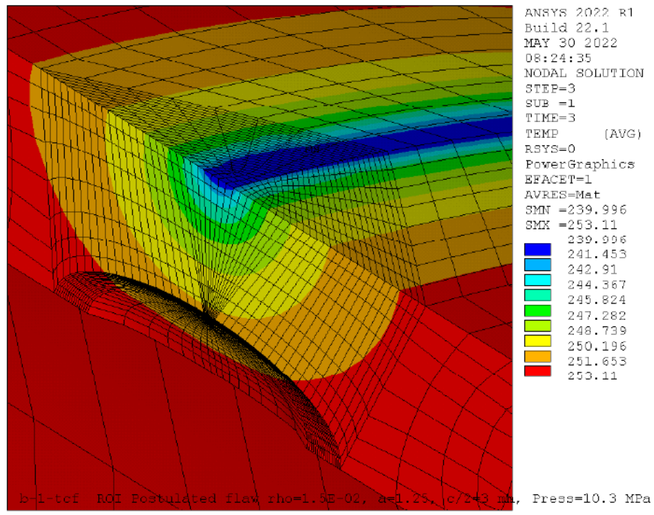

Figure 3. Thermal Gradients in PT From Local EF Taper Contact Due to Bearing Heat Conduction

Modelling of blip formation and evolution via thermal contact and the formation of locally colder regions, shows good agreement with observations, and also supports the temperature-driven redistribution mechanism.

Physical examination of PT OD surfaces at locations of blip formation by surface and chemical characterization methods has been performed. Physical examinations of these regions support that firm PT OD contact between the components is occurring at the end fitting taper location, however there is no direct evidence of metal-to-metal contact or loss of oxide that would result in localized ingress (i.e. oxide of the components remains present in the contact area). Consistent indicators of localized PT to end fitting contact ~10 mm inboard of the rolled joint burnish mark have been seen in ultrasonic inspections of fuel channels where blips have been found in corresponding ex-service examinations. Ex-service visual inspections of the PT OD also show local discoloration in these regions, and detailed examinations by SEM show evidence of firm contact between the two components. Figure 4 below provides an in-service ultrasonic inspection scan of the inlet rolled joint of Darlington pre-refurbishment pressure tube, showing an ultrasonic response at the location of the EF taper indicative of contact, as well as a visual examination showing a visual indication of contact with the EF taper.

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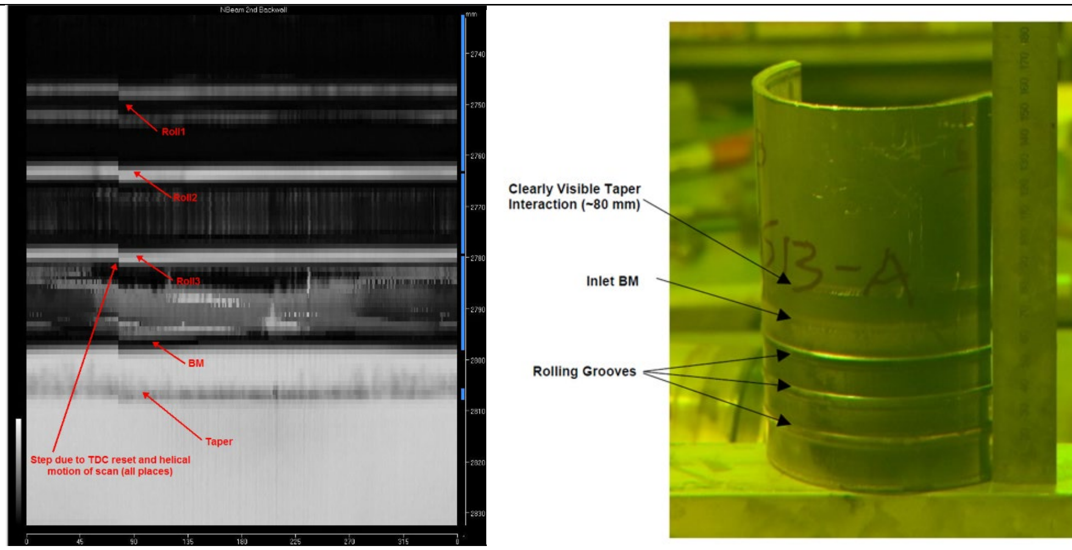

Figure 4. Ultrasonic Scan (Left) of the Inlet Rolled Joint of an Inlet Darlington Pre-Refurbishment PT Showing Ultrasonic Indication from OD Contact Between EF Taper and PT OD and a Visible Taper Indication on a RJ from a Bruce Pressure Tube (Right)

Localized PT to end fitting contact at the EF taper (as shown above) is understood to constrain the blip extent axially. As a result of bearing clearances, contact in the bearing occurs at specific circumferential orientations that are influenced by the load imparted by and through the end fitting resulting in colder temperatures on one orientation of the PT which constraints the blip extent circumferentially.

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<tr>
<td>Modelling Blip Formation and Evolution</td>
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Work is progressing. Industry has developed a 3D finite element model (ANSYS/HFE) that simulates loading and contact of fuel channel bearing components, heat transfer in the rolled joint region, and the migration of hydrogen isotopes with operating time. This ANSYS/HFE model has been used to simulate 3D [Heq] profiles of select ex-service rolled joints and shows good agreement with observations from [Heq] measurements and metallographic examinations of ex-service pressure tubes.

Figure 5 provides a comparison of the [Heq] contour profiles from the ANSYS/HFE 3D model and a corresponding through-wall metallographic image from an inlet rolled joint region, showing general agreement of the profiles. In the metallographic image, the darker features are zirconium hydrides with darker shaded regions indicating an increased hydride density and higher local [Heq] concentration, evident at the blip location.

Figure 6 provides a comparison of through-wall [Heq] profiles predicted by the ANSYS/HFE 3D model with the measured samples and analysis of metallographic images. Specifically, when the ANSYS/HFE result is integrated over a volume and compared to HVEMS measurements over the same volume, there is good agreement.

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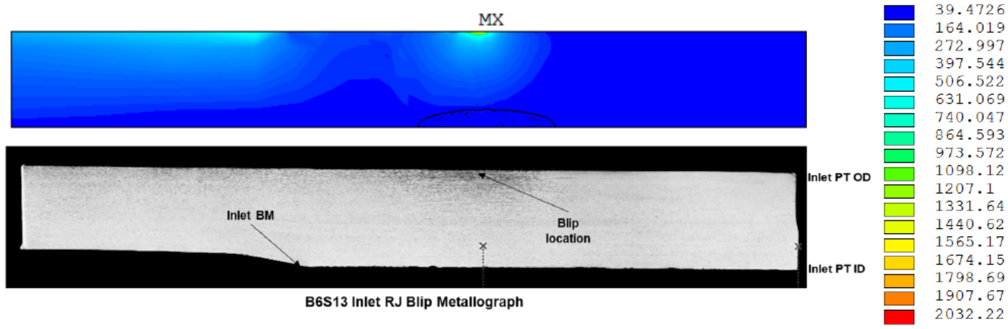


Figure 5. Comparison of [Heq] Contours from ANSYS/HFE to Metallography in the Axial-Radial Plane of the PT

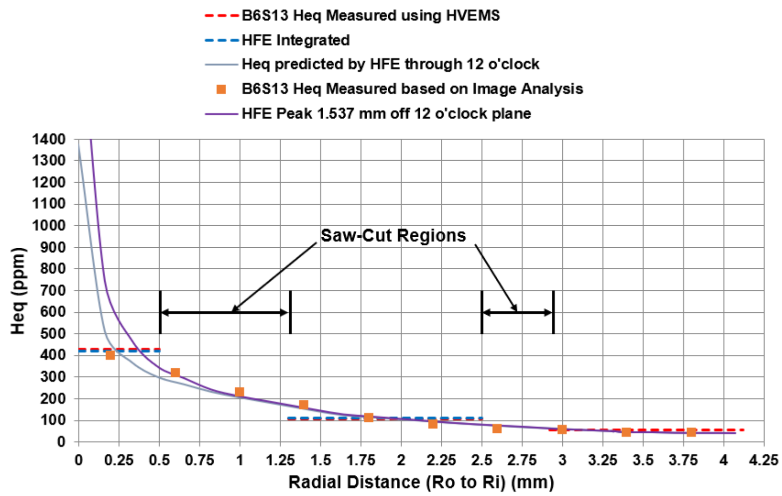
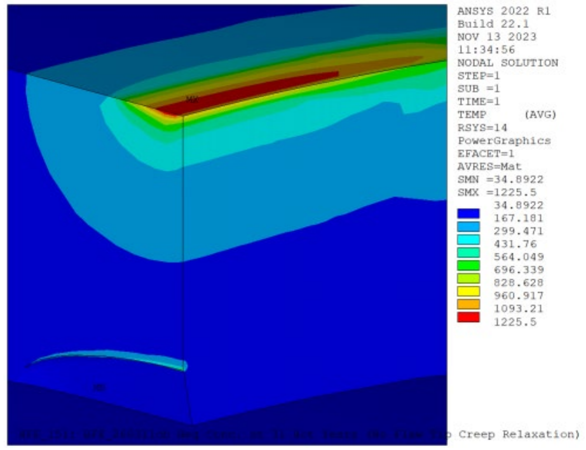


Figure 6. Comparison of ANSYS/HFE Predicted Through-Wall Concentration Profile to Measurements and Analysis of Through-Wall Metallographic Images

Industry is currently performing sensitivity cases with the intent of establishing potential bounding [Heq] 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 results show good agreement. Model refinements and sensitivity cases for understanding the evolution of the [Heq] levels at blips and possible limiting blip concentrations are ongoing.

The ANSYS/HFE model has also been utilized for investigating the potential interaction between PT ID flaws located at the PT ID coincident with locations of blip formation on the PT OD (Figure 7). These investigations conclude that there is no discernable effect of the blip on [Heq] at the tip of a postulated bounding flaw (i.e., the presence of a blip does not result in higher than expected levels of hydride accumulation at PT ID surface flaws (e.g. debris frets)). Additional modelling work in this area is ongoing as part of sensitivity case analysis.

	 *Figure 7. [Heq] Profiles Near a PT OD Blip and PT ID Flaw Showing Non-Interaction* Updates on benchmarking, sensitivity case results, and other modelling work are expected as part of the Q1 and Q3 2025 elevated [Heq] semi-annual update submission 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 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 initial testing is in-progress. The results of this work are expected to be included as part of the Q3 2025 elevated [Heq] submission to CNSC staff.
Material Property Testing at Elevated [Heq]	Currently ongoing. Material property tests at elevated bulk [Heq] are being performed to better establish the material properties at [Heq] levels consistent with blips, and to extend the validity of existing models to higher [Heq] 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 [Heq] on parameters relating to DHC initiation and DHC growth. There is an observed, limited adverse effect on threshold stress intensity for DHC initiation from a blunt flaw from experimental data obtained to date, and further investigations are ongoing. There is no evidence of an adverse effect of high [Heq] 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. • Note that these tests are performed in a high bulk [Heq]. In the case of the blip, the through-wall gradient provides that for a surface breaking flaw at the PT ID, the [Heq] at the flaw tip is significantly lower than at the PT OD. 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 blip elevated [Heq] on crack initiation properties.

	An update on material property tests at elevated [Heq] is planned as part of the Q1 2025 elevated [Heq] submission. OPG plans to submit available results and conclusions for material property tests at elevated [Heq] part of the Q3 2025 elevated [Heq] submission, consistent with the latest schedule targets for roadmap-related work packages [A-1]. Additional experiments are planned to examine the effect of large through-wall gradients in [Heq] on crack initiation behavior in PTs. Results of these experiments are expected to be reported in 2026.

References

[A-1] OPG Letter, M. Knutson to A. Mathai and R. Richardson, "Darlington and Pickering NGS – Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration Semi-Annual Update #4 (Quarter 3 2024)", OPG CD# N-CORR-00531-23913, September 27, 2024.

[A-2] OPG Letter, M. Knutson to A. Mathai and R. Richardson, "Darlington and Pickering NGS – Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration Semi-Annual Update #3 (Quarter 1 2024)", OPG CD# N-CORR-00531-23960, March 28, 2024.

[A-3] OPG Letter, M. Knutson to A. Mathai and R. Richardson, "Darlington and Pickering NGS – Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration Semi-Annual Update #2 (Quarter 3 2023)", OPG CD# N-CORR-00531-23799, September 29, 2023.

[A-4] OPG Letter, M. Knutson to A. Mathai and R. Richardson, "Darlington and Pickering NGS – Activities Related to the Discovery of Elevated Hydrogen Equivalent Concentration Semi-Annual Update #1 (Quarter 1 2023)", OPG CD# N-CORR-00531-23603, March 27, 2023.

Summary of Regulatory Commitments, Regulatory Obligations and Regulatory Management Actions Made/Concurrence Requested

CD# N-CORR-00531-24390 P

Submission Title: Darlington and Pickering NGS – Progress Update on Industry R&D Plan for Elevated Hydrogen Equivalent Concentrations in the Inlet Rolled Joint Region, Action Item 2023-OPG-27200

Regulatory Commitments (REGC):

No.	Description	Date to be Completed
	None	

Regulatory Management Action (REGM):

No.	Description	Date to be Completed
	None	

Regulatory Obligation Action (REGO):

No.	Description	Date to be Completed
	None	

Concurrence Requested: None