Canadian Nuclear Safety Commission
Commission canadienne de sûreté nucléaire

CMD 23-M3

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Written submission from CNSC Staff

Follow up from November 3, 2022 Commission Meeting

Responses to the questions from the External Advisory Committee regarding the update on the discovery of elevated hydrogen equivalent concentrations in the pressure tubes of reactors in extended operation

Commission Meeting

January 25, 2023

Mémoire du personnel de la CCSN

Suivi découlant de la réunion de la Commission du 3 novembre 2022

Réponses aux questions du Comité consultatif externe au sujet de la mise à jour sur la découverte de concentrations élevées d’hydrogène équivalent dans les tubes de force des réacteurs en exploitation prolongée

Réunion de la Commission

Le 25 janvier 2023

Canada

Canadian Nuclear Safety Commission
Commission canadienne de sûreté nucléaire
Government of Canada
Gouvernement du Canada

MEMORANDUM **NOTE DE SERVICE**

To
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Denis Saumure
Commission Registry
c.c.: R. Jammal, P. Elder, M. Rickard, M. Hornof, J. Burta, R. Richardson, V. Tavasoli, T. Nitheanandan, Y. Akl, B. Carroll, S. Yalaoui, C. Harwood, N. Kline, A. Robert, D. Carrière

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Date	Tel. No. - Nº de tél.
November 24, 2022	N/A

From
De

Alex Viktorov
Director General, Directorate of Power Reactor

Recoverable Signature

X

Subject
Objet

CNSC Staff Response to the External Advisory Committee Questions Regarding CMD 22-M37

Purpose

During the November 3rd, 2022 Commission Meeting regarding the update on the discovery of elevated hydrogen equivalent concentrations (Heq) in the pressure tubes of reactors in extended operation, the Commission directed CNSC staff to provide responses to the questions and comments posed by the external advisory committee (EAC) in regard to CMD 22-M37. The EAC questions and comments are documented in CMD 22-M37.8, "*Written submission from the External Advisory Committee*".

This memo provides CNSC staff's written responses to the EAC questions.

In addition to the responses to the EAC questions, CNSC staff have included Appendix A, which summarizes the role of Heq in the pressure tube fitness for service evaluations for pressure tube flaws. Appendix A was prepared in response to comments from the Commission requesting additional clarity regarding the different models that are potentially affected and how those models interact.

Responses to EAC Questions

EAC Question #1 (ref. p. 20, last paragraph, of CMD 22-M37):

> *"probabilistic evaluations ... (of fracture protection and leak-before-break) ... lack of evidence that ... appropriate for all PTs". Is the use of probabilistic assessments by the licensees in their current CMDs consistent with the Staff concern on applicability? – see for example OPG p. 12 item 3E*

CNSC staff response:

Until the licensees have completed the research and development activities related to Heq modelling, crack initiation and confirmation of the applicability of the fracture toughness model for material with elevated Heq, the results of the probabilistic assessments will not be relevant for flaws near the burnish marks. The approach described in the CNSC staff CMD 22-M37 will be the regulatory basis for continued operation of pressure tubes in extended operation as discussed in the response to Question #5. This approach does not use the results of the probabilistic assessments.

In the meantime, for the evaluation of flaws elsewhere in the pressure tubes, the probabilistic assessments are required to be consistent with the conditions that have been put in place to address Staff’s concern with the fracture toughness model. The licensees also have the option to undertake additional work to demonstrate to staff that the range in the fracture toughness distributions are appropriate for all pressure tubes. If successful, CNSC staff will remove the conditions on the use of the model for probabilistic assessments.

EAC Question #2 (ref. p. 22 of CMD 22-M37):

> *When the Risk Significance level is judged to be tolerable for 2-3 years, is that based on the projected rates of flaw and [Heq] progression or is it a “time at risk” argument? – “Time at risk” arguments are fraught with problems*

CNSC staff response:

At the time that the CNSC staff CMD 22-M37 was prepared, the RIDM assessment had just been completed. Since that time, further discussions have led to a proposed revision of the report, which includes an adjustment to the Bruce A timeframe from 2 years to 3 years of continued operation.

The period of 3 years is recommended by CNSC staff in a very conservative way, and it is based on the following 3 elements.

1. The first element is the consideration of defence in depth: It is demonstrated that Level 3 DiD is not affected following a Pressure Tube failure. In other words, the special safety systems will perform their intended functions to ensure that dose limits will not be exceeded in the event of a PTF. There is no risk of dose to the public.
2. The second element is the consideration of the recent licensees’ results of surveillance tests of pressure tubes activities which have demonstrated consistent behaviour with respect to elevated Heq.
3. The 3rd element is the consideration of the PSA results which showed that incremental risk increase due to pressure tube failure is very low. CNSC staff have run 3 sensitivity cases by increasing the frequency of the pressure tube failure up to one order of magnitude, and all results show that the incremental risk is very low.

> The recommendation for the 3 years of continued operation is based on very conservative assumptions and approximately matches the period of the ongoing licensee R&D to demonstrate the fitness for service. This time frame could change if new information warrants a reassessment.

EAC Question #3 (ref. p. 23, point 2, of CMD 22-M37):

> *"Material surveillance ... by removing ... pressure to provide a statistically significant sample size". What is the statistical level that must be met, and how many pressure tubes would be needed to satisfy this level? – Representing a population of several hundred pressure tubes in a unit requires a large number of samples, a major impact on the MCR or refurb*

CNSC staff response:

CNSC staff acknowledge that "statistically significant sample size" may not have been the best choice of phrasing. The intent was to mean a large enough sample sufficient to provide the desired confidence in validity of predictive models. At the time that the CNSC staff CMD 22-M37 was prepared, the RIDM assessment had just been completed. Since that time, further discussions have led to a proposed revision of the report, which includes the following change to Recommendation #2:

> *Licensees should undertake material surveillance activities by removing and testing pressure tubes during upcoming Refurbishments/MCRs, to provide an appropriate sample size in order to validate updated Heq models in the ORJ and IRJ regions.*

It is expected that the results of the R&D program will provide guidance regarding the number of surveillance tubes that will be appropriate. The revised Heq models should identify tubes that are most likely to be impacted by the phenomenon leading to elevated Heq near the rolled joints, which should reduce the population of tubes that are at risk.

EAC Question #4 (ref. p. 23, Section 4, of CMD 22-M37):

> *When is the RIDM report going to be issued?*

CNSC staff response:

CNSC staff will be issuing the report to licensees by January 2023.

EAC Question #5 (ref. p. 23, Section 4, of CMD 22-M37):

> *"... industry's R&D plans are in the right direction ...". But are the expected completion dates acceptable? – Completion dates are after most units have reached end of life*

CNSC staff response:

CNSC staff understood that it would take at least a couple of years to develop and validate Heq models to address the findings near the rolled joints. During this period, it would not be possible for CNSC staff to confirm that the compliance verification criteria that was traditionally adopted for pressure tube fitness for service would be satisfied in the ORJ and IRJ areas of interest.

To address this concern CNSC staff looked into alternate means of assessing the impact on nuclear safety that would accomplish the comparable objectives to the traditional approaches. For the outlet rolled joint region of pressure tubes, the alternate compliance verification criteria related to the likelihood of the presence of flaws was used. This approach could also be applied to the inlet region of the Pickering pressure tubes in extended operation. For the inlet region of pressure tubes for the Bruce Power and Darlington reactors, the Risk Informed Decision Making approach was used. These alternate approaches cover the timeframe that licensees have proposed for the key deliverables for the R&D plans, so the expected completion dates are acceptable.

CNSC staff recognize that many units will enter refurbishment prior to completion of the R&D project. Most of the Darlington units have entered refurbishment outages before they reached the same operating life in terms of Equivalent Full Power Hours that was achieved with Bruce Unit 6. The alternate approaches discussed above are sufficient to address operation to end of life of the Darlington units. On the other hand, current plans have Bruce Units 7 and 8 operating for several years beyond the completion dates in the R&D plans. The longer operating units are the primary focus of the R&D efforts.

EAC Question #6 (ref. p. 25 of CMD 22-M37):

> *The restriction on "front end" of tubes is 100 ppm if at the outlet and 80 ppm if at the inlet. The licensee CMDs quote the 120 ppm limit, but not the more restrictive "front end" limits. What is the number (estimated or measured) of tubes which fail to meet these higher limits?*

CNSC staff response:

The Revision 2 fracture toughness model application is limited to 100 ppm for front end material whether it is at the inlet or outlet end of the pressure tubes. The 80 ppm value was the limit for the Revision 1 model and no longer applies.

Half of the pressure tubes in Bruce Unit 3 are installed front end outlet. For the other reactors in extended operation, the pressure tubes are installed front end inlet.

However, until the issues associated with Heq modelling and the validity of the fracture toughness for the material with elevated Heq are addressed, CNSC staff do not consider the traditional approaches to fitness for service that use the fracture toughness model to be applicable near the burnish marks. The alternate approaches for assessing safe operation discussed in the CNSC staff CMD 22-M37 and the response to Question #5 are used instead.

Appendix A

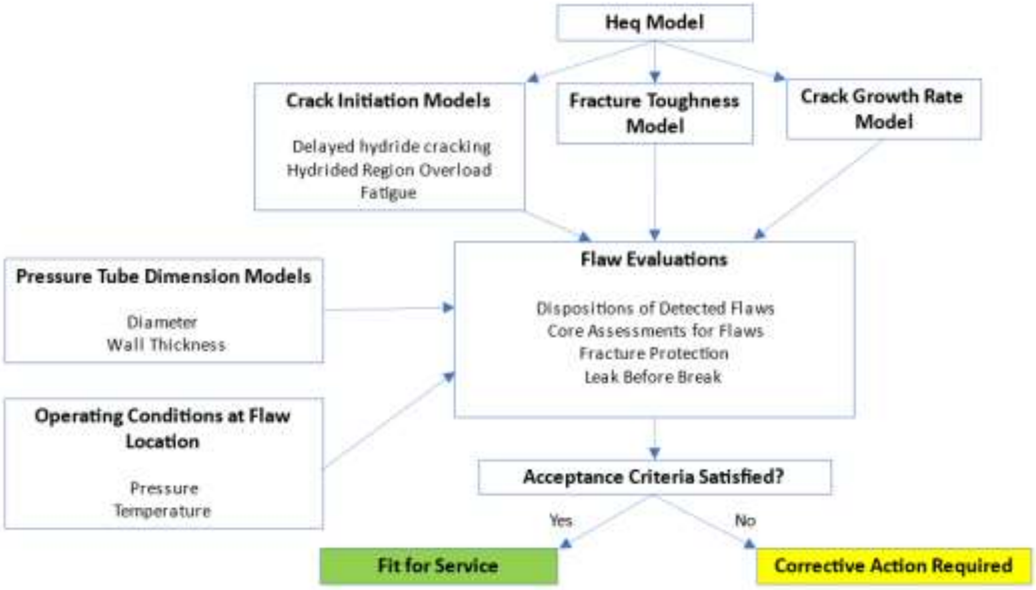
This Appendix is included in response to comments from the Commission requesting additional clarity regarding the different models that are potentially affected and how those models interact. It summarizes the role of Heq in the pressure tube fitness for service evaluations for pressure tube flaws.

Overview of Fitness for Service Evaluations for Flaws

The block diagram shown in Figure 1 below provides a general overview of how fitness for service is typically assessed by licensees for pressure tubes with flaws and the role of the Heq model predictions in that process. The following provides a brief description:

- The Heq model predicts a probability distribution for the Heq value at the location of the flaw. For deterministic evaluations (for example, dispositions for detected flaws) a lower bound value of Heq is selected from the distribution. For probabilistic flaw evaluations, the full distributions are used. These results feed into the crack initiation models, the fracture toughness model and the crack growth rate model.
- These three models are used in conjunction with models related to changes in pressure tube dimensions and the operating conditions to evaluate the impact of the pressure tube flaws for a specified operating period.
- Various flaw evaluations are performed in order to determine if all of the fitness for service acceptance criteria, detailed under licence condition 6.1 in the LCHs, have been satisfied. If the acceptance criteria are satisfied, pressure tube operation can continue for the specified operating period without restriction. Otherwise, corrective actions would be required, which could include shortening the operating period, replacing affected pressure tubes or shutting down the reactor.
- For the current situation, with regions of elevated Heq near the burnish marks, the uncertainty in the output from the models that predict and rely on the Heq in the pressure tube prevent definitive conclusions from being made regarding satisfying the acceptance criteria. Alternate approaches have been adopted on a temporary basis, as discussed in CNSC staff CMD 22-M37, to assess the impact of pressure tube flaws near the burnish mark on safe operation. The descriptions on the following pages present key issues that need to be addressed from the elevated Heq findings that would allow licensees to return to the process presented in Figure 1 for pressure tubes in extended operation.

Figure 1: Overview of fitness for service evaluations for flaws in pressure tubes

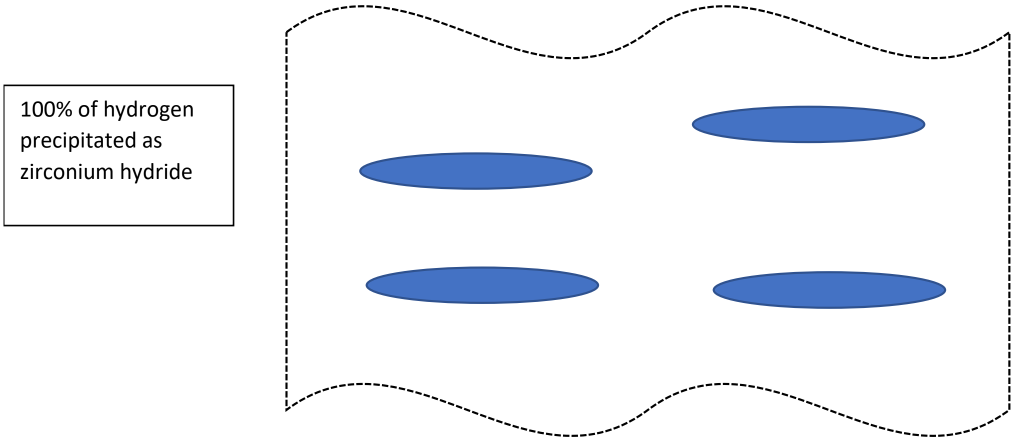


Updating Heq Models

Simple diffusion models related to temperature and concentration gradients may not be sufficient to model Heq gradients at elevated levels of Heq.

Consider material that operated with the average Heq = 100 ppm. When the unit is shut down the pressure tube is at a uniform temperature of 35^{o}C and the solubility limit for the material is 0 ppm. As a result, all of the Heq will be in the form of zirconium hydrides that are uniformly distributed through the material as depicted in Figure 2 by the blue ellipses.

Figure 2: Pressure tube material with 100% of hydrogen in form of solid hydrides at low temperatures



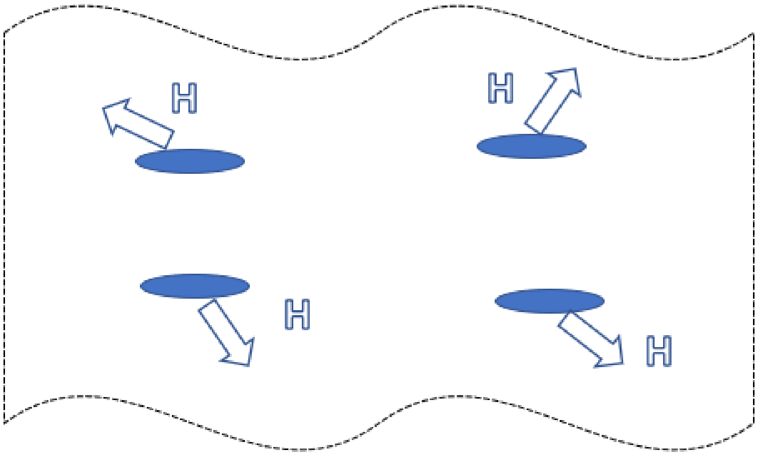
Uniformly increasing the temperature to the full power operating temperatures (which is nominally 300^{o}C at the outlet end, depending on the reactor), the solubility limit for the material increases to approximately 60 ppm. At this point, 40 ppm remains in the form of zirconium hydrides and 60 ppm enters the material in solution form, as illustrated in Figure 3.

Solubility limits are different when heating and cooling the material. When cooling the material, it will become supersaturated with hydrogen so all of the 60 ppm of soluble hydrogen that was released will not turn back into solid zirconium hydrides until the temperature is lowered to about 240^{o}C.

The preceding discussion assumes that the hydrogen is evenly distributed throughout the material, the material is uniformly heated or cooled and the stress is uniform in the material. When temperature and stress gradients are introduced, the situation becomes more complex. Hydrogen will be attracted to locations of lower temperature and higher stress. The Heq model uses information related to the ingress of hydrogen along with temperature and stress gradients to predict the movement of hydrogen in the material. However, the current Heq model does not predict the regions of elevated Heq near the rolled joint burnish marks that have been observed in pressure tubes in extended operation.

Figure 3: Release of hydrogen into solution as temperatures increase

40% of hydrogen remains as zirconium hydride, 60% free to diffuse ("in solution")



The current theory being proposed by licensees considers the potential for local regions of the pressure tube that are cooler than others when the reactor is at full power. So, for example if the temperature at the bottom of the pressure tube is 300°C and at the top of the pressure tube it is slightly lower at 290°C, the soluble hydrogen will be attracted to the cooler material at the top of the tube. This will potentially increase the amount of hydrogen at the cooler spot. If the material has an average Heq = 100 ppm, approximately 60 ppm would still go into solution, but some of the soluble hydrogen will diffuse to the colder spot. Moving hydrogen to the colder part of the tube will have a similar effect as cooling the material so the cool spot will become supersaturated.

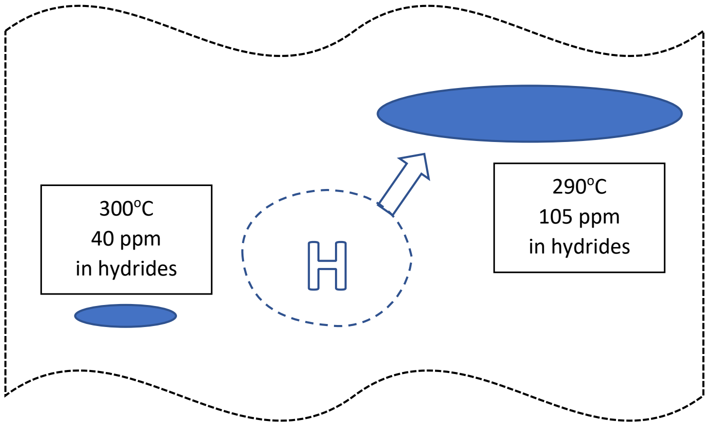
The solubility for cooling the material to 290°C is about 105 ppm. If sufficient hydrogen moves to this location to locally increase the concentration to this value, then hydrides will start to form at the cool location and become fixed. This process will lead to a variation in the Heq between the warmer and the cooler part of the pressure tube as illustrated in Figure 4. Then when the material is cooled further during a shutdown, all of the remaining soluble hydrogen will form hydrides. As more hydrogen is added to the material and thermal cycling continues with shutdown and restart cycles additional hydrogen can build up in the cooler parts of the pressure tube, locally elevating the Heq even further because only a fraction of the solid hydrides can be redissolved.

CNSC staff will consider the following when reviewing licensees' modelling activities:

- Does the modelling reproduce the Heq gradients that were measured in the in-service pressure tubes with elevated regions of Heq?
- Can the Heq gradients be explained by temperature, concentration and stress gradients alone or is there an indication that alternate sources of hydrogen ingress into the material are required?

- Do the regions of elevated Heq continue to expand axially and circumferentially and, if so, by how much?
- Can the model explain why only some tubes appear to be affected?

Figure 4: Potential impact on redistribution of hydrogen due to temperature gradients



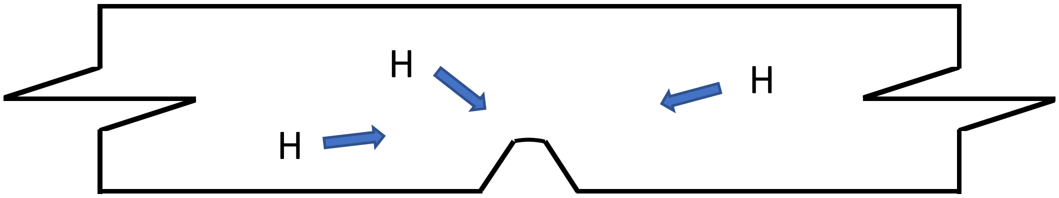
Verification of Delayed Hydride Cracking Initiation Model for Material with Elevated Heq

An overview of the potential effects of elevated Heq on crack initiation from delayed hydride cracking is presented below.

At 300°C, the solubility limit for Heq in pressure tubes is about 60 ppm. There will be no zirconium hydrides present during normal operation at Heq levels below 60 ppm.

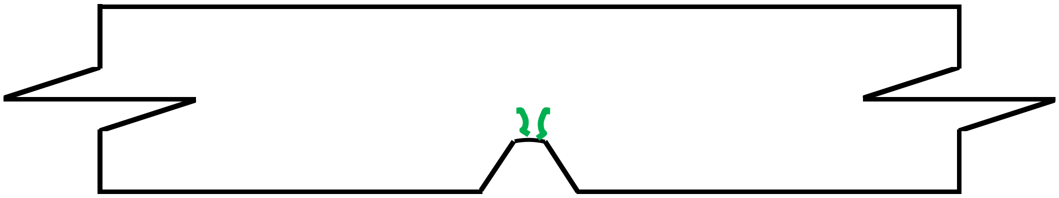
Introducing flaws on the ID surface of the pressure tubes will lead to local stress concentrations and hydrogen will diffuse to locations of higher stress (see Figure 5).

Figure 5: Pressure tube material with low Heq during full power operation



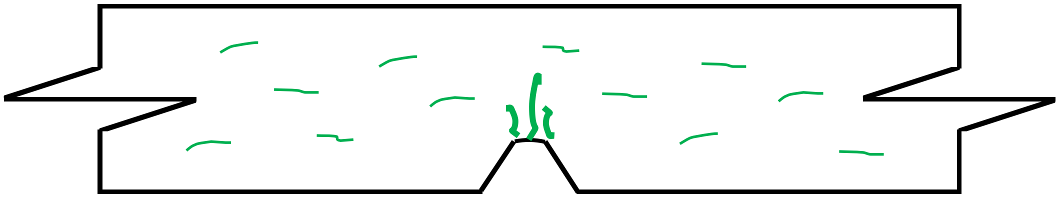
If the Heq at the flaw tip exceeds the solubility limit locally, solid zirconium hydrides will form at the tip of the flaw (see Figure 6). If the hydrides at the flaw tip grow large enough a crack will occur.

Figure 6: Pressure tube material with low Heq during full power operation with hydrides forming at flaw tip



The formation of flaw tip hydrides is most likely to occur during reactor cooldown because the solubility of hydrogen decreases with decreasing temperature. Below 50°C, no hydrogen remains in solution. All soluble hydrogen will precipitate out in the material and hydrides at the flaw tip will increase in size (see Figure 7). If the hydrides at the flaw tip grow large enough a crack will occur.

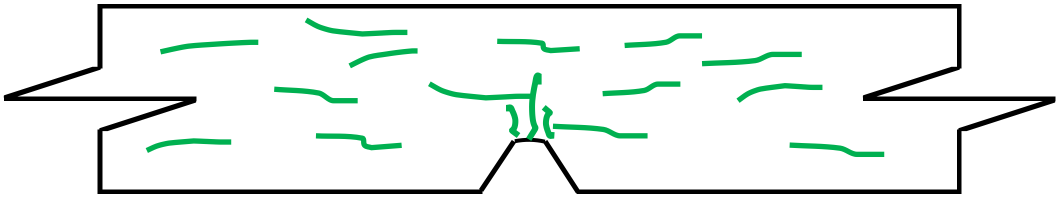
Figure 7: Pressure tube material with low Heq during shutdown with hydrides forming throughout the material and larger hydrides at flaw tip



When Heq increases to around 100 ppm, not all of the Heq will be in solution during full power operation and the material would appear similar to Figure 7 at temperatures around 300°C. At most only 60 ppm could be in solution and 40 ppm would remain in the form of solid hydrides.

At elevated Heq levels (i.e. 240 ppm) there would be more and larger hydrides at all temperatures (see Figure 8).

Figure 8: Pressure tube material with elevated Heq with larger hydrides forming throughout the material and larger hydrides at flaw tip



From the perspective of the planned crack initiation research, CNSC staff will expect the scope of work to assess whether the presence of the elevated Heq levels and larger hydrides in the material increase the potential for crack initiation.

With respect to crack growth rate models, this work is considered to be secondary in priority to the crack initiation research currently underway. It will be expected that once the crack initiation research is complete, the need to assess potential impacts of elevated Heq on crack growth rate modelling will be determined.

Potential Impact of Elevated Heq on Fracture Toughness Modelling

Figure 9 illustrates the fracture toughness behaviour of pressure tube material for a given Heq value. At low temperatures the material would behave in a predominantly brittle manner. In the transition temperature regime, the fracture toughness increases with increasing temperature and the material transitions from brittle behaviour to fully ductile behaviour. In the upper shelf regime the maximum toughness is achieved, the material behaves in a ductile manner and the fracture toughness remains constant with temperature.

Operating procedures restrict the internal pressure while the reactor is starting up and shutting down to maintain adequate fracture resistance in the transition temperature regime and at low temperatures. The temperature for the change from the transition temperature regime to the upper shelf regime should be less than the full power operating temperature to ensure the material behaves in a ductile manner during full power operation.

Figure 9: Fracture toughness behaviour for pressure tube material for a given Heq value

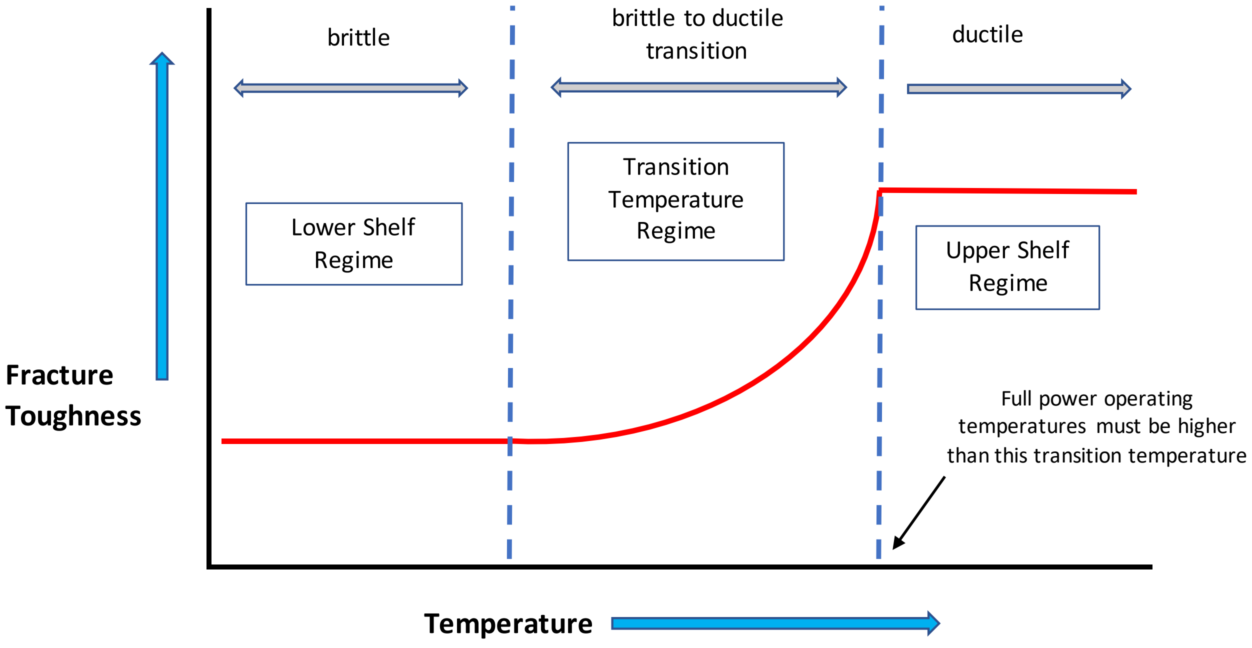


Figure 10 illustrates what happens to the fracture toughness when the material Heq increases. In the transition region, the fracture toughness reduces for a given temperature and it is also possible for the temperature for the change from the transition temperature regime to the upper shelf regime to increase.

Additional testing of material with higher Heq values is necessary to confirm that the shift in the fracture toughness will not impact safe operation of pressure tubes while starting up and shutting down the reactor and provide confirmation that the temperature for the change to upper shelf behaviour remains below the full power operating temperature.

Figure 10: Effect of increasing Heq on pressure tube fracture toughness