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Commission canadienne de sûreté nucléaire

CMD 23-H103.4

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Written submission from Frank Greening

Mémoire de Frank Greening

In the Matter of

À l'égard de

Bruce Power Inc.
Bruce Nuclear Generating Stations A and B

Bruce Power Inc.
Centrales nucléaires de Bruce-A et B

Application to amend the power reactor operating licence for the Bruce Nuclear Generating Stations (NGS) A and B

Demande visant à modifier son permis d'exploitation d'un réacteur de puissance pour les centrales nucléaires de Bruce-A et B

Hearing in writing based on written submissions

Audience par écrit fondée sur des mémoires

April 2023

Avril 2023

Canada

On February 1st, 2023, under control document Ref. 2023-H-103, we have the following announcement by the CNSC:

> *The CNSC is to conduct a Hearing in Writing on application from Bruce Power Inc. to amend the power reactor operating licence for Bruce Nuclear Generating Stations A and B to reflect recent Commission decisions. The CNSC will conduct a hearing based on written submissions to consider an application from Bruce Power Inc. (Bruce Power) to amend the power reactor operating licence for the Bruce Nuclear Generating Stations (NGS) A and B.*
>
> *The proposed amendment is as follows: to remove licence condition 15.3, Pressure Tube Fracture Toughness, and to include all fitness-for-service requirements applicable to pressure tubes under licence condition 6.1, Fitness for Service.*

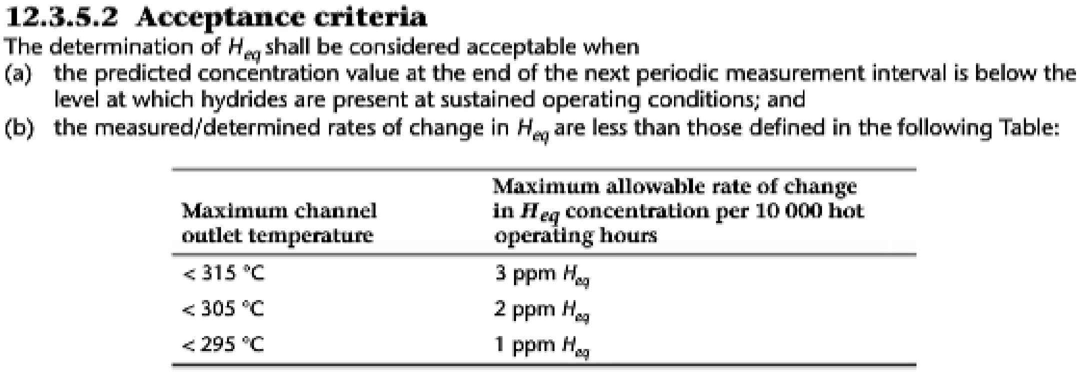
The events leading up to this Hearing in Writing are as follows. On July 5, 2021, Bruce Power reported that measurements obtained from a Unit 6 pressure tube after 271,729 hot hours of operation showed Hydrogen Equivalent Concentrations ([H_{eq}]) above the generic predictions and exceeding the Licence Condition 15.3 [H_{eq}] limit of 120 parts per million (ppm – by weight). Bruce Power reported that pressure tube B6S13 has a [H_{eq}] of 211 ppm at the burnish mark and 212 ppm at the burnish mark plus 10 mm. Also, on July 8, 2021, Bruce Power reported that measurements obtained from a Unit 3 pressure tube showed [H_{eq}] above the generic predictions and above the Licence Condition 15.3 [H_{eq}] limit of 120 ppm. For the Unit 3 pressure tube B3F16, Bruce Power indicated a preliminary measurement of 131 ppm [H_{eq}].

Additionally, on March 24th 2022, Bruce Power issued the Event Initial Report CMD 22-M16 stating:

> *Following the July 2021 discovery of elevated Heq near the outlet rolled joint, Bruce Power performed additional surveillance testing on the removed PT B6S13 and discovered that elevated Heq also exists near the inlet end of the PT. The reported Heq level from a through-wall punch sample was 126 ppm at approximately 10 mm in board of the burnish mark.*
>
> *Bruce Power does not have a mechanistic understanding of the phenomenon nor validated models as a result of this finding. In other words, their Heq model is invalid because the outputs of the Heq models do not align with the B6S13 measurement of 126 ppm at the inlet end of the PT. These Heq outputs are used as inputs into Fitness for Service Assessments such as leak-before-break (LBB) and fracture protection (FP) assessments. The uncertainty of the Heq inputs impact the LBB and FP assessments. CNSC staff are of the opinion that Bruce Power cannot confidently perform these assessments until the Heq phenomenon is understood and modelled.*

The licence condition for Bruce A & B with respect to pressure tube fitness for service has always been based on two CSA Standards as follows:

CSA Standard N285.4:



12.3.5.2 Acceptance criteria

The determination of H_{eq} shall be considered acceptable when

(a) the predicted concentration value at the end of the next periodic measurement interval is below the level at which hydrides are present at sustained operating conditions; and

(b) the measured/determined rates of change in H_{eq} are less than those defined in the following Table:

Maximum channel outlet temperature	Maximum allowable rate of change in H_{eq} concentration per 10 000 hot operating hours
< 315 °C	3 ppm H_{eq}
< 305 °C	2 ppm H_{eq}
< 295 °C	1 ppm H_{eq}

CSA Standard N285.8:

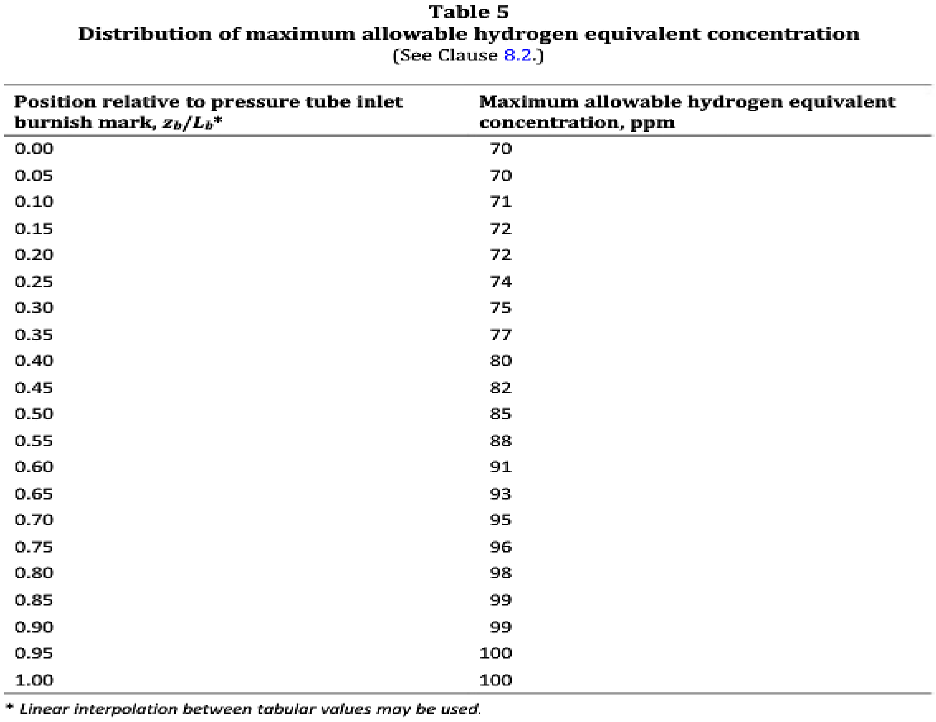


Table 5
Distribution of maximum allowable hydrogen equivalent concentration
(See Clause 8.2.)

Position relative to pressure tube inlet burnish mark, z_b/L_b*	Maximum allowable hydrogen equivalent concentration, ppm
0.00	70
0.05	70
0.10	71
0.15	72
0.20	72
0.25	74
0.30	75
0.35	77
0.40	80
0.45	82
0.50	85
0.55	88
0.60	91
0.65	93
0.70	95
0.75	96
0.80	98
0.85	99
0.90	99
0.95	100
1.00	100

* *Linear interpolation between tabular values may be used.*

The three fuel channel temperatures listed in Clause 12.3.5.2 of CSA N285.4, shown above, – namely, 315 °C, 305 °C, and 295 °C – correspond to the conditions for Darlington, Bruce and Pickering NGS fuel channel outlets, respectively. Thus, we see that CSA N285.4 sets the maximum allowable rate of increase in H_{eq} per 10,000 hot hours, ($\Delta H_{eq}/10^4$ HH), to be 3 ppm, 2 ppm and 1 ppm, for Darlington, Bruce and Pickering respectively.

In order to investigate if Bruce Power is in non-compliance with the CSA N285.4 Standard, I have reviewed the available data for Heq in Bruce B pressure tubes since the start of their commercial operations in the mid-1980s. The results of this review, and in particular estimates of $\Delta H_{eq}/10^4$ HH as a function of the hot hours of exposure of the pressure tubes, are summarized in Table 1, below.

Table 1: Average $\Delta H_{eq}/10^4$ HH (in ppm) for Bruce Units 5 - 8

Bruce B Units 5 - 8 Average Hot Hours	$\Delta H_{eq}/10^4$ HH (ppm)
50,000	0.4
100,000	1.0
150,000	2.0
200,000	3.4
250,000	4.9
300,000	6.5 [1]

Ref 1 = Extrapolated Value

The data in Table 1 show two important trends:

(i) After approximately 150,000 hot hours of exposure the $\Delta H_{eq}/10^4$ HH values are consistently *above* the Bruce B limit of 2 ppm per 10,000 hot hours

(ii) The *rate* of hydrogen pickup steadily *increases* as the hot hours of exposure increase

CSA Standard N285.8 has recently, (2019), been revised to an Heq of 80 ppm at a pressure tube's inlet and 120 ppm Heq at its outlet. Nevertheless, it is clear that the July 2021 high Heq concentrations measured at the inlet, (126 ppm), and the outlet, (212 ppm), of the B6S13 pressure tube place Bruce Power in violation of the requirements of the revised CSA Standard N285.8.

Thus, we see that Bruce Power is in non-compliance with regard to both the CSA N285.4 and the CSA N285.8 Standards. However, as noted above, the fact that the *rate* of hydrogen pickup is not only well *above* the 2 ppm per 10,000 hot hours licence limit, but is steadily *increasing*, is worrisome and needs to be explained. An important clue as to *why* $\Delta H_{eq}/10^4$ HH is increasing may be found in data on the oxidation kinetics of Bruce pressure tubes derived from a C-13 oxide dating technique I developed in the 1990s. This technique is based on SIMS (Secondary Ion Mass Spectrometry) depth-profiling, as described in the following references:

1. *The Detection and Interpretation of Carbon-13 Isotope Effects in the Oxide Scales of Irradiated Zr-2.5 wt% Nb Pressure Tubes.* OHRD Report 91-93-P, (June 1991).

2. *Post Irradiation Investigations of Corrosion and Deuterium Pickup by Zr-2.5 wt% Nb Alloy Pressure Tubes: Isotope Tracers in Inside Oxides.* OHT Report A-NFC-96-200-P, (December 1996).

The formation of radiogenic C-13 by the O-16(n,α)C-13 nuclear reaction allows a pressure tube's oxidation rate to be determined. C-13 SIMS data are available for a number of Bruce A and Bruce B pressure tubes, as in the examples shown in Figures 1a and 1b, below:

Figure 1a: Pressure Tube B3U11

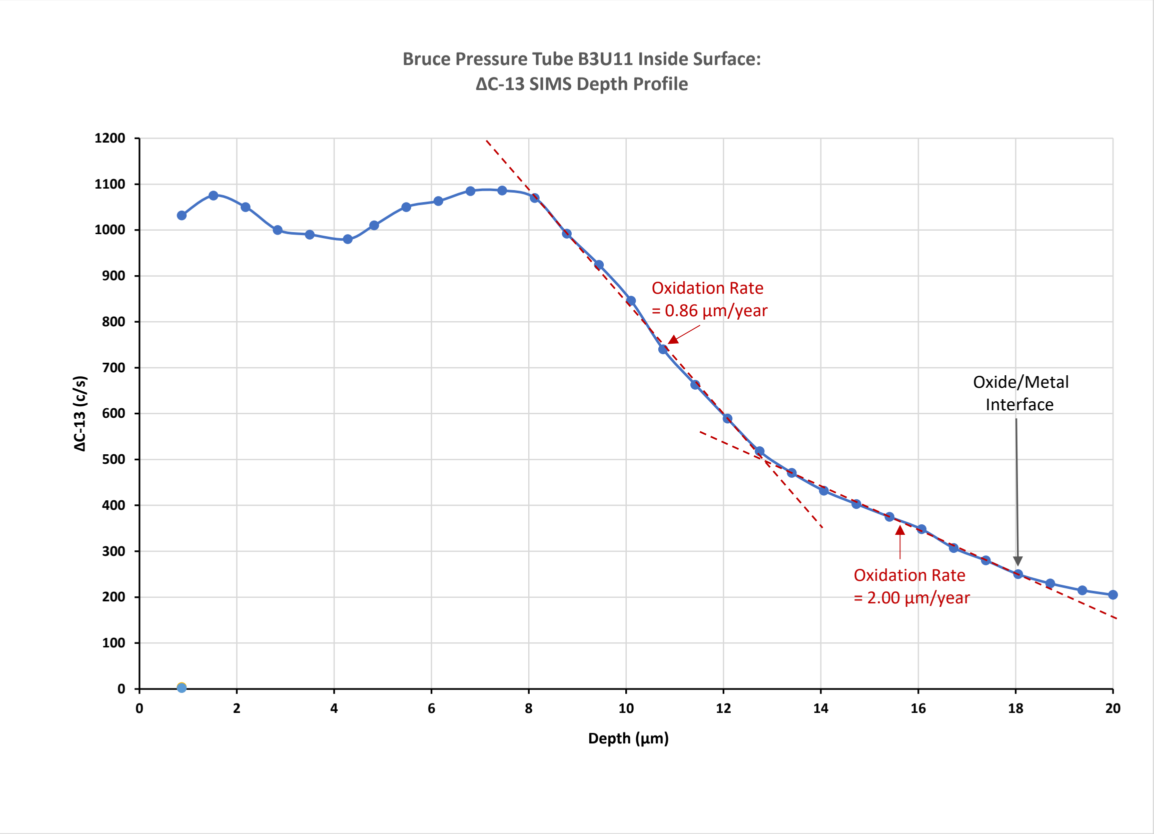
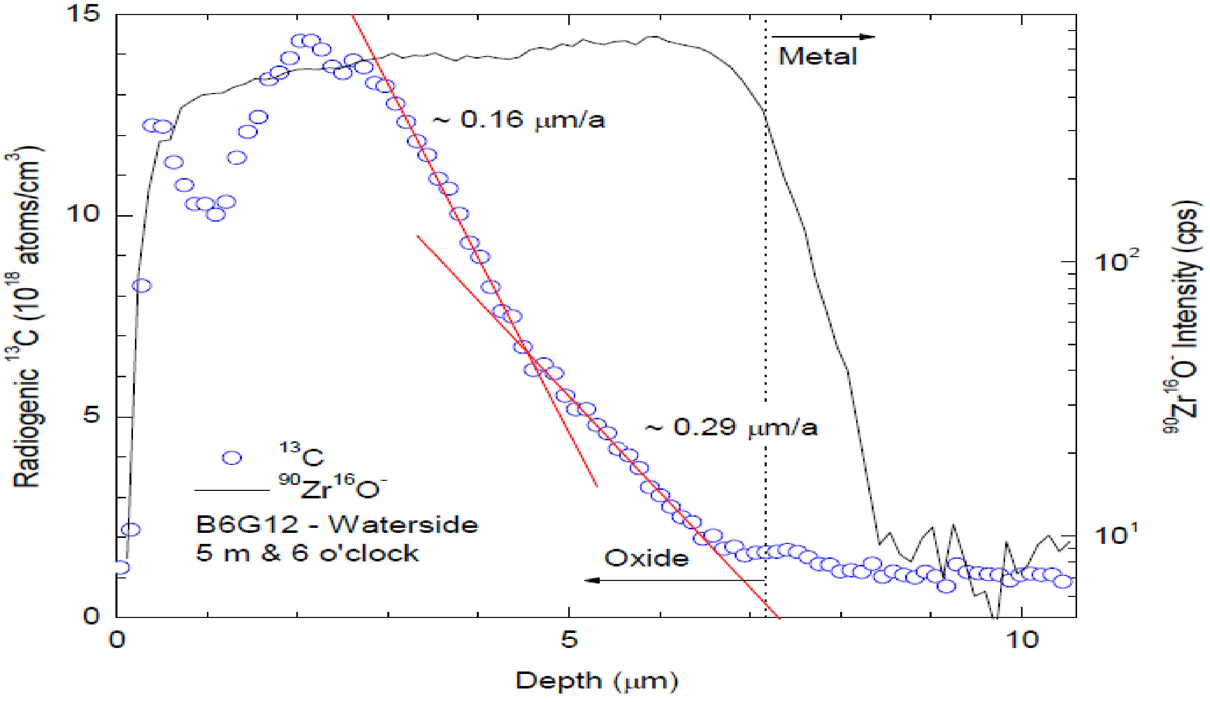


Figure 1b: Pressure Tube B6G12



The C-13 plots in Figures 1a and 1b exhibit the following features for the B3U11 and the B6G12 pressure tubes:

(i) The B3U11 tube's ID oxide is 20 µm thick, compared to only a 7 µm thick oxide for the B6G12 tube

(ii) An approximate doubling of the pressure tubes oxidation rate is observed after about 13 µm of growth for the B3U11 tube, compared to a similar doubling for the B6G12 tube, but after only about 5 µm of growth

These observations show that there is a great deal of variability in the oxidation rate of the inside surfaces of Bruce pressure tubes. However, these data also show that there is a tendency for the oxidation rate to increase at higher hot hours of exposure, and this occurs *regardless of the initial rate of oxide growth*. This acceleration in the rate of oxidation of pressure tubes is very significant because it has implications for the associated rate of H/D pickup by these tubes. This is because zirconium alloy pressure tubes pick up deuterium during zirconium corrosion in D_2O through the following two-step processes:

$$Zr + 2D_2O \;=\; ZrO_2 + 2D_2 \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$Zr + x/2\; D_2 \;=\; ZrD_x \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

It may be shown that the deuterium concentration for 100 % pickup by formation of 1 µm oxide is 14.3 ppm. However, measurements of pressure tube oxide thicknesses together with the associated deuterium concentrations generally show pickups in the range 5 - 15 % of the theoretical maximum.

A predictive model, referred to as the *Design Equation*, for corrosion and deuterium ingress by Zr-2.5Nb pressure tubes, was first developed by AECL in the late 1990s – see for example the 1996 COG Report No. COG-95-596/RC-1551. Specifically for Bruce tubes, the *Design Equation* predicts accelerating oxidation kinetics and accelerating deuterium pick up for exposures of more than about 150,000 hot hours. Hence, it is important to note that the acceleration of H/D pickup by aging pressure tubes was predicted by the Canadian nuclear industry more than 25 years ago. And, the fact that accelerated corrosion and H/D pickup have been a constant feature of CANDU pressure tube aging is confirmed in an article published by Chalk River Nuclear Laboratories – See CNL Nuclear Review Vol 5 (1), June 2016:

> *Along the main body of a pressure tube the deuterium concentration increases and peaks near the outlet end. Approximately 2% - 10% of the deuterium generated by the corrosion process is absorbed. In general, the deuterium concentration in the main body of the pressure tube increases with time. At the 1.5 m axial location the increase is approximately linear with time, whereas at the 4 m and 5 m axial locations the uptake rate is increasing with time.*

My emphasis in red

Nevertheless, it is of interest to see if this view of H/D pickup is currently also held by Bruce Power, especially in light of the discovery of very high Heq in some of its pressure tubes. In the months following the July 2021 reporting of high Heq concentrations in two Bruce pressure tubes, there have been several CNSC Meetings/Hearings to discuss these findings. At the Public Meeting held on September 3rd 2021, Bruce Power was asked by CNSC Commissioner Lacroix for its interpretation of the high [H_{eq}] observed in some of its operating pressure tubes, to which Bruce Power replied:

> "*We're not seeing a change in the rate of hydrogen uptake. What we're seeing is a redistribution (of the hydrogen) to the cooler region at the top of the pressure tube. So, it's not an acceleration but a redistribution*".

Based on the data presented in the first part of this intervention, the fact that Bruce Power still believes the high Heq data reported for some of its pressure tube is *<u>no</u>*t due to accelerated pickup, but is due to a *redistribution* of ingressed deuterium, is fraught with difficulties. And, it is important to note that Bruce Power provides no evidence or proof for its belief that there is no acceleration in H/D pickup by its pressure tubes. It is simply stated as a fact, when it is nothing more than a plausible hypothesis – *and a plausible hypothesis <u>is not necessarily true</u>*.

However, there are plenty of other reasons, including real physical evidence, to accept as a well-established fact that accelerated H/D pickup *<u>is</u>* occurring in Bruce pressure tubes, and has been for some time. For example, please consider:

(i) The data reported for ΔHeq previously shown in Table 1 of this intervention

(ii) A major problem with Bruce Power's redistribution hypothesis may be seen by eliminating the effects of diffusion and calculating the actual amount of H/D entering the B6S13 pressure tube. Thus, using data from Table 2, found in OPG's September 3rd 2021 *Written Submission* to the CNSC, CMD 21-M37.2, we may calculate an *average* concentration of H/D at a distance x from a pressure tube's inlet using the H/D concentrations measured at the 6 and 12 o'clock locations as follows:

$$[C_{Av}(x)] = \{[C_6(x)] + [C_{12}(x)]\}/2$$

Then, for B6S13, the average H/D concentration near its outlet burnish mark, [$C_{Av}(BM)$], is equal to (211 + 59)/2 or 135 ppm, *which is significantly above the CSA N285.8 limit of 120 ppm*. From this result I conclude that the postulated redistribution of H/D is unable to explain how or why the *<u>average</u>* circumferential [Heq] at the burnish mark of tube B6S13 is in excess of the CSA N285.8 limit.

At this point I would say that Bruce Power *must* accept that accelerated H/D pickup is occurring for the B6S13 and B3F16 pressure tubes. However, when Bruce Power states that: "*We're not seeing a change in the rate of hydrogen uptake. What we're seeing is a redistribution (of the hydrogen) to the cooler region at the top of the pressure tube. So, it's not an acceleration but a redistribution*." One needs to ask: What is the relevance of this statement? Because it has no bearing on the fact that Bruce Power was non-compliant with CSA N285.8. following the July

5th, 2021, discovery of elevated Heq concentrations in Unit 6 pressure tubes. Indeed, in a letter from Bruce Power to the CNSC dated July 15th, 2021, – See CNSC document CMD 21-M37.1 – we read, (with my emphasis in red):

> Bruce B Power Reactor Operating Licence, (PROL 18.01/2028), Conditions 6.1 and 15.3, require that Bruce Power, "*…implement and maintain a fitness-for-service program*" and that "***before*** *hydrogen equivalent concentrations exceed 120 ppm,* [Bruce Power] *shall demonstrate that pressure tube fracture toughness will be sufficient for safe operation beyond 120 ppm.*"

However, *nowhere* in Bruce B's current PROL, (18.01/2028), or in CSA Standard N285.8 is there a stipulation that exceedances of a Unit's 120 ppm Heq limit are permissible *if they are due to a redistribution of ingressed H/D*. So, again, I must ask why Bruce Power would believe that "*the redistribution of hydrogen*" is an acceptable excuse for a clear licence non-compliance?

Discussion:

In this intervention I have presented a brief history of events and actions following the discovery of high Heq concentrations in several Bruce pressure tubes in July 2021. And I have shown that, as a consequence of these high Heq measurements, Bruce Power is in non-compliance with regard to both the CSA N285.4 and CSA N285.8 Standards. This situation is, as it should be, of great concern to the CNSC because, as noted in the Event Initial Report CMD 22-M16:

> *Bruce Power does not have a mechanistic understanding of the phenomenon nor validated models as a result of this finding. In other words, their Heq model is invalid because the outputs of the Heq models do not align with the B6S13 measurement of 126 ppm at the inlet end of the PT. These Heq outputs are used as inputs into Fitness for Service Assessments such as leak-before-break (LBB) and fracture protection (FP) assessments. The uncertainty of the Heq inputs impact the LBB and FP assessments. CNSC staff are of the opinion that Bruce Power cannot confidently perform these assessments until the Heq phenomenon is understood and modelled.*

Unfortunately, OPG and Bruce Power are, by their own admission, unable to provide a new and improved model of hydrogen pickup by Zr-2.5%Nb pressure tubes, but acknowledge that the research required to validate a new fracture toughness model of pressure tube aging is "a work in progress" that will not be completed for years to come. And when I say "a work in progress," the record shows that problems stemming from discrepancies between Heq predictions and Heq measurements may be traced back many years, as shown by the examples below.

1. In 2013, the CNSC asked OPG to establish a fracture toughness model "of upper transition and lower shelf behavior" for Heq > 100 ppm. And in July 2014 the CNSC issued a Bid Solicitation for the provision of a "R565.1 Report" on the fracture toughness properties of Zr-2.5Nb pressure tube material with high hydrogen concentration. The contract was for $120,000 over two years and was awarded to Areva Canada in December 2014. The contract included the following description of the research project:

Determine parameters describing the fracture toughness of pressure tube material with high hydrogen concentrations. Develop a methodology or a model to predict fracture toughness of pressure tube material with elevated hydrogen concentrations (50 ppm and 120 ppm [H]eq). Validate the predictions against experimental results derived from a parallel experimental program commissioned by the CNSC.

2. In June 2015, OPG provided the following "update" on this issue:

Based on R&D work, ... a new fracture toughness model has been developed and is being integrated into the 2015 edition of CSA N285.8 Standard and will become part of the Licence Condition Handbook for Darlington.

However, in Darlington's 2016 Licence Condition Handbook, we read:

CNSC staff accepted (e-Doc 4272552 and 4369355) OPG's approach (e-Doc 4250561) to fitness for service assessment, regarding the application of new fracture toughness models and probabilistic Leak-Before-Break (LBB) assessments for pressure tubes at increased hydrogen content. OPG has planned continuing research & development to further validate and improve the fracture toughness models (e-Doc 4405852).

*In the probabilistic core assessments for flaw, Leak-Before-Break and Pressure Tube to Calandria Tube contact, OPG should provide a comparison of the derived 95 % upper bound PT failure frequency with the criterion identified in "Table C.1 of CSA N285.8-15" and "Table 3 of COG-JP-4363-V078-R02". CNSC staff will compare the 95% upper bound of the calculated PT failure frequency with Table 3 of COG-JP-4363-V078 R02, **until such time** as the CSA N285.8 committee completes its review of the application of Table C. l of the CSA N285.8-15.*

My emphasis in red

3. In August 2021, we have OPG's Progress Report to the CNSC on the status of its new fracture toughness model:

[Heq] MODELLING ENHANCEMENTS

*[Heq] modelling enhancements including use of 3D Finite Element Analysis considering fuel channel geometries, local temperatures, location-specific [Heq], and material stress states are being pursued. Note that these proactive enhancements were already in progress prior to the B3 and B6S13 findings. OPG, with industry alignment, intends to submit modelling enhancements for CNSC acceptance **once fully validated**.*

My emphasis in red

4. In an email from the CNSC I received on January 10th, 2023 we read:

The External Advisory Committee (EAC) will consider all of the relevant information that has been gathered to date, including your written intervention CMD-M37.4 and other submissions. The EAC's report, and the Commission's consideration of that report, will be *transparent and public, in accordance with the Commission's commitment to transparency.* ***We expect the EAC report to be submitted in Spring or early Summer 2023***.

High Heq concentrations, well in excess of Bruce Power's operating license limits, were first seen in Bruce Unit 6 pressure tubes in July 2021. By way of dealing with this problem the CNSC ordered Bruce Power to conduct a detailed assessment of the safe continued operability of Bruce Units 1, 2, 4, 5, 7 and 8. Bruce Power was also told, given the discrepancy between the current fracture toughness model predictions and inspection results for Units 3 and 6, to assess whether operation of these Units remains within the licensing basis. At the same time, the CNSC stressed the need for Bruce Power to carry out a **root cause analysis** to determine if the measured elevated hydrogen concentration was caused by a new phenomenon specific to these Units and their pressure tubes.

At its September 3rd, 2021, meeting, the CNSC promised there would be: "*a follow-up public Commission meeting on this topic in late Winter 2021 or early Spring 2022*". However, by July 2022, one year after the discovery of high Heq in some Bruce pressure tubes, no public Commission meeting on high Heq issues had taken place. In fact, the promised meeting was eventually held in early November 2022, *one year and 4 months after the high Heq problem was first recognized*. Now, this delay might be considered acceptable, if the November 2022 meeting did in fact provide a root cause analysis of the high Heq concentrations, but, regrettably, this was not the case.

As noted above, the CNSC stated in a January 10th, 2023, email: "*We expect the EAC report to be submitted in Spring or early Summer 2023*"; with such a timeline, the EAC's report would be issued *a full two years on from the first observation of high Heq at Bruce*. This leads me to conclude that the CNSC is in no hurry to find a root cause of the high Heq problem, but is apparently quite content to let CANDU reactors operate with deuterium ingress rates running well above the predictions of existing [Heq] models.

Interestingly, it appears that the Canadian nuclear industry is like-minded in this regard, which may be seen in the timeline proposed to develop a new and improved [Heq] model, as first reported at an industry workshop on elevated hydrogen equivalent ([H]eq) concentration held on March 25th, 2022. In an account of this meeting, published by Bruce Power in July 2022, we find Attachment B which provides "*a path forward with a target schedule and summary of key deliverables to improve hydrogen equivalent concentration predictions in the inlet/outlet rolled joint regions of pressure tubes*". Action Item 5G in Attachment B, described as "The Development of a Comprehensive [Heq] Model", gives the target date for the completion and issuance of a "comprehensive [Heq] Model" as **the 2nd Quarter of 2026**.

This target date means that the Canadian nuclear industry would have taken ***5 years*** to develop a new and improved [Heq] model as a response to the discovery of high Heq concentrations in some Bruce tubes in July 2021. However, it is important to note that the CNSC issued a bid solicitation document, No. 87055-18-0098, in November 2018 for an independent contractor to:

> "*Predict the fracture toughness of pressure tubes with elevated hydrogen concentrations (40 ppm to 160 ppm [H]eq), and validate the modelling predictions against the experimental results provided by CNSC staff*".

And what is most significant about this *Request for Proposal* document is that the CNSC stipulated that the requested work must be completed within ***fifteen months*** of the awarding of the contract, with a final report issued by March 2020.

5. The real situation with regard to the quest for a new and improved fracture toughness model for CANDU pressure tubes is well illustrated by the current status of one of the Standards on which the model is based – namely CSA N285.8. Thus, as described in clause C.5 of the latest update of CSA N285.8, we read, (with my emphasis in red italics):

C.5 Determination of statistically significant changes in pressure tube properties

C.5.1 General

Clause C.5 describes the method for determining whether statistical evidence exists signifying a change in pressure tube material property information.

C.5.2 Evaluation of hydrogen equivalent concentration

This evaluation procedure is under development. The evaluation procedure shall be justified and may be used provided that the procedure has been accepted by the regulatory authority.

C.5.3 Evaluation of fracture toughness

This evaluation procedure is under development. The evaluation procedure shall be justified and may be used provided that the procedure has been accepted by the regulatory authority.

C.5.4 Evaluation of DHC growth rate

This evaluation procedure is under development. The evaluation procedure shall be justified and may be used provided that the procedure has been accepted by the regulatory authority.

C.5.5 Evaluation of threshold stress intensity factor for delayed hydride cracking

This evaluation procedure is under development. The evaluation procedure shall be justified and may be used provided that the procedure has been accepted by the regulatory authority.

Clearly, these five clauses show that the key determinants of CSA Standard N285.8 are all "*under development*," and evidence already presented in this intervention suggests that this uncertainty in one of the key Standards governing the fitness for service of pressure tubes *will remain unresolved for years to come*.

Nevertheless, the CNSC claims that it provides "*Comprehensive and Effective Regulatory Oversight of pressure tube degradation mechanisms*." And, according to a CNSC presentation from a January 2018 Commission Meeting, this is achieved by setting goals and guidelines for reactor operators which include:

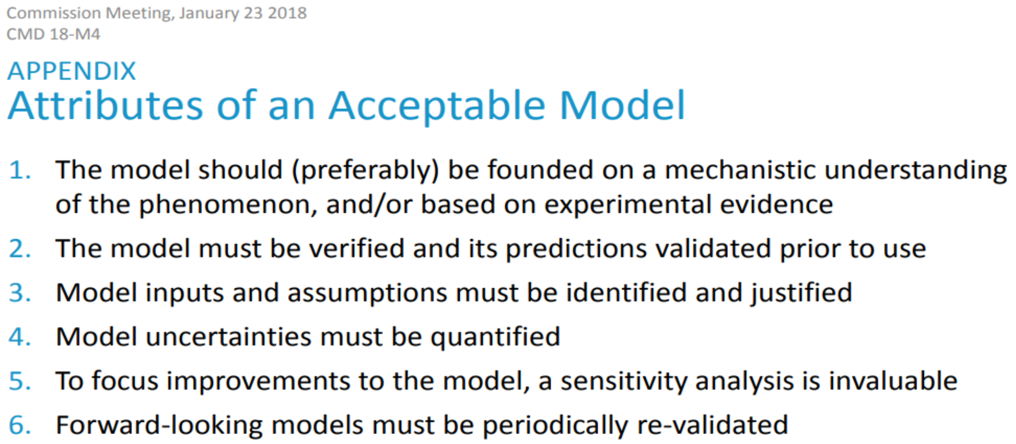
(i) Clear and well-documented expectations and Licence Compliance Plans through REGDOC-2.6.3 and CSA Standard N285.8

(ii) Effective Compliance Verification Criteria as presented in the Licence Condition Handbooks for a particular NGS

(iii) Licensees must have an in-depth understanding of pressure tube degradation phenomena

The Compliance Verification Criteria for Bruce Units may be found in Section 15.3 of Licence Conditions Handbook, LCH-PR-18.01/2028-R002. Through this license condition, Bruce Power is required to submit to the CNSC a fracture toughness model for review and acceptance and no Bruce Unit is authorized to operate above the 120 ppm [Heq] limit set in Clause 8.2 of CSA Standard N285.8. In addition, through a fracture toughness model, Bruce Power must verify that measured Heq changes between inspection periods are bounded by Heq concentrations predicted by an acceptable model.

But what constitutes an acceptable model? This question has been addressed by the CNSC, as shown by the overhead presented below taken from a January 2018 Commission Meeting:



Commission Meeting, January 23 2018
CMD 18-M4

APPENDIX

Attributes of an Acceptable Model

1. The model should (preferably) be founded on a mechanistic understanding of the phenomenon, and/or based on experimental evidence
2. The model must be verified and its predictions validated prior to use
3. Model inputs and assumptions must be identified and justified
4. Model uncertainties must be quantified
5. To focus improvements to the model, a sensitivity analysis is invaluable
6. Forward-looking models must be periodically re-validated

Of the six attributes listed above, No. 2 – "*The model must be verified and its predictions validated prior to use*" – is perhaps the most important, but is also the most problematic. This is because the required predictive modeling involves making estimates of *future* pressure tube performance parameters, such as hydrogen pickup rates and fracture toughness values; however, because we are dealing with *future* expectations, it follows that appropriate experimental data are obviously not yet available from real-world pressure tubes. And since it is not possible to verify or validate a model without the requisite experimental data, one has to ask how *any* fracture toughness model could ever be "*verified and validated prior to use*".

An issue that further complicates the validation of fracture toughness models is the fact that the fracture toughness of a pressure tube depends on many factors, including the [Heq], temperature, neutron fluence, trace impurities, etc., of the tube in question This leads to a large variability in measured values of fracture toughness parameters such as a pressure tube's crack growth resistance, dJ/da, as shown in the Figure below:

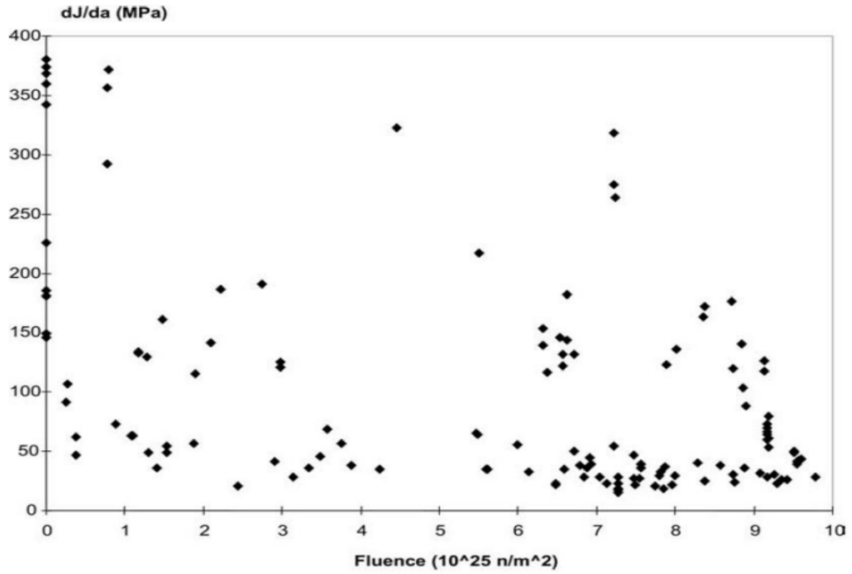


Figure 2.9: The fracture toughness of cold worked Zr-2.5Nb pressure tubes at 240-300 °C after service in a CANDU reactor showing large variability

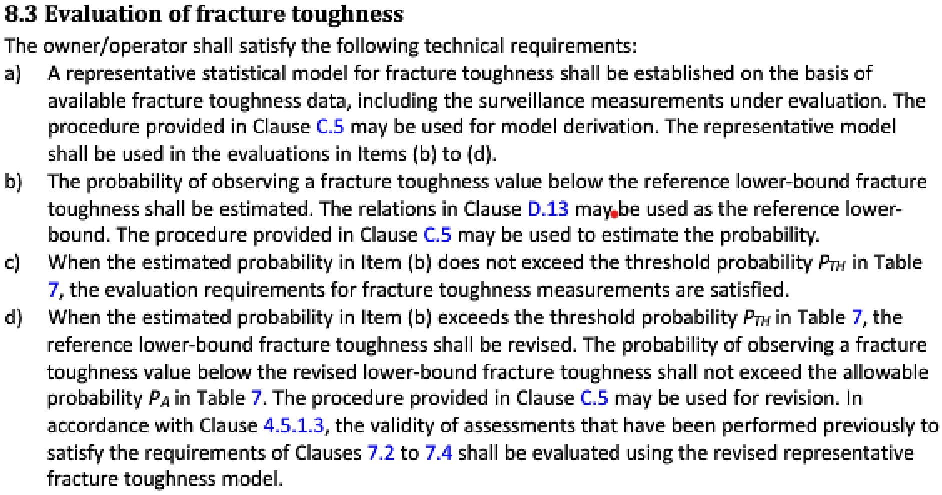
This extreme variability in a tube's fracture toughness – a variability that is also seen in many other pressure tube properties such as H/D pickup rates – means that predictive models themselves are inherently uncertain and can only offer upper bounds, for H/D pickups, or lower bounds, for fracture toughness parameters.

However, in addition to the model predictions provided annually by a reactor operator, the operator is also obligated to obtain scrape measurements during each planned outage to determine the level of [Heq] in sampled pressure tubes. These measurements serve as a means of comparison to model predictions and allow a reactor operator to determine if the validity limits of the fracture toughness model are satisfied. It follows that the predictions need only go as far as the next scheduled inspection – a time interval that is typically about 2 to 3 years.

Until the discovery of very high Heq concentrations in several Bruce pressure tubes in July 2021, the Canadian nuclear industry, and the CNSC, stated at many Public Hearings that Canadian reactors are operating in full compliance with the fracture toughness model described in CSA Standard N285.8-2015 Update 1, Clause D.13.2.3.1.2 (a). And such a claim was made by all parties concerned in spite of the fact, as shown above, that the required validation and verification of the 2015 fracture toughness model has *not* been accomplished. Of course, such an approach may appear to work as long as pressure tube corrosion and H/D uptake rates remain relatively constant. But this approach is doomed to failure if a tube is subject to the rapid onset of accelerated corrosion, which appears to be the case for Bruce pressure tubes B6S13 and B3F16.

Before completing this intervention, I wish to address an important issue that, (I believe), has been inadequately dealt with by our nuclear operators and regulators alike – namely the link between the concentrations of H/D in a pressure tube and the tube's fracture toughness.

The operational limits on a pressure tube's fracture toughness are specified in Clause 8.3 of CSA Standard N285.8-15 as shown below:



8.3 Evaluation of fracture toughness

The owner/operator shall satisfy the following technical requirements:

a) A representative statistical model for fracture toughness shall be established on the basis of available fracture toughness data, including the surveillance measurements under evaluation. The procedure provided in Clause C.5 may be used for model derivation. The representative model shall be used in the evaluations in Items (b) to (d).

b) The probability of observing a fracture toughness value below the reference lower-bound fracture toughness shall be estimated. The relations in Clause D.13 may be used as the reference lower-bound. The procedure provided in Clause C.5 may be used to estimate the probability.

c) When the estimated probability in Item (b) does not exceed the threshold probability P_{TH} in Table 7, the evaluation requirements for fracture toughness measurements are satisfied.

d) When the estimated probability in Item (b) exceeds the threshold probability P_{TH} in Table 7, the reference lower-bound fracture toughness shall be revised. The probability of observing a fracture toughness value below the revised lower-bound fracture toughness shall not exceed the allowable probability P_A in Table 7. The procedure provided in Clause C.5 may be used for revision. In accordance with Clause 4.5.1.3, the validity of assessments that have been performed previously to satisfy the requirements of Clauses 7.2 to 7.4 shall be evaluated using the revised representative fracture toughness model.

Here we see CSA Standard N285.8-15 imposing the license requirement that a reactor owner/operator shall establish a fracture toughness model "*on the basis of available fracture toughness data, including surveillance measurements under evaluation*." However, this apparently straightforward license requirement is actually quite complex and problematic because, as previously noted in this intervention, the fracture toughness of a pressure tube depends on a number of variables including the temperature, neutron fluence and Heq concentration, the effects of which need to be included in any meaningful evaluation.

Furthermore, in order to replicate a pressure tube's behavior as it approaches end-of-life, pressure tube data for samples with fast neutron fluences up to 2×10^{26} n/m^2, (E>1MeV), and Heq concentrations in excess of 100 mg/kg, are required. Unfortunately, the availability of such data for real-world pressure tube material is very limited.

CSA Standard N285.8-15 also includes a Table 7 which stipulates that a pressure tube's fracture toughness, K_c, should be evaluated "*on a case-by-case basis*". However, Table 7 also introduces the additional parameters V_a and V_r, the DHC axial and radial crack growth rates, respectively, and Clause 8.4 of CSA Standard N285.8 stipulates that the owner/operator shall establish a statistical model based on available delayed hydride cracking growth rate data. Table 7 sets limits on V_a and V_r in the form of threshold probabilities of observing a fracture toughness value below a reference lower-bound fracture toughness.

Interestingly, the methodology used to quantify DHC crack growth rates in CSA Standard N285.8 has varied considerably over time. Thus, for example, the 2005 model considers a Unit's operating temperature only, but the 2015 model also includes the neutron fluence – a parameter that depends on the axial position of a pressure tube. This means that the 2005 model assumes one DHC crack growth rate while, for the 2015 model, the DHC growth rate is different at the inlet and outlet locations. Furthermore, in the case of a probabilistic assessment, the 2005 fracture toughness model does not consider the known hydrogen concentration variations, while the 2015 fracture toughness model is segmented into different calculation regions according to the pressure tube's hydrogen content and temperature range. Thus, it is not surprising the 2005 and 2015 models give different answers to the same question.

CSA Standard N285.8 also runs into problems with regard to the methodology it recommends for a so-called Leak Before Break, (LBB), analysis. An LBB analysis is intended to evaluate the response of an annulus gas system to a leak, and specifies the required operator actions in the event of a pressure tube through-wall crack.

The concept of leak-before-break, (LBB), is an operational requirement that, in the event of a pressure tube leak from a through-wall crack, there will be sufficient time for the leak to be detected and the reactor shut down *before* the crack grows to the critical size for a fast-uncontrolled rupture. Thus, if a pressure tube develops a through-wall crack, it is assumed that there will always be a "window of opportunity" for the reactor operator to detect the leak and safely shut down the Unit. This assumption is the basis for the claim that CANDU reactors safety systems provide "*defense in depth*," a notion that is often touted by the Canadian nuclear industry – but is such a claim justified?

The practical implementation of LBB is described in Section C.4 of CSA Standard N285.8: *Technical requirements for in-service evaluation of zirconium alloy pressure tubes in CANDU reactors*. Clause C.4.1 of this Standard stipulates that:

> *LBB analysis shall demonstrate that the leak detection capability of the annulus gas system (AGS) provides the operator with sufficient warning time to shut down and depressurize the reactor in a controlled manner.*

Similarly, Clause C.4.2.2.6 of the Standard states that:

> *To perform a LBB analysis, the response of the AGS and operator to indications of leakage from a through-wall DHC crack must be defined..... The time needed to detect, confirm, and locate the leak varies from station to station and depends on the leak rate, and therefore is an important input into the LBB analysis.*

There are four key parameters that need to be evaluated in a LBB analysis:

(i) *The initial crack length at wall penetration*, L_p. This is typically in the range 20 – 30 mm.

(ii) *The location of crack initiation*. Cracks may originate anywhere in the body of a pressure tube, but are most likely to occur in the vicinity of the rolled joint between a pressure tube and its end-fitting.

(iii) *The axial crack growth rate*, V_a, which is usually expressed as a velocity, in m/s, and is typically in the range 1×10^{-7} to 2×10^{-6} m/s. As previously noted in this intervention, V_a depends on the temperature, irradiation history and hydrogen equivalent concentration in the pressure tube at the crack location.

(iv) *The critical crack length*, CCL. This refers to the point in the development of a crack in the *axial* direction of a pressure tube at which a slowly increasing crack, (e.g. ~ 2 mm/hr), accelerates to a fast rupture (e.g. to a crack velocity > 2 mm/s). The CCL of a pressure tube is dependent on the temperature and hoop stress at the crack location but is typically in the range 30 – 80 mm.

A CANDU station's operating procedures require immediate shutdown of a Unit at a confirmed D_2O leakage rate of 0.5 kg/s. It is therefore important to closely monitor D_2O leaks and it follows that a LBB analysis of a pressure tube should include an estimate of potential D_2O leak rates as a function of crack length. One approach that has been used to make such estimates is to collect data from tests on removed pressure tubes and look for a correlation between D_2O leak rate and crack length.

Unfortunately, data from hot tests on removed pressure tubes show considerable scatter – for example, tubes with crack lengths in the range 18 – 30 mm exhibit D_2O leak rates in the range 0.8 to 30 kg/hr. Nevertheless, in spite of these large variabilities, the approach used at CANDU stations is to simply average the available data. Using this approach, *typical* pressure tube LBB behavior, as presented in a station's AGS Design Manual, is as follows:

1. With a reactor at full power, a crack will penetrate a pressure tube wall at a crack length of 27 mm and grow at a velocity ~ 5.3×10^{-7} m/s, equivalent to 1.94 mm/hr.
2. After 0.5 hours, the crack length would extend to 28 mm and the leak rate would be 0.6 kg/hr.
3. After 1.5 hours, the crack length would be 30 mm and the leak rate would have increased to 1.79 kg/hr.
4. The Unit's AGS leak detection capability is expected to recognize such a leak within this time window, (i.e, ~ 2 hrs).

However, this approach is quite different to the methodology used in CSA N285.8 which recommends the following *cubic* leak rate equation for LBB analysis:

$$Q = -11.2 + 0.0014(2C)^3$$

Q = D_2O leak rate in kg/hr

2C = crack length in mm

For crack growth at a velocity ~ 5×10^{-7} m/s, this equation predicts a D_2O leak rate of 4 kg/hr after 0.5 hr and 15 kg/hr after 1.5 hrs. These values are more than 6 times higher than the AGS Design Manual values noted above. Nevertheless, regardless of the precise leak rate that occurs after a crack extends through the wall of a pressure tube and starts to leak, it is expected that D_2O will enter the AGS at a rate of at least 1 kg/hr within the first hour after leak initiation.

However, it is important to note that neither a station's AGS Design Manual nor the CSA Standard N285.8 have anything to say about the ***methodology*** to be used, or how well it should perform, for D_2O leak detection. Similarly, although Fitness for Service Guidelines for a CANDU power reactor do require the operator to establish a pressure tube leak detection capability that is active at all times during reactor operation, ***no leak detection methodology is specified***.

A theoretical basis for the LBB methodology as currently applied to CANDU pressure tubes is provided by the equation:

$$t = \frac{CCL - L_p}{2V_a} \text{ ……………………..(i)}$$

Where:

t is the time for a crack to propagate to a critical length for fast rupture

CCL is the critical crack length

L_p is the crack length when it penetrates through the pressure tube wall

V_a is the axial crack velocity

Equation (i) has *three* unknown variables – CCL, L_p and V_a – and the assignment of meaningful values to these parameters has proven to be quite difficult because of the tremendous scatter in the available experimental data. Thus, for example, we have the values of CCL quoted by Cheadle et al. in "*Operating Performance of CANDU Pressure Tubes*", AECL Report No. AECL-9939, (April, 1989). The CCL values are for Zr-2.5% Nb exposed to 240 – 300 °C D_2O and fast neutron irradiations up to 8×10^{25} n/m^2 and span the range from 40 to 90 mm. Similarly, the same report provides values for V_a in the temperature range 150 – 280 °C. These data show that V_a is strongly dependent on the pressure tube temperature, but even for a *fixed* temperature such as 250 °C, the values of V_a span the range 1×10^{-7} to 6×10^{-7} m/s, (equal to 0.36 to 2.16 mm/hr).

More recent research has confirmed most of these values for CCL and V_a. For example, consider the report by D. Rogers et al: "*Performance of Pressure Tubes in CANDU Reactors*," CNL Nuclear Review Vol 5, (1), pp 1 – 15, November 2015. Here we read: "*For a test temperature of 250 °C, the CCL ranges from a minimum of ≈ 41 mm to a maximum of >80 mm*". In addition, Rogers et al's 2015 publication includes a plot of a pressure tube's 95% upper bound mean, and lower bound crack growth velocity, as a function of temperature. At 250 °C the data span the range 1×10^{-7} to 4×10^{-7} m/s or 0.36 to 1.44 mm/hr which is similar to Cheadle's 1989 estimate noted above.

The value of L_p, the crack length when it first penetrates the pressure tube wall and D_2O starts leaking into the annulus gas system (AGS), is also subject to great uncertainty. It was initially assumed that the upper bound on L_p would be 4W, where W is the wall thickness of a pressure tube, (which is ≈ 4 mm). However, it was subsequently realized that a pressure tube crack may tunnel so that the length of a crack at wall penetration may be considerably larger than 4W – See report by Moan et al: "*Leak Before Break Experience in CANDU Reactors.*" AECL Report No. AECL-9609, issued April 1988.

Data collected from measurements of pressure tubes removed from Pickering and Bruce has shown that 27 mm is the longest initial crack opening size observed to date. For this reason, the initial crack length, L_p, for pressure tube LBB assessments is often conservatively assumed to be 27 mm. Using these bounding values for the parameters in question we then have:

$$t = \frac{CCL - L_p}{2V_a}$$

$$t = (40 - 27)/(2 \times 1.44) \text{ hours}$$

$$t = 4.5 \text{ hours}$$

It is very telling that estimates of the time it takes for a pressure tube crack to reach its critical crack length have varied considerably since the LLB approach to CANDU pressure tube fitness for service assessments was first introduced in the 1970s. Thus a 1988 review by E.G. Price et al. entitled *Leak Before Break Experience in CANDU Reactors* asserted that "*the time available for operator response is about 100 hours*." Remarkably, just two years later, the same authors reduced this estimate to a mere 18 hours in a paper published in the International Journal of Pressure Vessels and Piping in 1990.

However, by 1995, a Korean Atomic Energy Research Institute report entitled "*Safety Margin Improvement Against Failure of Zr-2.5Nb Pressure Tubes*", stated that the time for operator action in the event of a DHC-induced pressure tube rupture is 11.7 hours. But ten years later, a 2005 report from the same Korean Institute concluded: "*The time for the operator to take action against a LOCA is 1.7 hours*.

More details on the problems associated with the LBB methodology described in CSA Standard CSA N285.8 may be found in the journal article: *CANDU Pressure Tube Leak Detection by Annulus Gas Dew Point Measurement: A Critical Review*. Kerntechnik Volume 82, pages 1 -15, (2017).

Summary of Bruce Power's Position on High [Heq] Issues:

1. On July 5, 2021, Bruce Power reported that measurements obtained from a Unit 6 pressure tube after 271,729 hot hours of operation showed Hydrogen Equivalent Concentrations ($[H_{eq}]$) above the generic predictions and exceeding the Licence Condition 15.3 $[H_{eq}]$ limit of 120 parts per million (ppm – by weight). Bruce Power reported that pressure tube B6S13 has a $[H_{eq}]$ of 211 ppm at the burnish mark and 212 ppm at the burnish mark plus 10mm. Also, on July 8, 2021, Bruce Power reported that measurements obtained from a Unit 3 pressure tube showed

$[H_{eq}]$ above the generic predictions and above the Licence Condition 15.3 $[H_{eq}]$ limit of 120 ppm. For the Unit 3 pressure tube B3F16, Bruce Power indicated a preliminary measurement of 131 ppm $[H_{eq}]$.

2. On September 10th, 2021 CNSC held a Public Hearing where Bruce Power made the following three comments with reference to the high [Heq] data reported in July 2021:

> **MR. NEWMAN:** *For the record, Gary Newman. Chief Engineer and Senior Vice President of Engineering at Bruce Power:*
>
> **(i)**. *High hydrogen concentrations alone do not impact pressure tube integrity. This is why we evaluate, the combination of both hydrogen concentration and flaws. There are no flaws in the region of interest where the elevated hydrogen concentrations are observed on any Bruce unit. This means there is no driver for crack initiation. The higher hydrogen concentrations at the top of the tube is caused by hydrogen redistribution due to a temperature gradient at outlet ends. This is not an overall increase in the amount of hydrogen in the pressure tube, but rather a redistribution to the region of interest*
>
> **(ii).** *We do not see an incremental change in the rate of deuterium pick-up, and that's reflected in the modelling and bounding nature of the deuterium predictions we're doing in the largest part of the pressure tube. What we are seeing, though, where that model doesn't work and we've had to go to, now, a new model and a two-dimensional treatment is that we're getting a redistribution of H/D. But it's not a change in the corrosion rate or the pick-up rate; it's actually just -- it's just a redistribution of the hydrogen that's already there.*

3. In March 2022 Bruce Power submitted an Initial Event Report, CMD 22-M16, which informed the CNSC that *inlet rolled joint*, (IRJ), punch samples from pressure tube B6S13 showed an elevated [Heq] concentration of 126 ppm localized at ~ 10 mm inboard of the burnish mark (BM). Metallographic examinations on these IRJ punch samples showed a significant radial gradient in hydride concentration decreasing from the pressure tube outer diameter (OD) to inner diameter (ID). The radial gradient was confirmed by direct [H] and [D] measurement of radial sections of B6S13 IRJ. Bruce Power acknowledged that the root cause and impact of this discovery on the fitness for service of Bruce pressure tubes remains undetermined.

4. On October 11th, 2022 Bruce Power applied for an Amendment to its Power Reactor Operating Licence. In its application, Bruce Power is seeking to remove licence condition 15.3, which states that “Before hydrogen equivalent concentrations ([Heq]) exceed 120 ppm, the licensee shall demonstrate that pressure tube fracture toughness will be sufficient for safe operation beyond 120 ppm.” Bruce Power is, instead, proposing a Licence Amendment that all fitness-for-service requirements related to pressure tubes be incorporated into the existing Licence condition 6.1, which states simply that “The licensee shall implement and maintain a fitness for service program.”

Conclusions:

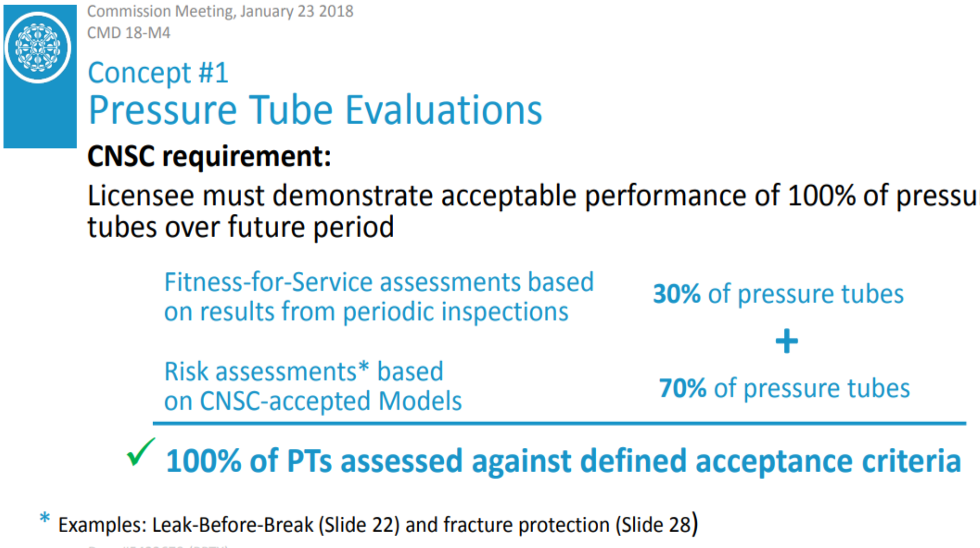
From the four points noted above it is clear that Bruce Power acknowledges that its pressure tubes have exhibited elevated [Heq] levels that potentially exceed current licence limits, (both at their inlet and outlet ends). Nonetheless, Bruce Power chooses to argue as follows:

1. Because there are no flaws in the region where elevated hydrogen concentrations are observed, the high [Heq] data reported by Bruce Power has no negative impact on the fitness for service of Bruce pressure tubes

2. Because there has been no change (sic) in the corrosion rate or the H/D pick-up rate of the affected tubes, there is no incremental change in the rate of deuterium pick-up by these tubes

For item (1): The claim that "*there are no flaws in the region where elevated hydrogen concentrations are observed*," needs to be tempered by the fact that not all pressure tubes in any given Unit at Bruce NGS have been inspected for flaws. In fact, the actual number of pressure tube inspections over the life of Bruce Units 3, 4, 5, 6, 7, and 8, was stated by Bruce Power in July 2021 to be about 480 – a number that is consistent with the value of about 80 inspections *per Unit* reported by Bruce Power in October 2021. However, this number of inspections per Unit is inconsistent with the number of pressure tube inspections required by the CNSC under the terms of CSA Standard N285.4, as shown in the two overheads below:

CNSC Overhead No. 1:



Commission Meeting, January 23 2018
CMD 18-M4

Concept #1
Pressure Tube Evaluations

CNSC requirement:

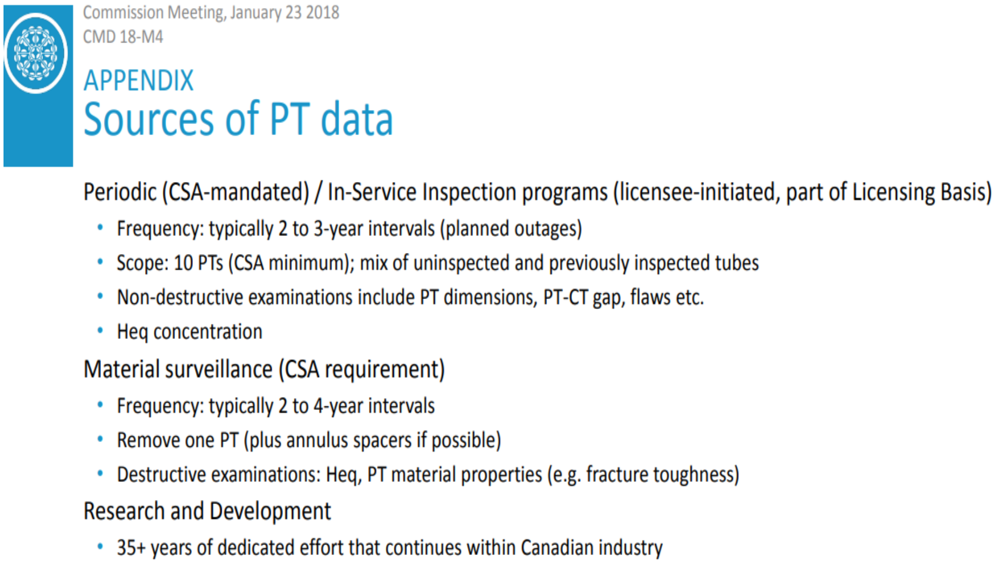
Licensee must demonstrate acceptable performance of 100% of pressure tubes over future period

Fitness-for-Service assessments based on results from periodic inspections	**30%** of pressure tubes
	+
Risk assessments* based on CNSC-accepted Models	**70%** of pressure tubes

✓ **100% of PTs assessed against defined acceptance criteria**

* Examples: Leak-Before-Break (Slide 22) and fracture protection (Slide 28)

CNSC Overhead No 2:



Commission Meeting, January 23 2018
CMD 18-M4

APPENDIX
Sources of PT data

Periodic (CSA-mandated) / In-Service Inspection programs (licensee-initiated, part of Licensing Basis)
- Frequency: typically 2 to 3-year intervals (planned outages)
- Scope: 10 PTs (CSA minimum); mix of uninspected and previously inspected tubes
- Non-destructive examinations include PT dimensions, PT-CT gap, flaws etc.
- Heq concentration

Material surveillance (CSA requirement)
- Frequency: typically 2 to 4-year intervals
- Remove one PT (plus annulus spacers if possible)
- Destructive examinations: Heq, PT material properties (e.g. fracture toughness)

Research and Development
- 35+ years of dedicated effort that continues within Canadian industry

Thus, Overhead No. 1 indicates that 30% of a Unit’s pressure tubes, or 144 tubes, must be inspected to satisfy CNSC’s fitness for service requirements for the Unit. Similarly, Overhead No. 2 states that at least 10 pressure tubes must be subject to in-service inspections every 2 to 3-years, which would amount to about 100 tubes over the lifetime of a Unit. It is noteworthy that the specifications provided by CSA Standard N285.4 have changed considerably over the years – thus prior to 1994 the requisite number of channels to be inspected was 5 over a 3-year period.

This incomplete inspection coverage is mainly because CANDU reactors are not readily accessible for inspection due to the largely unavoidable exposure of inspectors to high radiation fields at a reactor face. For this reason, only a relatively small number of pressure tubes are inspected at periodic intervals, so that only a small set of data is available for use as input to probabilistic analyses. Furthermore, with only a small number of sample flaws, there is significant uncertainty associated with the computed probability of DHC initiation. Consider, for example, a Bruce Unit with *three* undetected flaws on the inside surface of three separate pressure tubes. In an inspection campaign involving flaw assessments of 80 randomly selected pressure tubes, *there is a 50% probability of <u>not detecting any of these flaws</u>*.

For item (2): The claim that “*there has been no change in the corrosion rate or the H/D pick-up rate of the affected tubes, (*so that*) there is no incremental change in the rate of deuterium pick-up by these tubes*” **<u>is simply not true</u>**, as I first pointed out in my CNSC intervention CMD 22-M37.4 for the November 2022 Public Hearing on this topic. However, in this intervention I have included additional material, (See pages 3 – 7), that justifies **<u>a complete rejection</u>** of Bruce Power’s demonstrably false claim that Bruce Units are <u>*not*</u> subject to increasing corrosion and H/D pickup.

Final Words:

Dear Commissioners, at today's Public Hearing, you are faced with a simple choice: Do you accept Bruce Power's application to remove from the Licence Condition Handbook the hard requirements on [Heq], as stated in CSA Standards N285.4 and N285.8; or alternatively, do you retain the time-honored tradition that pressure tube fitness for service is mainly dependent on the H/D concentration and the rate of H/D pickup, which therefore should be monitored and kept below well-defined limits.

In its application to change its Licence Condition Handbook, Bruce Power argues that the removal of [Heq] as the principal determinant of a pressure tube's fracture toughness is justified on the grounds that "*there are no flaws in the region where elevated hydrogen concentrations are observed*." Unfortunately, however, the claim that there are no flaws in regions of high Heq is not acceptable *unless every pressure tube has been inspected in every region of interest*. This is clearly not the case because only a small percentage of pressure tubes in a Unit are ever inspected.

And it is interesting to note that Bruce Power's Chief Engineer, Garry Newman, stated at a CNSC Public Hearing: *"Even if you haven't found any flaws, you have to assume that maybe you've missed one"*. A remarkable admission from a Bruce Power Senior VP, which only serves to emphasize the fact that only *one* self-propagating flaw is needed to start a potentially catastrophic pressure tube leak.

However, Bruce Power's current position on the occurrence of high Heq concentrations in its pressure tubes is unacceptable for other reasons – the most important of which is that Bruce Power has failed to identify or even discuss the *root cause* of these high Heq concentrations. This is a very serious omission on the part of Bruce Power because the *root cause* of the high Heq observed in several Bruce pressure tubes would provide a much-needed hydrogen pickup *mechanism* that could be incorporated into fracture toughness models. The very fact that Bruce Power was using a model that was supposedly validated and verified against experimental observations, only to discover in July 2021 that the model was seriously underpredicting H/D pickup rates by a factor of about two, is very concerning. But the truth is that this discovery shows how little is really understood about the mechanism of zirconium alloy corrosion and hydrogen pickup.

Bruce Power's efforts to create a new and improved fracture toughness model were discussed at a nuclear industry workshop on elevated hydrogen equivalent ([H]eq) concentration that was held on March 25th, 2022. In an account of this meeting, we find Attachment B which provides "*a path forward with a target schedule and summary of key deliverables to improve hydrogen equivalent concentration predictions in the inlet/outlet rolled joint regions of pressure tubes*". Action Item 5G in Attachment B, described as "The Development of a Comprehensive [Heq] Model", gives the target date for the completion and issuance of such a model as the 2nd Quarter of 2026. This means that Bruce Power is content to continue operating its Units 3, 4, 5, 7 and 8 for three more years, even though it would be doing this *without first providing a root cause for the acceleration in the rate of hydrogen pickup by these Unit's pressure tubes*.

However, one has to ask: Is the CNSC also content to allow such a situation to continue unchecked? But, as already shown in this intervention, (See pages 7 – 10), the CNSC and the Canadian nuclear industry have, in fact, been struggling with "unexpected" discrepancies between Heq predictions and Heq measurements for over a decade. This has resulted in endless revisions of CSA Standards N285.4 and N285.8 – Standards that stipulate how a reactor owner/operator should deal with H/D ingress into pressure tubes.

Thus, far from trying to understand the reasons for the observed acceleration of hydrogen ingress into aging pressure tubes, and possibly find ways to mitigate this problem, Bruce Power is evidently more interested in rewriting its Licence Condition Handbook in a way that would eliminate the currently accepted hard limits on Heq and *d*Heq/*d*t. But I believe such a rewriting of a nuclear standard would set the dangerous precedent, namely that, if a reactor owner/operator fails to meet a standard, all it needs to do is have the standard changed.

In this regard, it is noteworthy that Bruce Power's application to amend is Operating Licence states:

> "*Bruce Power requests that PROL 18.02/2028, Licence Condition 15.3, be lifted and that Licence Condition 6.1 be updated to reflect the advancements in the licensing basis and the state of industry knowledge….*"
>
> (My Emphasis in red)

Here, one has to wonder what these "*advancements in the state of industry knowledge*" might be? Certainly, such alleged advancements, have been insufficient for Canada's nuclear industry to provide a *root cause* for the elevated Heq concentrations observed in Bruce pressure tubes. And without a root cause, how can our knowledge of pressure tube aging mechanisms possibly advance? But there are other reasons to question Bruce Power's suggestion that there has been a significant advancement in our understanding of hydrogen ingress mechanisms.

However, may I add that, a three-year period for Bruce Power to develop a predictive model of Heq pickup does not give one confidence that Canada's nuclear industry is "up to speed," or has "advanced knowledge," on this very important topic. And surely, it is dangerous and foolhardy for Bruce Power to continue operating these aging Units without a good understanding of how and why hydrogen entry into some of its pressure tubes is accelerating. But what strongly suggests that Bruce Power is not acting in good faith in the way it is dealing with its high Heq problems, is the fact that *three* Bruce Power Units – namely Units 3, 4 and 5 – will be shut down for Major Component Replacement projects by mid-2026, at which point cases of high Heq concentration in the pressure tubes of these Units will no longer be of concern. This is because high Heq concentrations in these Units will cease to be a fitness for service issue. Thus, it appears that Bruce Power's current position is simply to maintain the status quo for a few more years in order to avoid dealing with the problems associate with high H/D pickup.

To conclude this intervention, may I reiterate the fact that the CNSC itself is an organization that has stressed the need for Bruce Power to provide a root cause report for all cases of high Heq. For example, consider what the CNSC had to say about this issue in March 2022:

> "*Bruce Power does not have a mechanistic understanding of the phenomenon nor validated models as a result of this finding. In other words, their Heq model*

> *is invalid because the outputs of the Heq models do not align with the B6S13 measurement of 126 ppm at the inlet end of the PT. These Heq outputs are used as inputs into Fitness for Service Assessments such as leak-before-break (LBB) and fracture protection (FP) assessments. The uncertainty of the Heq inputs impact the LBB and FP assessments. CNSC staff are of the opinion that Bruce Power cannot confidently perform these assessments until the Heq phenomenon is understood and modelled*."

So, Dear Commissioners, please do not allow Bruce Power to continue denying the indisputable fact that, as of July 2021, Bruce Power was in non-compliance with CSA Standards N285.4 and N285.8; and, Commissioners, please do not approve Bruce Power's proposed amendments to its Licence Condition Handbook until it has issued the requisite high Heq root cause reports.

Sincerely,

Dr. F. R. Greening

March 25th, 2023

Addendum 1:

The CNSC's final position on the issue of high Heq – a topic to be debated in the upcoming Hearing in Writing as described in CNSC Document 2023-H-103 – was recently presented in CMD Document 23-H103, issued March 15th, 2023. This document was written by CNSC Staff and is an assessment of Bruce Power's Licence Amendment Application. In a Section on proposed changes to the Bruce Licence Conditions Handbook we read the following:

(i) On page 19:

> *Bruce Power shall submit annual reports by July 1 of each year indicating when each unit is predicted to reach a maximum [Heq] of 120 ppm.*

(ii) And again, on page 21

> *Bruce Power shall submit assessments of fracture protection and Leak-Before-Break, using a new fracture toughness model, to the CNSC prior to the predicted [Heq] exceeding 120 ppm in one or more pressure tubes in any unit. The assessments shall be submitted for each Unit no earlier than 1 year and no later than 6 months prior to the date that the [Heq] for a pressure tube in the given unit is predicted to exceed 120 ppm.*

These statements regarding Bruce Power's proposed amendment to the Licence Conditions Handbook are remarkable for a number of reasons. But, first and foremost, a Licence amendment that requires Bruce Power to make predictions of Heq uptake rates *fails to recognize that Bruce Power has already proven it is* ***unable*** *to reliably predict Heq concentrations in its pressure tubes* – which is why the CNSC felt it was necessary to hold Public Hearings on this problem in the first place.

And the CNSC needs to remember that Bruce Power's most recent attempt, (in 2021), to predict Heq concentrations in its pressure tubes, resulted in total failure because measurements made at that time on two Bruce Units were *double* the predicted values. It also follows that Bruce Power ***cannot*** provide a reliable estimate for the date that the [Heq] for a pressure tube is expected to exceed the CSA limit of 120 ppm, because the ΔHeq/dt values for its operating Units are so unpredictable and are lacking a sound theoretical basis.

All of these problems stem from the simple fact that Bruce Power is yet to provide a *root cause* for the high Heq concentrations measured in July 2021 near the rolled joints of several of its pressure tubes. And clearly, without an explanation for the elevated hydrogen ingress rates observed in some of its pressure tubes, *Bruce Power will never be able to make any meaningful predictions of future hydrogen uptake rates*.

H/D pickup near the rolled joints of operating pressure tubes has been extensively studied since the commissioning of the first large CANDU reactors at Pickering NGS in the early 1970s. And it has long been recognized that H/D pickup in the vicinity of a rolled joint is complicated by the coupling of two different alloys – namely 403 Stainless Steel and Zr-2.5Nb – because such a coupling is known to lead to galvanic and crevice corrosion effects that are difficult to quantify. In addition, H/D entry from a fuel channel's annulus gas system cannot be ruled out near a pressure tube rolled joint – a topic that has been previously discussed in this intervention.

Also, of potential interest is the fact that protium as well as deuterium, are known to enter a pressure tube from different sources and changes in the protium concentration may affect the validity of models if additional source terms are active and other potential phenomena need to be included in order to make reliable predictions. Thus, very recently, it has been proposed that gettering of protium from the Stainless Steel end fitting into the Zr-2.5Nb pressure tube is an important source of protium in pressure tubes at their rolled joints – See Journal of Nuclear Materials Volume 573, 154128, January 2023.

In a careful reading of CNSC Staff's comments on Bruce Power's position on the high Heq event, (as described in the CNSC Document CMD 23-H103), it is very significant that in the 38 pages of text on this issue, the question of the *root cause* of the high Heq concentrations in some of its pressure tubes *is never mentioned*. And this omission by the CNSC is in spite of the fact that, in March 2022, the Event Initial Report CMD 22-M16 stated:

> *Bruce Power does not have a mechanistic understanding of the phenomenon nor validated models as a result of this finding. In other words, their Heq model is invalid because the outputs of the Heq models do not align with the B6S13 measurement of 126 ppm at the inlet end of the PT. These Heq outputs are used as*

> *inputs into Fitness for Service Assessments such as leak-before-break (LBB) and fracture protection (FP) assessments. The uncertainty of the Heq inputs impact the LBB and FP assessments. CNSC staff are of the opinion that Bruce Power cannot confidently perform these assessments until the Heq phenomenon is understood and modelled.*

And consider what the IAEA has to say on this issue in its report IAEA-TECDOC-1278: *Review of Methodologies for the Analysis of Safety Incidents at NPPs*:

> *In order to objectively assess events, an adequate structured event investigation methodology has to be applied, which leads to the identification of appropriate root causes by which relevant corrective actions are established, implemented and closed out and corresponding lessons learned are circulated to interested parties. The primary goal of event investigation is the prevention of events and their recurrence and in so doing achieving an overall improvement in nuclear safety.*

(See also an updated version of this report: IAEA-TECDOC-1756: *Root Cause Analysis Following an Event at a Nuclear Installation: Reference Manuel*)

It is therefore abundantly clear that *root cause analysis* is an internationally accepted methodology that should be used to disposition any unexpected events in the day-to-day operation of a nuclear facility. Furthermore, it appears that back in March 2022, the CNSC fully expected a root cause analysis to be carried out by Bruce Power to explain how and why high Heq values could be observed in some Bruce pressure tubes. Indeed, under the heading "Potential Causes" in the Event Report CMD 21-M37.1, Bruce Power offered the following suggestion:

- *Circumferential variability in Heq from top of the tube to bottom of the tube.*

But later, in CMD 21-M39 Bruce Power concluded that:

> *The cause(s) of the [Heq] limit exceedances is/are not known at this time. Further investigation and analysis are being undertaken by Bruce Power to determine the cause of test observations.*

Nevertheless, at a Public Meeting held on September 3rd 2021, when Bruce Power was asked by CNSC Commissioner Lacroix for its interpretation of the high [H_{eq}] observed in some of its operating pressure tubes, Bruce Power replied:

> "*We're not seeing a change in the rate of hydrogen uptake. What we're seeing is a redistribution (of the hydrogen) to the cooler region at the top of the pressure tube. So, it's not an acceleration but a redistribution*".

However, in my previous November 2022 intervention on this issue, (See CMD 22-M37.4,), I explained why this proposed root cause of the high Heq observed in Bruce Units 3 and 6 pressure tubes is unacceptable. In the interest of brevity, I will not restate all of these reasons in this intervention, but I will add this: It is well known that the "redistribution of hydrogen" referred to by Bruce Power is caused by its thermal diffusion in a temperature gradient. This phenomenon has been studied for many years – See for example J. Markowitz's paper: "*Hydrogen Redistribution in Thin Plates of Zirconium Under Thermal Gradients*" WAPD-TM-104, Jan 1958, and S. Aiyeru's paper: "*Finite Element Modelling of Hydrogen Migration and Hydride Precipitation in Zr Alloys*", Computational Materials Science 218, 111942, Feb 2023.

These studies show that the thermal redistribution of hydrogen isotopes in zirconium alloys is a universal phenomenon that *should be observable at the outlet ends of all pressure tubes*. In order to investigate H/D ingress near this region, I have collected data for Bruce Unit 3 at a location 10 mm from the outlet rolled joint as shown in Table 1A, below. The Table includes values for the initial hydrogen in the pressure tube ingot which is used to correct the hydrogen pickup data in calculating the ratio $\{[H]_{Cor} /0.5[D]\}$.

Table 1A: Hydrogen and Deuterium Concentrations Near the Outlet Rolled Joints in Selected Pressure Tubes from Bruce Unit 3

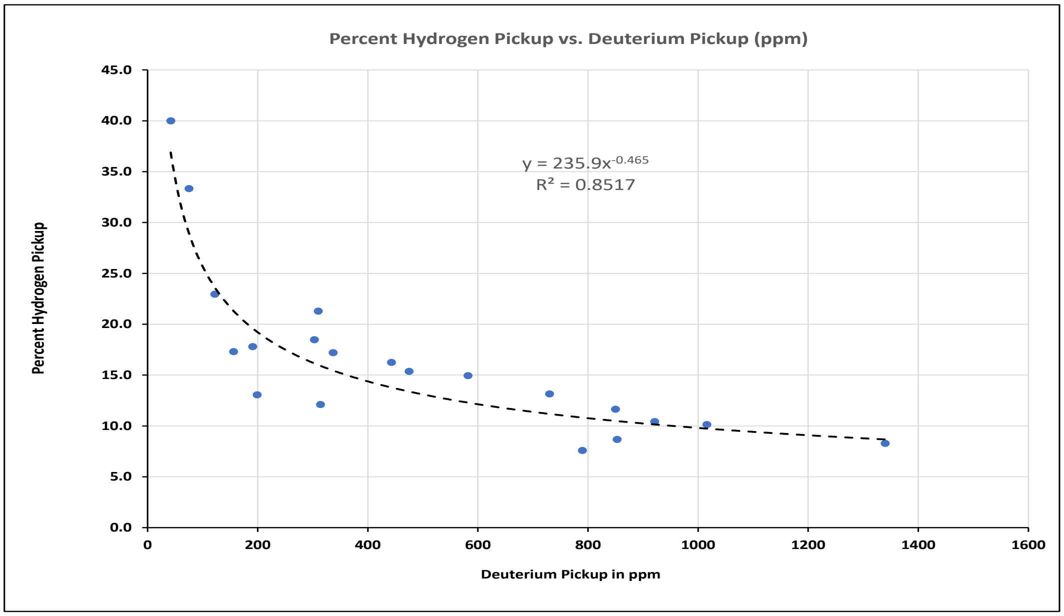
Bruce Unit 3 Pressure Tube ID (~10 mm from ORJ [Ref 1])	[D] (mg/kg)	[H] (mg/kg)	$[H_{Init}]$ (mg/kg)	Ratio $\{[H]_{Cor} /0.5[D]\}$
F16	1340	111	12.6	0.147
L11	790	60	9.3	0.128
G15	853	103	11.3	0.181
K10	1016	74	7.4	0.156
Q16	853	96	10.9	0.233
H06	730	66	15.0	0.329
X09	475	73	14.9	0.245
O20	921	96	12.3	0.182
Q12	850	99	10.2	0.209
N04	337	58	14.7	0.257
O15	303	56	8.7	0.312
O17	122	28	9.0	0.311
O13	443	72	12.5	0.269
P14	191	34	9.0	0.262
Q13	582	87	11.7	0.259
L12	156	27	6.7	0.260
F05	75	25	11.7	0.355
L22	42	24	9.3	–
R10	199	26	5.5	0.206
S13	314	38	6.0	0.204

Ref 1: ORJ = Outlet Rolled Joint

Inspection of the data in Table 1A shows that there is a great deal of variability in the deuterium concentrations in these samples: from a high of 1340 mg/kg for sample F16, to a low of 42 mg/kg in sample L22. In a few cases, such as sample X09, the pressure tube outlet temperatures are known to be somewhat lower, (~ 290 °C), than the temperatures for samples from high power channels such as L12, (~ 297 °C). However, the D pickups for these samples are *the reverse* of what might be expected based on these temperatures alone; thus, the D-pickup is 475 mg/kg for X09, but only 156 mg/kg for L12.

Also of interest in the data presented in Table 1A is the variation in the percent hydrogen (protium) pickup compared to the deuterium pickup at the same location, as plotted in Figure 1A. This plot shows that the percent of protium picked up by a tube, expressed as 100×[H]/[D] vs. [D], is *inversely* proportional to [D]. Thus, when [D] is low, the percent of protium picked up is high – as high as 40%. But when [D] is high the percent of protium picked up is as low as 8%.

Figure 1A: Plot of H/D Percent Pickup vs. Deuterium Pickup in ppm



This behavior indicates that H and D most probably enter pressure tubes by at least two different mechanisms which most likely occur over different timelines. We know for a fact that, as installed, each pressure tube contains an initial amount of H (protium), usually in the range 5 to 15 ppm, and essentially no deuterium. Then, with increasing years of service, deuterium enters a pressure tube at an unpredictable rate that depends on each tube's physico-chemical makeup.

Inspection of the data in Table 1A shows that tubes such as F05 and L22 are quite resistant to D (and H) pickup, while tubes such as F16 and G15 exhibit high, (accelerated), D (and H) pickup rates. This observation is counter to Bruce Power's diffusional redistribution hypothesis which, by its invocation of thermal diffusion, requires elevated concentrations of H and D to be observed at the outlets of ***all*** pressure tubes.

In short, Bruce Power's diffusional redistribution hypothesis cannot be considered a *root cause* of cases of high Heq in operating pressure tubes because it only describes what happens to H and D *after* they have entered a pressure tube. Unfortunately, however, the redistribution hypothesis has nothing to say about *how* H and D entered these tubes in the first place. Thus, this hypothesis must be rejected as a root cause of the high Heq observed in Bruce tubes. And without a justified and validated root cause of these cases of high Heq, Bruce Power's Licence Amendment Application must be rejected.

Dr. F. R. Greening
April 8th, 2023

Addendum 2:

On October 5th, 2021, the CNSC issued its *Record of Decision on Bruce Power's Request for Authorization to Restart Bruce NGS Unit 3*, which stated in part, (With my emphasis in red):

> *Bruce Power's discovery of [Heq] in Unit 3 pressure tubes in excess of the licence limit was not predicted by current modeling. Bruce Power submitted that although it identified elevated [Heq] concentrations in the region of interest, the overall uptake of hydrogen in the pressure tubes is not increasing beyond the predicted rate, and that hydrogen concentrations are below the limit for the balance of the pressure tubes. The Commission's view is that Bruce Power did not knowingly operate Unit 3 with [Heq] in excess of the licence limit, and that the consequent regulatory action taken by the CNSC, including the designated officer order, has been appropriate.*

Unfortunately, the claim by the CNSC that *Bruce Power did not knowingly operate Unit 3 with [Heq] in excess of the licence limit* is simply *not true* as demonstrated below.

In its September 2021 written submission to the CNSC – See CMD 21-M37.1 – Bruce Power reported values for [Heq] measured near the outlet end of pressure tube B3F16. Thus, In Table A2 of CMD 21-M37.1, we find [Heq] data for B3F16 measured in 2018, as well as repeat measurements on the same tube made in 2021.

Unfortunately, while the 2021 data were measured at *two* circumferential locations – namely the 12:25 and the 11:05 clock positions – the 2018 data were measured only at the 11:05 clock position. Nevertheless, it is possible to correct for this difference because [Heq] measurements at these clock positions consistently show that the 12:25 values are about 1.5 times *higher* than the 11:05 values measured at the same axial locations.

By applying this correction to the 2018 [Heq] data, and focusing on the 70 mm axial location, (which corresponds to the all-important burnish mark at the rolled joint), we find the 2018 [Heq] to be at least 145 ppm *which is well above the CSA N285.8 limit of 120 ppm*. Thus, as far back as 2018, Bruce Power was clearly well aware that it was starting the 2018 to 2021 period between inspections with an [Heq] in pressure tube B3F16 that was already well in excess of the licence limit.

May I therefore suggest that the CNSC reconsiders its claim that *Bruce Power did not knowingly operate Unit 3 with [Heq] in excess of the licence limit*. Bruce Power *knew* pressure tube B3F16 was non-compliant in 2018 and also knew this non-compliance could only get worse by 2021.

Addendum 3:

In response to an email I sent to the CNSC on April 23rd 2021, I received a reply from CNSC Vice President Peter Elder on May 18th, 2021, which read in part as follows: (With my emphasis added in red)

> *Dear Dr. Greening,*
>
> *Once again, I thank you for bringing your concerns to the CNSC's attention. I have raised them with our technical staff to confirm that they are aware of the issue and that*

> *the licensees take appropriate actions when performing pressure tube fitness for service evaluations…..*
>
> *The D-pickup rates used for forecasting the end-of-life Heq estimates are based upon the maximum deuterium measurements at axial locations along pressure tubes from the 12:00 orientation. The pickup rate models do not attempt to model the circumferential diffusion profile of deuterium. Assessments for flaws due to pressure tube to fuel bundle interactions, which are most likely to occur on the lower half of a pressure tube, conservatively use the Heq value predicted for the 12:00 orientation at the axial location of the flaw.*
>
> *The Heq predictions at end-of-life at the different axial locations along the pressure tubes use an upper bound to the D-pickup rates determined from the measurements obtained from the scrape samples from in-service tubes and the punch samples from surveillance tubes. As required by CSA N285.4, repeat scrape measurements from nominally the same axial locations are obtained from a subset of pressure tubes. These data are used to assess the rate of change of D-uptake during shorter intervals throughout the reactor operating life to determine if adjustments are required to the upper bound rate and verify that there is no significant acceleration of D-pickup during reactor operation that invalidate the model predictions. If the rate of change of D-pickup exceeds the rates specified in the CSA N285.4 acceptance standards, the impact on pressure tube safety must be evaluated in accordance with CSA N285.8. This process has worked effectively for the Canadian reactors since the 1990s, and CNSC staff actively monitor the modelling activities undertaken by all licensees.*

These comments by Vice President Elder reveal three important points to consider concerning the CNSC's approach to determining the fitness for service of pressure tubes in Canada's CANDU reactors:

(i) *The pickup rate models used to make Heq predictions do not attempt to model the circumferential diffusion profile of deuterium*

(ii) *CSA Standard N285.4 requires a reactor operator to verify that there is no significant acceleration of D-pickup during reactor operation that invalidate the model predictions.*

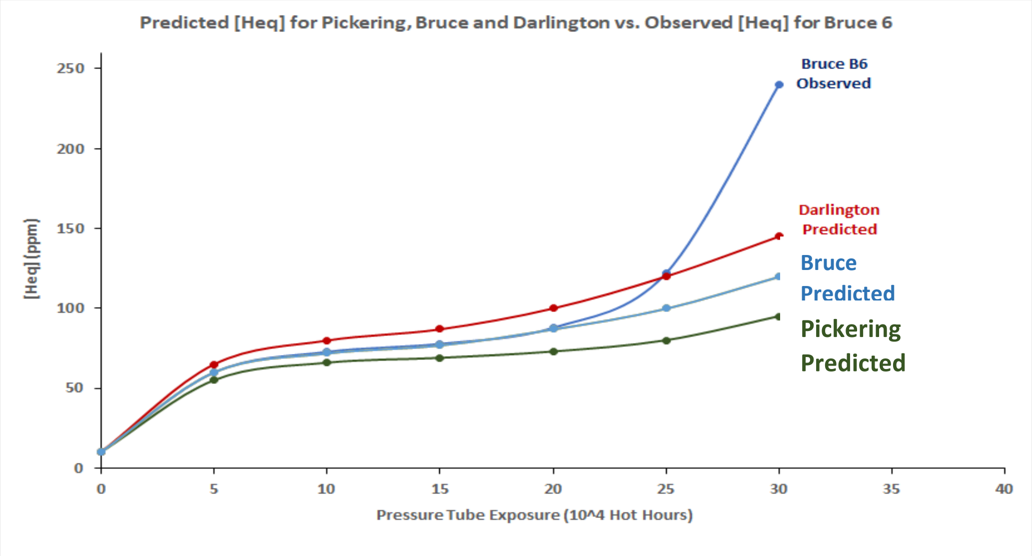
(iii) *The CNSC believes this approach has worked effectively for Canadian reactors since the 1990s.*

Now this level of confidence in CNSC's approach to assessing the fitness for service of pressure tubes was thrown into question just two months after this email was sent to me in May 2021. Thus, in July 2021, new Heq measurements reported for Bruce Units 3 & 6 pressure tubes showed hydrogen concentrations that were about *two times* higher than the predicted values. This automatically implies that the D pickups for these Units are accelerating. And, by CNSC's item (ii) above, we can say that Bruce Units 3 & 6 were, as of July 2021, in non-compliance with CSA Standard N285.4.

Bruce Power's reaction to this situation was to declare that hydrogen diffusion in the circumferential temperature gradient between the bottom and top of a pressure tube was responsible for the high Heq concentrations observed in these tubes. But by taking this position, Bruce Power is admitting that the failure to predict the high Heq measurements observed in July 2021 was not caused by accelerated pickup, but was due to the neglect of diffusion in predictive models. However, this neglect of diffusion implies that *all* predictions of Heq levels in mature pressure tubes will significantly *underestimate* measured Heq concentrations. But is this in fact the case?

I have used H_{eq} data from the CNSC's *Appendix G*, (pages 271 - 272), of its 2019 *Regulatory Oversight Report*, (ROR) to determine values for $\Delta H_{eq}/10^4$ HH in pressure tube samples in order to investigate if the reported values do in fact satisfy Clause 12.3.5. 2 of CSA N285.4. In this way it is evident that $\Delta H_{eq}/10^4$ HH increases significantly with increasing EFPHs for some Bruce pressure tubes. This is clearly in complete contradiction to the claim made by Bruce Power that [Heq] for pressure tube B6S13 "is *not showing a change in the rate of hydrogen uptake*".

The fact that the rate of change of [Heq] for pressure tube B6S13 shows *considerable acceleration* after about 200,000 Hot Hours of exposure is well illustrated by plotting the predicted (deterministic) values of [Heq] as a function of pressure tube exposure using published data for outlet rolled joints in Units at Darlington, Pickering B and Bruce B, as shown below:



These curves show the *predicted* [Heq] values for Pickering, Bruce and Darlington pressure tubes compared to the *measured* values for the B6S13 tube. The [Heq] values for Pickering and Darlington outlet rolled joints are taken from OPG's September 3rd 2021 *Written Submission* to the CNSC, CMD 21-M37.2, where we read:

> *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.*

> *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.*

Thus, we see that measured [Heq] values for Pickering and Darlington pressure tubes are well in line with the predicted values shown in the data plotted above, which were calculated assuming there is no circumferential thermal diffusion. Thus, to date, elevated values for [Heq] – namely values >120 ppm – have only been observed in Bruce Units 3 and 6. But this raises questions about the validity of Bruce Power's hypothesis that the root cause of cases of high [Heq] is thermal diffusion of ingressed hydrogen. The obvious problem with this hypothesis is that *all* pressure tubes in mature CANDU reactors should exhibit some degree of hydrogen redistribution to the cooler 12 o'clock location at the outlet of a tube – *which is clearly not the case*.

So, dear Commissioners, please consider *why* the neglect of hydrogen diffusion in the models currently used to predict Heq concentrations near the rolled joints of operating pressure tubes, is only a problem for Bruce tubes. And please ask CNSC Staff the following question: What would the inclusion of thermal diffusion effects in its Heq pickup models do to the Heq predictions for Pickering and Darlington Units? Or are we to believe that the circumferential diffusion of hydrogen only occurs in Bruce pressure tubes?

For over 50 years the Canadian nuclear industry has adopted the terms and conditions set out in CSA Standards N285.4 and N285.8 to ensure the fitness for service of pressure tubes in operating CANDU reactors. Now, to avoid the consequences of being in non-compliance with these time-honored Standards, Bruce Power has requested that the CNSC change Bruce Power's operating licence by simply dropping these Standards. However, should the CNSC choose to go along with this precedent setting licence amendment, it would clearly demonstrate to the world that the CNSC is willing to pander to a reactor operator's wishes and, in this particular instance, allow Bruce Power to continue operating reactors that have already proven to be unpredictable and subject to a poorly understood degradation mechanism.

And may I ask the Commissioners to please remember what the CNSC stated in September 2018 in regards to Bruce Power's 2018 Licence Renewal Application, (My emphasis in red):

> *CNSC staff confirmed Bruce Power's information and reported that the current fracture toughness models did not support Bruce Power's request to be able to operate any pressure tube with an [Heq] in excess of 120 ppm….. The Commission notes that pursuant to Licence Condition 15.3, approval by the Commission will be required for Bruce Power to operate with pressure tubes in excess of 120 ppm of [Heq]. CNSC staff further added that, should pressure tube [Heq] in any Bruce NGS reactor Unit reach 120 ppm and that the proposed fracture toughness model was not ready in time or not accepted by the CNSC, Bruce Power would have to shut down the reactor or shut down the reactor to start the refurbishment earlier.*

Dear Commissioners, may I ask that you uphold the CNSC's 2018 ruling on the 120 ppm limit on pressure tube Heqs, as spelled out in the above paragraph, and insist that:

(i) Bruce Power provide a new fracture toughness model which is accepted and validated by the CNSC *before* any Bruce Units are allowed to opearate.

(ii) Bruce Power provide a *root cause report* to explain how and why the rate of H/D entry is accelerating near some pressure tube rolled joints, leading to elevated levels of H/D – levels that exceed the 120 ppm CSA N285.8 limit.

Dr. F. R. Greening
April 12th, 2023