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Commission canadienne de sûreté nucléaire

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Written submission from Ontario Power Generation

Mémoire d' Ontario Power Generation

Hydrogen Equivalent Concentration in Pressure Tubes for Nuclear Power Plants

Responses from OPG to request pursuant to Subsection 12(2) of the *General Nuclear Safety and Control Regulations*: Issues Relating to Measurement of Hydrogen Equivalent Concentration in Pressure Tubes

Concentration d'hydrogène équivalent dans les tubes de force pour les centrales nucléaires

Réponses d'OPG à la demande en vertu du paragraphe 12(2) du *Règlement général sur la sûreté et la réglementation nucléaires* : Enjeux concernant la mesure de la concentration d'hydrogène équivalent dans les tubes de force

Commission Meeting

Réunion de la Commission

September 3, 2021

Le 3 septembre 2021

Canada

ONTARIO POWER GENERATION

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OPG Proprietary

July 19, 2021

CD# N-CORR-00531-22788

MR. M. LEBLANC
Commission Secretary

DR. A. VIKTOROV
Director General
Directorate of Power Reactor Regulation

Canadian Nuclear Safety Commission
280 Slater Street
Ottawa, Ontario
K1P 5S9

Dear Mr. Leblanc and Dr. Viktorov:

OPG Response to Request pursuant to Subsection 12(2) of the General Nuclear Safety and Control Regulations: Issues Relating to Measurement of Hydrogen Concentration in Pressure Tubes

Reference: 1. CNSC Letter, A. Viktorov to S. Gregoris and J. Franke, "Darlington and Pickering NGS: Request pursuant to Subsection 12(2) of the General Nuclear Safety and Control Regulations: Issues Relating to Measurement of Hydrogen Concentration in Pressure Tubes", OPG CD# N-CORR-00531-22783, e-Doc 6603931, July 13, 2021.

The purpose of this letter is to provide OPG's initial, formal response to CNSC staff's request (Reference 1) concerning the information reported to CNSC by Bruce Power, in relation to recent analysis of pressure tube sampling.

This response is prepared pursuant to Subsection 12(2) of the *General Nuclear Safety and Control Regulations*, and in accordance with Darlington's PROL 13.02/2025 and Pickering's PROL 48.01/2028 and respective Licence Condition Handbooks, Section G.1, "Licensing Basis for the Licensed Activities".

A report to the Commission regarding the following actions has been requested by no later than July 30, 2021 (Reference 1):

1. Confirm receipt of the information from Bruce Power related to this discovery;
2. Analyze the impact of this information on the demonstration of pressure tube fitness for service;

3. Conduct necessary tests and analysis to verify that operation of all reactors at OPG stations remains within their licensing basis; and
4. Inform CNSC of any other measures taken in response to this information.

CNSC also requested that OPG make a report to the Commission, by January 13, 2022, on:

5. Analysis of the hydrogen uptake model validity, reflecting the new information.

In addition, with respect to the above requested items, CNSC requires (Reference 1) that OPG file a report on the following information by July 19, 2021. OPG's response is provided immediately below.

CNSC Request:

a) Confirmation that the request will or will not be carried out or will be carried out in part;

OPG Response:

To the extent practicable and based on currently available information, OPG confirms it will carry out the CNSC's request.

CNSC Request:

b) Any action that OPG has taken to carry out the request or any part of it;

OPG Response:

OPG has begun a review of the Bruce Power information received to date. An engineering evaluation for continued operation of Pickering Units 1 and 4, 5-8 and Darlington Units 1, 2 and 4 has been initiated, via the Discovery Issue Resolution Process (DIRP), N-DIA-00531-10006, "Fitness For Service Impact of a High [Heq] Discovery Issue in a Non-OPG CANDU Unit", to document the condition and assessment.

CNSC Request:

c) Any reasons why the request or any part of it will not be carried out;

OPG Response:

Currently, there are no known reasons as to why this request, or any part of this request, cannot be carried out.

CNSC Request:

d) Any proposed alternative means to achieve the objectives of the request;

OPG Response:

No alternative means are presently proposed to achieve the requests.

CNSC Request:

e) Any proposed alternative period within which OPG proposes to carry out the request.

OPG Response:

At the time of writing this letter, OPG does not propose any alternative period within which OPG will carry out the requests. Should additional time be required, OPG will update the CNSC in an expeditious manner.

If you have any questions, please contact Mr. Paul Fabian, Department Manager, Major Components Engineering, at (289) 314-8521, or by e-mail at paul.fabian@opg.com.

Sincerely,

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

cc:
J. Burta - CNSC (Darlington)
K. Campbell - CNSC (Pickering)
R. Jammal - CNSC (Ottawa)
P. Elder - CNSC (Ottawa)
M. Rinker - CNSC (Ottawa)
V. Tavasoli - CNSC (Ottawa)
H. Overton - CNSC (Ottawa)
M. Ducic - CNSC (Ottawa)
S. Eisan-Kouznetsova - CNSC (Ottawa)

TABLE 1

Summary of Regulatory Commitments and Regulatory Management Actions Undertaken in this Submission

Submission Title: OPG Response to Request pursuant to Subsection 12(2) of the General Nuclear Safety and Control Regulations: Issues Relating to Measurement of Hydrogen Concentration in Pressure Tubes

Regulatory Commitments (REGC):

No.	Commitment Description	Target Completion Date
1.	Submission of a report to the CNSC, providing responses to Items 1-4, inclusively, as documented in CD# N-CORR-00531-22783, e-Doc 6603931.	July 30, 2021
2.	Provide CNSC with a report, documenting the results of the review of the hydrogen uptake model validity, reflecting new information, as documented in Item 5 of CD# N-CORR-00531-22783, e-Doc 6603931.	January 13, 2022

ONTARIO POWER GENERATION

MEMORANDUM

OPG Confidential

July 27, 2021

File No.: N-CORR-31100-0934853 P

Fitness for Service Impact of a High [Heq] Discovery Issue in a Non-OPG CANDU Unit: Assessment of Safety Impact

1.0 INTRODUCTION

In July 2021, Bruce Power reported two events related to hydrogen equivalent concentrations ([Heq]) measured in Bruce Units 3 and 6:

1) Measurements obtained from the A2131 outage scrape campaign showed elevated [Heq] values were greater than expected which potentially exceeded parameters of the fracture toughness model in CSA N285.8-15 Update 1, Clause D.13.2.3.1.2 (a), hence, potentially not meeting Clause 4.5.1.3 [1].

2) Following the removal of pressure tube S13 in Bruce Power Unit 6, higher than expected [Heq] values were found in the pressure tube which potentially exceeded the parameters of the fracture toughness model in CSA N285.8-15 Update 1, Clause D.13.2.3.1.2 (a), hence, potentially not meeting Clause 4.5.1.3 [2].

CNSC subsequently provided a letter to OPG [3] which was made pursuant to subsection 12(2) of the General Nuclear Safety and Control Regulations. OPG has been requested to review the impact of the Bruce Power [Heq] Pressure Tube (PT) sampling result, as it relates to OPG pressure tube fitness for service (FFS).

2.0 PURPOSE

This document presents the assessment of the safety impact of the [Heq] sampling results from the A2131 scrape campaign and material surveillance of PT B6S13.

3.0 ASSUMPTIONS AND METHODOLOGY

As a result of [3], OPG has obtained the engineering evaluation performed by Kinectrics to support continued operation of Bruce Units with higher than expected hydrogen equivalent concentrations in the back-end outlet (BEO) rolled joint (RJ) region of B6S13 [4]. A similar engineering evaluation is being completed to address operation of Pickering 1 and 4, 5-8 and Darlington 1, 2 and 4. The main assumption in this assessment is that the justifications discussed in this document remain applicable and technically justifiable for OPG units. This assumption will be validated upon review and acceptance of the OPG engineering evaluation and documented in [5].

For the B3 scrape campaign findings, the evaluation accounts for the information obtained at the writing of this document. The assumption is that the information available at this time is complete and any additional information would not alter the conclusions of the FFS assessment.

For the applicability of the Discovery Issue Resolution Process (DIRP), judgement is made whether there has been a significant decrease in the margin to the Derived Acceptance Criteria (DAC).

4.0 DETAILED INFORMATION FROM B3 AND B6 EVENTS

4.1 A2131 Scrape Results

Measurements from the A2131 outage Circumferential Wet Scrape Tool (CWEST) scrape campaign found elevated [Heq] in channels (eg. B3C11, B3F16, B3L11) [1]. The material was oriented in the front end outlet (FEO) configuration.

Scrape sampling at non-standard clock positions has identified that large circumferential gradients can exist resulting in large variations in repeat measured [Heq]. The trend in the [Heq] measurements between quadrants is similar to that observed in B6S13 from B1561 and B1761.

4.2 B6S13 Material Surveillance Results

B6S13 was removed from Bruce Unit 6 as part of the Unit 6 Major Components Replacement (MCR) project. The material was oriented in the back end outlet (BEO) configuration. High hydrogen and deuterium concentrations have been measured in the samples punched from the outlet RJ region. The results to date include samples from the 12, 3, 6 and 9 o'clock circumferential orientations at both the burnish mark and 20mm further inboard. Table 1 of [6] is shown below.

Table 1: Hydrogen and deuterium concentration measurements from through-wall punches obtained from the outlet end of the rolled joint region of tube B6S13.

Axial Location (mm)	Circumferential Location (clock)*	[H] (mg/kg)	[D] (mg/kg)	[Heq] (mg/kg)
8	12	55 ± 3	520 ± 30	315
13	12	55 ± 3	530 ± 20	320
28	12	57 ± 3	520 ± 30	317
44	12	51 ± 3	450 ± 20	276
59	12	44 ± 2	360 ± 20	224
69 (burnish mark)	12	46 ± 2	330 ± 20	211
	3	13 ± 1	94 ± 5	60
	6	12.0 ± 0.9	93 ± 5	59
	9	13 ± 1	95 ± 5	61
79	12	42 ± 2	340 ± 20	212
89/90 (burnish mark + 20mm)	12	22 ± 1	152 ± 8	98
	3	11.8 ± 0.9	89 ± 4	56
	6	12.5 ± 0.9	88 ± 4	57
	9	12.2 ± 0.9	87 ± 4	56
145	12	17 ± 1	109 ± 5	72

* clock position as viewed from the outboard end of the tube

Two observations are of interest:

a) There is strong circumferential variation in both hydrogen and deuterium concentrations at the burnish mark and 20mm inboard. These results are consistent with differences in [Heq] between B1561 and B1761 where large variation was observed in the compressive zone between the two scrape campaigns
  - Note that B1761 samples were acquired further from the top of the PT than B1561 samples

b) The measurement at the top of the tube at the 89/90mm axial position is 98ppm [Heq]. This is of interest as this is the [Heq] applicable in deterministic fracture protection (DFP) assessments.
  - Note that in DFP, a 20mm through-wall flaw in the outlet RJ with the highest [Heq] is postulated to be against the BM and its associated [Heq] is taken at its inboard end. [Heq] is predicted at the inboard crack tip as instability is more likely inboard than at the outboard end where constraint is provided by the end fitting [30].

OPEX SCR N-2021-11211, “OPEX SCR – Bruce Power High Heq Finding” has been initiated to track corrective actions.

The main concern for PT fitness for service with higher levels of [Heq] is reduced fracture toughness due to the presence of brittle hydrides that are highly influential in determining fracture toughness properties in the lower-shelf and transition temperature regimes. Flaws in a region of high [Heq] are at increased risk of crack initiation and growth and thus risk of PT fracture.

5.0 APPLICABILITY OF B3 AND B6 EVENTS TO OPG REACTORS

5.1 OPG OPEX FROM SCRAPE AND MATERIAL SURVEILLANCE ACTIVITIES

5.1.1 SCRAPE

Scrape sampling of inlet and outlet RJs has been performed in Pickering Units 1 and 4, 5-8, and Darlington 1 and 4, and scheduled per the Fuel Channels Life Cycle Management Plan [7]. In Darlington Unit 2, the first RJ scrape campaign after refurbishment is expected to occur in early 2024. Scrape sampling provides information to validate station-specific deuterium uptake models to support volumetric and dimensional inspections/flaw assessments. RJ scraping also confirms material properties against the CSA N285.4 inlet and outlet burnish mark acceptance criteria of 70ppm and 100ppm, respectively, and supports station operating envelopes in heatups/cooldowns by confirming the fracture protection envelope assumptions remain valid.

RJ scrapes are performed near the top of the PT circumferentially offset from top dead center (TDC) to facilitate repeats (especially in the compressive region where axial offset repeats cannot be performed) and as higher concentrations are expected at the top of the PT due to temperature differentials between the 12 o’clock and 6 o’clock positions.

The selection criteria for scrape inspection includes channels which are predicted to exceed terminal solid solubility of hydrogen dissolution (TSSD) in the body of tube (BOT) region prior to the target end of life. These channels are expected to be most limiting and are selected to monitor deuterium uptake to monitor possible changes in rates after exceeding this limit. BOT scrape inspections are often paired with RJ scrape in these channels.

With respect to RJ scrape results, the extracted Figures [8, 9, 10] below demonstrate that measured [Heq] inboard of the Burnish Mark (BM) to date is significantly lower in OPG units than that observed per the B3 and B6 OPEX. Note that the P5-8 outlet RJ [Heq] generic deterministic predictions shown below will be updated as previously committed in [11].

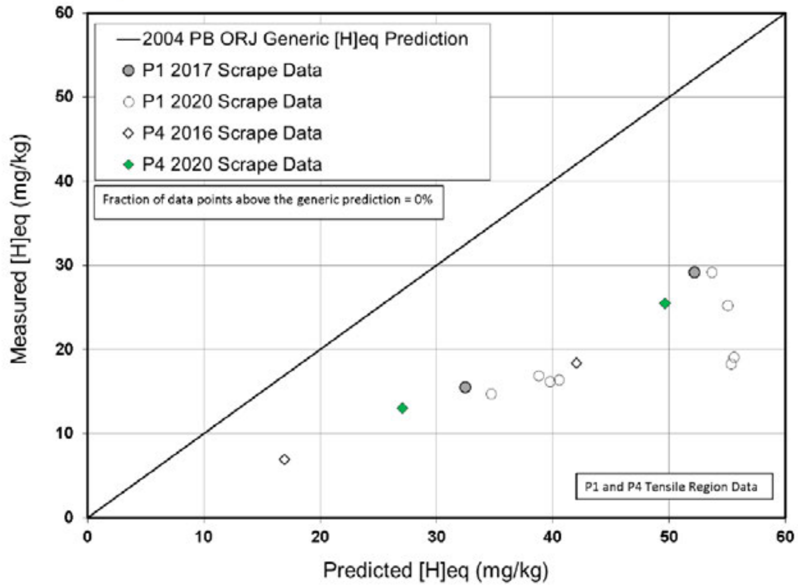

Figure 6: Comparison of Measured $[H]_{eq}$ and the 2004 Generic Deterministic Outlet RJ $[H]_{eq}$ Predictions for Tensile Region Locations of the P1 and P4 Outlet RJs

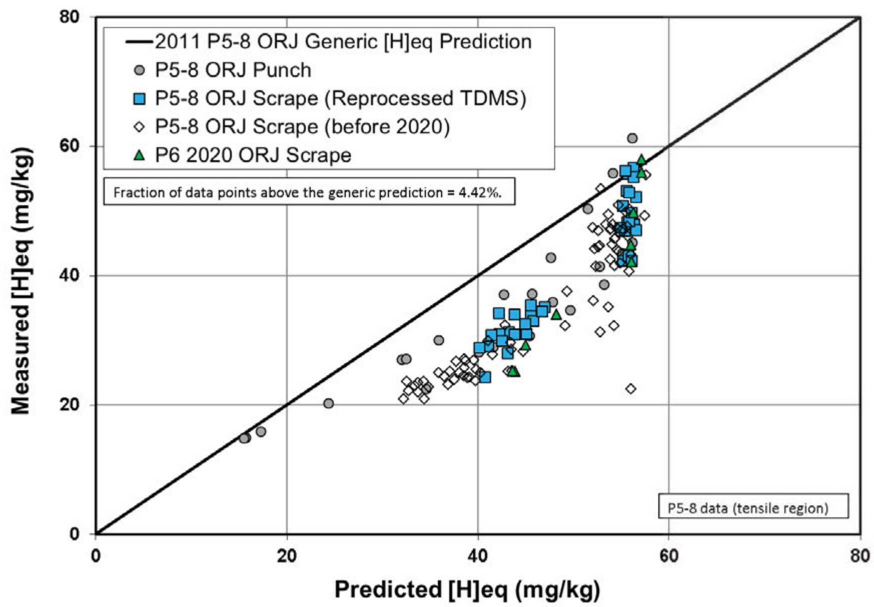

Figure 14: Comparison of Measured $[H]_{eq}$ and the 2011 Generic Deterministic Outlet RJ $[H]_{eq}$ Predictions for Tensile Region Locations of the P5-8 Outlet RJs

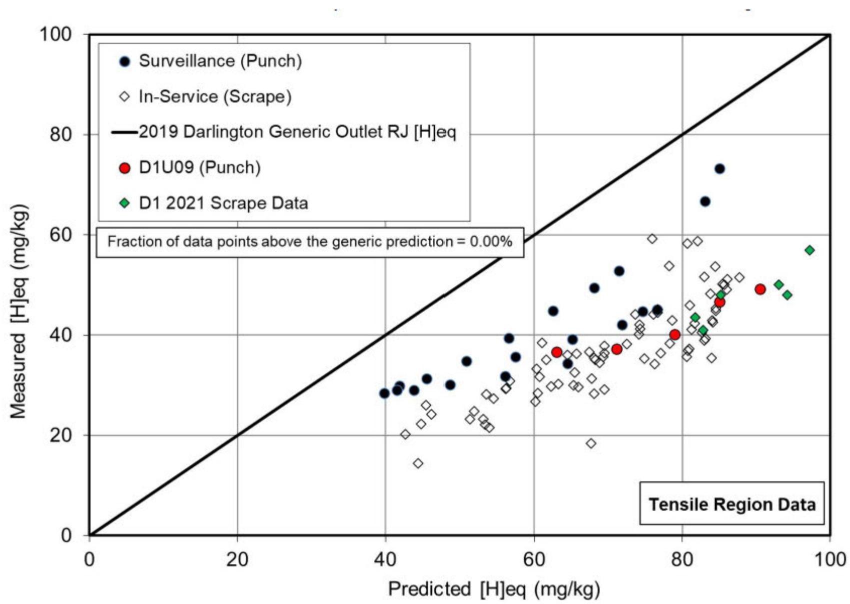

Figure 10: Comparison of All Darlington Measured $[H]_{eq}$ and the 2019 Darlington Units Outlet RJ $[H]_{eq}$ Generic Deterministic Predictions (Tensile Region Only)

Based on OPG punch and scrape sampling measurements to date, there is margin when compared to the B3 scrape results and justifications in subsequent sections of this document indicate the risk of PT failure is low.

For data that is available, OPG proactively compares scrape versus punch sampling as a validation exercise and provides this information to CNSC in material surveillance compliance reports.

Investigations are ongoing on potential enhancements to the scrape program to obtain additional data and further confirm adequate [Heq] margins in light of the Bruce 3 OPEX. Discussions are in progress on tooling enhancements to perform future scrape measurements across the 12 o'clock orientation of the PT (i.e., TDC).

5.1.2 MATERIAL SURVEILLANCE

As a result of the D1U09 (removed in 2017) localized high [Heq] region measured in the inlet RJ [12], [Heq] samples were obtained in both the inlet and outlet RJs of D3S13 (removed in 2020 immediately prior to D3 refurbishment) at several axial positions and all clock positions (samples from material surveillance are obtained via through-wall punches typically focused at the 12 o'clock TDC location and more recently, at multiple clock positions). The results from D3S13 have shown a localized [Heq] region just inboard of the outlet burnish mark (BM) with a peak [Heq] of 75ppm [13]. The maximum [Heq] measurement at nominally 20mm inboard of the BM is 60ppm. Table 2 below shows a subset of [Heq] measurements, at similar locations to B6S13. Figures 1 and 2 show D3S13 outlet RJ measurements at all clock positions and comparison to B6S13 at the 12 o'clock position, respectively.

Table 2: Select D3S13 Measurements from Outlet Rolled Joint [13] at Similar Locations to B6S13

Distance from PT End (mm)	Circumferential Location (Clock)	[H] (mg/kg)	[D] (mg/kg)	[Heq] (mg/kg)
8	12	12 ±1	109 ±5	67
15	12	12 ±1	110 ±6	67
28	12	11 ±1	112 ±6	67
43	12	12 ±1	113 ±6	69
63/65	11	11 ±1	100 ±5	61
	12	12 ±1	112 ±6	68
	1	11 ±1	101 ±5	62
	3	10 ±1	86 ±4	53
	6	9 ±1	85 ±4	52
	9	10 ±1	88 ±4	54
79	11	12 ±1	103 ±5	64
	12	14 ±1	122 ±6	75
	1	12 ±1	98 ±5	61
88 (nominally 20mm inboard of BM)	11	10.2 ±0.8	89 ±4	55
	12	12 ±1	96 ±5	60
	1	11.0 ±0.9	94 ±5	58
	3	9.7 ±0.8	79 ±4	49
	6	9.0 ±0.8	78 ±4	48
	9	9.1 ±0.8	80 ±4	49

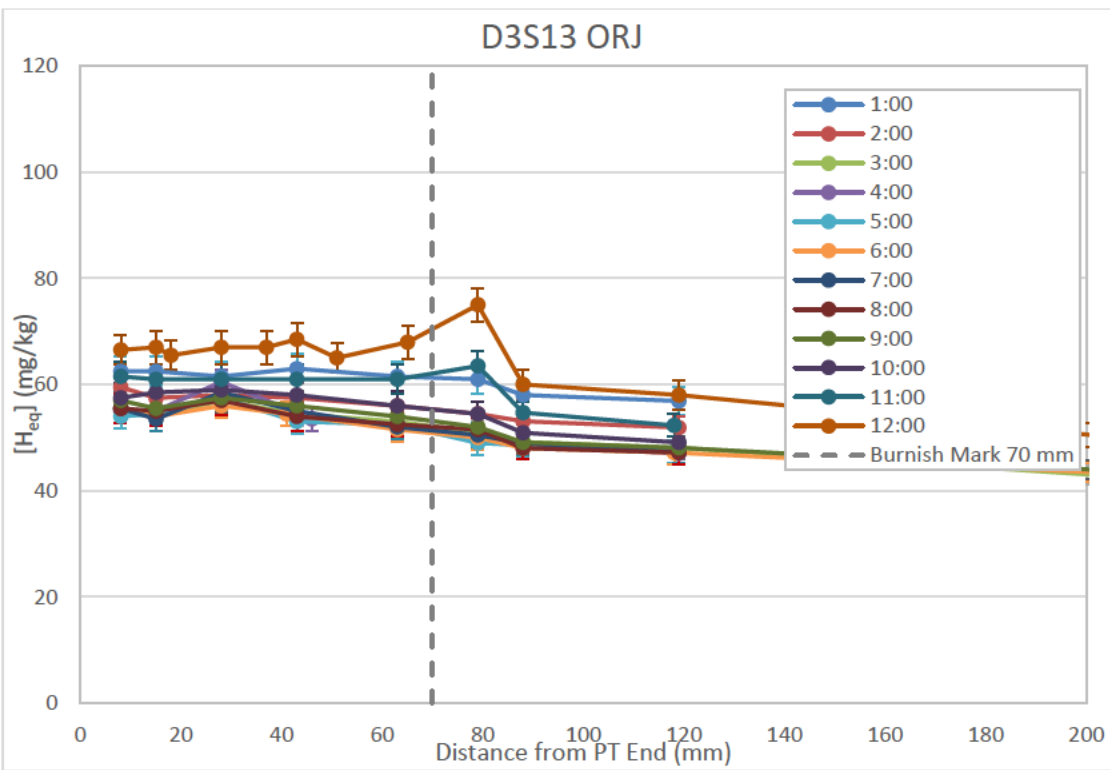

Figure 1: D3S13 outlet RJ Measurements from All Clock Positions

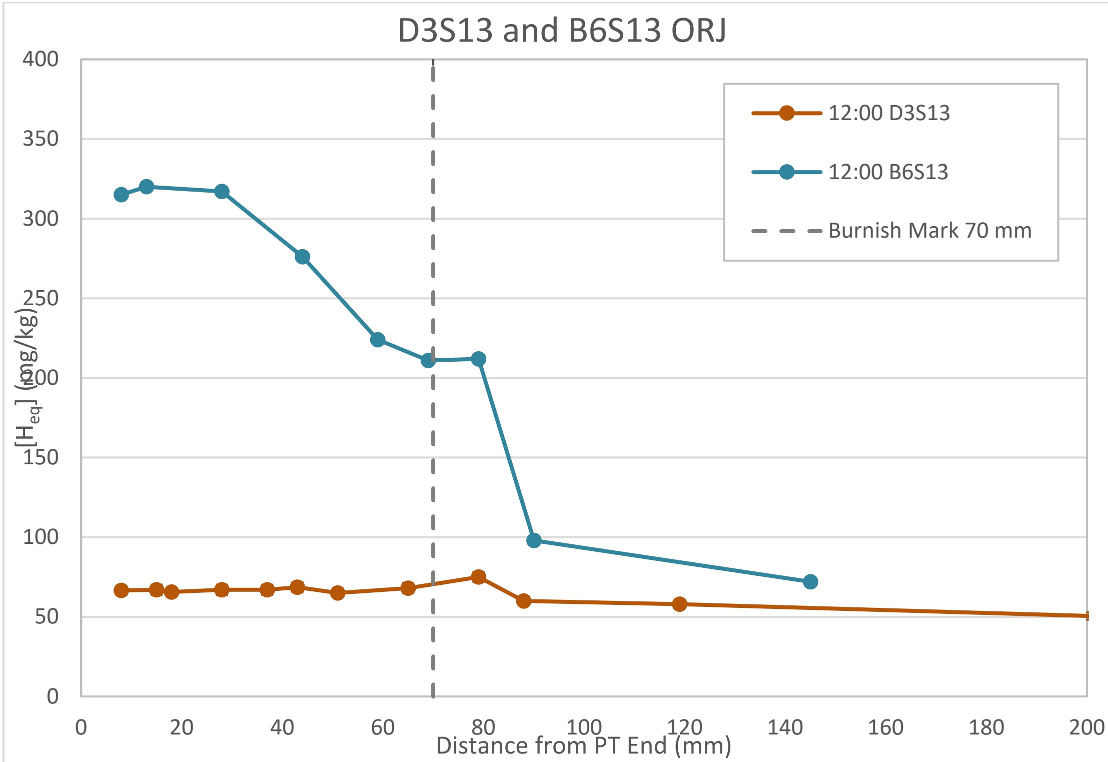

Figure 2: D3S13 and B6S13 Outlet RJ Measurements at 12 O'Clock Position

The results from D3S13 material surveillance are significantly lower than the B6 results, at approximately 60% of the B6 results at 20mm inboard of the BM. Additionally, there does not appear to be a gradient of similar magnitude from the 6 o'clock versus 12 o'clock measurements.

A COG research and development work package was proactively initiated in 2017 to investigate the extent of circumferential gradients in hydrogen isotope concentrations in the rolled joint region of pressure tubes. Extensive measurements were performed in the inlet RJs of D1U09 (removed in 2017), D2N15 (removed in 2016) and D2O23 (removed in 2016) at multiple axial and all clock positions where similar high localized [Heq] regions of 89ppm, 72ppm and 71ppm [12, 14] were measured just inboard of the inlet BM (over a very small axial and circumferential extent). High localized [Heq] observations in OPG PTs have been dispositioned in FFS assessments, as discussed in Section 5.7.

A Kepner Tregoe (KT) Problem Analysis has determined that the most probable cause of high localized [Heq] in OPG fuel channels (FC) is FC deformation leading to localized PT to end-fitting (EF) contact at the EF taper blended radius. Based on available data, circumferential non-linearity of BP outlet RJ [Heq] currently is a unique observation, and not directly related to high localized [Heq] measured just inboard of the BM in OPG PTs. While it is expected that local PT temperature variation may play a role in the evolution of both conditions, it is understood that these conditions are separate and that the observation of one condition does not indicate the presence of the other.

- *Details on FC deformation leading to localized PT to EF contact at the EF taper blended radius*

- Preliminary Finite Element Analysis (FEA) of the FC predicts that with aging, a combination of EF overhang weight, PT diametral expansion, and journal bearing clearances can lead to a transition from nominally 6 to nominally 12 o'clock contact at the inboard bearing sleeve. As a result, a localized temperature gradient from the PT to the end shield is established, resulting in local concentration of [Heq] at the cold contact location. Channel specific feeder moments are understood to modify EF alignment laterally, accounting for high localized [Heq] observed at clock orientations away from the 6 and 12 clock positions.

Additional [Heq] testing is either currently underway or planned to be performed in P8P10 (removed in 2021) and P5N09 (planned removal in 2022). For inlet RJs, removal of 4 additional RJ sections is scheduled during Darlington Unit 3 Refurbishment (planned removal in 2021) as part of Inconel X-750 spacer retrieval to allow for additional [Heq] testing, as required.

5.2 FUTURE [Heq] PREDICTIONS

Considering all material surveillance testing and in-service scrape inspections performed to date, Pickering and Darlington PTs are not experiencing similar levels of degradation as observed during the recent B3 and B6 findings. Monitoring through scrape sampling of all Pickering and Darlington units will continue for confirmation. For Darlington Unit 2, the B3 and B6 events are considered not applicable at this time, as it is expected that the low number of operating hours (<10,000 hours as of June 2021) and low hydrogen from manufacturing (<5ppm) provide ample margin.

As a proactive short term measure in the engineering evaluation being completed for Pickering and Darlington, sensitivity cases with excess [Heq] will be incorporated into the DFP assessment, as this assessment is the most sensitive to changes in [Heq]. Long term strategies for [Heq] modelling include use of 3D FEA considering fuel channel geometries, local temperatures, location-specific [Heq], and material stress states.

5.3 STATION OPERATING ENVELOPES FOR HEATUP/COOLDOWN

Station operating envelopes for heatup/cooldown were modified in 2014 to account for changing fracture toughness properties due to increased bulk [Heq] levels. The purpose of the operating envelope is to maintain the temperature and pressure conditions to reduce the risk of PT rupture or initiation of delayed hydride cracking (DHC) at a flaw due to precipitation of hydrides at lower temperatures. Based on OPG observations to date, the axial extent of the high [Heq] in OPG PTs remains localized within a small span. Thus, it is expected that the current operating envelopes remain applicable.

5.4 INSPECTED FLAW POPULATIONS

Flaw populations in Pickering Units 1 and 4, 5-8 and Darlington 1 and 4 were reviewed against the requirements of N285.8 for continued operation. In Darlington Unit 2, the first volumetric and dimensional campaign after refurbishment is expected to occur in early 2024. It was found that one flaw in

Pickering Units 1 and 4 and three flaws in Pickering Unit 5 reside within the region 20mm inboard of the outlet burnish mark [15]. No flaws reside within this region for Darlington Units 1 and 4 [16]. The OPG engineering evaluation will update flaw populations reflecting the most recent inspection campaigns since [15, 16].

5.5 CONSERVATISMS IN THE BURST TEST PROGRAM

Rising pressure burst tests are conducted as part of industry surveillance activities and to continue to validate the cohesive zone fracture toughness model used in the fuel channel FFS assessments. It is important to note that increased hydrogen concentrations alone do not result in pressure tube fracture at station operating pressures. In order to perform a rising pressure burst test in a laboratory environment, an approximately half meter long piece of ex-service pressure tube is artificially hydrided to a high level of [Heq] (e.g. 160ppm or more) and a 55 mm long axial through-wall flaw is machined at the center and pressurized to burst. The 55mm long notch induced in the tube in a laboratory condition, is a significant flaw that has never been observed in an OPG pressure tube. OPG and industry partners have an active burst test program in place and continue to perform rising pressure burst tests at different conservative test conditions to support fuel channel FFS assessments.

The burst test program is conservative. If a through-wall crack was experienced during operation, the Annulus Gas System (AGS) would detect the leak and station procedures would be executed to cool down and depressurize the Unit appropriately. A burst test of this nature assumes that the through-wall flaw is not leaking and remains undetected by the AGS, which is highly conservative.

5.6 SAFETY ANALYSIS

The OPEX review of the B3 and B6 [Heq] measurements event has concluded that there continues to be adequate margins to support the leak before break assumptions used in the Probabilistic Safety Assessment (PSA) and Deterministic Safety Analysis (DSA). OPG safety analysis, more specifically the PSA models, credit the annulus gas system to detect PT leaks and facilitate a timely and effective operator response to prevent event propagation into a PT rupture. As such, there is no impact on the existing OPG PSA models and their resultant plant risk predictions. In addition, there is no change to the event classification for PT initiating events as analyzed in the safety report and the existing conclusions remain valid.

5.7 FITNESS FOR SERVICE ASSESSMENTS

As a result of the D1U09 inlet rolled joint high localized [Heq] region, impact assessments for Pickering and Darlington [15, 16] were performed for the deterministic flaw assessments, probabilistic core assessments (PCA), leak before break (PLBB), and deterministic or probabilistic fracture protection (DFP/PFP) assessments.

For flaw assessments, all Pickering flaws residing within 20mm of the outlet burnish mark were predicted to have [Heq] exceeding TSSD at normal operating conditions. Thus, increasing the predicted level of [Heq] in the region would have no effect on flaw acceptability since flaws evaluated as planar would already have postulated DHC growth at normal operating conditions and flaws evaluated as volumetric would already be under flaw-tip hydride ratcheting conditions. Thus, increasing the predicted level of [H]eq in the region of interest (burnish mark to 20 mm inboard of the burnish mark) would have no effect on the Pickering pressure tube flaw dispositions.

For reactor core assessments, probabilistic [Heq] profiles were axially-shifted to bound the D1U09 measurement values. This is conservative since increased [Heq] is applied to the entire axial RJ region as opposed to a localized area and was applied to both inlet and outlet RJs. Shifted [Heq] profiles were applied to all clock positions for the PCA and select clock positions for PLBB and PFP. All reactor core assessments for Darlington Units 1 and 4 (PCA, PLBB, PFP), and lead Pickering Units 1 (PCA, PLBB, DFP) and 7 (DFP), 8 (PCA, PLBB) met the acceptance criteria of N285.8, and in some cases, with significant margin (assessments from lead units in Pickering are judged to be applicable to remaining units in each station).

Based on review of existing fitness for service (FFS) assessments, additional [Heq] at the outlet RJ for PCA, PLBB and FP assessments is judged to be low risk with respect to meeting the acceptance criteria for demonstration of FFS. Although there is no current evidence that the B3 or B6 conditions occur in Pickering and Darlington Units, additional justifications in Section 5.8 provide further assurance that the risk of localized [Heq] at the top of the outlet RJ presents a low risk to PT failure.

5.8 JUSTIFICATIONS FROM BRUCE POWER ENGINEERING EVALUATION

5.8.1 DETERMINISTIC FRACTURE PROTECTION

A DFP evaluation based on a postulated 20mm axial through-wall flaw was completed in accordance with the CSA N285.8 calculation procedure, utilizing the Revision 2 engineering fracture toughness model [17] for Bruce Units 4, 5, 7 and 8. The calculations were performed using an [Heq] level of 160ppm and sensitivity case of 180ppm, with a focus of the calculations at the inboard tip of the postulated 20mm flaw with the outboard tip at the BM (i.e., axial position of 20mm inboard of the BM). Although the burst test specimens applicable for the back end (BE) material validity limit were performed up to 140ppm, the Revision 2 model was developed for a range of [Heq] up to 160ppm [17]. Per [4], application of the model for [Heq] levels up to 160ppm was not considered an extrapolation and application to 180ppm was considered a reasonable extrapolation. The safety factors (SFs) for heatup/cooldown and the cold over pressure transient (COPT, most limiting transient) were calculated for Bruce Units 4, 5, 7 and 8.

Companion DFP evaluations are also performed as part of the current PFP methodology, starting with heatup/cooldown [18, 19] and requested to be expanded to all Level B and C transients [20]. Select design basis Level B transients (e.g., rapid cooldown, abnormal cooldowns) remain the most limiting transients when calculating SFs for Pickering 5-8 and Darlington. Although the safety factors (SFs) for these transients will be below the applicable acceptance criterion (which was the rationale for transition to PFP), tracking of these transients demonstrates an extremely low frequency of occurrence or no occurrences in the operating history [21-28].

Pickering and Darlington DFP sensitivity cases with these transients assessed against Service Level B and C loading acceptance criterion and 20mm and 18mm postulated through-wall flaw length will demonstrate adequate SFs for the purposes of FFS.

Additionally, the DFP/PFP evaluation includes a number of conservatisms:

a) For a through-wall flaw to exist, there needs to be a pre-existing service-induced flaw which would be a site for crack initiation and growth. Additionally, the likelihood of flaws existing in the top of tube are significantly lower than the bottom of tube.
b) Relaxation of residual hoop stresses at the outlet RJ will contribute to mitigation of crack initiation from a flaw
c) Postulated through-wall flaw is assumed to be not leaking and undetected by the annulus gas system (AGS)
d) Fracture toughness properties are based on a conservative statistical bound of burst test data.

5.8.2 RELAXATION OF RESIDUAL HOOP STRESS IN OUTLET RJ

An evaluation of the relaxation due to creep of residual hoop stresses in the outlet RJ of Bruce units was performed. From the assessment, there is a significant reduction in the residual hoop stress due to relaxation from creep. These lower levels of residual hoop stress will significantly mitigate any potential for crack initiation from a flaw.

Creep relaxation calculations were also performed for Pickering and Darlington units which also demonstrated reductions in tensile residual stress with increasing operating hours [29] and thus creep relaxation is expected to mitigate any potential for crack initiation for Pickering and Darlington Units.

5.8.3 SENSITIVITY OF CRACK INITIATION MECHANISMS AT HIGH [Heq]

A review of experimental data on the known crack initiation mechanisms of DHC, hydrided region overloads and fatigue have been shown to be insensitive to high [Heq] levels under hydride ratcheting conditions. Therefore crack initiation models remain applicable at high levels of [Heq].

6.0 DISCOVERY ISSUE RESOLUTION PROCESS

Declaration of a DIRP depends on the following from N-PROC-RA-0094:

1) **Balance between new information vs. current information: "***Within the context of this process, it should be recognized SA* (Deterministic Safety Analysis) *is a time constrained iterative process that attempts to strike a*

balance between analytical effort and conservative methods, analyses, assumptions, models, etc.. As such, many issues initially identified as having a potential impact on safety may be dismissed upon investigation and/or application of more rigorous analyses. The need to take immediate action upon discovery of a possible issue should be mitigated because of the underlying approach to SA. Nevertheless, the impact of an issue should be confirmed in a timely manner to meet the requirements of due diligence."

2) **Downstream impact of new information (impact on Safe Operating Envelope (SOE)):** *"When operation of a nuclear facility conforms with its defined SOE but the SA upon which the SOE is based is itself suspect, or when there is a change in analytical basis (a gap is discovered in the definition of the SOE, e.g. new safety analysis with new functional requirements for a particular SSC* (Structures, Systems and Components)*), then the DIRP is initiated to confirm regulatory limits are met and risk is maintained at an acceptable level, or to put in place mitigating provisions."*
3) **Severity of margin reduction to Derived Acceptance Criteria (DAC):** A DIRP is considered *"Low Priority"* when *"Significant reduction in margin to DAC or Level 2 RIL* (Risk Increase Limit) *based on licensing analysis or PRA* (Probabilistic Risk Assessment)*"*. DAC is defined as *"acceptance criteria established in the Safety Analysis as sufficient but not necessary conditions for demonstrating the Regulatory Limits are met for DBAs* (design basis accidents)*."*

Item 1 is addressed as follows:

- The B3 and B6 findings are evaluated in this document based on Pickering and Darlington [Heq] measurements, supported by justifications from the Bruce Power engineering evaluation. The timeframe for completion is within 9 days from DIRP initiation (July 14, 2021). OPG-specific engineering evaluation will be completed for submission to CNSC by July 30, 2021. Issuance of a revised assessment [5] and DIRP is targeted for submission to CNSC by July 30, 2021 and 21 days from DIRP initiation, respectively.

Items 2 and 3 are addressed as follows:

- Pickering Units 1 and 4, 5-8:
    - CNSC has established regulatory limits on the [Heq] levels in Pickering pressure tubes under License Condition 15.3: *"Before Hydrogen equivalent concentration exceeds 120 ppm, the licensee shall demonstrate that pressure tube fracture toughness will be sufficient for safe operation beyond 120 ppm.*" In this case, this has been selected as the applicable DAC as 120ppm [Heq] also corresponds to the validity limit on the Revision 1 cohesive zone (CZ) fracture toughness model for BE material under N285.8 Clause D.13.2.3.
    - Based on scrape sampling to date at Pickering and using current projection methods, margin exists to the 120ppm limit[1].

[1] For Pickering Unit 1, half of the PTs are installed with FEO configuration. Therefore, the applicable fracture toughness limit is 80ppm for front end (FE) material. Based on scrape sampling to date at Pickering Unit 1 and using current projection methods, margin exists to the 80ppm limit [15].

- Darlington Units 1, 2 and 4:
    - o The applicable DAC has been selected as 120ppm [Heq] since this corresponds to the validity limit on the Revision 1 CZ fracture toughness model for BE material under N285.8 Clause D.13.2.3.
    - o Based on scrape sampling to date at Darlington, and using current projection methods, margin exists to the 120ppm [Heq] limit.
    - o For Darlington Unit 2, the margin reduction is deemed not applicable due to the low number of operating hours and manufacturing process controls to maintain low initial hydrogen levels.
- Investigations are ongoing on potential enhancements to the scrape program to obtain additional data and further confirm adequate [Heq] margins in light of the Bruce 3 OPEX.

7.0 CONCLUSIONS

It is concluded that based on a review of the B3 and B6 events:

- The [Heq] results from OPG material surveillance and scrape results are significantly lower than the B3 and B6 results,
- Based on the current projection methods, margin exists to the current fracture toughness validity limits,
- The axial extent of the high localized [Heq] in OPG PTs remains within a small span. Thus, it is expected that the current operating envelopes remain applicable,
- OPG volumetric inspections have indicated that flaw populations in the outlet RJ top of tube within 20mm inboard of the BM are very low.
- Industry continues to perform burst tests at high [Heq] levels with conservative through-wall notches that have not been observed in-service, and
- There continues to be adequate margins to support the leak before break inputs used in the PSA. As such, there is no impact on the existing OPG PSA models and their resultant plant risk predictions.

In summary, based on a review of Bruce Power’s Units 3 and 6 relevant data, Pickering and Darlington [Heq] measurements collected to date and existing FFS assessments, there is minimal impact on pressure tube FFS at Pickering and Darlington and hence, continued safe operation of all OPG units is assured.

8.0 REFERENCES

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[2] Bruce Power CNSC Event Report, “Pressure Tube Surveillance Hydrogen Equivalent Concentration Measurements on Unit Shutdown for Major Component Replacement”, B-2021-98077, July 5, 2021.

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[13] D. Broad to J. Lam et al., “Results of Hydrogen Isotope Concentration Analysis from Pressure Tube D3S13”, OPG CD# NK38-CORR-31100-0935379, July 16, 2021.

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[redacted]

ONTARIO POWER GENERATION

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OPG Proprietary
(with Confidential Enclosures)

July 30, 2021

CD# N-CORR-00531-22801

MR. M. LEBLANC
Commission Secretary

DR. A. VIKTOROV
Director General
Directorate of Power Reactor Regulation

Canadian Nuclear Safety Commission
280 Slater Street
Ottawa, Ontario
K1P 5S9

Dear Mr. Leblanc and Dr. Viktorov:

OPG Response to Request pursuant to Subsection 12(2) of the *General Nuclear Safety and Control Regulations*: Responses to Items 1-4 Related to Measurement of Hydrogen Concentration in Pressure Tubes

The purpose of this letter is to provide OPG's response to Items 1-4 of CNSC staff's request (Reference 1) concerning information reported to CNSC by Bruce Power in relation to recent Pressure Tube (PT) Hydrogen Equivalent ([Heq]) analysis results. Submission of requested information was committed in Reference 2 and an interim assessment was provided to the CNSC in Reference 3.

This response is prepared pursuant to Subsection 12(2) of the *General Nuclear Safety and Control Regulations*, and in accordance with Darlington's PROL 13.02/2025 and Pickering's PROL 48.01/2028 and respective Licence Condition Handbooks, Section G.1, "Licensing Basis for the Licensed Activities".

An update to the interim assessment submitted to the CNSC in Reference 3 is provided with this submission as Enclosure 1. This updated assessment is supported by engineering evaluation performed in consideration of Bruce Power OPEX and is provided as Enclosure 2.

OPG's response to CNSC requests 1 to 4 of Reference 1 are provided below (these responses are also included in Section 4.0 of Enclosure 1):

CNSC Item 1: Confirm receipt of the information from Bruce Power related to this discovery;

OPG Response: Bruce Power information related to the discovery of elevated [Heq] in the outlet Rolled Joint (RJ) regions of B6S13 and B3 Pressure Tubes (PTs) has been received, including:

- A copy of the B6S13 Technical Operability Evaluation (TOE), and
- Preliminary information on B3 scrape results (from 19-Jul-2021).

This information has been considered in the assessments completed in Enclosures 1 and 2. Additional details on the information that OPG has received from Bruce Power are provided in Section 5.0 of Enclosure 1.

CNSC Item 2: Analyze the impact of this information on the demonstration of pressure tube fitness for service;

OPG Response: Engineering analysis to verify that PT Fitness for Service (FFS) continues to be demonstrated in consideration of Bruce Power OPEX is documented in Enclosure 2. This conservative analysis concludes that Pickering Units 1, 4, 5, 6, 7, 8 and Darlington Units 1 and 4 PTs remain fit for service. Darlington Unit 2 has been recently refurbished and remains fit for service. Darlington Unit 3 is currently shutdown for refurbishment.

CNSC Item 3: Conduct necessary tests and analysis to verify that operation of all reactors at OPG stations remains within their licensing basis;

OPG Response: OPG has a robust scrape sampling and material surveillance program. For years, RJ scrape sampling, as well as additional RJ punch sampling (which are both beyond CSA N285.4 requirements) have been performed to enhance understanding of RJ deuterium ingress. A review of existing OPG data has been performed and compared with the Bruce Power B3 and B6S13 results (see Section 6.0 of Enclosure 1) which indicates that such high levels of [Heq] have not been observed in any OPG units. Based on a review of all past measured [Heq] data, [Heq] values for all OPG units are confirmed to be within the licensing basis, including samples taken from ex-service material in the area of interest from the Bruce Power OPEX.

CNSC Item 4: Inform CNSC of any other measures taken in response to this information;

OPG Response: Despite OPG never having observed elevated [Heq] at the levels seen in B3 and B6S13 PTs, the following [Heq] program enhancements are planned as proactive measures:

- Scrape sampling across the 12 o'clock orientation of the PT is being pursued for implementation during the next planned outages (P2171, D2141, and P2211). Additional details are provided in Section 6.1.1 of Enclosure 1.
- Continued sampling of ex-service PT material at multiple axial and all clock positions in the rolled joint regions is being pursued for up to 6 additional OPG PTs from Pickering Units 5 and 8, and Darlington Refurbishment Unit 3 (Note: detailed examination of 5 OPG PTs has already been completed under this program). Additional details are provided in Section 6.1.2 of Enclosure 1.
- [Heq] modelling enhancements to account for Bruce Power B3 and B6S13 observations are being pursued. OPG, in collaboration with industry, intends to submit modelling enhancements for CNSC acceptance once fully validated.

Engineering Evaluation based on B3 and B6S13 OPEX has been completed. The evaluation demonstrates and validates the case for ongoing safety and fitness for service for OPG nuclear units. In summary:

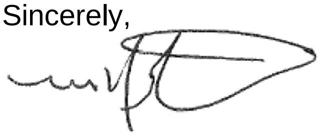
- OPG's material surveillance program covers the same PT areas of interest as for Bruce Power's B3 and B6S13 results, and OPG measurements show significantly lower [Heq] values at Pickering and Darlington.
- Based on the current [Heq] projection methods, margin exists in the current fracture toughness validity limits.
- The axial extent of the high localized [Heq] in OPG PTs remains within a small span. Thus, the current operating envelopes remain applicable.
- OPG has high confidence in the distribution of flaws throughout the pressure tubes, and past volumetric inspections have indicated that flaw populations in the outlet rolled joint (RJ) top of tube within 100mm inboard of the burnish mark (BM) are very limited.
- OPG and industry partners have an active burst test program in place and continue to perform rising pressure burst tests at conservative test conditions (with high [Heq]) to support continued fuel channel FFS assessments. During these burst tests a significant artificial flaw is induced into the pressure tube. These flaws have never been observed in any OPG Units. If such a condition is encountered during operations, the Annulus Gas System (AGS) would alarm and trigger safe shutdown of the Unit.
- Notwithstanding the rigor of the PT inspections and conservative FFS assessments that support the prevention of PT failures, such scenarios are postulated as part of the licensing basis safety analysis and demonstrated to meet the applicable regulatory requirements (e.g., via deterministic and probabilistic safety analyses).

In conclusion, based on a review of Bruce Power's B3 and B6S13 relevant data, Pickering and Darlington [Heq] measurements collected to date, the assessment provided as Enclosure 1, and the Engineering Evaluation provided as Enclosure 2, OPG's existing FFS assessments remain valid. OPG has a high degree of confidence that PT [Heq] values for all OPG units are within the licensing basis, and that our population of flaws in the area of observed high [Heq] from the Bruce Power OPEX is very limited. Thus, continued safe operation of all OPG units is assured, and supported by OPG's robust FFS program and extensive defence-in-depth measures that are in place.

OPG will provide CNSC with a report documenting the results of review of hydrogen update model validity, reflecting new information, as committed in Reference 2.

If you have any questions, please contact Mr. Paul Fabian, Department Manager, Major Components Engineering, at 289-314-8521, or by e-mail at paul.fabian@opg.com.

Sincerely,



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Enc.

cc: J. Burta - CNSC (Ottawa)
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C. Chan - CNSC Site Office (Pickering)
C. Krasnaj - CNSC Site Office (Darlington)

References:

1. CNSC Letter, A. Viktorov to S. Gregoris and J. Franke, "Darlington and Pickering NGS: Request pursuant to Subsection 12(2) of the General Nuclear Safety and Control Regulations: Issues Relating to Measurement of Hydrogen Concentration in Pressure Tubes", July 13, 2021, e-Doc 6603931, CD# N-CORR-00531-22783.

2. OPG Letter, M.R. Knutson to M. Leblanc and A. Viktorov, "OPG Response to Request pursuant to Subsection 12(2) of the General Nuclear Safety and Control Regulations: Issues Relating to Measurement of Hydrogen Concentration in Pressure Tubes", July 19, 2021, CD# N-CORR-00531-22788.

3. OPG Letter, M.R. Knutson to A. Viktorov, "OPG Interim Assessment of High Hydrogen Equivalent Concentration ([Heq]) Discovery Issue at Bruce Power's Units 3 and 6 on Pickering and Darlington Nuclear Generating Stations Pressure Tube Fitness For Service", July 27, 2021, CD# N-CORR-00531-22809.

List of Enclosures:

1. OPG Memorandum, "*Fitness For Service Impact on Pickering Units 1 and 4, 5-8 and Darlington Units 1, 2 and 4 of a High [Heq] Discovery Issue in a Non-OPG CANDU Unit*", N-CORR-31100-0934854 P.

2. OPG Report (Prepared by Kinectrics), "*Evaluation of Postulated High [H]eq Levels on OPG Pressure Tube Fitness for Service Based on Recent Bruce Power Measurements*", N-REP-31100-50118.

ONTARIO POWER GENERATION

MEMORANDUM

OPG Confidential

July 28, 2021

File No.: N-CORR-31100-0934854 P

Fitness for Service Impact of a High [Heq] Discovery Issue in a Non-OPG CANDU Unit

1.0 INTRODUCTION

In July 2021, Bruce Power reported two events related to hydrogen equivalent concentrations ([Heq]) measured in Bruce Units 3 and 6:

1) Measurements obtained from the A2131 outage scrape campaign showed elevated [Heq] values were greater than expected which potentially exceeded parameters of the fracture toughness model in CSA N285.8-15 Update 1, Clause D.13.2.3.1.2 (a), hence, potentially not meeting Clause 4.5.1.3 [1].

2) Following the removal of pressure tube S13 in Bruce Power Unit 6, higher than expected [Heq] values were found in the pressure tube which potentially exceeded the parameters of the fracture toughness model in CSA N285.8-15 Update 1, Clause D.13.2.3.1.2 (a), hence, potentially not meeting Clause 4.5.1.3 [2].

CNSC subsequently provided a letter to OPG [3] which was made pursuant to subsection 12(2) of the General Nuclear Safety and Control Regulations. OPG has been requested to review the impact of the Bruce Power [Heq] Pressure Tube (PT) sampling result, as it relates to OPG PT fitness for service (FFS).

2.0 PURPOSE

This document presents the FFS impact of the [Heq] sampling results from the A2131 scrape campaign and material surveillance of PT B6S13.

This document also provides responses to CNSC Items 1, 2, 3 and 4 of [3].

3.0 ASSUMPTIONS AND METHODOLOGY

As a result of [3], OPG has completed an engineering evaluation [4] to address operation of Pickering 1 and 4, 5-8 and Darlington 1, 2 and 4 based on higher than expected hydrogen equivalent concentrations in the back-end outlet (BEO) rolled joint (RJ) region of B6S13 [2] and front-end outlet (FEO) rolled joint of B3 scrape channels [1].

For the Discovery Issue Resolution Process (DIRP), judgement is made whether there has been a significant decrease in the margin to the Derived Acceptance Criteria (DAC).

4.0 RESPONSES TO CNSC ITEMS 1-4 OF REFERENCE 3

Per [3], CNSC requested a report to the Commission, with respect to the following actions:

Item 1: *Confirm receipt of the information from Bruce Power related to this discovery;*

OPG Response:
Bruce power information related to the discovery of elevated [Heq] in the outlet RJ regions of B6S13 and B3 PTs has been received, including:

- A copy of the B6S13 Technical Operability Evaluation (TOE), and
- Preliminary information on B3 scrape results (from 19-Jul-2021).

This information has been considered in the assessments completed in this document and [4]. Additional details on the information that OPG received from Bruce Power are provided in Section 5.0.

Item 2: *Analyze the impact of this information on the demonstration of pressure tube fitness for service;*

OPG Response:
Engineering analysis to verify that PT FFS continues to be demonstrated in consideration of Bruce Power OPEX has been conducted as documented in [4]. This conservative analysis concludes that Pickering Units 1, 4, 5, 6, 7, 8 and Darlington Units 1 and 4 PTs remain fit for service. Darlington Unit 2 has been recently refurbished and remains fit for service. Darlington Unit 3 is currently shutdown for refurbishment.

Item 3: *Conduct necessary tests and analysis to verify that operation of all reactors at OPG stations remains within their licensing basis;*

OPG Response:
OPG has a robust scrape sampling and material surveillance program that is above and beyond the requirements in CSA N285.4 per Pickering and Darlington's operating licences. RJ scrape sampling, as well as additional RJ punch sampling (which are both beyond CSA N285.4 requirements) are performed to improve understanding of RJ deuterium ingress. A review of existing OPG data has been performed and compared with the Bruce Power B3

and B6S13 results (see Section 6.0) which indicates that such high levels of [Heq] have not been observed in OPG. Based on a review of all past measured [Heq] data, OPG [Heq] values for all Units are confirmed to be within the licensing basis.

Item 4: *Inform CNSC of any other measures taken in response to this information*

OPG Response:
Despite OPG never having observed elevated [Heq] at the levels seen in B3 and B6S13 PTs, the following [Heq] program enhancements are planned as proactive measures:

- Scrape sampling across the 12 o'clock orientation of the PT is being pursued for implementation during the next planned outages (P2171, D2141, and P2211). Additional details are provided in Section 6.1.1.
- Continued sampling of ex-service PT material at multiple axial and all clock positions in the RJ regions is being pursued for up to 6 additional OPG PTs from Pickering Units 5 and 8, and DNGS Refurbishment Unit 3. (Note: detailed examination of 5 OPG PTs has already been completed under this program.) Additional details are provided in Section 6.1.2.
- [Heq] modelling enhancements to account for B3 and B6S13 observations are being pursued. OPG, with industry alignment, intends to submit modelling enhancements for CNSC acceptance once fully validated.

5.0 DETAILED INFORMATION FROM B3 AND B6 EVENTS

5.1 A2131 Scrape Results

To support [1], a preliminary summary table of B3 scrape sample results obtained from the A2131 campaign (as of July 19, 2021) were provided by Bruce Power.

Measurements from the A2131 outage Circumferential Wet Scrape Tool (CWEST) scrape campaign found elevated [Heq] in channels (eg. B3C11, B3F16, B3L11) [1]. The material was oriented in the front end outlet (FEO) configuration.

Scrape sampling at non-standard clock positions has identified that large circumferential gradients can exist resulting in large variations in repeat measured [Heq]. The trend in the A2131 [Heq] measurements between quadrants is similar to that observed in B6S13 from B1561 and B1761 scrape campaigns.

5.2 B6S13 Material Surveillance Results

To support [2], the TOE and associated attachments on B6S13 were provided by Bruce Power.

B6S13 was removed from Bruce Unit 6 as part of the Unit 6 Major Components Replacement (MCR) project. The material was oriented in the back end outlet (BEO) configuration. High hydrogen and deuterium concentrations have been measured in the samples punched from the outlet RJ region. The results to date include samples from the 12, 3, 6 and 9 o'clock circumferential orientations at both the burnish mark and 20mm further inboard. Table 1 of [5] is shown below.

Table 1: Hydrogen and deuterium concentration measurements from through-wall punches obtained from the outlet end of the rolled joint region of tube B6S13.

Axial Location (mm)	Circumferential Location (clock)*	[H] (mg/kg)	[D] (mg/kg)	[Heq] (mg/kg)
8	12	55 ± 3	520 ± 30	315
13	12	55 ± 3	530 ± 20	320
28	12	57 ± 3	520 ± 30	317
44	12	51 ± 3	450 ± 20	276
59	12	44 ± 2	360 ± 20	224
69 (burnish mark)	12	46 ± 2	330 ± 20	211
	3	13 ± 1	94 ± 5	60
	6	12.0 ± 0.9	93 ± 5	59
	9	13 ± 1	95 ± 5	61
79	12	42 ± 2	340 ± 20	212
89/90 (burnish mark + 20mm)	12	22 ± 1	152 ± 8	98
	3	11.8 ± 0.9	89 ± 4	56
	6	12.5 ± 0.9	88 ± 4	57
	9	12.2 ± 0.9	87 ± 4	56
145	12	17 ± 1	109 ± 5	72

* clock position as viewed from the outboard end of the tube

Two observations are of interest:

a) There is strong circumferential variation in both hydrogen and deuterium concentrations at the burnish mark and 20mm inboard. These results are consistent with differences in [Heq] between B1561 and B1761 where large variation was observed in the compressive zone between the two scrape campaigns
   - Note that B1761 samples were acquired further from the top of the PT than B1561 samples

b) The measurement at the top of the tube at the 89/90mm axial position is 98ppm [Heq]. This is of interest as this is the [Heq] applicable in deterministic fracture protection (DFP) assessments.
   - Note that in DFP, a 20mm through-wall flaw in the outlet RJ with the highest [Heq] is postulated to be against the BM and its associated [Heq] is taken at its inboard end. [Heq] is predicted at the inboard crack tip as instability is more likely inboard than at the outboard end where constraint is provided by the end fitting [6].

OPEX SCR N-2021-11211, "OPEX SCR – Bruce Power High Heq Finding" has been initiated to track corrective actions.

The main concern for PT fitness for service with higher levels of [Heq] is reduced fracture toughness due to the presence of brittle hydrides that are highly influential in determining fracture toughness properties in the lower-shelf and transition temperature regimes. Flaws in a region of high [Heq] are at increased risk of crack initiation and growth and thus risk of PT fracture.

6.0 APPLICABILITY OF B3 AND B6 EVENTS TO OPG REACTORS

6.1 OPG OPEX FROM SCRAPE AND MATERIAL SURVEILLANCE ACTIVITIES

6.1.1 SCRAPE

Scrape sampling of inlet and outlet RJs has been performed in Pickering Units 1 and 4, 5-8, and Darlington 1 and 4, and scheduled per the Fuel Channels Life Cycle Management Plan [7]. In Darlington Unit 2, the first RJ scrape campaign after refurbishment is expected to occur in early 2024. Scrape sampling provides information to validate station-specific deuterium uptake models to support volumetric and dimensional inspections/flaw assessments. RJ scraping also confirms material properties against the CSA N285.4 inlet and outlet burnish mark acceptance criteria of 70ppm and 100ppm, respectively, and supports station operating envelopes in heatups/cooldowns by confirming the fracture protection envelope assumptions remain valid.

RJ scrapes are performed near the top of the PT circumferentially offset from top dead center (TDC) to facilitate repeats (especially in the compressive region where axial offset repeats cannot be performed) and as higher concentrations are expected at the top of the PT due to temperature differentials between the 12 o'clock and 6 o'clock positions.

The selection criteria for scrape inspection includes channels which are predicted to exceed terminal solid solubility of hydrogen dissolution (TSSD) in the body of tube (BOT) region prior to the target end of life. These channels are expected to be most limiting and are selected to monitor deuterium uptake to monitor possible changes in rates after exceeding this limit. BOT scrape inspections are often paired with RJ scrape in these channels.

Tables 2 and 3 provide a summary of body of tube (BOT) and RJ scrape sampling for each station and history of initial, most recent and next planned scrape campaigns, respectively. Tables 2 and 3 demonstrate that OPG has a long history of performing BOT and RJ scrape campaigns and exceeds the CSA N285.4 requirements. Furthermore, additional scrapes are planned in the upcoming outages prior to each unit's respective shutdown date.

Table 2: Summary of BOT and RJ Scrape Channels in OPG Stations

Station	Number of BOT Scrape Channels	Number of RJ Scrape Channels	Number of Future BOT Scrape Channels	Number of Future RJ Scrape Channels
Pickering 1&4	70	9	20	4
Pickering 5-8	278	116	80	80
Darlington	199	87	15	6

Table 3: History of Initial, Most Recent and Next Planned Scrape Campaigns

	BOT Scrape Campaigns (Year)			RJ Scrape Campaigns (Year)		
Unit	Initial	Most Recent	Next Planned	Initial	Most Recent	Next Planned
Pickering 1	2004	2020	2022	2017	2020	2022
Pickering 4	2014	2018	2023	2016	2020	N/A[2]
Pickering 5	1992	2019	2022	2009	2019	2022
Pickering 6	1995	2020	2023	2009	2020	2023
Pickering 7	2000	2019	2021	2010	2019	2021
Pickering 8	1999	2021	2023	2010	2021	2023
Darlington 1	2011	2021	Post-refurbishment	2008	2021	Post-refurbishment
Darlington 2	2001	2013[1]	Post-refurbishment	2010	2013[1]	Post-refurbishment
Darlington 3	2002	2018[1]	Post-refurbishment	2009	2018[1]	Post-refurbishment
Darlington 4	2010	2019	2021	2010	2019	2021

Notes:
1. Most recent scrape campaign occurred pre-refurbishment.
2. No further RJ scrape in Pickering unit 4 prior to shutdown.

With respect to RJ scrape results, the extracted Figures [8, 9, 10] below demonstrate that measured [Heq] inboard of the Burnish Mark (BM) to date is significantly lower in OPG units than that observed per the B3 and B6 OPEX. Note that the P5-8 outlet RJ [Heq] generic deterministic predictions shown below will be updated as previously committed in [11].

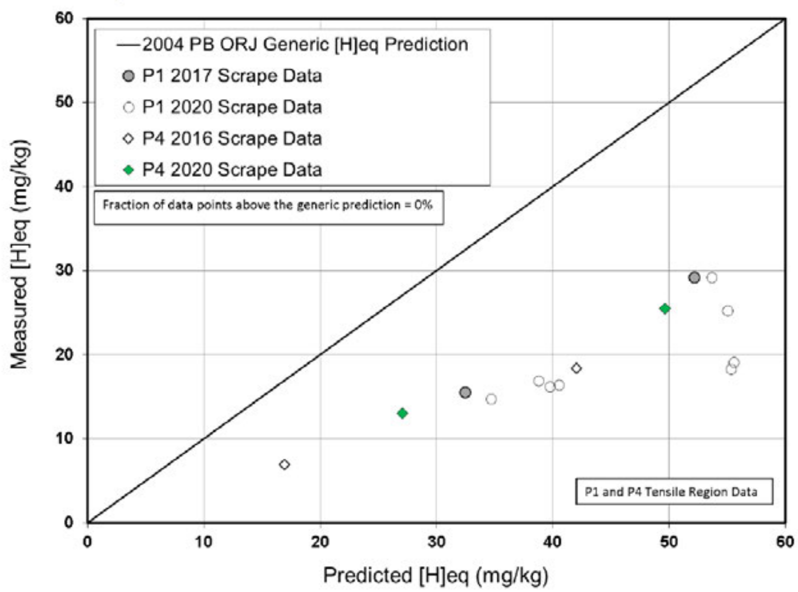

Figure 6: Comparison of Measured $[H]_{eq}$ and the 2004 Generic Deterministic Outlet RJ $[H]_{eq}$ Predictions for Tensile Region Locations of the P1 and P4 Outlet RJs

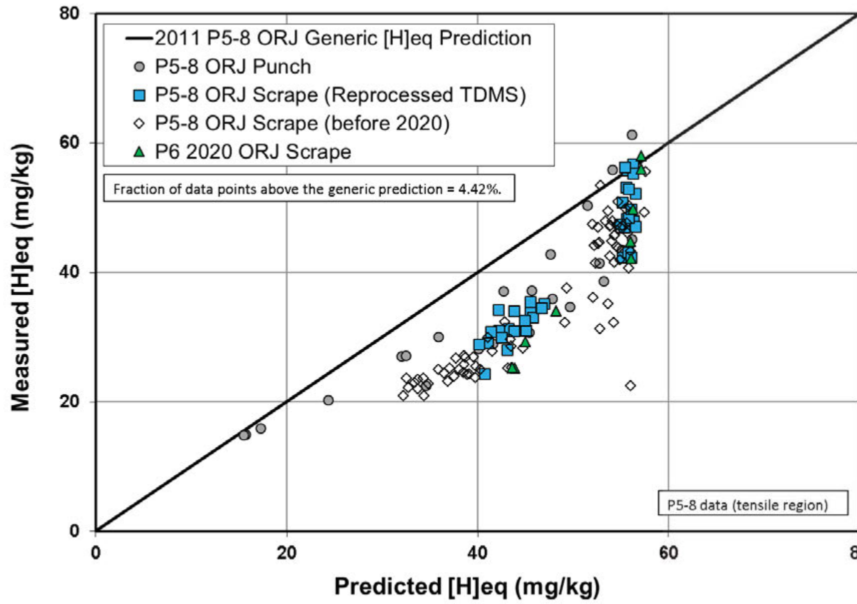

Figure 14: Comparison of Measured $[H]_{eq}$ and the 2011 Generic Deterministic Outlet RJ $[H]_{eq}$ Predictions for Tensile Region Locations of the P5-8 Outlet RJs

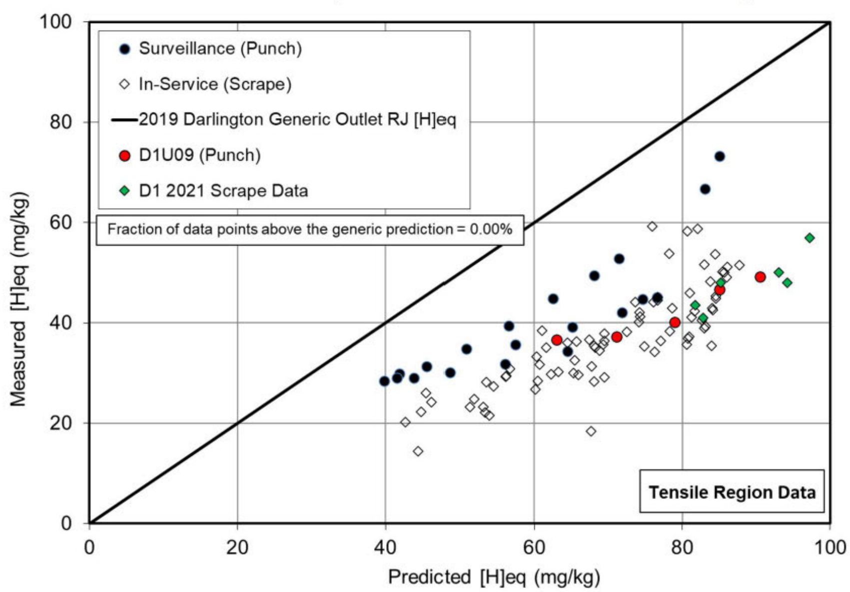

Figure 10: Comparison of All Darlington Measured $[H]_{eq}$ and the 2019 Darlington Units Outlet RJ $[H]_{eq}$ Generic Deterministic Predictions (Tensile Region Only)

Based on OPG punch and scrape sampling measurements to date, there is margin when compared to the B3 scrape results and justifications in subsequent sections of this document indicate the risk of PT failure is low.

For data that is available, OPG proactively compares scrape versus punch sampling as a validation exercise and provides this information to CNSC in material surveillance compliance reports.

Investigations are ongoing on potential enhancements to the scrape program to obtain additional data in the next planned outages (P2171, D2141, and P2211) and further confirm adequate [Heq] margins in light of the Bruce 3 OPEX. Discussions are in progress on tooling enhancements to perform future scrape measurements across the 12 o'clock orientation of the PT (i.e., TDC).

6.1.2 MATERIAL SURVEILLANCE

As a result of the D1U09 (removed in 2017) localized high [Heq] region measured in the inlet RJ [12], [Heq] samples were obtained in both the inlet and outlet RJs of D3S13 (removed in 2020 immediately prior to D3 refurbishment) at several axial positions and all clock positions (samples from material surveillance are obtained via through-wall punches typically focused at the 12 o'clock TDC location and more recently, at multiple clock positions). The results from D3S13 have shown a localized [Heq] region just inboard of the outlet burnish mark (BM) with a peak [Heq] of 75ppm [13]. The maximum [Heq] measurement at nominally 20mm inboard of the BM is 60ppm. Table 4 below shows a subset of [Heq] measurements, at similar locations to B6S13. Figures 1 and 2 show D3S13 outlet RJ measurements at all clock positions and comparison to B6S13 at the 12 o'clock position, respectively.

Table 4: Select D3S13 Measurements from Outlet Rolled Joint [13] at Similar Locations to B6S13

Distance from PT End (mm)	Circumferential Location (Clock)	[H] (mg/kg)	[D] (mg/kg)	[Heq] (mg/kg)
8	12	12 ±1	109 ±5	67
15	12	12 ±1	110 ±6	67
28	12	11 ±1	112 ±6	67
43	12	12 ±1	113 ±6	69
63/65	11	11 ±1	100 ±5	61
	12	12 ±1	112 ±6	68
	1	11 ±1	101 ±5	62
	3	10 ±1	86 ±4	53
	6	9 ±1	85 ±4	52
	9	10 ±1	88 ±4	54
79	11	12 ±1	103 ±5	64
	12	14 ±1	122 ±6	75
	1	12 ±1	98 ±5	61
88 (nominally 20mm inboard of BM)	11	10.2 ±0.8	89 ±4	55
	12	12 ±1	96 ±5	60
	1	11.0 ±0.9	94 ±5	58
	3	9.7 ±0.8	79 ±4	49
	6	9.0 ±0.8	78 ±4	48
	9	9.1 ±0.8	80 ±4	49

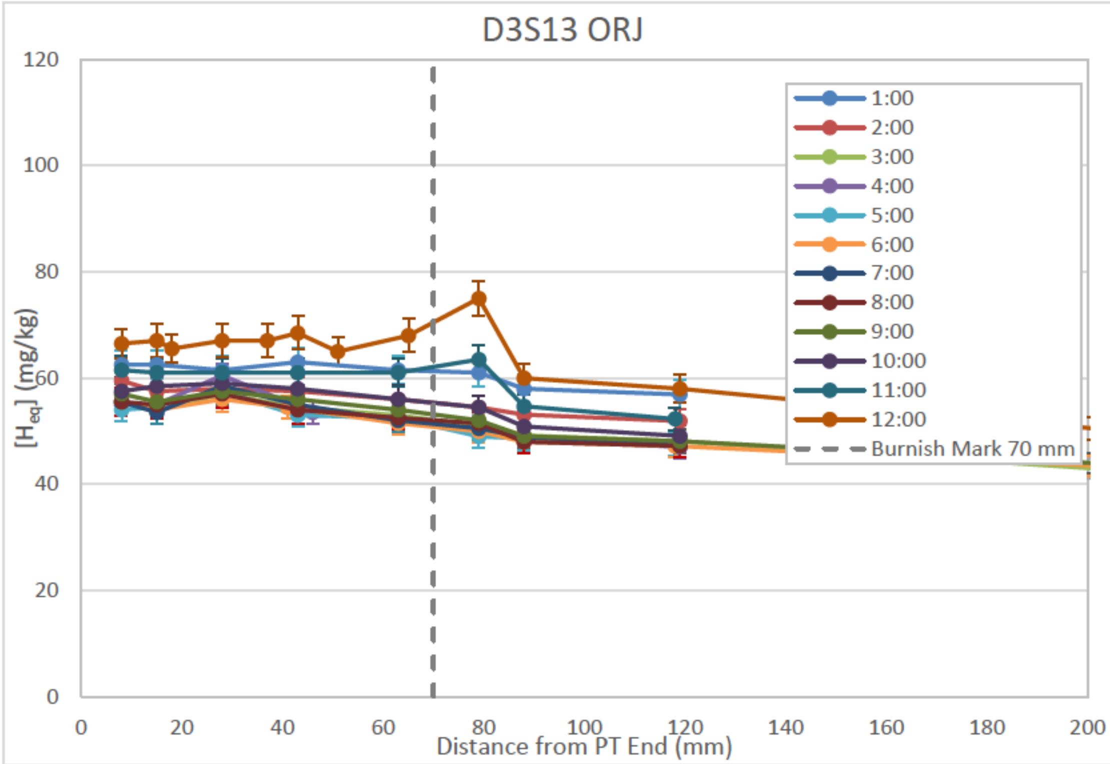

Figure 1: D3S13 outlet RJ Measurements from All Clock Positions

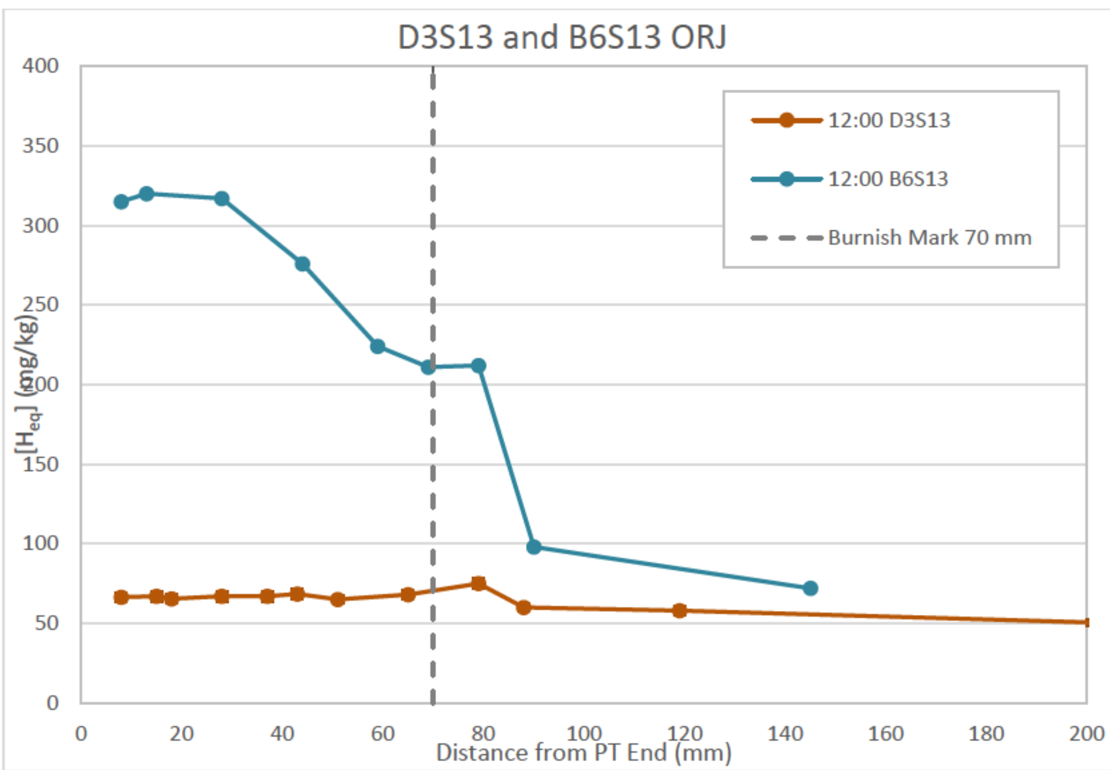

Figure 2: D3S13 and B6S13 Outlet RJ Measurements at 12 O'Clock Position

The results from D3S13 material surveillance are significantly lower than the B6 results, at approximately 60% of the B6 results at 20mm inboard of the BM.

Additionally, there does not appear to be a gradient of similar magnitude from the 6 o'clock versus 12 o'clock measurements.

A COG research and development work package was proactively initiated in 2017 to investigate the extent of circumferential gradients in hydrogen isotope concentrations in the rolled joint region of pressure tubes. Extensive measurements were performed in the inlet RJs of D1U09 (removed in 2017), D2N15 (removed in 2016) and D2O23 (removed in 2016) at multiple axial and all clock positions where similar high localized [Heq] regions of 89ppm, 72ppm and 71ppm [12, 14] were measured just inboard of the inlet BM (over a very small axial and circumferential extent). Similar measurements were also performed in the outlet RJ of D2M09 (removed in 2013) and no direct evidence of high localized [Heq] was identified. High localized [Heq] observations in OPG PTs have been dispositioned in FFS assessments, as discussed in Section 6.7.

A Kepner Tregoe (KT) Problem Analysis has determined that the most probable cause of high localized [Heq] in OPG fuel channels (FC) is FC deformation leading to localized PT to end-fitting (EF) contact at the EF taper blended radius. Based on available data, circumferential non-linearity of BP outlet RJ [Heq] is understood to be a unique observation, not directly related to high localized [Heq] measured just inboard of the BM in OPG PTs. While it is expected that local PT temperature variation may play a role in the evolution of both conditions, it is understood that these conditions are separate and that the observation of one condition does not indicate the presence of the other.

- *Details on FC deformation leading to localized PT to EF contact at the EF taper blended radius*
    - Preliminary Finite Element Analysis (FEA) of the FC predicts that with aging, a combination of EF overhang weight, PT diametral expansion, and journal bearing clearances can lead to a transition from nominally 6 to nominally 12 o'clock contact at the inboard bearing sleeve. As a result, a localized temperature gradient from the PT to the end shield is established, resulting in local concentration of [Heq] at the cold contact location. Channel specific feeder moments are understood to modify EF alignment laterally, accounting for high localized [Heq] observed at clock orientations away from the 6 and 12 clock positions.

Additional [Heq] testing is either currently underway or planned to be performed in P8P10 (removed in 2021) and P5N09 (planned removal in 2022). For inlet RJs, removal of 4 additional RJ sections is scheduled during Darlington Unit 3 Refurbishment (planned removal in 2021) as part of Inconel X-750 spacer retrieval and to allow for additional [Heq] testing.

6.2 FUTURE [Heq] PREDICTIONS

Considering all material surveillance testing and in-service scrape inspections performed to date, Pickering and Darlington PTs are not experiencing similar levels of degradation as observed during the recent B3 and B6 findings. Monitoring through scrape sampling of all Pickering and Darlington units will continue for confirmation. For Darlington Unit 2, the B3 and B6 events are considered not applicable at this time, as it is expected that the low number of operating hours (<10,000 hours as of June 2021) and low hydrogen from manufacturing (<5ppm) provide ample margin.

Since high [Heq] levels such as those observed in Bruce Power units have not been measured in OPG, the engineering evaluation [4] postulates a bounding [Heq] in each station for the purposes of the base and sensitivity cases for the DFP assessment as this assessment is the most sensitive to changes in [Heq]. In the engineering evaluation for Bruce Power [15], 160ppm and 180ppm were used as the base and sensitivity cases for the DFP assessment, respectively. These values are considered overly conservative for OPG units based on the lower operating time and significantly lower [Heq] observations, including from multiple surveillance measurements in the region of interest. Therefore, the [Heq] values presented in Section 6.8.1 of this document are bounding [4].

For evaluations of pressure tube flaws performed for the reactor core, the engineering evaluation concluded there is no basis for postulating the high [Heq] levels observed in B3 and B6 in formal fitness for service assessments based on OPG's lower measured concentrations and top-to-bottom [Heq] differences which are significantly lower than B6S13.

Long term strategies for [Heq] modelling including use of 3D FEA considering fuel channel geometries, local temperatures, location-specific [Heq], and material stress states are being pursued. OPG, with industry alignment, intends to submit modelling enhancements for CNSC acceptance once fully validated.

6.3 STATION OPERATING ENVELOPES FOR HEATUP/COOLDOWN

Station operating envelopes for heatup/cooldown were modified in 2014 to account for changing fracture toughness properties due to increased bulk [Heq] levels. Station operating envelopes are re-validated prior to each outage or when input models/parameters are updated. The purpose of the operating envelope is to maintain the temperature and pressure conditions to reduce the risk of PT rupture or initiation of delayed hydride cracking (DHC) at a flaw due to precipitation of hydrides at lower temperatures. Based on OPG observations to date, the axial extent of the high [Heq] in OPG PTs remains localized within a small span. Thus, the current operating envelopes remain applicable.

6.4 INSPECTED FLAW POPULATIONS

Flaw populations in Pickering Units 1 and 4, 5-8 and Darlington 1 and 4 were reviewed against the requirements of CSA N285.8 for continued operation. In Darlington Unit 2, the first volumetric and dimensional campaign after refurbishment is expected to occur in early 2024. It was found that a relatively small number of dispositionable flaws[1] exist in Pickering Units within the region 100mm inboard of the outlet burnish mark [4]. No dispositionable flaws reside within this region for Darlington Units 1 and 4 [4].

[1] There are 9 dispositionable flaws in this region between Pickering Units 1, 5 and 6. These flaws were shown to be acceptable to the target operating life when assessed with the postulated [Heq] used in the DFP evaluation in [4].

Based on inspection data, flaw distributions are developed and considered representative for the uninspected channels. For Darlington, the absence of flaws for crack initiation and growth results in a low risk of fracture.

For Pickering, there is a relatively small flaw population in the region. Therefore, FFS is demonstrated through the positive fracture protection results (Section 6.8.1) and lower likelihood of crack initiation due to reduced outlet RJ residual stresses (Section 6.8.2).

6.5 CONSERVATISMS IN THE BURST TEST PROGRAM

Rising pressure burst tests are conducted as part of industry surveillance activities and to continue to validate the cohesive zone (CZ) fracture toughness model used in the fuel channel FFS assessments. It is important to note that increased hydrogen concentrations alone do not result in pressure tube fracture at station operating pressures. In order to perform a rising pressure burst test in a laboratory environment, an approximately half meter long piece of ex-service pressure tube is artificially hydrided to a high level of [Heq] (e.g. 160ppm or more) and a 55 mm long axial through-wall flaw is machined at the center and pressurized to burst. The 55mm long notch induced in the tube in a laboratory condition, is a significant flaw that has never been observed in an OPG pressure tube. OPG and industry partners have an active burst test program in place and continue to perform rising pressure burst tests at different conservative test conditions to support fuel channel FFS assessments.

The burst test program is conservative. If a through-wall crack was experienced during operation, the Annulus Gas System (AGS) would detect the leak and station procedures would be executed to cool down and depressurize the Unit appropriately. A burst test of this nature assumes that the through-wall flaw is not leaking and remains undetected by the AGS, which is conservative.

6.6 SAFETY ANALYSIS

The OPEX review of the B3 and B6 [Heq] measurements event has concluded that there continues to be adequate margins to support the leak before break assumptions used in the Probabilistic Safety Assessment (PSA) and Deterministic Safety Analysis (DSA). OPG safety analysis, more specifically the PSA models, credit the annulus gas system to detect PT leaks and facilitate a timely and effective operator response to prevent event propagation into a PT rupture. As such, there is no impact on the existing OPG PSA models and their resultant plant risk predictions. In addition, there is no change to the event classification for PT initiating events as analyzed in the safety report and the existing conclusions remain valid.

6.7 FITNESS FOR SERVICE ASSESSMENTS

As a result of the D1U09 inlet rolled joint high localized [Heq] region, impact assessments for Pickering and Darlington [16, 17] were performed for the deterministic flaw assessments, probabilistic core assessments (PCA), leak before break (PLBB), and deterministic or probabilistic fracture protection (DFP/PFP) assessments.

For flaw assessments, all Pickering flaws residing within 20mm of the outlet burnish mark were predicted to have [Heq] exceeding TSSD at normal operating conditions. Thus, increasing the predicted level of [Heq] in the region would have no effect on flaw acceptability since flaws evaluated as planar would already have postulated DHC growth at normal operating conditions and flaws evaluated as volumetric would already be under flaw-tip hydride ratcheting conditions. Thus, increasing the predicted level of [Heq] in the region of interest (burnish mark to 20 mm inboard of the burnish mark) would have no effect on the Pickering pressure tube flaw dispositions.

For reactor core assessments, probabilistic [Heq] profiles were axially-shifted to bound the D1U09 measurement values. This is conservative since increased [Heq] is applied to the entire axial RJ region as opposed to a localized area and was applied to both inlet and outlet RJs. Shifted [Heq] profiles were applied to all clock positions for the PCA and select clock positions for PLBB and PFP. All reactor core assessments for Darlington Units 1 and 4 (PCA, PLBB, PFP), and lead Pickering Units 1 (PCA, PLBB, DFP), 7 (DFP), and 8 (PCA, PLBB) met the acceptance criteria of N285.8, and in some cases, with significant margin (assessments from lead units in Pickering are judged to be applicable to remaining units in each station).

The OPG engineering evaluation [4] concludes that there is no basis for postulating the high [Heq] levels observed in B3 and B6 in formal fitness for service assessments based on OPG's lower measured concentrations and top-to-bottom [Heq] differences which are significantly lower than B6S13.

Based on review of existing fitness for service (FFS) assessments, the PCA, PLBB and fracture protection (FP) assessments with additional [Heq] at the outlet RJ meet the acceptance criteria for demonstration of FFS. Although there is no current evidence that the B3 or B6 conditions occur in Pickering and Darlington Units, additional justifications in Section 6.8 provide further assurance that the risk of localized [Heq] at the top of the outlet RJ presents a low risk to PT failure.

6.8 JUSTIFICATIONS FROM OPG ENGINEERING EVALUATION

6.8.1 DETERMINISTIC FRACTURE PROTECTION

A DFP evaluation based on a postulated 18mm or 20mm axial through-wall flaw was completed in accordance with the CSA N285.8 calculation procedure, utilizing the Revision 1 and Revision 2[2] [18] engineering fracture toughness models for Pickering Units 1, 5-8 and Darlington 1 and 4 [4]. With respect to fracture toughness, Pickering Unit 1 is bounding for Pickering Units 1 and 4 as half of the tubes are oriented in the FEO configuration. Darlington Unit 2 has been operating for a little over one year with new pressure tubes and would not have sufficient enough [Heq] uptake to observe this finding. The calculations were performed using [Heq] levels based on postulating a bounding [Heq] in

[2] OPG acknowledges that CNSC staff's review of the Revision 2 CZ FT model is in progress. The technical basis report was submitted to CNSC staff in Reference [19]. Revision 2 FT model was utilized for comparison with Revision 1 FT model and where much higher bounding [Heq] values are postulated.

each station for the purposes of the base and sensitivity cases for the DFP assessment (Pickering 1 and 4: 80ppm/100ppm; Pickering 5-8: 120ppm/140ppm; Darlington 1 and 4: 120ppm/140ppm), with the focus of the calculations at the inboard tip of the postulated 18mm or 20mm flaw with the outboard tip at the BM (i.e., axial position of 18mm or 20mm inboard of the BM). The [Heq] values are conservative when compared against the maximum projected outlet RJ [Heq] at the target operating life. The safety factors (SFs) for heatup/cooldown and the rapid cooldown transient (most limiting transient) were calculated. The rapid cooldown transient for Pickering 5-8 and Darlington was treated as a Level B transient with postulated flaw lengths of 18mm and 20mm, and as a Level C transient for Pickering 1, 5-8 and Darlington with a postulated flaw length of 20mm. The flaw length of 18mm was used in the technical basis for the SF of 1.20 proposed for companion DFP assessments that is performed with PFP [20]. Based on [20], 18mm is a reasonable representation for the flaw length for the evaluation [4].

All of the SFs for the heatup/cooldown transients based on a 20mm flaw met the required SFs. For Pickering 5-8 rapid cooldown transient (Level B), the SF based on an [Heq] of 120ppm and 18mm flaw is 1.26, which is slightly lower than the required safety factor of 1.3. For Darlington rapid cooldown transient (Level B), the majority of SFs are below 1.0. It is recognized that these safety factors are based on the conservative 97.5% lower prediction bound on the fracture toughness that was predicted using the Revision 1 or Revision 2 engineering fracture toughness models. Based on operating experience that a rapid cooldown transient has never occurred in Pickering 5-8 or Darlington [21-26], it was considered more appropriate to treat the rapid cooldown transient as Service Level C. With the exception of Darlington with an [Heq] of 140ppm, all of the safety factors on internal pressure are greater than the required SF of 1.0 for Service Level C. The SF on internal pressure for Darlington with an [Heq] of 140ppm is 0.98, which is slightly lower than the required safety factor. The SFs are considered adequate for the purpose of demonstrating FFS in this engineering evaluation [4]. Darlington has transitioned to a probabilistic methodology for demonstration of FP in accordance with the requirements of CSA N285.8.

Additionally, the DFP evaluation in [4] includes a number of conservatisms:

a) For a through-wall flaw to exist, there needs to be a pre-existing service-induced flaw which would be a site for crack initiation and growth
b) Relaxation of residual hoop stresses at the outlet RJ will contribute to mitigation of crack initiation from a flaw, but this is not considered in the assessment
c) Postulated through-wall flaw is assumed to be not leaking and undetected by the annulus gas system (AGS)
d) Fracture toughness properties are based on a conservative statistical bound of burst test data
e) The level of [Heq] of 100 ppm for Pickering Unit 1, and 140 ppm for Pickering 5-8 and Darlington Units 1 and 4, which were used in the sensitivity cases to determine the impact of the higher levels of [Heq] on the SFs, are conservative values. As stated in Section 6.8.1, the [Heq] are conservative when compared against the maximum projected outlet RJ [Heq] at the target operating life.

6.8.2 RELAXATION OF RESIDUAL HOOP STRESS IN OUTLET RJ

An evaluation of the relaxation due to creep of residual hoop stresses in the outlet RJ of OPG units was performed [4]. Mock-up RJ ZC-16 (contains highest measured residual hoop stress distribution in low-clearance RJs) stress relaxation calculations were completed for the range of hot hours based on operating conditions in Pickering and Darlington. From the assessment, there is a significant reduction in the residual hoop stress due to relaxation from creep. Similar or lower levels of relaxed residual hoop stress would be predicted for zero clearance outlet RJs in OPG units. These lower levels of residual hoop stress will significantly mitigate any potential for crack initiation from a flaw.

6.8.3 SENSITIVITY OF CRACK INITIATION MECHANISMS AT HIGH [Heq]

A review of experimental data on the known crack initiation mechanisms of DHC, hydrided region overloads and fatigue have been shown to be insensitive to high [Heq] levels under hydride ratcheting conditions [4]. Therefore crack initiation models remain applicable at high levels of [Heq].

7.0 DISCOVERY ISSUE RESOLUTION PROCESS

Declaration of a DIRP depends on the following from N-PROC-RA-0094:

1) **Balance between new information vs. current information:** *"Within the context of this process, it should be recognized SA* (Deterministic Safety Analysis) *is a time constrained iterative process that attempts to strike a balance between analytical effort and conservative methods, analyses, assumptions, models, etc.. As such, many issues initially identified as having a potential impact on safety may be dismissed upon investigation and/or application of more rigorous analyses. The need to take immediate action upon discovery of a possible issue should be mitigated because of the underlying approach to SA. Nevertheless, the impact of an issue should be confirmed in a timely manner to meet the requirements of due diligence.*"
2) **Downstream impact of new information (impact on Safe Operating Envelope (SOE)):** *"When operation of a nuclear facility conforms with its defined SOE but the SA upon which the SOE is based is itself suspect, or when there is a change in analytical basis (a gap is discovered in the definition of the SOE, e.g. new safety analysis with new functional requirements for a particular SSC* (Structures, Systems and Components)*), then the DIRP is initiated to confirm regulatory limits are met and risk is maintained at an acceptable level, or to put in place mitigating provisions."*
3) **Severity of margin reduction to Derived Acceptance Criteria (DAC):** A DIRP is considered *"Low Priority"* when *"Significant reduction in margin to DAC or Level 2 RIL* (Risk Increase Limit) *based on licensing analysis or PRA* (Probabilistic Risk Assessment)*"*. DAC is defined as *"acceptance criteria established in the Safety Analysis as sufficient but not necessary conditions for demonstrating the Regulatory Limits are met for DBAs* (design basis accidents)*."*

Item 1 is addressed as follows:

- The B3 and B6 findings are evaluated in this document based on Pickering and Darlington [Heq] measurements, supported by justifications from the engineering evaluation [4]. The timeframe for completion is within 9 days from DIRP initiation (July 14, 2021). OPG's engineering evaluation will be submitted to CNSC by July 30, 2021. Issuance of a revised assessment (this document) and DIRP is targeted for submission to CNSC by July 30, 2021 and 21 days from DIRP initiation, respectively.

Items 2 and 3 are addressed as follows:

- Pickering Units 1 and 4, 5-8:
    - CNSC has established regulatory limits on the [Heq] levels in Pickering pressure tubes under License Condition 15.3: *"Before Hydrogen equivalent concentration exceeds 120 ppm, the licensee shall demonstrate that pressure tube fracture toughness will be sufficient for safe operation beyond 120 ppm.*" In this case, this has been selected as the applicable DAC as 120ppm [Heq] also corresponds to the validity limit on the Revision 1 CZ fracture toughness model for BE material under CSA N285.8 Clause D.13.2.3.
    - Based on scrape sampling to date at Pickering and using current projection methods, margin exists to the 120ppm limit[3]. There has been no change to margin from the previous assessment [27].
- Darlington Units 1, 2 and 4:
    - The applicable DAC has been selected as 120ppm [Heq] since this corresponds to the validity limit on the Revision 1 CZ fracture toughness model for BE material under CSA N285.8 Clause D.13.2.3.
    - Based on scrape sampling to date at Darlington, and using current projection methods, margin exists to the 120ppm [Heq] limit. There has been no change to margin from the previous assessment [27].
    - For Darlington Unit 2, the margin reduction is deemed not applicable due to the low number of operating hours and manufacturing process controls to maintain low initial hydrogen levels.
- Investigations are ongoing on potential enhancements to the scrape program to obtain additional data in the next planned outages (D2141, P2171 and P2211) and to further confirm adequate [Heq] margins in light of the Bruce 3 OPEX.

[3] For Pickering Unit 1, half of the PTs are installed with FEO configuration. Therefore, the applicable fracture toughness limit is 80ppm for front end (FE) material. Based on scrape sampling to date at Pickering Unit 1 and using current projection methods, margin exists to the 80ppm limit [4].

8.0 CONCLUSIONS

It is concluded that based on a review of the B3 and B6 events:

- The [Heq] results from OPG material surveillance and scrape results and the top-to-bottom [Heq] differences observed are significantly lower than the B3 and B6 results.
- Use of 80/100ppm [Heq] for Pickering 1 and 4, and 120/140ppm for Pickering 5-8 and Darlington in the DFP assessment in the engineering evaluation is conservative when compared against the maximum projected outlet RJ [Heq] at the target operating life.
- The DFP assessment of the engineering evaluation concluded that the calculated SFs for heatup/cooldown and rapid cooldown are considered adequate for the purpose of demonstrating FFS.
- Based on the current projection methods, margin exists to the current fracture toughness validity limits.
- An evaluation of the relaxation due to creep of residual hoop stresses indicates there is a significant reduction in the residual hoop stress due to relaxation from creep. These low levels of residual hoop stress will mitigate any potential for crack initiation from a flaw.
- The axial extent of high localized [Heq] observed in OPG PTs remains within a small span. Thus, the current operating envelopes remain applicable.
- OPG volumetric inspections have indicated that flaw populations in the outlet RJ top of tube within 20mm inboard of the BM are relatively low.
- There is no impact to engineering models for crack initiation, since the models have been shown to be insensitive to higher [Heq] levels under hydride ratcheting conditions.
- Industry continues to perform burst tests at high [Heq] levels with conservative through-wall notches that have not been observed in-service.
- There continues to be adequate margins to support the leak before break assumptions used in the PSA. As such, there is no impact on the existing OPG PSA models and their resultant plant risk predictions.

In conclusion, based on a review of Bruce Power’s Units 3 and 6 relevant data, Pickering and Darlington [Heq] measurements collected to date and existing FFS assessments, there is no impact on pressure tube FFS at Pickering and Darlington and hence, continued safe operation of all OPG units is assured.

9.0 REFERENCES

[1] Bruce Power CNSC Event Report, “A2131 Outage Scrape Campaign Hydrogen Equivalent Concentration Measurements”, B-2021-93819, July 8, 2021.

[2] Bruce Power CNSC Event Report, “Pressure Tube Surveillance Hydrogen Equivalent Concentration Measurements on Unit Shutdown for Major Component Replacement”, B-2021-98077, July 5, 2021.

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Re: Evaluation of Postulated High $[H]_{eq}$ Levels on OPG Pressure Tube Fitness for Service Based on Recent Bruce Power Measurements

1.0 INTRODUCTION

During measurement of Hydrogen Equivalent Concentration ($[H]_{eq}$) in the Bruce B Nuclear Generating Station surveillance pressure tube (PT) B6S13, a $[H]_{eq}$ measurement inboard of the outlet rolled joint (ORJ) burnish mark at the 12:00 o'clock orientation was found to exceed the current CSA N285.4 limit of 100 ppm, as shown in Figure 1. These measurements are documented in Reference [1] which was provided to OPG.

The B6S13 $[H]_{eq}$ measurements from Reference [1] share some common features with other observations, still under investigation, from Bruce Unit 3 rolled joints, specifically:

- Higher than expected $[H]_{eq}$ levels outboard and just inboard of the outlet burnish mark,
- Evidence of large circumferential variations in $[H]_{eq}$, with significantly higher levels in the top of the pressure tube,
- $[H]_{eq}$ in the lower portion of the pressure tube are generally bounded by $[H]_{eq}$ predictions currently used in fitness-for-service evaluations.

In response to the CNSC request on this finding [2], this letter provides an engineering evaluation that analyses the impact of postulated higher than expected ORJ region $[H]_{eq}$ levels (in consideration of the Bruce Power measurements) on the fitness for service of Pickering and Darlington pressure tubes.

In the engineering evaluation for Bruce Power units [3], 160 ppm was used as a base case and 180 ppm was used for the sensitivity. The magnitude of measurements from the affected region of Bruce Power tubes has not been observed in OPG tubes, despite detailed outlet end surveillance examinations of multiple high power tubes removed from various units at advanced operating times in recent years. Accordingly, for the purposes of analyzing possible impact on fitness for service, the approach herein is to postulate OPG station-specific conservative bounding outlet RJ $[H]_{eq}$ at end of life given station age, operating conditions and scraping/surveillance OPEX as compared to that of B6S13. This is done for both a baseline case and a sensitivity case for each OPG station, but there is not currently any evidence from Pickering and Darlington measurements that such concentrations exist in OPG pressure tubes and there is no basis for including such concentrations in formal fitness for service evaluations.

The main concern for PT fitness-for-service with higher levels of $[H]_{eq}$ is reduced fracture toughness due to the presence of hydrides that are highly influential in determining PT fracture toughness in the lower-shelf and transition temperature regimes. As such, the primary fitness for service evaluation is the demonstration of fracture protection for the very localized region at the top of the tube near the outlet burnish mark using postulated elevated $[H]_{eq}$ concentrations. This is accompanied by supporting defense-in-depth discussion of the very low likelihood of the existence of a through wall crack that would be a prerequisite for fracture in this region in the first place.

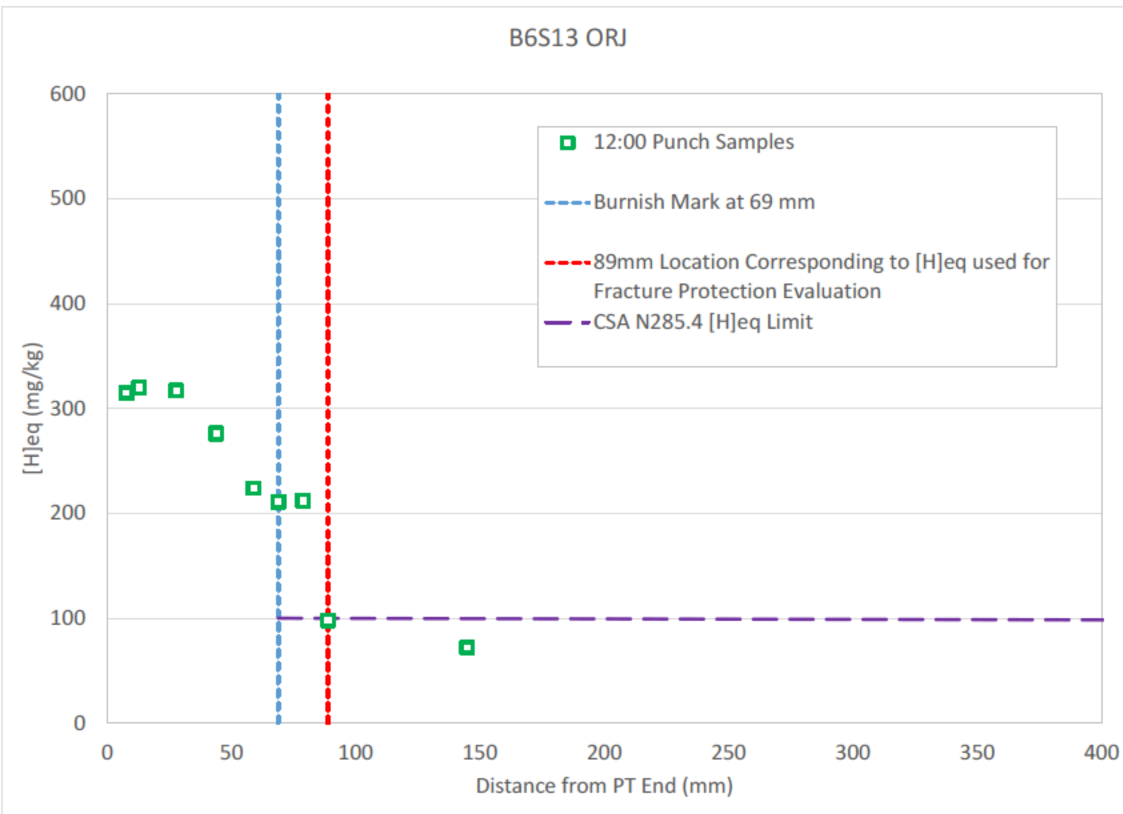

Figure 1: B6S13 ORJ $[H]_{eq}$ from Punch Samples Measured at 243,773 EFPH or 271,729 HH [1].

2.0 ENGINEERING EVALUATION

This engineering evaluation in response to the CNSC 12(2) request [2] was performed for Pickering A Units 1 and 4; Pickering B Units 5 to 8; and Darlington Units 1 and 4 with consideration given to the higher than expected ORJ region $[H]_{eq}$ measurements from Bruce Power. Darlington Unit 2 has been operating for a little over one year with new pressure tubes. Darlington Unit 3 is currently shutdown for refurbishment.

2.1 Localized Nature of Higher than Expected $[H]_{eq}$ at Bruce Power

A review of the $[H]_{eq}$ axial profile of B6S13 ORJ indicates that the higher than expected measurements are limited to within about 80 mm of the end of the PT, beyond which there is a steep decrease in measured $[H]_{eq}$ (i.e., a decrease of 114 ppm over 10 mm in the inboard direction). The high concentrations are also thought to be confined within a relatively narrow circumferential extent at the top of the PT.

Similar localized high $[H]_{eq}$ regions have also been observed in some recent Bruce Unit 3 ORJ scrape sampled pressure tubes, showing localized elevated $[H]_{eq}$ measurements near the outlet burnish mark with a central tendency about the top of the pressure tube.

Figure 2 below compares the B6S13 ORJ measurements and some recent DNGS and PNGS ORJ punch measurements. Among them, D2M09 and P6M14 exhibited the highest $[H]_{eq}$ levels observed in DNGS and PNGS (among both removed tubes and scrape sampled), respectively. As shown the DNGS removed tubes exhibit circumferential variations in $[H]_{eq}$ with consistently higher levels at the top of the pressure tube (12 o'clock), suggesting locally high concentration at the top. This behaviour is believed to be due mainly to a lower temperature at the top caused by flow by-pass at the outlet end. However, measured concentrations as well as the top-to-bottom concentration differences observed in these OPG removed pressure tubes are significantly lower than those observed for B6S13.

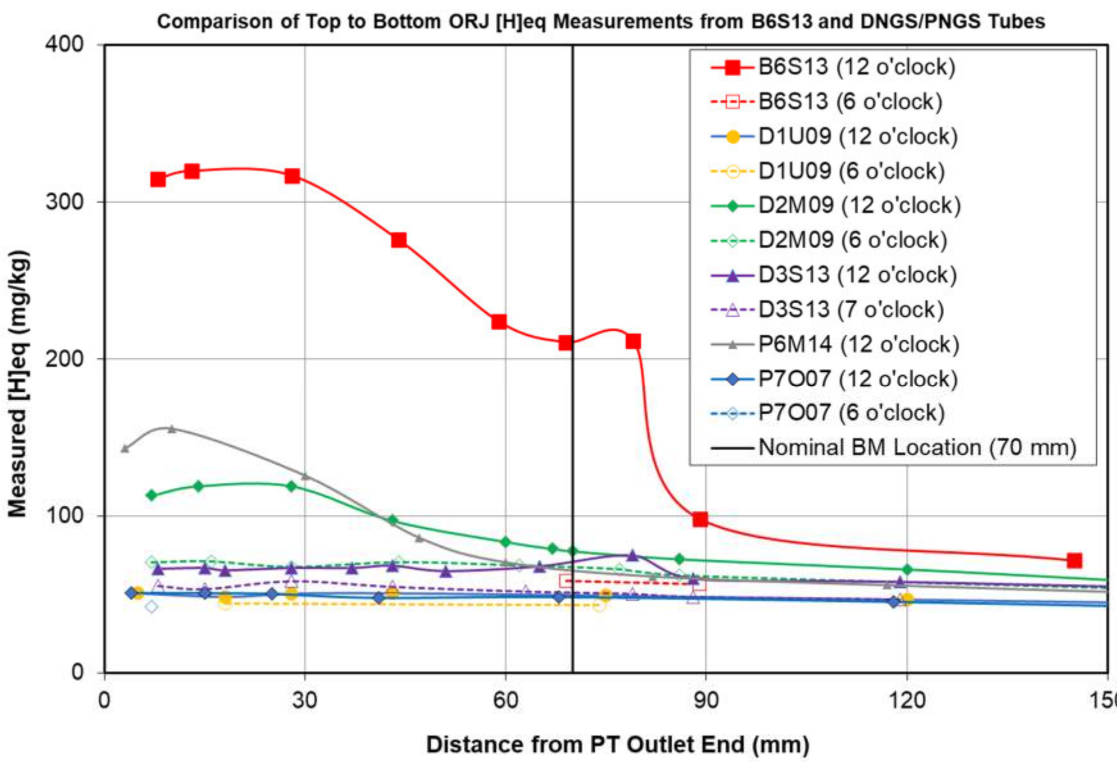

Figure 2 :Comparison of B6S13 ORJ $[H]_{eq}$ and some DNGS and PNGS ORJ $[H]_{eq}$ results from removed tubes.

2.2 Postulation of Bounding ORJ $[H]_{eq}$ in Pickering A, Pickering B and Darlington Given Bruce Power Observations

As described in Section 2.1, high $[H]_{eq}$ levels such as those seen in Bruce Power units have not been measured in any Pickering or Darlington units. To postulate the bounding $[H]_{eq}$ in each of the Pickering A, Pickering B and Darlington stations for the purpose of this assessment, the following was conducted:

a) A review of all the available outlet RJ measurements (punch and scrape) from all OPG stations.
b) Projections of $[H]_{eq}$ for all outlet RJ measurements at the end of life (EOL) using linear extrapolation based on a combination of the measured lifetime averaged D-uptake rate as well as corresponding outlet RJ deterministic and probabilistic predictions.
c) The resulting estimates were conservatively incremented (with consideration given to Bruce Power measurements) to obtain postulated bounding values for OPG stations for the purpose of this engineering evaluation.

In Pickering Units 1 and 4, four (4) scrape campaigns were performed for RJ measurements. The measured outlet RJ $[H]_{eq}$ levels are substantially lower than those observed from other OPG stations. The highest projected $[H]_{eq}$ (including the compressive region) at target EOL is less than 45 ppm based on the measurements. It should be noted that half of the Pickering Unit 1 tubes are installed in the front end outlet (FEO) orientation while all other OPG tubes are in the back end outlet (BEO) orientation. There are no notable $[H]_{eq}$ differences between FEO and BEO tubes in Pickering Unit 1 outlet RJ measurements. Therefore, use of 80 ppm $[H]_{eq}$ as a base case and 100 ppm $[H]_{eq}$ as a sensitivity case were conservatively selected for investigating the possible impact on the assessment of deterministic fracture protection (regardless of tube orientation).

In Pickering Units 5-8, ORJ measurements were acquired during nineteen (19) in-service scrape sampling campaigns and from four (4) removed tubes. The P5-8 measurements are substantially lower than B6S13 data. Among them, the highest $[H]_{eq}$ projected at EOL ranges from 85 ppm - 108 ppm corresponding to P6M14 removed tube data measured at outlet BM + 16 mm location. Therefore, use of 120 ppm $[H]_{eq}$ as a base case and 140 ppm $[H]_{eq}$ as a sensitivity case were conservatively selected for investigating the possible impact on the assessment of deterministic fracture protection in Pickering Units 5-8.

In Darlington Units 1-4, ORJ measurements were acquired during fifteen (15) in-service scrape campaigns and from five (5) removed tubes. The D1-4 measurements are substantially lower than B6S13 data. Among them, the highest $[H]_{eq}$ projected at EOL ranges from 81 ppm - 97 ppm corresponding to D2M09 removed tube data measured at outlet BM + 16 mm location. Therefore, use of 120 ppm $[H]_{eq}$ as a base case and 140 ppm $[H]_{eq}$ as a sensitivity case were conservatively selected for investigating the possible impact on the assessment of deterministic fracture protection in Darlington Units 1 and 4.

In the engineering evaluation for Bruce Power units [3], 160 ppm was used as a base case and 180 ppm was used for the sensitivity. These values are overly conservative for OPG reactors in this assessment based on the lower operating time and significantly lower $[H]_{eq}$ observations including from multiple surveillance measurements in the region of interest. Therefore, the aforementioned 80/100 ppm for Pickering A and 120/140 ppm for Pickering B and Darlington (base/sensitivity, respectively) are bounding for this assessment.

Table 1 below provides a summary of the maximum projected $[H]_{eq}$ estimates and recommendations which are bounding at the outlet BM + 20 mm location considered in the deterministic fracture protection evaluation in Section 2.3.

Table 1: Maximum Projected EOL Outlet RJ $[H]_{eq}$ and Postulated Bounding Levels Used for Evaluation

Station	P1&4 (Note 2)	P5-8 (Note 3)	DNGS (Note 4)
EOL (Hot Hours)	202,300	312,140	243,750
Max Projected Outlet RJ $[H]_{eq}$ at EOL	45 ppm	85-108 ppm	81-97 ppm
Postulated (Note 1) Bounding $[H]_{eq}$ Levels Used for Evaluation (Base Case/Sensitivity Case)	80ppm/100ppm	120ppm/140ppm	120ppm/140ppm

Notes: The max EOL HH from each station is used.

1. Probabilistic lookup tables for the ORJ shifted by 32 mm were used for P5-8 and DNGS, consistent with the impact assessments on P5-8 and DNGS due to observations of high localized $[H]_{eq}$ at the inlet RJ of the removed tube D1U09.
2. P1 EOL, Max [H]eq projections from all locations.
3. P6 EOL, Max $[H]_{eq}$ projections from tensile region locations. The max 108 ppm is projected when the 32 mm shifted probabilistic ORJ lookup table (P7 option) is used, which gives considerably conservative predictions compared to ORJ $[H]_{eq}$ measurements in Pickering Units 5-8.
4. D4 EOL, Max $[H]_{eq}$ projections from tensile region locations.

2.3 Deterministic Fracture Protection Evaluation

A deterministic fracture protection evaluation based on a postulated axial through-wall flaw in the front-end outlet rolled joints in Pickering Unit 1, and the back-end outlet rolled joints in Pickering B and Darlington Units 1 and 4, was performed.

2.3.1 Method of Calculation and Inputs

The safety factor on internal pressure was calculated as the critical internal pressure at flaw instability divided by the actual internal pressure at the location of the postulated flaw. The calculation procedure was in accordance with the CSA Standard N285.8 [4] except that the Revision 2 engineering fracture toughness model in Reference [5] was used in some of the calculation cases instead of the Revision 1 engineering fracture toughness model.

The provisions for fracture protection in Clause 7.2 of the CSA Standard N285.8 require that the length of the postulated axial through-wall flaw be justified, and do not specify the flaw length. Calculations were performed for the standard length of a postulated axial through-wall flaw of 20 mm. In some cases in this evaluation, calculations were also performed for a postulated axial through-wall flaw length of 18 mm to demonstrate the higher safety factors on internal pressure associated with this postulated flaw length. A postulated axial through-wall flaw length of 18 mm was used in the technical basis for the safety factor of 1.20 that is proposed in Reference [6] for the companion deterministic fracture protection evaluation that is performed with a probabilistic fracture protection evaluation.

From the technical basis for the Revision 2 engineering fracture toughness model [5], for the same set of conditions, the fracture toughness predicted by the Revision 2 model for the back-end outlet rolled joints in Pickering Units 1 and 4 will be higher than for the front-end outlet rolled joints. Calculations were performed for the front-end outlet rolled joints in Pickering Unit 1 as bounding for Pickering Units 1 and 4.

For Pickering Unit 1, the calculations were performed using a baseline level of $[H]_{eq}$ of 80 ppm where the focus of the calculations was at the inboard tip of the postulated 20 mm long flaw that is a distance of 20 mm inboard of the burnish mark. Calculations were also performed for an $[H]_{eq}$ of 100 ppm to determine the sensitivity of the safety factor on internal pressure to $[H]_{eq}$. For Pickering B, and Darlington Units 1 and 4, the calculations were performed using a baseline level of $[H]_{eq}$ of 120 ppm where the focus of the calculations was also at the inboard tip of the postulated 20 mm long flaw that is a distance of 20 mm inboard of the burnish mark. Calculations were also performed for an $[H]_{eq}$ of 140 ppm to determine the sensitivity of the safety factor to $[H]_{eq}$.

Pressure tube dimensions, and pressures and temperatures for the transients, were taken from Reference [7]. The majority of the other inputs for the calculations were taken from Reference [8]. Calculations were performed for the Service Level A reactor Heatup/Cooldown transients. Calculations were performed for the design-basis Pickering A Service Level C Rapid Pressurization transient. Calculations were also performed for the design-basis Pickering B and Darlington Rapid Cooldown transients that were first treated as Service Level B and then treated as Service Level C. The reactor Heatup/Cooldown, Rapid Pressurization and Rapid Cooldown transients are considered to be the most limiting transients in terms of meeting the acceptance criteria for deterministic fracture protection.

In one of the cases for the Darlington Units 1 and 4 Rapid Cooldown transient that was treated as Service Level C, the lower prediction bound on the fracture toughness corresponding to a safety factor of 1.0 on internal pressure was calculated. The procedure to calculate the lower prediction bound on the fracture toughness corresponding to a safety factor of 1.0 was in accordance with the CSA Standard N285.8 [4] except that the Revision 2 engineering fracture toughness model in Reference [5] was used.

2.3.2 Fracture Toughness Models

The Revision 1 engineering fracture toughness model that is provided in Clause D.13.2.3 of the CSA Standard N285.8 [4] was used within the model validity limits on $[H]_{eq}$. For a distance within 1.5 m from the front end of the pressure tube, the Revision 1 engineering fracture toughness model is valid for levels of $[H]_{eq}$ up to 80 ppm [4]. For a distance greater than 1.5 m from the front end of the pressure tube, the Revision 1 engineering fracture toughness model is valid for levels of $[H]_{eq}$ up to 120 ppm.

The Revision 2 engineering fracture toughness model that is provided in Reference [5] was also used within the model validity limits on $[H]_{eq}$. From Section 8.2 of Reference [5], for a distance within 1.5 m from the front end of the pressure tube, the Revision 2 engineering fracture toughness model is valid for levels of $[H]_{eq}$ up to 100 ppm [5]. For a distance greater than 1.5 m from the front end of the pressure tube, the Revision 2 engineering fracture toughness model is valid for levels of $[H]_{eq}$ up to 140 ppm [5].

The lower prediction bound on the fracture toughness that was used depended on the Service Level of the transient in the fracture protection evaluation as described below.

(a) The 97.5% lower prediction bound on the fracture toughness that was predicted using the Revision 1 or Revision 2 engineering fracture toughness model was used to calculate the safety factors on internal pressure for the Service Level A reactor Heatup/Cooldown transients.

(b) The 97.5% lower prediction bound on the fracture toughness that was predicted using the Revision 1 or Revision 2 engineering fracture toughness model was used to calculate the safety factors on internal pressure for the Pickering B and Darlington Rapid Cooldown transients that were treated as Service Level B.

(c) The 90% lower prediction bound on the fracture toughness that was predicted using the Revision 1 or Revision 2 engineering fracture toughness model was used to calculate the safety factors on internal pressure for the Pickering A Service Level C Rapid Pressurization transient. The 90% lower prediction bound on the fracture toughness was also used to calculate the safety factors on internal pressure for the Pickering B and Darlington Rapid Cooldown transients that were treated as Service Level C. The industry practice is to use the 90% lower prediction bound on the fracture toughness for deterministic fracture protection evaluations of Service Level C transients, which is consistent with Clause D.13.2.3.4 of the CSA Standard N285.8.

2.3.3 Safety Factors on Internal Pressure for Reactor Heatup/Cooldown

As stated above, the safety factor on internal pressure is the ratio of the calculated critical internal pressure at flaw instability divided by the actual internal pressure at the location of the postulated flaw.

The safety factors on internal pressure for the Service Level A reactor Heatup/Cooldown transient based on a postulated axial through-wall flaw length of 20 mm in the front-end outlet rolled joints in Pickering Unit 1 are given in Table 2 for levels of $[H]_{eq}$ of 80 and 100 ppm.

The safety factors on internal pressure for the Service Level A reactor Heatup/Cooldown transient based on a postulated axial through-wall flaw length of 20 mm in the back-end outlet rolled joints in Pickering B and Darlington Units 1 and 4 are given in Table 2 for levels of $[H]_{eq}$ of 120 and 140 ppm.

All of the safety factors on internal pressure are greater than the required safety factor of 1.30 for Service Level A in the CSA Standard N285.8 [4]. The safety factors on internal pressure in Table 2 demonstrate fitness-for-service of Pickering Units 1 and 4, Pickering B, and Darlington Units 1 and 4, in the context of the reactor Heatup/Cooldown transient.

Table 2: Safety Factors from Deterministic Fracture Protection Evaluation of Reactor Heatup/Cooldown for Front-End Outlet Rolled Joints in Pickering Unit 1 and Back-End Outlet Rolled Joints in Pickering B and Darlington Units 1 and 4 for a Postulated Axial Through-Wall Flaw Length of 20 mm

Reactor Units	**$[H]_{eq}$ (ppm)**	**Safety Factors from Deterministic Fracture Protection Evaluation Based on a 97.5% Lower Prediction Bound on Fracture Toughness**	
		Based on Revision 1 Fracture Toughness Model	**Based on Revision 2 Fracture Toughness Model**
Pickering Unit 1	80	1.39	1.56
Pickering Unit 1	100	Not applicable(1)	1.44
Pickering B	120	1.36	1.58
Pickering B	140	Not applicable(1)	1.51
Darlington Units 1 and 4	120	1.32	1.39
Darlington Units 1 and 4	140	Not applicable(1)	1.32

Note:

1) The Revision 1 engineering fracture toughness model is not valid for this level of $[H]_{eq}$.

2.3.4 Safety Factors on Internal Pressure for Pickering B and Darlington Rapid Cooldown Transients that are Treated as Service Level B

The safety factors on internal pressure for the Pickering B and Darlington Rapid Cooldown transients that are treated as Service Level B and based on postulated axial through-wall flaw lengths of 18 and 20 mm in the back-end outlet rolled joints in Pickering B and Darlington Units 1 and 4 are given in Table 3 for levels of $[H]_{eq}$ of 120 and 140 ppm.

For the Pickering B Rapid Cooldown transient, all of the safety factors on internal pressure are less than the required safety factor of 1.30 for Service Level B in the CSA Standard N285.8. Based on Reference [6], a postulated axial through-wall flaw length of 18 mm is considered to be a reasonable representation for the evaluation. From Table 3, for the baseline level of $[H]_{eq}$ of 120 ppm, the safety factor on internal pressure for a postulated axial through-wall flaw length of 18 mm is 1.26. This safety factor is not significantly lower than the required safety factor of 1.30 in the CSA Standard N285.8.

For the Darlington Rapid Cooldown transient, all but one of the safety factors on internal pressure are less than 1.0. It is recognized that these safety factors are based on the conservative 97.5% lower prediction bound on the fracture toughness that was predicted using the Revision 1 or Revision 2 engineering fracture toughness model.

In addition, as described in Section 2.3.5 below, a Rapid Cooldown transient has never occurred in a Pickering B or Darlington reactor.

Table 3: Safety Factors from Deterministic Fracture Protection Evaluation of Rapid Cooldown Transients for Back-End Outlet Rolled Joints in Pickering B and Darlington Units 1 and 4 that are Treated as Service Level B for Postulated Axial Through-Wall Flaw Lengths of 18 and 20 mm

Reactor Units	**Length of Postulated Axial Through-Wall Flaw (mm)**	**$[H]_{eq}$ (ppm)**	**Safety Factors from Deterministic Fracture Protection Evaluation Based on a 97.5% Lower Prediction Bound on Fracture Toughness**	
			Based on Revision 1 Fracture Toughness Model	**Based on Revision 2 Fracture Toughness Model**
Pickering B	18	120	1.09	1.26
Pickering B	18	140	Not applicable(1)	1.20
Pickering B	20	120	1.00	1.16
Pickering B	20	140	Not applicable(1)	1.10
Darlington Units 1 and 4	18	120	0.99	1.02
Darlington Units 1 and 4	18	140	Not applicable(1)	0.97
Darlington Units 1 and 4	20	120	0.91	0.93
Darlington Units 1 and 4	20	140	Not applicable(1)	0.89

Note:

1) The Revision 1 engineering fracture toughness model is not valid for this level of $[H]_{eq}$.

2.3.5 Safety Factors on Internal Pressure for Pickering Unit 1 Service Level C Rapid Pressurization Transient and for Pickering B and Darlington Rapid Cooldown Transients that are Treated as Service Level C

Based on the service experience that a Rapid Cooldown transient has never occurred in a Pickering B [9] [10] [11] [12] or Darlington [13] [14] reactor, it is considered more appropriate that the Pickering B and Darlington Rapid Cooldown transients are treated as Service Level C. In addition, the Darlington Abnormal Cooldown (i), (i) and (iii) transients have never occurred [13] [14]. The safety factors on internal pressure were calculated using the 90% lower prediction bound on the fracture toughness that was predicted using the Revision 1 or Revision 2 engineering fracture toughness model. The safety factors on internal pressure for the Pickering A Service Level C Rapid Pressurization transient based on a postulated axial through-wall flaw length of 20 mm in the front-end outlet rolled joints in Pickering Unit 1 are given in Table 4 for levels of $[H]_{eq}$ of 80 and 100 ppm. The safety factors on internal pressure for the Pickering B and Darlington Rapid Cooldown transients that are treated as Service Level C and based on a postulated axial through-wall flaw length of 20 mm in the back-end outlet rolled joints in Pickering B and Darlington Units 1 and 4 are given in Table 4 for levels of $[H]_{eq}$ of 120 and 140 ppm. With the exception of Darlington Units 1 and 4 with an $[H]_{eq}$ of 140 ppm, all of the safety factors on internal pressure are greater than the required safety factor of 1.0 for Service Level C in the CSA Standard N285.8. The safety factor on internal pressure for Darlington Units 1 and 4 with an $[H]_{eq}$ of 140 ppm is 0.98. The safety factors in Table 4 are considered adequate for the purpose of demonstrating fitness-for-service of Pickering Units 1 and 4 for the Rapid Pressurization transient, and for Pickering B and Darlington Units 1 and 4 for the Rapid Cooldown transients.

The statistical confidence level for the lower prediction bound on the Revision 2 engineering fracture toughness model corresponding to a safety factor of 1.0 for Darlington Units 1 and 4 with an $[H]_{eq}$ of 140 ppm was calculated to be 87.5%. This statistical confidence level for the lower prediction bound is not significantly lower than the 90% lower prediction bound that is used for Service level C transients.

Table 4: Safety Factors from Deterministic Fracture Protection Evaluation of Service Level C Rapid Pressurization Transient for Front-End Outlet Rolled Joints in Pickering Unit 1, and for Rapid Cooldown Transients for Back-End Outlet Rolled Joints in Pickering B and Darlington Units 1 and 4 that are Treated as Service Level C, for a Postulated Axial Through-Wall Flaw Length of 20 mm

Reactor Units	$[H]_{eq}$ (ppm)	Safety Factors from Deterministic Fracture Protection Evaluation Based on a 90% Lower Prediction Bound on Fracture Toughness(1)	
		Based on Revision 1 Fracture Toughness Model	Based on Revision 2 Fracture Toughness Model
Pickering Unit 1	80	1.65	1.76
Pickering Unit 1	100	Not applicable(2)	1.64
Pickering B	120	1.11	1.28
Pickering B	140	Not applicable(2)	1.22
Darlington Units 1 and 4	120	1.01	1.03
Darlington Units 1 and 4	140	Not applicable(2)	0.98

Notes: (continued on following page)

1) The industry practice is to use the 90% lower prediction bound on the fracture toughness for deterministic fracture protection evaluations of Service Level C

transients, which is consistent with Clause D.13.2.3.4 of the CSA Standard N285.8.

2) The Revision 1 engineering fracture toughness model is not valid for this level of $[H]_{eq}$.

2.3.6 Conservatisms

The deterministic evaluation of fracture protection in this engineering evaluation involves a number of conservatisms as described below.

a) For a through-wall flaw to exist there needs to be a pre-existing service-induced flaw, such as due to fretting, which would need to be a site for crack initiation and growth.

b) The postulated through-wall flaw is assumed to be not leaking and not detected.

c) The level of $[H]_{eq}$ of 100 ppm for Pickering Unit 1, and 140 ppm for Pickering B and Darlington Units 1 and 4, which were used in the sensitivity cases to determine the impact of the higher levels of $[H]_{eq}$ on the safety factors, are considered to be conservative values.

d) The fracture toughness that is used in the evaluations is a conservative statistical bound.

e) The Rapid Cooldown transient with the relatively severe design-basis pressure and low temperature was included in the evaluation. However, as described in Section 2.3.5, a Rapid Cooldown transient has never occurred in a Pickering B or Darlington reactor.

2.3.7 Existing Deterministic Fracture Protection Evaluations for OPG Reactors

The existing deterministic fracture protection evaluations that are based on the Revision 1 engineering fracture toughness model that is in the CSA Standard N285.8 are considered to still be applicable to all portions of the pressure tubes in Pickering Units 1 and 4, Pickering B, and Darlington Units 1 and 4, that are not affected by the potential high levels of $[H]_{eq}$ just inboard of the outlet rolled joint burnish mark at the top of the pressure tube that are addressed in this engineering evaluation. The safety factors that would be calculated in these evaluations using the Revision 2 engineering fracture toughness model are expected to be not less than the safety factors in the existing evaluations that are based on use of the Revision 1 engineering fracture toughness model.

2.4 Incidence of Pressure Tube Flaws in the ORJ Region

As indicated in Section 2.1, the axial and radial extent of the higher than expected outlet RJ $[H]_{eq}$ surveillance measurements from B6S13 has thus far been found to be a localized region just inboard[1] of the outlet burnish mark with a central tendency about the top of the PT.

In Darlington units, this is a region that has proven through volumetric inspections to be effectively absent of pressure tube flaws. A recent review of all D1-D4 volumetric inspection results (~197 unique channel inspections including the outlet end, collectively) revealed only 2 reportable flaws whose entire axial extent is within the first

[1] $[H]_{eq}$ measurements outboard the PT burnish mark are generally not a fitness-for-service concern.

100 mm inboard of the outlet burnish mark (both debris flaws are non-dispositionable with a maximum depth of 0.12 mm and occur up to ~3 mm inboard of the outlet burnish mark at the bottom of the PT). There is no reason to believe that the flaw intensity in this region of the inspected population of pressure tubes from D1-D4 would be different for the uninspected population of pressure tubes in D1-D4. Therefore, it can be concluded that a small region of a Darlington PT that is postulated to have the elevated concentrations discussed in this letter is very likely absent of any precondition for crack initiation and growth and thus would have a very low corresponding risk of fracture as a result. This is considered particularly true in that PT fretting is not observed at the top of tube where these elevated concentrations were detected in Bruce Power pressure tubes.

In Pickering A & B units, although there is a reduced incidence of fretting in this region as compared to the rest of the channel, it cannot be considered effectively free of flaws as is the case for Darlington units. This is due to the presence of a relatively small number of reportable and dispositionable[2] flaws in this small region from within the inspected population of PA & PB. Accordingly, the fitness for service argument for PA & PB units (in light of postulated elevated $[H]_{eq}$) is based primarily on the positive deterministic fracture protection evaluation results from Section 2.3 and the lower likelihood for crack initiation due to significantly reduced outlet rolled joint residual stresses as detailed in Section 2.5.

2.5 Relaxed Levels of Residual Hoop Stress in the Outlet Rolled Joints in Pickering B and Darlington Units

An evaluation of the relaxation due to creep of residual hoop stresses in outlet rolled joints in Pickering B and Darlington units was performed. The evaluation results at a given number of hot hours for Pickering B also applies to Pickering Units 1 and 4. The highest residual hoop stresses in rolled joints in Pickering B and Darlington units are considered to be in the low-clearance rolled joints, which occur in the relatively small number of replaced fuel channels. One-half of the rolled joints in Pickering Units 1 and 4 are low clearance. One of the highest measured residual hoop stress distributions for low-clearance rolled joints corresponds to the measurements from the mock-up rolled joint ZC-16 that is given in Figure 6.2 of Reference [15]. The relaxation due to creep of the residual hoop stresses in the low-clearance mock-up rolled joint ZC-16 was calculated over a range of hot hours based on the operating conditions in the Pickering B and Darlington outlet rolled joints using the stress relaxation model that is provided in Reference [16]. For the low-clearance mock-up rolled joint ZC-16, the as-rolled residual hoop stress at the burnish mark was compressive. Calculations were performed based on the measured tensile residual hoop stresses on the inside surface at distances of 5, 10, 15 and 20 mm inboard of the burnish mark as the initial stress levels. The relaxation of the initial upper-bound residual hoop stress for low-clearance rolled joints of 157 MPa that is used in flaw evaluations was also calculated over a range of hot hours.

The predicted variation with hot hours of the levels of residual hoop stress measured from the mock-up rolled joint ZC-16 based on the operating conditions in the Pickering B outlet rolled joints is shown in Figure 3. The time-averaged normal operating temperature was 289°C [16]. Each curve for rolled joint ZC-16 corresponds to a different distance inboard of the burnish mark. The predicted variation with hot hours of

[2] Deterministic flaw assessments were carried out for these 9 dispositionable flaws in units P1, P5 and P6 using the methodology described in CSA N285.8-15 [4], and they were found to be acceptable to the respective unit EOL when assessed with postulated elevated $[H]_{eq}$ in line with Section 2.2.

the residual hoop stress with the initial upper-bound value of 157 MPa is also shown in this figure. From Figure 3, there is a significant reduction in the residual hoop stress due to relaxation from creep. For example, at 250,000 hot hours, the initial upper-bound value of 157 MPa is predicted to have relaxed to 35 MPa.

The predicted variation with hot hours of the levels of residual hoop stress measured from the mock-up rolled joint ZC-16 based on the operating conditions in the Darlington outlet rolled joints is shown in Figure 4. The time-averaged normal operating temperature was 307°C [16]. Each curve for rolled joint ZC-16 corresponds to a different distance inboard of the burnish mark. The predicted variation with hot hours of the residual hoop stress with the initial upper-bound value of 157 MPa is also shown in this figure. Similar to Figure 3, there is a significant reduction in the residual hoop stress due to relaxation from creep. For example, at 250,000 hot hours, the initial upper-bound value of 157 MPa is predicted to have relaxed to less than 20 MPa. The higher time-averaged normal operating temperature at the outlet rolled joints in Darlington as compared with Pickering B has resulted in a greater extent of predicted relaxation of the rolled joint residual hoop stresses.

Similar or lower levels of relaxed residual hoop stress would be predicted for zero-clearance outlet rolled joints in OPG units. These low levels of residual hoop stress will significantly mitigate any potential for crack initiation from a flaw.

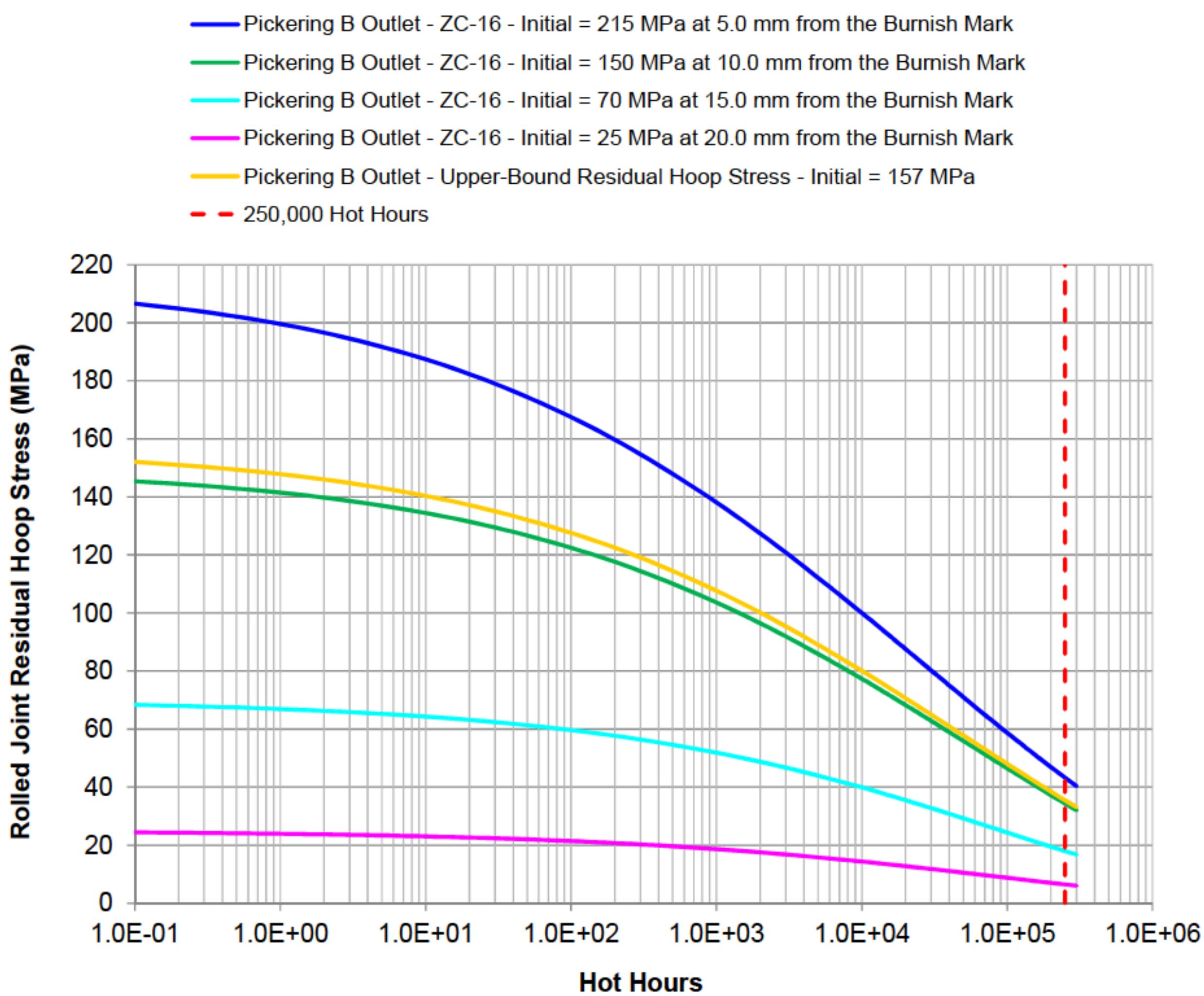

Figure 3: Predicted Variation with Hot Hours of Residual Hoop Stress in Low-Clearance Outlet Rolled Joints Based on Conditions in Pickering B

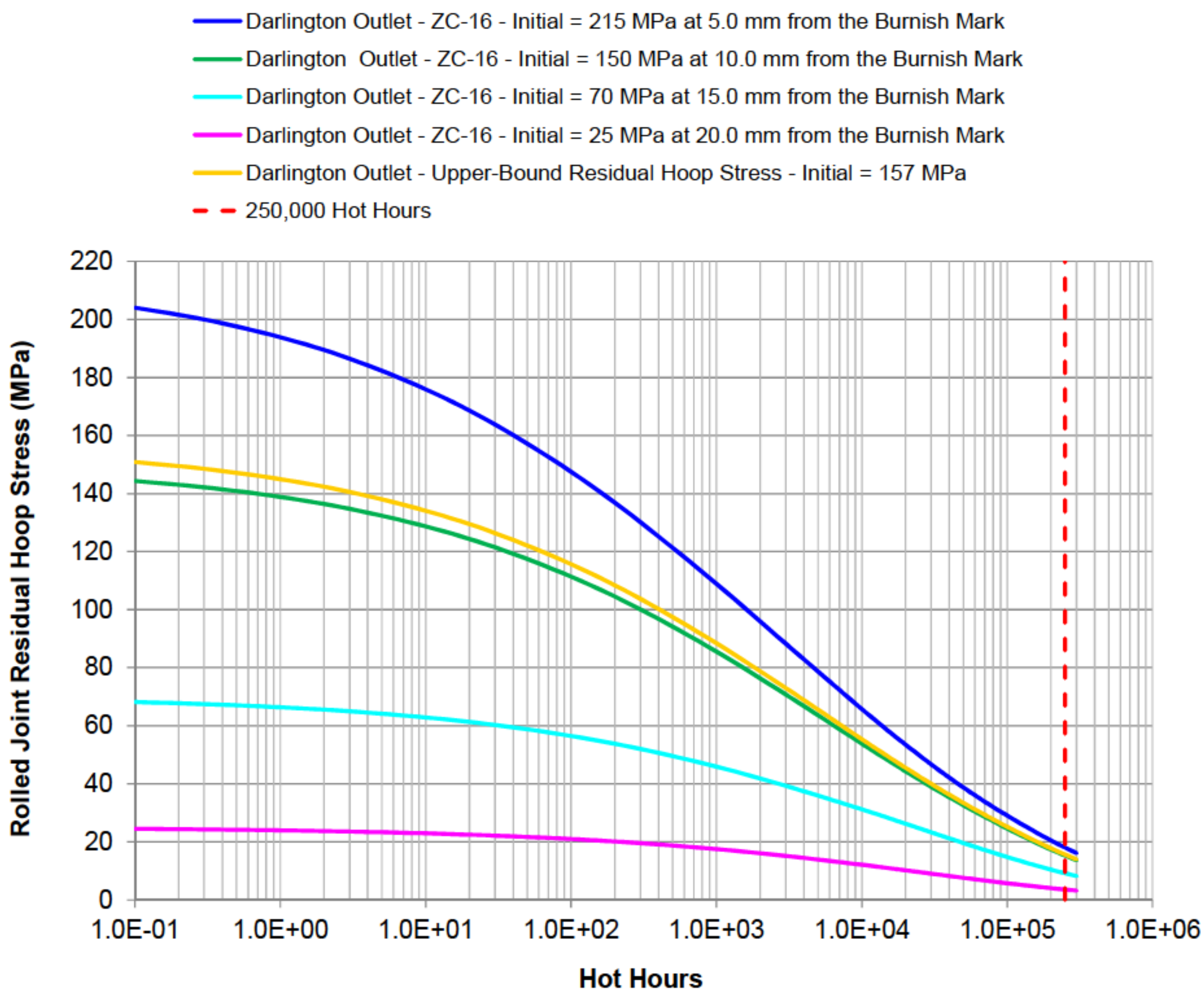

Figure 4: Predicted Variation with Hot Hours of Residual Hoop Stress in Low-Clearance Outlet Rolled Joints Based on Conditions in Darlington

2.6 Sensitivity of Crack Initiation Mechanisms to High Levels of $[H]_{eq}$

As per the responses provided for 'Attachment A' items 2a) in the presentation provided for the industry meeting on HIC issues on August 11, 2020 [17], the amount of hydrogen isotope in solution available for hydride accumulation at the flaw is limited by the operating temperature. Over the operating range from 250-310°C, the maximum $[H]_{eq}$ concentration in solution would range from 37 – 84 ppm, conservatively assuming the Khatamian TSSD equation. $[H]_{eq}$ above the TSSD concentration at the operating temperature will remain as bulk hydrides and would not affect flaw-tip hydride accumulation and hence the threshold stress for Delayed Hydride Cracking (DHC) initiation. This is supported by the results in [18] which demonstrated that the threshold stresses for DHC initiation from flaws are not affected by the hydrogen concentrations under outlet end temperature cycles at $[H]_{eq}$ levels up to 110 ppm. Hydrogen in excess of the TSSD concentration at 310°C would remain as bulk hydrides which should have no effect on the DHC initiation and growth processes that encompass diffusion of hydrogen, formation and fracture of reoriented hydrides at the flaw-tip. Ex-service test data has shown that the threshold stress intensity factor for DHC initiation from sharp flaws (K_{IH}) is not affected by $[H]_{eq}$ concentrations up to 153 ppm.

Similarly for crack initiation by a hydrided region overload, the amount of hydrogen isotope in solution available for hydride accumulation at the flaw is limited by the operating temperature, and the overload resistance for flaws under hydride ratcheting conditions is not affected by the $[H]_{eq}$ concentration. A model to predict crack initiation due to a hydrided region overload that was developed in Reference [19] is based on test data with levels of $[H]_{eq}$ up to 110 ppm. There was no effect of $[H]_{eq}$ on the differences between model predictions and the test data. The work demonstrated the applicability of the hydrided region overload resistance model to high levels of $[H]_{eq}$.

The potential influence of $[H]_{eq}$ on fatigue crack initiation was investigated in Reference [20]. The test data that was analyzed had two levels of $[H]_{eq}$ of 60 and 100 ppm. The work concluded that the effect of $[H]_{eq}$ on the number of load cycles to fatigue crack initiation is statistically insignificant for $[H]_{eq}$ in the range of 60 to 100 ppm. This finding is consistent with the understanding that the amount of $[H]_{eq}$ in solution available for hydride accumulation at the flaw is limited by the peak temperature and the maximum inventory of $[H]_{eq}$ in solution is less than the total $[H]_{eq}$ for the tests.

The known crack initiation mechanisms that are DHC, hydrided region overloads and fatigue have therefore been shown to be insensitive to high $[H]_{eq}$ levels under hydride ratcheting conditions. There is no concern that the crack initiation models are not applicable at higher levels of $[H]_{eq}$. More details on the effect of $[H]_{eq}$ on DHC and overload crack initiation properties can be found in Reference [21].

2.7 Evaluations of Pressure Tube Flaws Performed for the Reactor Core

Of the reactor core fitness for service evaluations, the deterministic fracture protection evaluation documented in Section 2.3 was deemed the most crucial for this engineering evaluation due to the effects of high ORJ $[H]_{eq}$ on pressure tube fracture toughness. However, as summarized in Section 2.1, measured concentrations as well as the top-to-bottom concentration differences observed in the bounding OPG removed pressure tubes are significantly lower than those observed for B6S13 and there is currently no basis for postulating these concentrations in formal fitness for service assessments, including the core assessment for pressure tube flaws. This will continue to be confirmed through periodic analysis and assessment of $[H]_{eq}$ from scrape and punch sampling.

3.0 CONCLUSIONS

The impact of postulated higher than expected ORJ region $[H]_{eq}$ levels (in consideration of the Bruce Power measurements) on the fitness for service of Pickering and Darlington pressure tubes has been analysed. The primary fitness for service evaluation is the demonstration of fracture protection for the very localized affected region at the top of the tube near the outlet burnish mark using postulated elevated $[H]_{eq}$. This is accompanied by supporting defense-in-depth discussion of the very low likelihood of the existence of a through wall crack that would be a prerequisite for fracture in this region in the first place. The engineering evaluation demonstrates that Pickering Unit 1, 4, 5, 6, 7, 8 and Darlington Unit 1 and 4 pressure tubes remain fit for service based on the following considerations:

(a) A review of the $[H]_{eq}$ axial profile of B6S13 ORJ indicates that the higher than expected measurements are limited to within about 80 mm of the end of the PT, beyond which there is a steep decrease in measured $[H]_{eq}$. The high concentrations are thought to be confined to a relatively narrow circumferential extent at the top of the PT. Similar localized high $[H]_{eq}$ regions have also been observed in some recent Bruce Unit 3 ORJ scrape sampled pressure tubes, showing localized elevated $[H]_{eq}$

measurements near the burnish mark with a central tendency about the top of the pressure tube. These observations were compared to those from the tubes with the highest $[H]_{eq}$ measurements from DNGS and PNGS. The measured concentrations as well as the top-to bottom concentration differences observed in these pressure tubes are significantly lower than those observed in B6S13.

(b) To postulate a conservative ORJ $[H]_{eq}$ at each station for use in this evaluation in light of the Bruce Power observations, a review of all ORJ $[H]_{eq}$ measurements available from all operating Pickering and Darlington Unit 1 and 4 pressure tubes was performed. Projections of EOL $[H]_{eq}$ were made using a combination of these measurements and model predictions. Using this methodology, the use of 80/100 ppm $[H]_{eq}$ for Pickering A and 120/140 ppm $[H]_{eq}$ for Pickering B and Darlington for investigating the impact on deterministic fracture protection at the 20 mm distance inboard of the burnish mark was judged to be a conservative bound for the purposes of this engineering evaluation.

(c) A deterministic fracture protection evaluation based on a postulated axial through-wall flaw in the front-end outlet rolled joints in Pickering Unit 1, and the back-end outlet rolled joints in Pickering B and Darlington Units 1 and 4, was performed. For Pickering Unit 1, the calculations were performed using a baseline level of $[H]_{eq}$ of 80 ppm, and an $[H]_{eq}$ of 100 ppm to determine the sensitivity of the safety factor on internal pressure to $[H]_{eq}$. For Pickering B, and Darlington Units 1 and 4, the calculations were performed using a baseline level of $[H]_{eq}$ of 120 ppm, and an $[H]_{eq}$ of 140 ppm also to determine the sensitivity of the safety factor to $[H]_{eq}$. Calculations were performed for the reactor Heatup/Cooldown transients. Calculations were also performed for the design-basis Pickering A Service Level C Rapid Pressurization transient, as well as the design-basis Pickering B and Darlington Rapid Cooldown transients that were first treated as Service Level B and then treated as Service Level C.

(1) All of the safety factors on internal pressure for the reactor Heatup/Cooldown transients based on a postulated axial through-wall flaw length of 20 mm are greater than the required safety factor of 1.30 for Service Level A in the CSA Standard N285.8.

(2) For the Pickering B Rapid Cooldown transient, all of the safety factors on internal pressure are less than the required safety factor of 1.30 for Service Level B in the CSA Standard N285.8. For the baseline level of $[H]_{eq}$ of 120 ppm, the safety factor on internal pressure for a postulated axial through-wall flaw length of 18 mm is 1.26, which is not significantly lower than the required safety factor of 1.30. For the Darlington Rapid Cooldown transient, all but one of the safety factors on internal pressure are less than 1.0.

(3) Based on the service experience that a Rapid Cooldown transient has never occurred in a Pickering B or Darlington reactor, it is considered more appropriate that the Pickering B and Darlington Rapid Cooldown transients are treated as Service Level C. The safety factors on internal pressure based on a postulated axial through-wall flaw length of 20 mm for the Pickering A Service Level C Rapid Pressurization transient, and the Pickering B and Darlington Rapid Cooldown transients that are treated as Service Level C, are 0.98 or greater.

(d) There is no basis for postulating these high levels of $[H]_{eq}$ in formal fitness for service assessments for OPG. This will continue to be confirmed through periodic measurement and assessment of $[H]_{eq}$ from scrape and punch sampling.

(e) An evaluation of the relaxation due to creep of residual hoop stresses in low-clearance outlet rolled joints in Pickering B and Darlington units was performed. There is a significant reduction in the residual hoop stress due to relaxation from creep. For example, at 250,000 hot hours, the initial upper-bound value of 157 MPa is predicted to have relaxed to 35 MPa in Pickering B and to less than 20 MPa in Darlington. Similar or lower relaxed levels of residual hoop stress would be predicted for zero-clearance outlet rolled joints in OPG units. These low levels of residual hoop stress will significantly mitigate any potential for crack initiation from a flaw.

(f) The axial and radial extent of interest of the higher than expected ORJ $[H]_{eq}$ has been found to be a localized region just inboard of the outlet burnish mark with a central tendency about the top of the tube. This is a region that has proven through volumetric inspection to be effectively absent of flaws in Darlington units. There is no reason to believe that the flaw intensity close to the outlet burnish mark would be significantly different for the uninspected population of PTs. Therefore, it can be concluded that the small region of a Darlington PT that is postulated to have the elevated concentrations discussed in this letter is very likely absent of any precondition for crack initiation and growth and, as such, would have a very low corresponding risk of fracture as a result. In Pickering, although there is a significantly reduced incidence of fretting in this region as compared to an average similarly sized region in the rest of an average channel, the same conclusions cannot be drawn as for Darlington units. The fitness for service argument for PA & PB units (in light of postulated elevated $[H]_{eq}$) is based primarily on the positive deterministic fracture protection evaluation results and the lower likelihood for crack initiation due to significantly reduced outlet rolled joint residual stresses.

(g) At high levels of $[H]_{eq}$ the growth of hydrides is primarily controlled by the amount of hydrogen isotope in solution, which is governed by the operating temperature, and crack initiation has been shown to be insensitive to higher $[H]_{eq}$ levels under hydride ratcheting conditions. There is no concern that the related engineering models are not applicable at higher levels of $[H]_{eq}$.

4.0 RECOMMENDATIONS

The following recommendations are not considered prerequisites to the conclusions of this operability evaluation, but should be undertaken in the appropriate timeframes pending OPG agreement:

Medium term recommendations:

(a) Continue to acquire and review punch and in-service $[H]_{eq}$ sample measurements for future model development. The targeting of non-traditional pressure tube sampling locations should be continued in material surveillance PTs.

(b) OPG should stay informed on the punch sampling and analysis of $[H]_{eq}$ in the ORJ of B6S13 ORJ. OPG should continue to perform these activities on ex-service Pickering and Darlington tubes. OPG should also stay informed on the ongoing Bruce Unit 3 scrape sampling and analysis. Kinectrics can be consulted for specific recommendations on targeted axial and circumferential locations for future $[H]_{eq}$ measurement.

(c) Although Rapid Cooldown transients have not occurred in Pickering B and Darlingon reactors, review options for preventing the occurrence of these transients.

(d) Continue to review incidence of flaws in the upper half of pressure tubes.

Long term recommendations:

(e) Enhancements to $[H]_{eq}$ modelling to account for Bruce Power B3 and B6S13 observations should be pursued.

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[redacted]

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