Directorate of Power Reactor Regulation

December 5, 2019

Mr. Mark Knutson
Senior Vice-President
Nuclear Engineering and Chief Nuclear Engineer
Ontario Power Generation
889 Brock Road, P82-5A1
Pickering, ON, L1W 3J2

Subject: Darlington and Pickering NGS – Measurement and Prediction Methodologies of Hydrogen Equivalent Concentration

Dear Mr. Knutson:

The objective of this letter is to provide Ontario Power Generation (OPG) with an update on Canadian Nuclear Safety Commission (CNSC) staff position on measurement and prediction methodologies of Hydrogen Equivalent concentration [Heq] in pressure tubes.

In June 2016 CNSC staff hosted a joint workshop on [Heq] measurement, where thirteen topics of regulatory interest were presented [1]. Following the workshop, CNSC identified [Heq] as one of three broad issues where resolution would be needed to confirm that OPG has the technical basis and tools in place to conservatively assess fuel channel structural integrity up to the expected end of commercial operation of Pickering Units [2]. Subsequently, OPG provided two updates on the aforementioned topics [3] [4].

Measurement Methodologies

While the industry has made progress on some of the topics identified at the workshop as requiring further development [1], a number of questions remain to be resolved as explained in Attachment 1 to this letter. For instance, despite on-going efforts, the issue of denuded zones and representative scrape sampling has not been resolved to CNSC staff satisfaction. It is further noted that the technical basis for tool-independent scraping [5] does not fully address the challenges observed during the scraping process.

280 Slater Street, Post Office Box 1046, Station B,
Ottawa, Ontario K1P 5S9 Canada
Fax: 613-995-5086 nuclearsafety.gc.ca

Canada

280 rue Slater, Case postale 1046, Succursale B,
Ottawa (Ontario) K1P 5S9 Canada
Télécopier: 613-995-5086 suretenucl A0083305_1-000001

Prediction Methodologies

The [Heq] Body-of-Tube models are empirically-based, with limited mechanistic understanding, and their model forms are updated on a continual basis. Similarly, despite its semi-mechanistic nature, the code used for [Heq] predictions in the Rolled Joint area lacks a mechanistic understanding of several processes. As a result, either some issues are not modelled in their entirety (e.g. circumferential ingress gradients, stress gradients, protium elevation at outboard locations) or are attempted to be modelled via fitting exercises.

As [Heq] predictions for the end of target service life are paramount for accurate assessment of the fracture toughness and overall operation, OPG is reminded that the Licence Conditions Handbook for Pickering NGS provides recommendations for the pertinent models. It is important that OPG submit, for acceptance, the methodology that will be employed for those predictions.

Attachment 1 to this letter provides the CNSC position on the measurement and prediction of [Heq], and consists of two parts: an update to the topics with respect to Reference 1, and the addition of four new topics of regulatory interest.

To conclude, OPG needs to increase its efforts in two fronts: acquisition of high quality inspection data, and improvements to existing models used for long-term projections. OPG is expected to keep CNSC updated with progress in addressing the topics in Attachment 1.

CNSC review of Rolled Joint Scrape Assessment Methodology Using Probabilistically Generated Predictions & Assessment of Rolled Joint Ingress in Ex-Service Pressure Tubes

OPG stated its intent to utilize Enclosures 3 and 4 from Reference 4 to demonstrate conformance with Clause 12.3.5.2.2 in CSA Standard N285.4-14. OPG has requested CNSC concurrence with this approach. CNSC review of OPG responses [6] to staff comments and questions [7] related to the stated enclosures is presently underway.
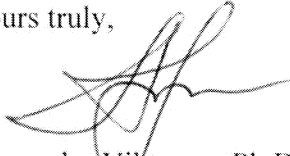
CNSC review of Pressure Tube Scrape Sampling Procedures

CNSC acceptance of three scrape sampling procedures was requested by OPG [8], in accordance with Clause 12.3.4.2 of CSA Standard N285.4-05.

CNSC staff acknowledge the scrape sampling procedures need to be followed in order to execute the Periodic Inspection Program plans, however, resolution of the topics of regulatory interest in Attachment 1 must precede CNSC acceptance of any such procedures.

If you have any questions related to this letter, please do not hesitate to contact
Mr. Milan Ducic at milan.ducic@canada.ca or at 613-947-8593 or
Mr. Ram Kameswaran at ram.kameswaran@canada.ca or at 613-995-2908.

Yours truly,

Alexandre Viktorov, Ph.D.   Nathalie Riendeau
Regulatory Program Director   Regulatory Program Director
Pickering Regulatory Program Division   Darlington Regulatory Program Division

Attachment (1): An Update on Measurements & Predictions of $[H_{eq}]$ Since June 2016

c.c.:   V. Tavasoli, T. Tsembelis, Pickering RPD, Darlington RPD

References:

[1] CNSC/Licensee Workshop on Hydrogen Equivalent Concentration Measurement, June 21, 2016, Agenda and Presentation Material, e-Doc 5022925.

[2] CNSC Letter, A. Viktorov to R. Lockwood, "Pickering NGS - Assurance of Fuel Channel Fitness-for-Service for the Assumed Target Service Life of the Pickering Units", August 25, 2017, e-Doc 5309704.

[3] OPG Letter, M. Knutson to A. Viktorov and N. Riendeau, " Hydrogen Equivalent [Heal Measurements and Deuterium Ingress Modeling", May 31, 2018, CD# N-CORR-00531-19161, e-Doc 5570295.

[4] OPG Letter, M. Knutson to A. Viktorov and N. Riendeau, "Pressure Tube Hydrogen Equivalent [Heq] Measurements and Deuterium Ingress Modeling", May 31, 2019, CD# N-CORR-00531-19672, e-Doc 5918890.

[5] OPG Letter, R. Lockwood to A. Viktorov, "Pickering NGS: Submission of Tool-Independent Scrape Technical Basis, Pickering Integrated Implementation Plan Action G01-RS4-06-04", October 25, 2018, CD# NK30-CORR-00531-07687, e-Doc 5691226.

[6] OPG e-mail, C. Bhagan to M. Ducic, "Response to CNSC Comments on Enclosures 1, 2, 3 and 4 of OPG Submission N-CORR-00531-19672", November 8, 2019, e-Doc 6039472.

[7] CNSC e-mail, M. Ducic to C. Bhagan, "CNSC comments regarding Enclosures 2-4 of OPG submission N-CORR-00531-19672", July 15, 2019, e-Doc 5956480.

[8] OPG Letter, M. Knutson to A. Viktorov, "Pickering NGS – Submission of Pressure Tube Scrape Sampling Procedures", July 2, 2019, e-Doc 5940478.

Attachment 1

An Update on Measurements & Predictions of [H$_{eq}$] Since June 2016

Contents

PART I: Update on the Topics Covered during the 2016 Workshop & Follow-Up Response

Topic 1: Initial Protium Concentration

Short Reminder of the Issue
Measurements of the initial protium concentration from off-cuts indicated differences from the manufacturer's recommended values in the non-conservative direction.

Update since June 2016
Both OPG [1], [2], and Bruce Power [3] have provided updates. Effectively, both licensees have performed initial protium measurements from almost all available offcuts. Consequently, these values are used in the pertinent assessments.

Overall Updated Status: CLOSED

Topic 2: Repeated Scrape Measurements Exhibit a Decrease in [H_{eq}]

Short Reminder of the Issue
Continuous OPEX from some repeated RJ and BoT scrape measurements by both OPG and Bruce Power indicated a reduction in [D] levels, and subsequently, in [H_{eq}], when compared to previous measurements of the same PTs at the same nominal axial locations. Such phenomenon contradicts the fact that deuterium can only accumulate over time and is not expected to diffuse out of the PTs. It is noted that this is one of the most pertinent issues for [H_{eq}] as the models used to predict the [H_{eq}] are based on scrapes.

Update since June 2016
Industry has always placed most of its emphasis to explain this issue on the existence of '*denuded zones*' near the internal surface of the PT. A denuded zone is a near-surface region adjacent to the oxide/metal interface which is relatively free of hydrides. An Industry-only expert workshop was organized after the joint CNSC-Industry workshop on the prediction of hydrogen isotope denuded zones. The discussions were summarized in the COG Report [4]. Potential effects of various parameters, such as cooling rate, irradiation conditions, stress, TSS[1], etc., were investigated. The report concluded that it was not possible to identify a specific correlation between any of the considered parameters and denuded zones. The authors of the report

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[1] TSS: Terminal Solid Solubility

suggested the use of 100 μm as the 'maximum' depth of this zone for up to 75 ppm [H_{eq}]. This value was mainly based on results from the removed tube in D2M09, as elaborated in [5].

The report in [5] investigated several potential sources of error to account for decreasing deuterium concentrations. It is noted that scrape samples taken using the Circumferential Wet Scrape Tool (CWEST) system were not considered in the analysis. Overall, it was concluded that there is a correlation between decreasing or lower-than-expected [D] with light (less than 200 mg) oxide scrape masses, which, in turn, relates to shallow oxide scrape thicknesses. It is known that, if the oxide scrape is not thick enough to remove the denuded zone, the actual sample will contain some of the denuded zone. As mentioned above, metallographic results from the examination removed pressure tube D2M09 indicate that the denuded zone had a depth of 100 μm. However, an oxide scrape with a mass of 200 mg only corresponds to a depth of 50 μm, which is still below the measured 100 μm denuded zone. Actually, any oxide scrape less than 200 mg is considered as having a low mass, as mentioned above. Therefore, we can conclude that oxide scrapes with masses in excess of 200 mg are required. This is an important finding that needs to be considered during the scraping process. Notwithstanding, it is noted that additional research is needed to verify that 100 μm is an upper limit for the zone, especially as the [H_{eq}] applicability limit is 75 ppm. It is noted that the oxide scrape should be deep enough to remove both the oxide layer and the denuded zone material.

In [6], OPG tried to elaborate that the current overall approach employed in Pickering Units for the scraping process, independent of specific tooling employed, is adequate for obtaining representative samples and construct appropriate [H_{eq}] profiles. OPG reasoned that an overall oxide scrape depth of 95 μm is required in order to provide representative sampling; however, OPG did not detail whether the available tools are capable of systematically doing so. Further, the overall depth of 95 μm was derived by OPG based on the following two assumptions, remembering that the total oxide scrape must be deep enough to remove both the oxide layer and the denuded zone:

- Based on Figure 3 of [5], the growth rate of the oxide layer is conservatively estimated at ~ 1 μm/HY. Thus, based on Pickering 5-8 target EoL[2], the oxide layer thickness is expected to be ~ 35 μm. It is noted that Figure 3 is based on only three (3) data points from Darlington removed tubes at the 5.6 m location up to 16 HY of operation and additional information should be provided in order to have confidence on this result. For instance, what about areas where D-uptake is higher, such as the RJ? The submission is silent on this.

- Based on Figure 3 of [7], the denuded zone depths measured in Pickering surveillance tubes are all less than 60 μm. However, it is not clear where the data came from. Notwithstanding, on page 7 of [6], OPG notes that *"Very limited metallography information is available from Pickering ex-service pressure tube material or oxide scrapes in either the body-of-tube or rolled joint regions."*

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[2] EoL: End of Life

Thus, OPG concluded that a total of 95 μm (35 + 60 μm) for the oxide scrape depth is required, such that the sample scrape provides a [D] measurement representative of the bulk pressure tube [D]. While, this can be considered a 'hard' requirement, in [6], OPG did not reason whether this target is actually systematically achieved; that was more of a desirable outcome. In addition, OPG noted that, while there are no specific requirements for oxide scrape or sample curl weights (obviously, the higher the weight, the deeper the scraping), a minimum target weight of 50 mg is recommended for sample curls.

Overall, a good technical basis for tool-independent scraping ought to provide the following information, backed by appropriate evidential support:
- The adequate depths for both the oxide scrape and sample curls for all tools.

- Correlations of masses vs. depths for the oxide and sample scrapes for all tools. It is noted that there is always a range of masses for the oxide and sample curls. Consequently, the licensees must provide the correlation between these mass values and their equivalent depths.

OPG provided a value for the maximum depth required for the oxide scrape in Pickering Units with some rationale and the minimum sample curl mass without adequate support. In addition, it should be noted that OPG has not provided any similar technical basis for Darlington Units. Equally, Bruce Power has not provided this information for their PTs.

When OPG requested CNSC's acceptance of CWEST [8], it was noted that the first cut, i.e. the oxide scrape, is designed to remove material to a depth of 130 μm. The second cut, i.e. the actual sample curl, is designed to remove material to a depth of 254 μm. While these values are nominal values, the submission did not provide any possible range for the masses and, subsequently, for the depths.

Based on all the aforementioned information, it can potentially be concluded that, at least for Pickering Units, there should be no issues regarding obtaining representative scrapes for CWEST. For older tools, in [2] referencing [1], OPG explicitly stated that "insufficient oxide depth is not considered an issue at Pickering Units. From the 580 scrape data points used for developing the 2008 PNGS Units 5-8 BOT model, less than 5% of data points had oxide weights less than those corresponding to the required depth to obtain a representative sample." For Darlington, "up to 13% of sample scrapes in the database could have included a volume of denuded zone".

In the case of Bruce Power, in [9] (similar to the time of OPG's original response in [1]), it was asserted that only 19 instances of decreasing or no change in [D] were identified and these points are not used in the analysis. Bruce Power also asserted that, moving forward, it was planning to identify the scrape data affected by the denuded zone by means of a statistical analysis. Further, Bruce Power was of the opinion that regarding the tooling, "there is no issue as all the scrape campaigns are now performed with the CWEST tool, which scrapes much deeper than the damp tools of the past". Bruce Power is of the opinion that only a few old scrapes may have an issue; however, moving forward, no issues are expected due to the use of CWEST.

In August 2018, OPG submitted the BoT and RJ scrape reports for the 2018 Pickering Unit 6 campaign (P1861) which was performed using CWEST [10]. After the analysis, it was seen that twelve (12) out of twenty (20) repeat BoT scrape measurements exhibited decreased or unaltered [D] when compared to previous measurements. Further, for the remaining seven (7) (one scrape was rejected) only a marginal increase in [D] was observed. As such, a metallography examination was initiated and further investigation was recommended. The metallographic results were submitted to CNSC [11] and reviewed by staff. Based on the above, it can be concluded that OPG's aforementioned assumption regarding lack of issues with CWEST is not valid.

The objective of the metallographic results was to examine seven (7) oxide scrapes for the presence of a denuded zone. During the analysis, no denuded zones were observed. As a result, OPG claimed that the sample scrapes are likely representative of the through-wall [D]. However, it is noted that a reduction or lack of change in [D] is not physical. OPG did not provide any justification for the challenged scrape results. The continuous challenges and the overall lack of understanding is very worrisome; it is reminded that scrapes are used in the development and update of models, which, in turn, are used for forward-looking [H$_{eq}$] predictions. After the review of the P1861 related submissions, CNSC sent a letter to OPG [12] stating the view that additional margin to BoT predictions may need to be applied.

The issue of reduced values at BoT scrapes is not only seeing using the CWEST in Pickering Units. For instance, during the Unit 1 2017 campaign (P1711) [13], similar issues were observed with the repeat scrapes. It was suspected that since the oxide samples were within expectations, the denuded zone effect was not likely, although no metallography was performed. OPG asserted that a small contamination during the scraping procedure may have been the reason. While, this may always be possible, such assertions should be backed by evidential support with additional R&D. The issue of potential contamination of scrapes was briefly investigated in [5], but without clear conclusions. In one case, a relatively large reduction was seen. OPG decided to remove the elevated measurement from the database, as it suspected that the elevated measurement was not in line with expectations and historical data. This is a very worrisome issue because it is an ad-hoc removal of scrapes without proper justification in the non-conservative direction. Consequently, CNSC staff communicated their expectation regarding removal of higher-than-expected scrapes in [12].

Despite Bruce Power's reassurance pertaining to the use of CWEST during its scrape campaigns, similar issues have also been exhibited during Bruce Power scrape campaigns. For instance, during the Unit 7 2017 scrape campaign (B1761) [14], which was performed with the CWEST, several repeat BoT measurements exhibited slight decreases compared to previous measurements. In one case, a large reduction was seen. Bruce Power also decided to remove the previous measurement from the database as it reasoned that the elevated measurement was not in line with expectations and historical data.

While reductions of repeat BoT scrape measurements and lack of overall understanding are worrisome, the issue has also been observed with RJ scrapes. For instance, during the repeat RJ scrapes for channel B6S13 during the B1761 campaign [14] reductions by up to 329 ppm [D]

were observed. Consequently, the [H_{eq}] prediction at the BM[3] location varied by 10 ppm. However, in the case of the RJ area, the issue becomes more complex due to the possibility of circumferential gradients, which is detailed in Topic #11.

To conclude, while some progress has been achieved since 2016, there are still a lot of unknowns. Even the technical basis for tool-independence scraping does not seem to address the ongoing challenges observed during the scraping process. It is noted that the issue of non-representative scraping was first identified in the mid-nineties.

In May 2019, OPG provided an update through the submission of COG-18-1029, for which CNSC staff provided comments in August 2019 [e-Doc 5962486]. Similarly, CNSC acknowledges OPG's recent pertaining to the metallographic results of the 2018 Pickering Unit 8 scape analysis. Based on a high-level review of the submission, CNSC preliminarily concludes that CWEST continues to provide results that are not fully understood.

It is noted that all scraping tools predate the submitted Technical Basis (TB). The TB is a consequence of CNSC's insistence on the issue. As the TB is, to some extent, an afterthought, it should include specific provisions for the existing tools and their compliance to representative scraping.

Overall Updated Status: OPEN

Topic 3: [D] from RJ Scrapes are lower than Pellets at Same Axial Locations

Short Reminder of the Issue

During the material property testing of the removed tube from Darlington Unit 2, location M09 (D2M09), it was observed that [D] values from the pellets were significantly higher than [D] values from scrapes, especially at the RJs. CNSC recommended to the licensees to scrape a tube prior to removing it for material property testing purposes.

Update since June 2016

Both OPG [2] and Bruce Power [3] responded that they will consider CNSC's recommendation. Both licensees seem to be of the opinion that this issue is resolved. However, performing scrapes at the same nominal time as removing the tube does not provide a technical justification of the observed discrepancy between scrapes and pellets.

Since the workshop, two tubes were removed from Pickering and Darlington Units. One tube was removed from P7O07 in 2016 (P1671 outage) after 220,521 EFPH (229,101 HH) [15] and one tube from D1U09 in 2017 (D1711 outage) after 191,100 EFPH (198,321 HH) [16]. Inlet and outlet RJ scrapes were also taken from P7O07 during the P1671. A comparison between data

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[3] BM: Burnish Mark

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from scrapes and pellets did not show any deviations. Also, for tube D1U09 both BoT and outlet RJ scrape were taken. The BoT scrapes exhibited slightly higher values than pellets and cuts, while the outlet RJ scrapes were within the uncertainty of the pellets.

While, an understanding for the potential differences is needed, provided that the licensees are monitoring the situation by performing scrapes of removed tubes, CNSC staff can consider the issue resolved until new OPEX.

Overall Updated Status: CLOSED

Topic 4: Spot Welding of Scrapes prior to Measurements

Short Reminder of the Issue

Licensees in the past exclusively employed the services of CNL[4] to perform the $[H_{eq}]$ measurement of the scrapes. As the scrapes arrive in small pieces, CNL staff spot-weld them together to form a single piece.

Update since June 2016

CNSC has accepted OPG's response and no longer considers it an issue [17]. Furthermore, both licensees start utilizing an alternative technique that does not require any spot-welding, which has been accepted by CNSC [18].

Overall Updated Status: CLOSED

Topic 5: [H] Measured from Scrapes are not used due to Contamination

Short Reminder of the Issue

During the scraping process protium contamination may take place. As a result, [H] levels from mass spectrometry are not considered representative of the tube. Consequently, these values are taking into consideration for $[H_{eq}]$ values.

Update since June 2016

In CNSC letter [17], staff considered the issue to be resolved until adverse OPEX becomes available. In the P1861 submission pertaining to the RJ scrapes campaign (enclosure 1 of [10]);

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[4] CNL: Canadian Nuclear Laboratories

trends in [H] were observed, despite the possible contamination. Effectively, trends resembling the ones identified in surveillance tubes (discussed under Topic #7) appeared in scrapes. As a result, in the CNSC letter pertaining to P1861 [12] staff communicated their expectation that a [H] value to the total RJ [H_{eq}] which is more representative should be included, when trends in [H] are observed. CNSC staff is monitoring the situation and can re-open the issue if additional challenges manifest during future scrape campaigns.

Overall Updated Status: CLOSED

Topic 6: Use of Multiple TSSd Curves

Short Reminder of the Issue

The TSSd curve is an important input to many assessments. For instance, RJDIM 2.0 [19], which is used to predict [H_{eq}] in the RJ area, requires this input. Further, it is noted that [H_{eq}] in the RJ area is also a direct input to various assessments, such as flaw assessments and fracture protection. At the same time, the TSSd curve is also used in other parts of the aforementioned assessments. It is noted that Terminal Solid Solubility is supposed to be a material property and cannot change ad-hoc. In particular, it does not make physical sense for the same location to utilize different TSSd curves depending on the assessment..

In general, there are three overall approaches pertaining to the use of TSSd curves. First, the licensees use the TSSd curve found in CSA N285.8 for some aspects of the assessment related to structural integrity due to the existence of flaws and for compliance of BoT [H_{eq}] scrapes with CSA N285.4, Clause 12.3.5.2 (a).

Second, for RJ [H_{eq}] predictions, which are based on a probabilistic methodology and used as inputs in various assessments, such as probabilistic core assessments (PCAs), the licensees utilize the Khatamian TSSd based on the peak temperature interpretation of the DSC[5] signal. This TSSd differs from the established CSA N285.8 curve and more importantly, it is mutually exclusive, as it is based on a different interpretation of the experimental DSC results. In other words, under the same experimental conditions to establish the TSSd curve, Khatamian's TSSd differs from CSA N285.8 curve only because the interpretation of the experimental results is different, that is, a different part of the DSC signal is chosen.

Third, for actual RJ scrapes or punches, the utilities may use different TSSd curves in order to better fit the [H_{eq}] profile; essentially they try to 'calibrate' a material property based on the profile. However, this is not the only material property that is adjusted. Others, such as diffusivity, are also calibrated in a similar way, depending on the [H_{eq}] profile. This is further discussed in Topic #9, as well.

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[5] DSC: Differential Scanning Calorimetry

It should be noted that CNSC staff considers this topic to be of high importance because it has direct ramification to the RJ [H_{eq}] predictions at EoL of various Units.

Update since June 2016

CNSC provided three comments to the licensees:

(i) CNSC asked to be informed regarding Prof. Holt's deliberation on the use of TSSd and recommended to move towards a consensus for an appropriate TSSd curve for all assessments.

(ii) CNSC asked to be sent a comparison of [H_{eq}] at the BM for the top three (3) percentiles between predictions using the Khatamian and CSA TSSd curves.

(iii) CNSC recommended that the conservatism assertion should be regularly demonstrated when the inputs to probabilistic RJDIM 2.0 are updated.

The first responses to the aforementioned comments were sent by both OPG and Bruce Power in [1] and [3], respectively. It is noted that both responses are similar in nature:

(i) The Industry proposed to set-up a task team to address the issue and that an update will be provided by May 2018. It is noted that CNSC agreed with that timeline and provided and communicated that to OPG in [17].

(ii) The Industry asserted that there is a limited value to perform a comparison because:

  a. The use of Khatamian's TSSd was agreed by the Industry for appropriate predictions or probabilistic models.

  b. The probabilistic models have been validated using measured data from scrape and surveillance campaigns.

  c. The model based on CSA TSSd would require validation before use for generating [H_{eq}] predictions.

  d. Comparison of the predictions is valid only if models are properly validated.

  CNSC staff would like to see the validation of the use of Khatamian's TSSd in probabilistic assessments. Consequently, licensees should provide this information. In addition, the TSSd is considered a material property, and, if such a validation exists, licensees should use Khatamian's TSSd in all assessments. It should be noted that licensees continue to use the same rationale as before; that is, it is considered acceptable to use different TSSd curves depending on the assessment. CNSC staff do not accept this approach because it is not a physically-based scientific approach, and conservatism has not been shown for all uses of TSSd. Additionally, the fact that certain TSSd models have been used extensively for many applications is not a

substitute for validation.. Licensee us of use Khatamian's TSSd suggests that the CSA TSSd is not adequate for probabilistic [H_{eq}] predictions; effectively, asserting that a material property which is referenced in a CSA standard cannot be utilized. If this material property is no longer appropriate, thenIndustry should update the model providing supporting evidence.

(iii) OPG concurred that conservatism should be demonstrated, while Bruce Power would consider CNSC's recommendation. Both licensees, referenced COG-16-1043 [20] which pertains to uncertainty analysis in probabilistic evaluations. However, it does not address the issue of conservatism.

In May 2018, OPG provided a second update, as mentioned in the introduction. The proposed task group confirmed the need for a proper technical basis for the appropriate use of TSSd equations, and a document was submitted to CNSC in May 2019 [Enclosure 2 of e-Doc 5918890]. CNSC staff have reviewed the technical basis document for its scientific merit (as solubility is a material property) and provided comments to OPG in July 2019 [e-Doc 5950430].

Three surveillance reports were submitted to CNSC after the 2016 Workshop for B8J18 [21], P7O07 [22] and D1U09 [23] removed tubes. The TSSd and diffusivity used for the optimized [H_{eq}] profiles from punched samples are provided in Table 1 below. Although this topic pertains only to TSSd, diffusivity is provided as the Industry is also often 'calibrating' this material property as well. Topic #9 addresses this issue overall.

Table 1: TSSd and Diffusivity values in RJDIM for optimized profiles from recent removed tubes

	B8J18 [21]		P7O07 [22]		D1U09 [23]	
	TSSd	*Diffusivity*	*TSSd*	*Diffusivity*	*TSSd*	*Diffusivity*
Inlet	CSA+30%	Sawatzky-30%	CSA	Sawatzky-30%	Khatamian	Sawatzky-30%
Outlet	CSA	Sawatzky-50%	CSA	Sawatzky-25%	CSA	Sawatzky

Note: Sawatzky Diffusivity is currently considered the established value as it is mostly used; however, it is not referenced in CSA standards like TSS.

It is noted that during the fitting process of the two material properties, no technical justification was provided. During CNSC staff review of the P7O07 report [22], OPG provided [24] which details the 'allowable' range of TSSd and diffusivity:

- Deuterium diffusivity: the use of other pre-set diffusivity values [2] may be used, or Sawatzky diffusivity may be reduced by up to 50%. The use of a decreased diffusivity is consistent with an increase in diffusion distance (as opposed to a straight axial line) as a result of circumferential gradients in deuterium ingress in the rolled joint and a reduction in diffusivity resulting from the presence of hydrides [3]. An increase in deuterium diffusivity is not technically justifiable.

- TSSD: the use of other pre-set TSSD values [2] may be used, or TSSD may be increased up to 30%. The increase in TSSD is to enhance the flow of deuterium inboard, to be consistent with

the Khatamian equation (25% higher than FFSG), which is based on an alternate interpretation of the DSC curve. Increases in TSSD above 30% of the FFSG equation are not technically justifiable.

CNSC staff note that a technical basis and methodology for choosing the appropriate values has not been provided.

In enclosure 2 of P7O07 [22] pertaining to the acceptance criteria and evaluation procedures for material surveillance, OPG affirmed that '*A technical justification specifying the permissible range of parameter adjustment shall be documented*'.

The issue of multiple TSSd curves, including fitting of material properties, has also been seen in various scrape-related assessments over the years. For instance, during the assessment of the RJ scrapes of P1861 [10], the TSSd curve was increased relative to the accepted CSA in two occasions. Consequently, CNSC sent a letter to OPG [12] requesting technical justification specifying the permissible range of parameters adjustment for all inputs adjusted in the development of any $[H_{eq}]$ profile. If such a justification is not currently available due to on-going R&D programs, a sensitivity analysis based on already used values for material properties, such as diffusivity and TSSd, and the most conservative prediction could be considered.

In conclusion, while some information has been provided, the licensees continue the material property fitting to $[H_{eq}]$ profiles unabated, including utilizing multiple values, without proper physical justification. More concerning is the continue use of different values for the same material property at the same location of a pressure tube depending on the assessment type.

Overall Updated Status: OPEN

Topic 7: Protium Concentration from Removed Tubes

Short Reminder of the Issue

Pellets from removed tubes have indicated that [H] is elevated at the RJs. While those results can be used for generating a dedicated RJ $[H_{eq}]$ profile for the removed tube using RJDIM 2.0, in

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general, this increase at the RJs is largely ignored and protium values from either manufacturer's data or offcuts are used in various assessments.

Update since June 2016

In OPG and Bruce Power responses ([1], [2], [3]) the licensees essentially accept that there is an issue; and OPG stated that it is working with its industry partners to investigate how protium concentration values could be established as an input term, with guidance, for incorporation into RJDIM [e-Doc 5918890].

As mentioned above, three surveillance reports were submitted to CNSC after the 2016 Workshop for B8J18 [21], P7O07 [22] and D1U09 [23] removed tubes. The [H] maximum and minimum values from RJ samples are provided in Table 2 below.

Table 2: Maximum and minimum [H] values for RJ samples from recent removed tubes

	B8J18		P7O07		D1U09	
	Max	*Min*	*Max*	*Min*	*Max*	*Min*
Inlet	20 ± 1	9.0 ± 1	17 ± 2	12 ± 1	27 ± 2	8.6 ± 0.8
Outlet	14 ± 1	12.1 ± 1	16 ± 2	12 ± 1	14 ± 1	13 ± 1

Note: Maximum values are found at the most outboard location, while minimum values are found at the most inboard location.

From the above table, it can be seen that protium values can vary in RJ punches of removed tubes. This implies that there is a process with which protium is either re-distributed in areas of elevated deuterium or there is a source of additional protium which could effect[H_{eq}] predictions both outboard and inboard of the BM. It is noted that this effect is more prevalent at the outboard locations under the RJ where the stresses are compressive. Inboard of the BM, where the stresses become tensile, and thus DHC is a pertinent cracking mechanism, [H] values have diminished substantially. However, in outboard areas, where [D] values are already significantly elevated, increases in [H] can result in increases of the overall [H_{eq}] values. Elevated [H_{eq}] values are a concern for the compressive properties of FCs, as detailed in Topic #13.

Traditionally, the aforementioned effect has been observed in samples from removed tubes. In scrapes, this is harder to observe due to contamination issues. However, during the P1861 scrape campaign [10] some trends in [H] were also observed. Consequently, CNSC sent a letter to OPG [12] requesting the use of a more representative [H] value in the calculation of RJ [H_{eq}].

Overall Updated Status: OPEN

Topic 8: Deuterium Mass from Repeated RJ Scrapes

Short Reminder of the Issue

During RJ scrape campaigns up to four (4) samples per RJ end are taken. Using results from those samples the Industry is constructing a full profile, which, in turn, provides the total deuterium mass that has entered the system due to RJ ingress. Occasionally, the same PT is re-inspected later in life and another estimation of the total D-mass is performed. For some PTs the repeated D-mass either decreases, when compared to the previous measurement, or increases significantly faster than established rates.

It is noted that the D-mass is an important parameter that provides one of the most critical inputs in RJDIM for predicting [H_{eq}] profiles. Thus, any uncertainties in D-mass will propagate in the pertinent [H_{eq}] predictions.

Although some of those significant differences may be attributed to circumferential gradients (see Topic #11), overall lack of understanding and adequate quantification can cast doubt on the [H_{eq}] predictions needed for comparison against the pertinent CSA Acceptance Criteria.

Update since June 2016

In OPG and Bruce Power responses ([1], [2], [3]), the licensees stated that they are reviewing whether inclusions of plots of deuterium mass, versus hot years, are required in their rolled joint reports. During the May 2019 submission from OPG, it states "The industry task group agreed that due to the uncertainties in the approach to calculate the deuterium mass from four scrape data points, the plots of deuterium mass versus hot years will no longer be included in RJ scrape assessment reports."

It is irrelevant whether such plots are included or not in the reports, as the issue of D-mass will remain. The Industry should concentrate on understanding the issue and reducing uncertainties, instead of removing plots from reports. They could look into increasing the number of scrapes, updating the pertinent models and codes and calculating overall uncertainties. Removal of information doesn't fix the issue as the information will continue to be used for [H_{eq}] predictions.

Bruce Power's submission pertaining to operation exceeding TSSd [25] referred to the possibility of D-ingress rate increase once TSSd has been reached. If this is a true phenomenon, D-mass will increase with time faster than established rates. Existing models do not account for this increase, potentially underestimating [H_{eq}] predictions.

Overall Updated Status: OPEN

Topic 9: Optimization of RJ Scrape Profile

Short Reminder of the Issue

Individual RJ [H_{eq}] profiles from scrapes and removed surveillance tubes are manually fitted with expert judgment by adjusting several parameters in RJDIM 2.0. (E.g. TSSd, diffusivity, etc.). CNSC staff want to know what measures are in place to ensure that an optimum profile fit has been achieved, and what uncertainties are associated with the process. It is noted that this is an overarching issue, which encompasses several topics discussed herein, such as Topic #6.

Update since June 2016

In OPG and Bruce Power responses ([1], [2], [3]), the licensees suggested the creation of a task group to address the issue. After the Many 2018 update, it was decided by the Industry to develop and document a procedure based on probabilistic models. Accordingly, OPG submitted two documents for the assessment of deuterium uptake from RJ scrape and material surveillance measurements based on probabilistic [Heq] predictions. The documents are intended to "eliminate the inconsistencies that were present due to generating the optimum profile from the differing number of data points from material surveillance versus scrape activities and is expected to reduce uncertainties in [Heq] from use of different methodologies." CNSC staff have reviewed the two document and provided informal comments to OPG in July 2019 [e-Doc 5950430].

It needs to be noted that it is challenging for the CNSC to accept probabilistic methodologies for CSA N285.4 deterministic assessments. The RJ profiles are based on actual inspections, either from scrapes or from punches. A probabilistic assessment implies that there are uncertainties that the Industry does not understand and has not quantified. Further, the issues with material properties detailed in Topic #6 cannot be resolved through application of uncertainty distributions. Material property values cannot change ad-hoc or be distributed without solid physical foundation backed by strong technical basis.

Overall Updated Status: OPEN

Topic 10: Use of Fit Optimization Engine

Short Reminder of the Issue

The Industry has introduced a Fit Optimization Engine (FOE) for RJDIM 2.0 to derive input distributions for SF and BoT ingress for inspected tubes, which are used in probabilistic methodologies for predicting [H_{eq}]. As there is already a manual methodology for estimating these parameters licensees should address the consistency and conservatism between the two methodologies.

Update since June 2016

Both licensees tried to address the issue in a similar way ([1], [2], [3]), that is, explain how the FOE is used and what the differences are between in the input values for the FOE and the manual

fit method. The licensees reasoned that they expect the results obtained using the two approaches to be different since they are based on different methodologies and assumptions. For manual fits, the focus is fitting the data conservatively around the BM locations, while the FOE treats all data the same and provides inputs to probabilistic RJ models. In addition, different TSSd curves are used. As a result, for the most part, the vast majority of the BoT values from the FOE are lower than the manual fits. On the other hand, the RJ SF values from the optimizer are higher or similar when compared to the manual fits.

While, both licensees consider the issue closed, the aforementioned details raise several concerns. First, it becomes apparent that there is a clear lack of consistency between the derived values. Effectively, the licensees utilize the same data sets (scrapes and surveillance data) to derive different input values for the BoT and RJ contributions. This is not physical, as the contributions due to RJ and BoT ingress cannot differ as a result of different fitting methods. Second, once again, we see the licensees using different TSSd values, ignoring the fact that TSSd is a material property and cannot change on an ad-hoc basis (see Topics #6 and #9). Further, while the licensees are silent of the issue of diffusivity, it is highly likely that different values for diffusivity are also utilized. Third, while the licensees claim that the manual fits are centered on conservative fitting around the BM, it is not clear whether the actual predictions to the future will remain conservative. Finally, the licensees have yet to clarify which of the two methods will give the most conservative predictions. To conclude, this topic will remain open while the issues of consistency and conservatism remain unanswered.

Overall Updated Status: OPEN

Topic 11: Circumferential [H_eq] Gradients and RJDIM Symmetry

Short Reminder of the Issue
OPEX from pellets of removed tubes showed a significant difference in RJ [D] values at the same axial location, but at different clock positions. Consequently, the basic assumption of 1-D circumferential symmetry at the RJ is no longer valid, with potential deleterious ramifications to predictions.

It is noted, however, that circumferential gradients were not only observed in pellets; scrapes have also exhibited significant gradients.

Update since June 2016
In OPG and Bruce Power responses ([1], [2], [3]), the licensees claimed that while COG R&D is continuing, results show circumferential variations in the outboard region of the end fittings RJ, while concentrations are converging to a similar value in the BM region and further inboard. Effectively, the licensees re-iterated the rationale that circumferential gradients may not be relevant at the BM location.

It is noted that CNSC staff do not agree with the aforementioned rationale for two reasons. First, if circumferential gradients are responsible for elevated $[H_{eq}]$ values at outboard locations, they may potentially affect the compressive properties of the material; this is discussed in Topic #13. Second, these gradients will affect the overall calculation of the deuterium mass that has entered through the rolled joint. The calculation of deuterium mass is performed at a single rotary location and, as such, it is one-dimensional. Therefore, if the specific punched or scraped rotary location does not correspond to the highest values of $[D]$, the overall calculated deuterium mass won't be conservative, which, in turn, can be reflected in the $[H_{eq}]$ predictions at future operating times, as required by CSA N285.4 or in other assessments.

A recent attempt to quantify the circumferential gradient in removed tubes can be found in [26], where punch samples from the inlet ends of B8J18 and D2M09 tubes were taken at various rotary and axial locations. Based on the results, the total deuterium mass that entered the inlet RJs was calculated to be 103±3 mg and 148±3 mg for B8J18 and D2M09 RJs, respectively. While, $[H_{eq}]$ predictions at the BM for future operational times were not provided, it is unlikely that a ~3% deviation will be able to significantly affect the predictions.

Notwithstanding, as mentioned above, circumferential gradients have also been observed in RJ scrapes but are manifested differently. In removed tubes, the circumferential gradients are observed when $[D]$ is measured from punches at different rotary positions. On the other hand, scrapes are performed at a single rotary location at a time, while repeated scrapes in future campaigns are scraped at a different rotary locations. It is the differences between repeated scrapes that led to the conclusion of potentially large circumferential $[D]$ gradients. This is obviously directly related to Topic #8. It should be noted that only one scrape repeat per RJ end is allowed due to constraints.

One such example is the outlet end of the channel B6S13. Between the 2015 Unit 6 scrape campaign [27] and the 2017 Unit 6 campaign [14], huge variations in $[D]$ were observed. Table 3 provides a summary of the $[D]$ measurements. It can be seen that there is a big difference in the actual scrape values. This is expected to manifest itself in $[H_{eq}]$ predictions.

Table 3: Comparison of Repeat Measurements for B6S13

Distance from PT end	[D] (ppm)	
	B1561 [27]	*B1761* [14]
12	470.0	142.1
43	320.0	119.0
130	103.0	85.6
371	58.0	56.8

Table 4 below provides estimations for the Deuterium mass based on the scrape values, the estimated BM [Heq] at inspection time and the predicted [Heq] at the next periodic measurement. For the B1561 the next periodic measurement was ~June 2019 (~273 kHH), while for the B1761 the next outage is actually the MCR (~272 kHH); consequently both outages provide a projection to approximately the same time.

Table 4: Estimated Dmass and [Heq] for B6S13

Outage/Time	Estimated Deuterium mass (mg)	Estimated BM [Heq] at inspection time	Predicted BM [Heq] at the next interval (~273 kHH)
B1561 / 233,970 HH	345.0	70	87.8
B1761 / 253,093 HH	171.1	60	68.6

Two important points should be noted. First, as a consequence of the circumferential gradients, the [H_{eq}] at the BM was decreased by ~ 10 ppm at the 2017 outage compared to the 2015 campaign. Second, the actual projections to EoL decreased by ~ 20 ppm between successive outages. While in this particular example, the repeat measurement exhibited a reduction, it is equally possible that a repeat campaign will exhibit opposite trends. Such uncertainties in the scrape process and their manifestation into overall predictions are challenging for overall compliance and FFS assessments. For instance, the predictions to the next interval are directly compared against CSA N285.4 and N285.8 AC. In addition, as explained in Topic #10, the RJ scrapes are subjected to an optimization process in order to provide input distributions for RJ models. In turn, these models provide tabular data for [H_{eq}] predictions for several assessments, such as PCAs. Without an accurate quantification and appropriate physical understanding of the potential uncertainties due to circumferential gradients, all pertinent assessments and their outcomes may be challenged.

Overall Updated Status: OPEN

Topic 12: Probabilistic RJDIM predictions in Deterministic Flaw Dispositions

Short Reminder of the Issue

OPG had informed the CNSC of their intent to use [H_{eq}] predictions at RJs based on probabilistic methodologies for deterministic flaw assessments, with Bruce Power expressing a similar interest. This is a deviation from the accepted approach of utilizing deterministic generic predictions which are bounded for Stations.

Update since June 2016

In June 2017 CNSC granted concurrence to OPG's request [28] with two conditions:
- OPG utilizes the most conservative value between the generic prediction and the 97.5 percentile upper bound probabilistic prediction for each flaw assessment.

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- When the inputs to the probabilistic predictions are updated, an impact assessment is performed on CNSC accepted pressure tube component dispositions pertaining to flaw assessments.

In a recent submission [2], CNSC staff were notified that OPG elected to only use deterministic RJ predictions in deterministic flaw assessments.

In November 2018 an informal meeting between Bruce Power and CNSC staff took place regarding the potential use of probabilistic predictions in various FFS assessments [29], including flaw assessments for disposition, scrapes and surveillance tubes. CNSC staff informally provided initial responses and comments to Bruce Power [30]. CNSC staff will provide responses if and when Bruce Power submits an official request to the CNSC. Notwithstanding, as regulatory requirements cannot be different between OPG and Bruce Power, it is expected that CNSC staff will follow the same response as in [28]. Further, issues such as, material property fitting (Topics #6 and #9) create additional challenges in accepting a methodology that can be potentially be less conservative.

Unless there is a clear understanding of all the possible pathways of uncertainties, followed by adequate technical justification for their values, no probabilistic methodology is capable of accounting for the possible errors.

Overall Updated Status: CLOSED FOR OPG – OPEN FOR Bruce Power

Topic 13: Operation above TSSD

Short Reminder of the Issue

CSA N285.4 Clause 12.3.5.2 stipulates that $[H_{eq}]$ measurement at the BoT will be acceptable provided that the values are below the level at which hydrides are present at sustained operation conditions to the end of the next evaluation period, i.e. values remain below TSSd during operation. However, $[H_{eq}]$ levels for some tubes are exceeding TSSd. While a similar criterion does not exist for the RJ area, it is also expected that areas of RJs will also exceed TSSd during operation.

CNSC staff identified two issues. First, the possibility of D-ingress acceleration when exceeding TSSd, and subsequently, TSSp[6]. Second, the Industry has not provided information about material properties and overall ductility in the compressive region of the RJ where the $[H_{eq}]$ values are at the highest.

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[6] TSSp: Terminal Solid Solubility of Precipitation

Update since June 2016

In OPG responses ([1], [2]), it was reasoned that a TB to support operation above TSSd for Darlington Units was submitted to CNSC [31], which was subsequently accepted in 2015 [32]. For Pickering Units, OPG referenced [33] pertaining to OPG's approach should the Units exceed TSSd during operation. OPG is planning to follow a similar approach to Darlington Units. CNSC staff are presently reviewing Enclosure 5 of [e-Doc 5918890].

In Bruce Power response [3], no updates were provided on either the two aforementioned issues or on overall operation when TSSd is exceeded. However, in September 2018 [34], Bruce Power included a generic rationale for dispositioning pressure tube operation above TSSd as part of a disposition for B6K10 which, was predicted to exceed TSSd in the BoT. Bruce Power's submission was heavily based on the same approach as Darlington's; however, there were several updates to reflect current knowledge, including an update on the issue of D-ingress acceleration. Overall, material property understanding above 100 ppm is not complete. Further, as there is evidence of D-ingress acceleration, margins in $[H_{eq}]$ predictions should be incorporated.

Overall Updated Status: OPEN

(Additional) Topic 14: Stress Gradients and their Effects on RJ $[H_{eq}]$

Short Reminder of the Issue

The BM is a region where the stresses transition from compressive to tensile. On top of this axial stress gradient, there is also a through-thickness stress gradient. In general, a stress-gradient is a 'driver' mechanism for hydrogen diffusion. CNSC is not aware how $[H_{eq}]$ predictions and onset of ratcheting of bulk hydrides are affected by stress gradients.

Update since June 2016

Staff acknowledges that industry has started investigating stress gradients in the RJ based on an OPG update provided in May 2019 [e-Doc 5918890]. However, staff note that OPG has not explained how additional measurements will help in the understanding of stress gradient effects and [Heq] at the RJs and the consequent modeling.

Overall Updated Status: OPEN

(Additional) Topic 15: Transition Point between RJ and BoT in FFS Assessments

Short Reminder of the Issue

In accordance with CSA Standards, the RJ extends up to 300 mm passed the BM, which is ~370 mm inboard. However, the effect of diffusion due to D-ingress at RJs can be observed in axial locations in excess of 500 mm inboard of each RJ. As different [H_{eq}] models are used for the RJ and BoT regions, the transition point at which RJ [H_{eq}] predictions become less conservative is not a single value. Thus, the point at which the transition takes place is potentially beyond the CSA recommended location and use the most conservative value inboard of the 370 mm location may be required.

Update since June 2016

First, it is noted thata CSA technical group was established to update Clause 12 of CSA N285.4 and in particular the parts related to RJ [H_{eq}] measurements [36]. The issue of the RJ-BoT transition was also discussed during the various meetings but it was decided to leave it unchanged for now as it pertains to the application of the [H_{eq}] AC [37]. However, the group did not deal with the ramification of the transition region to various assessments.

In OPG responses ([1], [2]), it was noted that an assessment was submitted to the CNSC of the sensitivity of the LBB and fracture protection to the BoT and RJ transition zone [38]. That submission was reviewed by staff and an official letter was issued to OPG [39] concurring with OPG's overall approach and recommending the continuation of applying the 'interim conservative approach' in the absence of published guidance from industry experts. It is noted that that approach pertained to the use of the most conservative value between the Body of Tube and Rolled Joint model predictions in the transition zone, up to 1 m from the end of the pressure tube, in all pertinent assessments.

In Bruce Power response [3], it was reasoned that RJ [H_{eq}] predictions are used up to 500 mm instead of 370 mm. However, no sensitivity analysis similar to OPG's aforementioned assessment has been submitted by Bruce Power.

Overall Updated Status: CLOSED FOR OPG – OPEN FOR Bruce Power

Part II: New Issues Necessitating Commenting after the 2016 Workshop

(New Issue) Topic 16: Use of TDMS for Concentration Measurements

In February 2018 [40], OPG requested CNSC acceptance of the technical documentation in support of using the TDMS system for measurement of hydrogen isotope concentration in

pressure tube material. Staff reviewed the submission replied to OPG in [41], effectively concurring with the request. However, an action item was raised to address a trend observed during the P1861 scrape campaign ([11], [12]) where an increasing number of repeat BoT scrapes exhibited either decreasing or unchanged [D]. It is noted that the concentration measurements for P1861 were performed with TDMS. Consequently, an informal tele-conference between OPG and CNSC staff took place on October 19, 2018 to discuss the findings from P1861. During the meeting, OPG claimed that the campaign introduced two new tools: CWEST, which was used to acquire the scrapes, and TDMS, which was used to perform the concentration measurements. OPG staff suggested that a direct comparison between TDMS and HVEMS can be performed in order to discount a potential issue arising from the use of TDMS. As a comparison cannot be performed with scrape samples due to their low masses. However, OPG suggested that a comparison can be performed with samples from surveillance tubes, such as punches or cuts. CNSC concurred with the suggestion, that is, there was a verbal agreement between CNSC and OPG staff. Consequently, when CNSC staff granted acceptance for the use of TDMS [41], they raised an action item to discount the potential discrepancy introduced by the measurement tools by performing a one-to-one comparison of hydrogen isotope concentration measurements between TDMS and HVEMS, as mutually agreed. Since that time OPG has committed [e-Doc 5918980] to submit a HVEMS vs. TDMS Comparison Report by February 28, 2020. No information exists for Bruce Power.

(New Issue) Topic 17: [H_{eq}] EoL Predictions

As many Units are approaching their EoL, it is important to know what the projected [H_{eq}] values are. Predictions at the RJ areas are of particular importance due to the fracture toughness related limitation of 120 ppm. Section 15.3 of both the Pickering [44] and Bruce Power [45] LCH documents include specific requirements for this limitation.

During relicensing, both licensees provided updated [H_{eq}] values based on both deterministic and probabilistic assessments. During the May 2018 hearing, Bruce Power provided predictions [46] for RJ BM [H_{eq}] values and time-to-reach 120 ppm at the outlet RJ; these are provided in Figure 1, for information. The author could not identify similar information provided by OPG during the June 2018 Pickering relicensing. However, two presentations by CNSC staff provided various [H_{eq}] predictions. In CNSC's main presentation [47], [H_{eq}] predictions for all Pickering Units were given in Slide 13, which is reproduced in Figure 2 below. In addition, in CNSC's supplemental presentation [48], which contained an internal technical update on fuel channels FFS from a previous commission meeting in January 23, 2018 [49], [H_{eq}] predictions were also provided. These are reproduced in Figure 3 below. From Figures 1-3 it can be seen that several values have been provided for each Unit. Consequently, it becomes apparent that it is somewhat challenging to know the exact prediction for each Unit.

Figure 1: Bruce Power RJ [Heq] predictions in Bruce Power Presentation during the May 2018 Hearing [46]

Outlet RJ Heq predictions

Probabilistic – MCR (97.5 percentile upper bound)			Deterministic – MCR		
Unit	EFPH	Heq, ppm	Unit	EFPH	Heq, ppm
3	~245000	92	3	~245000	102
4	~255000	81	4	~255000	104
5	~300000	120	5	~300000	151
6	~245000	99	6	~245000	121
7	~300000	120	7	~300000	147
8	~300000	103	8	~300000	139

Note: Current fracture toughness model validated to 120 ppm, further updates planned for end of 2018 (140 ppm) and 2019 (160 ppm)

Time to reach 120 ppm at the outlet RJ

Based on Deterministic Heq Predictions			Based on Probabilistic Heq Predictions		
Unit	EFPH	Date	Unit	EFPH	Date
3	Beyond MCR		3	Beyond MCR	
4			4	Beyond MCR	
5	247609	Feb 2020	5	Beyond MCR	
6	243128	Nov 2019	6	Beyond MCR	
7	252818	Jan 2022	7	299603	April 2028
8	274126	Oct 2026	8	Beyond MCR	

Figure 2: Pickering RJ predictions in CNSC Presentation during the June 2018 Hearing [47]

Predicted EFPH and H[eq] of Pressure Tubes

Unit	EFPH, April 2018	EFPH, December 2024	Inlet Rolled Joint H[eq] in 2024, ppm	Outlet Rolled Joint H[eq] in 2024, ppm
1	136,927	192,000	35.8	84
4	110,082	167,500	34.3	64
5	231,895	287,500	48.5	97
6	236,952	295,000	47.9	90
7	230,856	287,000	48.1	91
8	218,765	274,000	47.9	86

EFPH - Effective Full Power Hours, H[eq] - equivalent hydrogen concentration

Figure 3: [H$_{eq}$] Predictions for all Units from CNSC staff Presentation in January 2018 Commission Meeting [48], [49]

Projected Heq Concentrations for Ontario PTs: Near-Inlet

Station		Projections	
		June 2018	Target Service-life
Pickering-B	EFPH	234,680	289,000
	Heq, ppm	38	55-60
Darlington Units 1, 3, 4	EFPH	192,790	234,000
	Heq, ppm	45	66
Bruce-A (Units 3, 4)	EFPH	215,035	255,000
	Heq, ppm	50	(unknown)
Bruce-B	EFPH	229,260	298,000
	Heq, ppm	40	70

Projected Heq Concentrations for Ontario PTs: Near-Outlet

Station		Projections	
		June 2018	Target Service-life
Pickering-B	EFPH	234,680	289,000
	Heq, ppm	55	82
Darlington Units 1, 3, 4	EFPH	192,790	234,000
	Heq, ppm	52	127
Bruce-A (Units 3, 4)	EFPH	215,035	255,000
	Heq, ppm	71	105
Bruce-B	EFPH	229,260	298,000
	Heq, ppm	90	160

In the latest Pickering Condition Assessment Report [50] plots regarding BoT and RJ predictions were provided. The BoT predictions were based on the 97.5[th] percentile of the BoT model, while the RJ values were based on the deterministic generic models. However, it is noted that no tables with projections were provided; just various plots were included.

Finally, Bruce Power has provided an advanced copy [51] of an upcoming submission with predictions for all Units and time-to-reach 120 ppm. These values, presented in Figure 4 below, are different than those presented by Bruce Power during the relicensing hearing, as given in Figure 1 above. What becomes pertinent, is the change by ~ 20 kEFPH. This is a significant difference and can substantially affect overall licensing decisions.

To conclude, it has become apparent that $[H_{eq}]$ predictions to EoL are important since they are directly related to the 120 ppm limit for fracture toughness. At the same time, differences between probabilistic and deterministic methodologies, some of which are presented herein and in, and continuous updates and challenges to the models, create difficulties for CNSC staff to have a clear understanding of $[H_{eq}]$ predictions to EoL.

Figure 4: Updated Bruce Power Time Predictions for 120 ppm from. [51]

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Unit	Channel	Zone	Max [H]initial	Time to reach 120 ppm (HH)[2]	Time to reach 120 ppm (kEFPH)	Time to reach 120 ppm (date)
1	B1J19	IZ	4.6	>302,220	>256	> Feb 2046
1	B1A11	OZ	5.0	>302,220	>256	> Feb 2046
2	Note 1	IZ	5.0	>302,220	>257	> Mar 2046
2	Note 1	OZ	5.0	>302,220	>257	> Mar 2046
3	B3H06	IZ	15.0	>302,220	>257	> MCR in 2023
3	B3X09	OZ	13.0	>302,220	>257	> MCR in 2023
4	B4E07	IZ	13.0	>359,160	>308	> MCR in 2025
4	B4D21	OZ	16.5	328,270	281.7	> MCR in 2025
5	B5F11	IZ	14.8	304,519	274.8	Sept 2023
5	B5A16	OZ	14.2	328,317	296.3	> MCR in 2026
6	B6P09	IZ	18.3	294,687	264.2	> MCR in 2020
6	B6A17	OZ	17.3	316,806	284.1	> MCR in 2020
7	B7M14	IZ	15.0	303,945	272.0	Jul 2024
7	B7P23	OZ	18.9	310,841	278.2	Apr 2025
8	B8E18	IZ	17.8	336,280	298.3	Mar 2030
8	B8P11	IZ-TG3	9.0	309,937	275.0	Jan 2027
8	B8E04	OZ	15.7	335,422	297.6	Feb 2030

Note 1: More than one channel has the same maximum value of 5 ppm [H]initial.
Note 2: For Units 1 through 3 the [Heq] predictions were generated for up to 302,220 HH and for Units 4 through 8 the H[eq] predictions were generated for up to 359,160 HH

(New Issue) Topic 18: Challenges with BoT Models

A big part of the focus to the 2016 Workshop, together with subsequent communication with the licensees, was the RJ [Heq] predictions and pertinent models. However, predictions at the BoT are also of importance. First, BoT ingress is an input to RJDIM 2.0 to calculate the overall projections at the RJ area. Second, BoT predictions are needed for several assessments related to flaws and PT-CT contact. Actually, the calculations of reaching BFT[7] in various PT locations are solely based on the BoT [Heq] predictions and their pertinent models. In addition, the frequency-based results of probabilistic contact and blister susceptibility assessments are very sensitive to the BoT models. It is worth noting that the Industry is also concerned regarding the long-term projections and applicability of the BoT models. Indeed, in COG work package #10363 it is stated that "*There is little technical basis supporting the current models, which can be problematic for long-term predictions*" [52]. The reason is that licensees' current BoT models are based purely on statistical fits. As a result, frequent model revisions take place and are attributed to poor model fitting of new inspection data for some Stations. A typical example, which will be further elaborated below, is the BoT model of Bruce Units 5-7. Since 2014, there

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[7] BFT: Blister Formation Threshold

have been two additional updates to the model, in 2017 [53] and, then, in 2018 [54]. It is noted that every time a model is updated, the licensee is performing impact assessments on various evaluations, in accordance with their compliance plan [55]. For instance, the impact of the 2018 Bruce Power Units 5-7 model [54] has been a key issue during the Unit 6 component disposition of PT-CT contact[56].

Based on staff review of the above noted models, some key findings are as follows:

- BoT models in Darlington and Bruce Power Stations are challenged by new inspection data more frequently, even as soon as the first outage after the model was created. An example, is the 2018 Bruce Power Units 5-7 [54] version which was a consequence of Unit 6 2017 B1761 [14] scrape campaign and the issue of heteroscedasticity detailed below.

- Lack of consistency in model forms and inputs as not all model forms account for relevant material properties or flux, and flux terms vary between models. For instance, some models account for irradiation effects with a ϕHH or $\phi \ln(HH)$ terms, while other models don't have any irradiation predictor.

- Residual heteroscedasticity has been shown to lead to under-estimating the variability for some axial locations and units, reducing the predicted [D]. This can potentially reduce the conservatism for some FFS assessments, particularly at the EoL. For instance, the 2018 Bruce Power Units 5-7 model [54] was partly updated in order to reduce heteroscedasticity near the 1.5 m location. As a result, upper bound predictions for the pickled outer zone tubes in locations 1-4 m are increased compared to the 2017 version of model [53].

Overall, updates to the models can have profound effects on the $[H_{eq}]$ predictions and, in turn, on various FFS assessments. For instance, the difference in the UB of the 2018 and 2017 Bruce Power Units 5-7 model is provided in Figure 5 below and taken from [54]. Without an overall and consistent approach to modelling BoT [D] data, including elements of mechanistic understanding, $[H_{eq}]$ long-term predictions at the BoT are challenged, with potential ramifications for EoL projections and pertinent FFS assessments. Although new COG R&D programs for understanding and inclusion of mechanistic effects is welcome [52], it has been introduced late in the operation of many Units. Consequently, the development of new models capable to provide confidence for the long-term predictions and overall operation of the pressure tubes is of great interest to the CNSC.

(New Issue) Topic 19: Ramifications of Newly Published Peer-Reviewed Articles

Two peer-reviewed articles were published in 2018 by Canadian experts in pressure tube material, which challenge the established theory of Terminal Solid Solubility (TSS) [57] and Diffusivity [58]. The findings in these articles could have ramifications for the overall operation of the plants. .

Figure 5: Difference in UB Predictions between the 2018 and 2017 Bruce Power Units 5-7 Models [54]
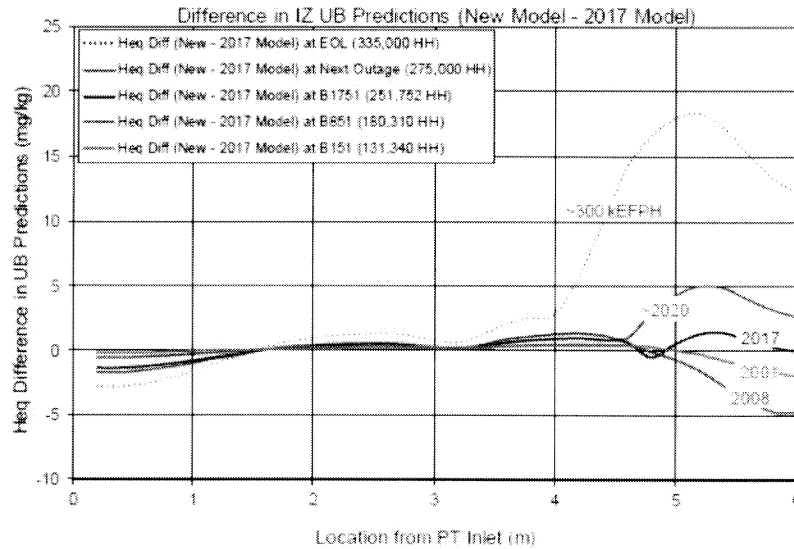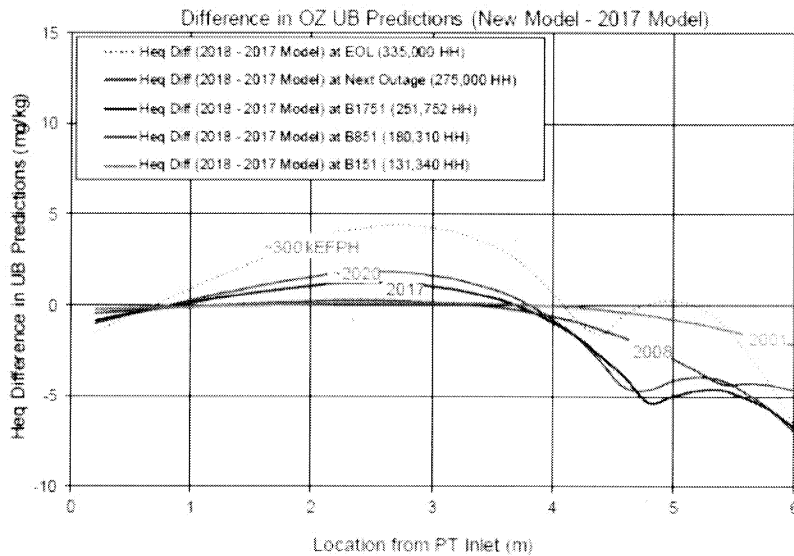

Comparison of the Upper Bound (97.5[th] percentile) Predictions of the 2018 5-7 Model and the 2017 Bruce 5-7 Model for IZ with Hot Hour

Overall Conclusion

While the Industry has progressed in several areas of [H$_{eq}$] measurements and predictions methodologies, several challenges still remain. For instance, the issue of denuded zones and

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representative scrape sampling has not been resolved, despite on-going efforts. This is potentially one of the biggest issues currently faced by the Industry. Scrapes provide the vast majority of data that are utilised for the construction of models that are, in turn, used to provide both short-term and long-term predictions for all FFS assessments. When inspection data techniques are challenged, that can have ramifications in the overall methodologies and eventually in the long-term operation of pressure tubes.

Challenges also exist in the modelling efforts for both BoT and RJ areas. BoT models, which are purely statistical in nature, suffer from frequent updates due to overall lack of mechanistic understanding and inadequate prediction capabilities of updated inspection data. At the same time, the code used for predictions in the RJ area (RJDIM 2.0) also suffers from lack of mechanistic understanding of several processes, despite its semi-mechanistic nature. As a result, either some issues are not modelled in their entirety (e.g. circumferential ingress gradients, stress gradients, protium elevation at outboard locations) or attempted to be modelled via inadequate fitting exercises (e.g. TSSd and diffusivity scaling) without appropriate technical justifications. In addition, the use of probabilistic methods for $[H_{eq}]$ predictions cannot solve the aforementioned issues. If the uncertainties are unknown and cannot be quantified appropriately, no probabilistic approach can provide trusted results.

Potentially unexplored mechanisms, such as ingress acceleration when TSSd and TSSp are reached during operation, or compressive properties being affected by elevated $[H_{eq}]$ values, impose additional difficulties that can have direct ramifications for the predictions to EoL.

As $[H_{eq}]$ EoL predictions are paramount for fracture toughness and overall operation, licensees should be more transparent with the methodology employed to derive those predictions. The LCH for both OPG and Bruce Power provide recommendations for the pertinent models. It is important that all licensees submit, for acceptance, the methodology that will be employed for those predictions.

To conclude, CNSC staff have two overarching concerns: First, acquisition of high quality inspection data that can be trusted to provide the required database for the development of the models, and second, improving the existing models that are currently used for long-term projections.

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