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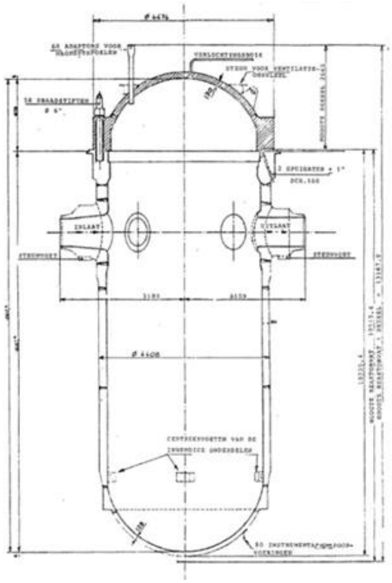

Doel 3 and Tihange 2 issue
International Review Board
Final Report

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Content

Executive Summary

FANC Part

During the outage of the Doel 3 nuclear power plant in June 2012, an in-service inspection revealed the existence of numerous quasi-laminar indications in the reactor pressure vessel. Comparable, yet fewer, indications were found three months later in the Tihange 2 reactor pressure vessel after a similar inspection.

In May 2013, the Belgian Safety Authorities finalized the review of the safety justification of the two RPVs proposed by Electrabel. The two reactors were then restarted. However, to complement the safety cases, the Belgian Safety Authorities requested the licensee Electrabel to fulfil several requirements (mid-term actions) during the first cycle of the two reactors (before May 2014).

In this framework, in March 2014, the licensee Electrabel informed the Belgian Safety Authorities that a mid-term action showed an unexpected behaviour of the tested flaked material. Consequently, the licensee decided to anticipate the planned outages of the two reactors by two months as a precautionary measure. This mid-term action was the evaluation of the evolution of the mechanical properties under irradiation. Some specimens from a flaked material similar to the steel of the RPVs had been irradiated in a research reactor at SCK•CEN, Belgium. The unexpected behaviour consisted in an embrittlement higher than expected on the basis of the current scientific knowledge while the material hardening remained in line with the literature expectations.

The licensee decided to run additional irradiation campaigns in April and July 2014 and in February 2015 in order to understand this unexpected phenomenon and confirm or discount the licensee hypotheses for justifying this behaviour. Taken into account the time necessary to realize the irradiation campaign (about 1 month) and the time necessary to realize the mechanical tests and to analyse the results, the last test results on this issue were transmitted to the Belgian Safety Authorities between March and April 2015.

The Belgian Safety Authorities asked an International Review Board to conduct an independent assessment of this unexpected behaviour and to evaluate the transferability of this result to determine the mechanical properties of the RPVs of Doel 3 and Tihange 2. The Belgian Safety Authorities provided the International Review Board with technical reports on the issue and organized two workshops to discuss this issue. The first meeting was organized in the beginning of November 2014. Following this first meeting, the IRB released its preliminary report concluding that the licensee studies were not yet mature enough. IRB consequently asked for complementary information. The Licensee Electrabel provided this information in the beginning of 2015. A second meeting was therefore organized in April 2015. The present document presents the final evaluation following this second meeting and the conclusions of the International Review Board.

IRB Part

The IRB considered the approach proposed by Electrabel for estimating the fracture toughness bounds for the Doel 3 and Tihange 2 RPV core shells to a 40 year life. It was not within the Board's remit to assess the other aspects of the structural integrity assessment. However, its judgements on the fracture toughness issues were made in the context of the size of the residual margins between the fracture toughness bound and the calculated crack driving forces presented by Electrabel in the safety case. The IRB assumes that the materials property data, the defect distributions and the crack driving force values presented to it, are correct or conservative.

The IRB assessed the fracture toughness aspects of the safety cases on the basis of their scientific and engineering soundness, rather than whether they conform fully to the codes and practices of any particular country. Codes and practices can differ between countries for design, operational, technical and historical reasons; what is important to the IRB is whether the methods used by Electrabel are adequate to ensure structural integrity, from a technical perspective, in the context of the Doel 3 and Tihange 2 RPV core shells. Conversely, by accepting a particular method, the IRB does not imply that it would necessarily be acceptable in other cases, in Belgium or elsewhere, or that it is accepted in the codes and practices of any specific country.

In the judgement of the majority of Board members, and based on the information available to it on 24th April 2015, there are no major concerns with the approach proposed by Electrabel for estimating the fracture toughness bounds for the Doel 3 and Tihange 2 RPV core shells to a 40 year plant life. One member of the Board, however, remains concerned that the residual margins in the safety case are inadequate. The reasons for these concerns are given in Appendix B

The IRB's assessment was made by considering four separate factors; the majority Board opinion on each of these is as follows:

- The IRB considers that the proposed method of estimating the shift of fracture toughness due to irradiation is adequately conservative. The shift is estimated in a way that is not inconsistent with the approaches used in other countries, but also includes an allowance (bias) to take into account the possibility that the unexpectedly high irradiation embrittlement found for the VB395 steam generator shell material might also apply to the Doel 3 and Tihange 2 RPV core shells. In the opinion of the Board, VB395, in terms of irradiation embrittlement, is most likely to be an anomalous and unrepresentative material. It considers that the addition of the bias, though not yet proven, is probably unnecessary.

- The uncertainty margin on the estimated end of life toughness bound has been estimated in a way that is consistent with the approach used in other countries. This uncertainty margin combines allowances for uncertainties in beginning of life toughness and for uncertainties in the effect of irradiation. The approach used by Electrabel to calculate the uncertainty margin is not inconsistent with those used in other countries. However, the Board has a minor concern that the uncertainties in the beginning of life toughness bound might be too small relative to the possible difference in toughness properties between the location from which test data were obtained and the macro-segregated regions of the vessels, which contain the hydrogen flakes. However, it considers that any such underestimate is likely to be mitigated by the probably unnecessary addition of the bias added for the anomalous embrittlement of VB395 material.

- The toughness bound used in the case was defined using the well-established and widely used ASME RT_{NDT} approach. The robustness of this was demonstrated by Electrabel by showing that the use of the more recently introduced ASME RT_{T0} approach produces similar residual margins on the overall safety case. The residual margins calculated by Electrabel are high in terms of both temperature and crack driving force, providing considerable confidence that they are adequate relative to any unknown factors that might affect the toughness bounds.

- The root cause of the anomalous irradiation embrittlement in VB395 has not been clearly identified, despite a significant amount of work done in consultation with another international expert group. However, the IRB accepts the conclusion of this work that the effect is not due to a hydrogen, or a hydrogen-flaking, related mechanism. The IRB is not fully convinced with the Electrabel conclusion that the mechanism is a form of non-hardening embrittlement, but does not regard this as a concern since it does not consider the behaviour of VB395 to be relevant to the Doel 3 and Tihange 2 core shells.

Although the majority of the members of the Board consider that further work is not necessary, it suggests that the case could be strengthened by assessing internationally-available data on fracture toughness variations in forgings, and by assessing the use of the Master Curve to define the fracture toughness lower shelf. In addition, further work to resolve the root cause would be valuable to strengthen the case and ensure that similar problems to those encountered for VB395 can be avoided in future steels production.

Preface by Belgian Federal Agency for Nuclear Control

During the 2012 outage at the Doel 3 nuclear power plant (NPP) operated by Electrabel, which is a GdF-SUEZ Group Company, specific ultrasonic (UT) in-service inspections were performed to check for underclad cracking in the reactor pressure vessel (RPV), following the feedback experience of Tricastin[1]. No underclad defects were found but a large number of quasi-laminar indications were detected mainly in the lower and upper core shells.

A second inspection was performed in July 2012 with UT probes able to inspect the whole thickness of the vessel. This inspection identified a large number of such indications deeper in the material. A similar inspection performed in September at the Tihange 2 NPP showed similar indications but to a lesser extent. Following those inspection results that indicated a potential safety concern, the Doel 3 and Tihange 2 NPPs remained in cold shutdown while the licensee performed an engineering evaluation to determine if either NPP can be safely returned to service. This safety demonstration has been presented to the Belgian Safety Authorities as two safety cases, in the beginning of 2013.

The Safety Authorities required a short-term action plan and a mid-term action plan to confirm some assumptions of the safety cases. The short-term actions were due for a decision on a restart while the mid-term actions were due during the first cycle of the two NPPs. Following the analysis of the result of the short-term action plan by the Belgian Safety authorities, Electrabel received the authorization to restart the two power plants in May 2013. More information on this subject can be found on the Federal Agency for Nuclear Control (FANC) – website. For completeness, the 16 requirements asked by the Belgian regulatory body are repeated here:

N°	Requirement	Status
1	The licensee shall reanalyse the EAR acquisition data for Tihange 2 in the depth range of 0 to 15 mm in the zones with hydrogen flakes to confirm whether or not some of these technological cladding defects have to be considered as hydrogen flakes.	Short-term
2	The licensee shall demonstrate that no critical hydrogen flake type defects are expected in the non-inspectable areas.	Short-term
3	The licensee shall demonstrate that the applied Ultrasonic Testing (UT) procedure allows the detection of the higher tilt defects in the Doel 3/Tihange 2 data (2012 inspections) with a high level of confidence.	Short-term
4	The licensee shall present the detailed report of all macrographical examinations including the sample with the 45°T reflections and shall also analyse and report additional samples with 45°T reflectivity.	Short-term
5	The licensee shall include a set of defects partially hidden by other defects for macrographic examination, to confirm whether the sizing method continues to function well.	Short-term
6	The licensee shall re-analyse the tilts of the defects in the block VB395/1 with the same method as applied on-site.	Short-term
7	The licensee shall achieve a full qualification program to demonstrate the suitability of the in-service inspection technique for the present case. The qualification shall give sufficient confidence in the accuracy of the results with respect to the number and features (location, size, orientation…) of the flaw indications. Where appropriate, the process shall be substantiated by appropriate experimental data using representative specimens. The full qualification program shall be achieved before the next planned	Mid-term

[1] Tricastin is a French Nuclear Power Plant.

	outage for refuelling.	
8	The licensee shall perform follow-up in-service inspections during the next planned outage for refuelling to ensure that no evolution of the flaw indications has occurred during operation.	Mid-term
9	The licensee shall complete the material testing program using samples with macro-segregations containing hydrogen flakes. This experimental program shall include: small-scale specimen tests (local toughness tests at hydrogen flake crack tip, local tensile tests on ligament material near the flakes) and large scale (tensile) specimen tests (see also §9.3.2)	Short-term
10	The licensee shall perform additional measurements of the current residual hydrogen content in specimens with hydrogen flakes, in order to confirm the results of the limited number of tests achieved so far. For example, the licensee has estimated an upper bound on the amount of residual hydrogen that might still be present in the flaws. The licensee should demonstrate that the chosen material properties are still valid, even if the upper bound quantity of hydrogen would still be present in critical flaws.	Short-term
11	A further experimental program to study the material properties of irradiated specimens containing hydrogen flakes shall be elaborated by the licensee.	Mid-term
12	The licensee shall further investigate experimentally the local (micro-scale) material properties of specimens with macro-segregations, ghost lines and hydrogen flakes (for example local chemical composition). Depending on these results, the effect of composition on the local mechanical properties (i.e. fracture toughness) shall be quantified.	Mid-term
13	The licensee shall further evaluate the effect of thermal ageing of the zone of macro-segregation	Mid-term
14	Taking into account the results of the actions related to the previous requirement on the detection of higher tilt defects during in-service-inspections, the licensee shall evaluate the impact of the possible non reporting of flaws with higher tilts on the results of the structural integrity assessment.	Short-term
15	The licensee shall complete the ongoing test program by testing larger specimens containing hydrogen flakes, with the following objectives: *Objective 1 :* Tensile tests on samples with (inclined) multiple hydrogen flake defects, which shall in particular demonstrate that the material has sufficient ductility and load bearing capacity, and that there is no premature brittle fracture. *Objective 2 :* An experimental confirmation of the suitability and conservatism of the 3D finite elements analysis.	Short-term
16	In addition to the actions proposed by the licensee and the additional requirements specified by the FANC in the previous sections, the licensee shall, as a prerequisite to the possible restart of both reactor units, perform a load test of both reactor pressure vessels. The objective of the load test is not to validate the analytical demonstration on the reactor pressure vessel itself but to demonstrate that no unexpected condition is present in the reactor pressure vessels. The methodology and associated tests (acoustic emission and ultrasonic testing...) will be defined by the licensee and submitted to the nuclear safety authority for approval. The acceptance criterion will be that no crack initiation and no crack propagation are recorded under the pressure loading.	Short-term

Table 1 : Lists of the 16 requirements (in grey, still ongoing actions)

However, on March 25th 2014, the licensee Electrabel informed the Belgian Federal Agency for Nuclear Control (FANC) that the preliminary tests of one of the mid-term actions (Action #11) had given unexpected results. This action concerns the evolution of the mechanical properties of a flaked material under irradiation. The chosen flaked material steel from which some specimens were irradiated in the Belgian research reactor BR2 at SCK•CEN, came from an AREVA steam generator (VB395) similar but not identical to the Belgian RPV steel. The mechanical tests on irradiated pieces had shown unexpected discrepancies between the material properties: the material embrittlement appeared to be greater than expected from the existing trend curves from the literature while the material hardening appeared to be in line with the licensee's predictions. Consequently to this higher than expected irradiation induced embrittlement, the licensee Electrabel decided to anticipate the planned outages of the two reactors as a precautionary measure.

The licensee has studied in details the test results from this first irradiation campaign in order to explain these unexpected mechanical properties after irradiation. As the advanced investigations confirmed the unexpected behaviour of the flaked material, the licensee Electrabel planned a second irradiation campaign in April 2014 in order to answer the various questions raised by this issue and eventually confirm or discount some potential explanations. This second irradiation campaign has confirmed the unexpected behaviour and without any explanation of the non-hardening embrittlement phenomenon that appeared in the VB395 flaked material. At that stage, the preliminary results from the irradiation of some unflaked specimens from the VB395 but also from the nozzle cut-out of Doel 3 and the surveillance program during this second campaign brought some indications that the unexpected behaviour seems to be limited to the flaked area of the VB395 material. A third irradiation campaign was launched in July 2014 in order to study the material properties from various pieces at lower fluence and deepen understanding of the non-hardening irradiation issue.

Electrabel continuously keeps the Belgian regulatory bodies informed on the RPV issue in Doel 3 and Tihange 2. The evolution and the results of the ongoing studies are continuously reviewed by the Belgian safety authorities. However, because of the high technical complexity of the irradiation issue, its very specific scientific area and of its impact on the safety demonstration of the two reactors, FANC decided to submit the licensee's results and analysis to a panel of international scientists, experts in the field of radiation damage mechanisms and/or mechanical testing. These experts were gathered in an International Review Board (IRB). The Board's composition differs from the International Expert Review Board (IERB) gathered in 2012-2013 by the Belgian Safety Authorities. Indeed, the requested expertise was even more specific than asked for the IERB in 2012-2013 for the review of the structural integrity of the two RPVs. The composition of this expert panel is detailed in Section 6.

In September 2014, Electrabel gave advanced notice to the FANC on its approach to integrate, in the revaluation of the safety cases of the two RPVs, the unexpected irradiated mechanical behaviour of the flaked VB395. To take into account this unexpected additional embrittlement in the safety demonstration, Electrabel presented a methodology justifying the transferability of the unexpected additional embrittlement under irradiation from the VB395 to the RPV's properties.

To assess the acceptability of this methodology and to review the unexpected irradiation results, the FANC requested a meeting of the international experts. Given the very specific scope of the required review, this International Review Board met from November 3th to November 7th, 2014.

The International Review Board summarized its conclusions on the unexpected mechanical behaviour and on the transferability of the results to the two Belgian RPVs in the preliminary report of the IRB, issued to FANC on December 2014. The IRB concluded that the evidence presented by the licensee were not sufficient to confirm at that stage the acceptability of the transfer methodology.

The IRB made several suggestions to the licensee in order to deepen their comprehension of the issue and then consolidate or invalidate the acceptability of the methodology.

In December 2014, the Belgian Safety Authorities reached in parallel to IRB similar conclusions and estimated that at that stage the transfer methodology was not mature enough to be accepted by the Safety Authorities. In consequence, FANC required Electrabel to fulfil several additional studies in order to strengthen the proposed methodology.

A short time before the IRB workshop of November 2014, Electrabel brought some evidence indicating that contrarily to the first analyses the unexpected behaviour of the VB395 in the flaked area extends also in the area far from the macro-segregation zones where are located the hydrogen flakes.

Since the IRB workshop of November 2014, Electrabel has continued its analysis of the unexpected phenomenon and deepened its understanding of the root cause of the over expectation irradiation induced embrittlement. In particular, the licensee focused its additional work on another flaked material, referenced as KS02, which came from a German research program performed in the 80's. In this framework, a fourth irradiation campaign took place in February 2015 in order to irradiate some samples from this material. The licensee also deepened their investigations on the particular manufacturing and forging of the VB395 in order to provide an explanation of the unexpected embrittlement of this flaked material.

By the end of March 2015, the licensee Electrabel had finalized their answers to all recommendations and most suggestions issued by the IRB and the Belgian Safety Authorities. Electrabel concluded from their studies that the VB395 material was affected by an unexpected and not yet fully explained phenomenon, not related to the presence or the origin of the hydrogen flaking. Electrabel considers in consequence that there are no reasons for a similar phenomenon to be present in the RPV core shells of Doel 3 and Tihange 2.

FANC proposed then a second workshop in order to position the IRB experts on the impact of these new developments on the acceptability of the Electrabel transfer methodology.

This second workshop took place from April 22th to April 24th in Belgium. During this meeting, the Belgian Regulatory Body gave the licensee Electrabel and its technical supports on this issue (Tractebel, Laborelec and SCK•CEN) the opportunity to present and explain the current irradiation issue. Similarly, the Belgian Safety Authorities presented their concerns to the IRB and provided the experts with the two topics to be assessed during this meeting.

The present report summarizes the final conclusions of the IRB on the unexpected mechanical behaviour and on the transferability of the results to the two Belgian RPVs.

Analysis by the Belgian Regulatory Body

Due to the complexity of the issue and its safety relevance, the Belgian Regulatory Body decided to follow an exceptional process for the review and the analysis of the RPV issue. The process mainly consists in reviewing the licensee's approach for demonstrating the safety before reviewing in details its application and the associated results presented in the safety cases. The aim of this approach is to give the Regulatory Body's opinion on the licensee's approach as soon as possible to permit additional information or alternative approaches to be developed by the licensee.

The first step of the review by the Belgian Regulatory Body is then the analysis of the approach proposed by the licensee. The meeting of the International Review Board is in line with this first step and focus on the transferability of the irradiation test results into the justification of the RPV's structural integrity. The Belgian Safety Authorities are performing their own review on the irradiation issue in parallel to the International Review Board. Indeed, this transferability method is a key point of the safety cases for the Belgian Regulatory Body.

In the same time, the Belgian Safety Authorities are reviewing the Electrabel conclusions on the other still on-going mid-term actions (see table 1, above), required to be fulfilled before the restart of the two reactors: the formal UT qualification of the MIS-B device and the follow-up of the RPV inspections.

The second step of the review by the Belgian Regulatory Body will start whenever the licensee's approach has been considered as acceptable and the details on its applications have been transferred by the licensee to the Safety Authorities. The second step will focus then on the analysis of the applications of the methodology and detailed calculations.

1. Scope of this document

The Belgian Regulatory Body has gathered the International Review Board in the framework of the review process of the flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2, following the unexpected behaviour of material properties under irradiation.

The scope of this review (initially described in the terms of reference of the IRB, see in Appendix A) is restricted to the assessment of the unexpected behaviour of mechanical properties of a flaked material similar to RPV's under irradiation and focuses on the transferability of these material properties into the safety demonstration of the structural integrity of these RPV's. This review does not aim to consider other potential challenges to the reactor primary circuit integrity or to the safety of these NPPs in general.

In order to put the unexpected behaviour into a global context, the International Review Board was given a summary of the structural integrity assessment and of the UT inspection results, performed by the licensee Electrabel.

The scope of the International Review Board is first the evaluation of the licensee results concerning the material properties, in particular the evolution under irradiation of the mechanical properties of a material, similar to the steel of the reactor pressure vessel. In this framework, the International Review Board has reviewed the results of the four irradiation campaigns and the various material investigations realized by the licensee in order to assess the unexpected behaviour.

In a second part, the International Review Board has reviewed the transferability approach proposed by the licensee in order to evaluate the reactor pressure vessels properties on the basis of the results from the tested materials. This transfer methodology needed to take into account the unexpected results of the Action 11 of the mid-term requirements requested by the Belgian regulatory body.

In a third part, the International Review Board has assessed a concern of the Belgian Regulatory Body on the results of the Action 15 (Large Scale Tensile) on mechanical properties of non-irradiated material. This part was already closed by the end of the first IRB meeting. The conclusions were presented in the preliminary report of the IRB and are no more considered in this final report.

The Board had the opportunity to examine documents developed by the licensee, and to discuss with the licensee's experts on issues related to the acceptability of the transferability of the results as these may affect the final conclusion of the Board. The conclusions of the Board are based on the documentation provided by the licensee before the meeting, copies of presentation and verbal information provided during the meeting. The Board presumes that all information provided in these reports is correct.

2 Basis of the IRB Assessment

FANC requested that the IRB address two specific topics:

> **T1.** *Assessment of the predicting formula for the transition temperature shift as proposed by Electrabel for use in the structural integrity evaluation of the Doel 3 and Tihange 2 RPV core shells and in prevention of brittle failure (P-T limit curve, PTS). In particular, the transferability of the results of the tests performed on the (French) VB 395 material and (German) KS02 material to the Doel 3 and Tihange 2 RPV core shells material shall be assessed.*
>
> **T2***. Assessment of the following Electrabel conclusion on the root cause analysis: precise mechanism of NHE and precise root cause of NHE of VB395 remain unidentified but hydrogen-related and hydrogen-flaking related mechanisms are excluded.*

The IRB addresses these in Section 3 of this report; this section provides background to the assessment.

2.1 Context, technical basics and terminology

There is no single worldwide practice for producing safety cases (SCs) to justify RPV operation. However, all countries use a broadly similar process, and broadly similar methods within each part of the process. In general, the methods used for RPVs are simply a special case of well-established engineering methods, based on fracture mechanics, which are used to ensure the safety of a wide range of structures. Over time, advances in engineering and computer technology have made more accurate methods available. In general, the older methods are more conservative than the newer ones. For this reason, new methods are not used routinely to re-analyse existing structures. In the event that a new method is to be used, it must usually be approved by the national regulator responsible, and accepted into that country's codes and standards before it sees widespread use. In the nuclear industry safety is paramount and, as a result, the approval process is cautious and lengthy. For these reasons, and because different countries have reactor fleets of different ages and designs, the methods used to justify safe RPV operation can differ to some extent from country to country.

The members of the IRB are from seven different countries and have wide experience not only of the methods used within the Electrabel SC, but also of acceptable alternative methods, which are formally approved by some, but not necessarily all, national regulators and engineering advisory and standards organizations. IRB members have assessed the elements of the SC discussed in this report on the basis of their scientific and engineering judgement of whether or not the methods and assumptions used could be regarded as conforming with, or would be potentially acceptable into, nuclear regulatory codes and safety assessment practices. However, the Board's acceptance of an element of the case does not imply that it is necessarily accepted into the codes and practices of any individual country. Furthermore, the conclusions in the present report are endorsed only by the IRB, and would not necessarily be endorsed by the organizations that employ its members.

The IRB assessment contained in this report is based on the information provided to it on or before 24th April 2015. This information was provided in technical documents made available to it before its second meeting, and in the presentations and responses to questions made to it during the meeting, which ended on that date. The information provided gave the context and scope of the proposed Electrabel Safety Case, which at that time had not been formally submitted to FANC, and information and argument to be potentially used in support of it.

As for all RPVs, the SC for the Doel 3 (D3) and Tihange 2 (T2) RPVs requires Structural Integrity Assessment (SIA) to demonstrate that there is an extremely low likelihood of brittle failure. It is not the purpose of this report to describe how an SIA is carried out in general, nor to describe the specific approach and methods used by Electrabel. These are well-known and documented in the Electrabel reports and in standard texts, including regulatory codes and standards. However, a brief summary is provided in the remainder of this section to ensure that the understanding of the Board and the terminology within this report are clear.

SIA comprises three main elements, which are described in the current context most simply as: estimation of the defect sizes in the component; estimation of the crack driving forces (defined here as the crack opening mode stress intensity, K_I) that could potentially initiate brittle fracture from those defects; and estimation of the resistance of the material to those forces (K_{Jc}), more loosely described as its fracture toughness (FT). The IRB remit was to accept the first two of these elements as “black boxes” (that is, not to assess their accuracy or appropriateness, but to focus on the materials (FT) aspects of the case). For each of the RPV upper core shell (UCS) and lower core shell (LCS) in D3 and T2, an estimate is required of the lower bound K_{Jc} (hereafter designated K_{LB}) after irradiation. If the K_I for any defect were to reach a value as high as (K_{LB}) there would be a small chance that fracture would initiate. However, this chance is mitigated by the requirement of regulatory codes to estimate values of both K_I and K_{LB} conservatively. The derivation of K_{LB} values and the issue of safety margins are discussed in the following paragraphs.

As described in its technical documents, Electrabel estimated K_{LB} using the widely used American Society of Mechanical Engineers (ASME) Code K_{IC} or K_{IR} curves. The shape of these curves is the same for all RPV steels, but the location of the curve relative to temperature varies within and between components. In the standard ASME practice, the location of the curve with respect to temperature is fixed by determining the value of a reference temperature parameter, RT_{NDT}.

In ASME-based approaches, the RT_{NDT} used in an SC, $RT_{NDT(SC)}$, is estimated by determining the RT_{NDT} of the component at beginning of life (BOL), $RT_{NDT(BOL)}$, and adding the estimated increase in RT_{NDT}, ΔRT_{NDT}, due to irradiation damage for the age (service usage) of the RPV up to which the SC is to apply. A margin is also added to account for uncertainties, M_U, in the estimates of $RT_{NDT(BOL)}$ and ΔRT_{NDT}.

$$RT_{NDT(SC)} = RT_{NDT(BOL)} + \Delta RT_{NDT} + M_U \qquad \text{(Eqn 1)}$$

In forgings such as those in D3 and T2, $RT_{NDT(BOL)}$ is normally determined by testing Charpy V-notch (CVN) and drop-weight nil-ductility transition temperature (NDT) specimens taken from material machined from one end of the component. ΔRT_{NDT} depends on neutron fluence (F), which varies with location in the RPV (F generally produces insignificant embrittlement beyond the core shell region). At any given location, ΔRT_{NDT} increases not only with F, but also depends on materials factors including the chemical composition of the steel and its microstructure. ΔRT_{NDT} is normally estimated using CVN specimens to determine the increase in the temperature at which a specified amount of energy is absorbed. This is known as the ‘irradiation shift’ or ‘Charpy shift’ and is denoted by ΔCV. Values of ΔCV for an SIA are generally estimated from ‘trend curves’ fitted to previous surveillance data from a fleet of RPVs of similar design and materials, or based on material heat specific surveillance test data.

For the D3 and T2 core shells, Electrabel has generally followed the above practice, with RT_{NDT} estimated by testing component material, and ΔRT_{NDT} estimated using the French RSE-M trend curve, which has been shown to be applicable to Belgian RPV steels. However, an additional shift,

Δ_{VBUx} has been added to allow for the possibility that the unexpectedly high irradiation sensitivity[2] found in the VB395 steam generator shell material might also apply to the macro-segregated (MS) and the macro-segregated and hydrogen flaked (MSF) regions of the D3 and T2 shells:

$$\Delta RT_{NDT} = \Delta_{RSE\text{-}M} + \Delta_{VBUx} \qquad \text{(Eqn. 2)}$$

Where:

$\Delta_{VBUx} = \Delta_{VB395/B6BF(meas)} - \Delta_{VB395/B6BF(RSE\text{-}M)}$

$\Delta_{RSE\text{-}M}$ is the predicted shift for the core shell considered using RSE-M

$\Delta_{VB395/B6BF(meas)}$ is the measured shift in VB395, Block 6 between flakes

$\Delta_{VB395/B6BF(RSE\text{-}M)}$ is the RSE-M predicted value for the VB395 macro-segregated zone between flakes

The value of Δ_{VBUx} used in the SIA is assumed in the SC to be an upper bound estimate for any additional shift in the MS and MSF regions of D3 and T2. The empirical evidence for this assumption is presented in Electrabel technical documents. In addition, Electrabel (through Laborelec, which worked in consultation with a number of external experts), concluded that the unexpectedly high embrittlement in VB395 is not due to hydrogen flaking or any other hydrogen-related mechanism. The precise cause has not been identified, but is, they believe, a form of non-hardening embrittlement (NHE) due to either segregation of impurities to carbide or precipitate interfaces with the matrix, or to loss of strength of the segregation matrix; possibly interacting.

Electrabel estimated the value of M_U by combining the uncertainties in the estimation of $RT_{NDT(BOL)}$ and ΔRT_{NDT}, assuming that these are independent of each other, which is common practice. The uncertainty in $RT_{NDT(BOL)}$ accounts for measurement uncertainty, but assumes that the values obtained by testing materials from one end of a core shell are representative of the rest of the shell. The uncertainty on ΔRT_{NDT} is taken to be the standard deviation associated with the RSE-M trend curve.

For a safety case to be acceptable, a margin, in this report described as the residual safety margin, M_R, must exist between the K_I and the K_{LB}. M_R could be expressed as the difference between the K_I and the K_{LB} at the temperature at which these values are closest, or as the temperature difference between K_I and K_{LB} at closest approach during a transient. K_I and K_{LB}, and hence M_R, vary with crack tip location, RPV age and loading, and the SIA is developed to find the minimum values of M_R and demonstrate that these are above zero. As described earlier, regulatory codes require that K_I and K_{LB} be estimated conservatively such that, even with an M_R of zero, the probability of failure is incredibly low. Therefore in a safety case, when the calculated M_R is small there must be a very high level of demonstrable confidence that the values of K_I and K_{LB} contain an appropriate degree of conservatism and that no unknown factors have been overlooked. Conversely, if the value of M_R is large, it can be appropriate to substitute a degree of expert judgement for direct experimental evidence. It should be noted that M_R is usually an underestimate of the overall safety margin M_O. This is because, if M_R is acceptable, it is not necessary to estimate K_I and K_{LB} to the least degree of conservatism acceptable in codes, and it would waste resource to do so.

[2] Irradiation sensitivity is used to denote the rate of increase of irradiation shift with fluence; irradiation shift is the change since BOL.

While the ASME Code RT_{NDT} approach is widely used and has an indirect fracture mechanics basis, it is being replaced, or is allowed to be replaced, in some regulatory frameworks by a more direct fracture mechanics approach. There are two main alternatives. In the first, which is allowable within ASME, RT_{NDT} is replaced by the parameter RT_{T0}, $RT_{T0} = (T_0 + 19.4°C)$. This allows the ASME K_{IC} curve to be indexed using the Master Curve (MC) fracture toughness reference temperature T_0. The latter provides more accurate indexing than RT_{NDT}, an accuracy that justifies the removal of unnecessary conservatism; at the same time the RT_{T0} approach maintains continuity with the original technical intent of the ASME Code. The other alternative is to use a full MC approach in which the ASME K_{IC} curve is replaced by a MC bound. The ASME Code, Section XI, has recently approved Code Case N-830, which allows this replacement using a 5% lower tolerance bound to the MC.

2.2 IRB approach to the assessment

The FANC topics (T1 and T2) to be discussed by the IRB concerned the irradiation shift part of the FT estimation process. However, the IRB considered that it was appropriate to assess this in the context of two other issues. The first was the BOL FT. The main reason for discussing this was that correct estimation of the BOL toughness is as important (Eqn. 1) to SIA as estimation in the shift in FT. In addition, there can potentially be interactions between BOL toughness and shift, both because of materials factors and also because of the ways in which they are measured. The second issue was the residual safety margin M_R between K_I and K_{LB}, which as discussed above, impacts the degree of judgement that is acceptable. The IRB also deviated somewhat from its remit to treat the other parts of the safety case as a "black box". Although the three elements of SIA are generally independent, and the responsibility of different technical specializations, there can potentially be some interface issues.

The FANC topics were, appropriately, open-ended. This allowed the IRB to assess for itself the key elements within each topic, and to scrutinize the case for gaps and inconsistencies.

2.3 Limitations to the scope and applicability of the IRB assessment

As stated in the IRB's terms of reference, it is the IRB's responsibility to provide expert advice (on the topics identified at the beginning of Section 2), but FANC's responsibility to decide whether or not it is safe to resume operation of the RPVs. The IRB was not asked to provide an opinion on the acceptability of the Electrabel SC, and residual safety margin, R_M, nor did it have the technical information which would have been required in order to do this.

The IRB assessment was carried out in the context implicitly and explicitly defined in the Electrabel technical documents and presentations provided, and with the assumption that the information provided is correct. In particular, the assessment is applicable only to the core shells of the Doel 3 and Tihange 2 RPVs for the defect distribution and crack driving forces identified to the IRB, and up to the 40-year fluences identified in the Electrabel technical documents. Although small changes to the context, information or understanding are unlikely to affect the IRB assessment significantly, it is possible that they could.

2.4 Definition of IRB levels of concern

To reduce the chance of misinterpretation of its assessment, the IRB has used the following terminology:

- **Major concern:** one that must be resolved by further work before the Electrabel approach could be considered to be acceptable

- **Minor concern:** further work is not required but could probably increase confidence in the safety case. Such work would be very unlikely to reduce M_R to an unacceptable level.
- **Acceptable or adequate:** there is confidence that a method or element of the safety case has been sufficiently well demonstrated , in the context of the residual safety margin in the case, M_R, as estimated by Electrabel, that no further work on this method or element is required.
- **Observation:** an issue that the IRB considers potentially important in the context of the SC, but which is outside its remit, and was not presented in the detail required for the IRB to reach a judgement.

The IRB's use of any of the above terms does not mean that it would necessarily agree that the case would remain acceptable should it be subsequently shown that the margins are smaller than have been presented to it. The IRB assessment is of whether acceptable conservatism exists, not the degree of conservatism.

3 Results of the IRB Assessment

3.1 Beginning of life toughness

The IRB considers that the Electrabel approach to estimating BOL fracture toughness is adequate, but with a minor concern, which is discussed at the end of this section.

The IRB considers the key factors as:

a) The BOL FT bound has been estimated using the ASME Code approach with RT_{NDT} values estimated by testing material taken from one end of each shell. The ASME K_{IC} curve is widely regarded as acceptably conservative to low temperatures relative to RT_{NDT}. The value of the absolute lower shelf is, however, a little non-conservative. Alternative methods of defining K_{LB} have addressed this issue in different ways. For example, the RSE-M Code now uses a modified ASME K_{IC} curve that bounds all lower shelf data. The ASME Code itself treats the issue through operational procedures, for example through low temperature overpressure protection (LTOP) set-points. The ASME Code also accepts an alternative methodology using the MC 5% tolerance bound. Whether or not the ASME K_{IC} lower shelf is conservative for use within the D3 and T2 safety cases can only be assessed by comparing the K_I versus temperature curves for the most limiting transients against alternative approaches to defining K_{LB}, taking into account the potential inhomogeneity of the core shell material. However, since the temperature margins and the driving force margins are large (see Section 3.4), the absolute magnitude of the lower shelf is probably not significant. However, the IRB does not have the SIA data required to evaluate this issue, which is in any case outside its remit. It therefore records the lower shelf toughness issue as an **observation**.

b) Although no testing was possible on the segregated and flaked regions of the core shells in D3 and T2, the IRB considers that the RT_{NDT} values for the available material have been estimated adequately:
    i. On the basis of composition and manufacture, the values for the four shells would be expected to be similar.
    ii. All test results on D3 and T2 materials are not inconsistent with the expectation from b) i. above: the BOL RT_{NDT} and T_0 values for nozzle shells and core shells of D3 do not differ by more than 15°C and 13°C, respectively. Similar observations were made for T2.

iii. The differences in BOL T_{41J} and in BOL T_0 between segregated and unsegregated zones in the D3 nozzle shell cut-outs are equal to 6°C (for T_{41J}) and -8°C (T_0), respectively.

iv. The differences in plastic flow properties between segregated and unsegregated zones in the D3 nozzle shell cut-outs are small.

c) Although a segregation effect was observed in KS02, where a 47°C difference was observed in CVN transition temperature between segregated and non-segregated zones, the IRB judge that it is not necessary to apply this to D3 and T2, given that the extra VB395 shift (Δ_{VBUx}) is considered in the estimation of the RT_{NDT} at the end of life:

i. The available evidence (in b) above) suggests that there is little effect of segregation on the BOL properties of D3 and D2. KS02 is a significantly different steel (high Ni and Cr) from D3 and T2 and a much larger and thicker forging (approximately 770 mm cf approximately 200 mm). These factors are expected to produce greater inhomogeneity in BOL properties due to greater segregation.

ii. Although it is possible that there is a greater degree of segregation in the flaked regions of D3 and T2, compared with that in the D3H1 nozzle cut-out, these are relatively small forgings and any detrimental effect of this in the near-surface (less than quarter thickness) region should, unlike the case of KS02, be mitigated by the more effective heat treatment normally associated with this region.

iii. A study by Electrabel, at the request on the IRB, has compared the effect of assuming that the KS02 segregation effect applies but the VB395 shift does not with the same SIA case assumptions (no segregation effect on BOL, but the extra VB395 shift applies). The difference between the two cases is small with the SIA case more conservative at the EOL fluence.

iv. Even if both factors (i.e., the effect of segregation on initial RT_{NDT} and the added embrittlement sensitivity observed in VB395) were to apply, the residual safety margin, M_R, on RT_{NDT} would be about 30°C.

d) The use of the ASME or any other FT approach implicitly assumes that the tip of a crack behaves like a fatigue pre-crack used in fracture toughness testing. There is no reason to believe that a hydrogen flake would behave more adversely from a fracture mechanics point of view than a fatigue pre-crack or any other type of defect in an RPV steel. There is no evidence for a ‘flake effect’ in the experiments on VB395 with flake as pre-crack, or with pre-cracked specimens extracted in between flakes; the variations of T_0 between these types of specimen are below 15°C (with CT12.5 specimens).

Although the IRB considers that the Electrabel approach to estimating BOL FT is adequate, it considers that further work could be done to strengthen the case, and records a **minor concern.** This issue is that the Electrabel approach assumes that the variability in BOL RT_{NDT} within a core shell is fully accounted by an uncertainty margin of 8.3°C, derived from experimental and curve fitting uncertainty. This approach is consistent with international practice (and in some cases beyond regulatory requirements). However, there is a possibility, for reasons described above, that the flakes in D3 and T2 are associated with regions where the FT values are systematically lower than the regions of the core shells sampled by more than is accommodated in the uncertainty margin used. Although there is no evidence that the segregation in the D1H3 nozzle cut out has significantly degraded FT, it would be useful to investigate other cases, and, if judged necessary, to add a margin to BOL RT_{NDT}. The Board notes that there have been a number of investigations of the variability of FT in RPV forgings that could provide useful data.

However, one member of the Board feels that the residual margins may be inadequate to accommodate the uncertainties and considers the estimation of BOL toughness is a **major concern**. This is because the degree of the segregation in some shells and particular in the Lower Core Shell of D3 (manifested by the high density of UT indications specifically in the near inner surface region) might be a special condition, which is not covered by the bulk of available experience, including that from the investigation of the non-flaked D3 nozzle cut-out. See Appendix B.

3.2 Shift in the toughness bound

The Electrabel approach assumes that it is conservative to estimate the irradiation shift in the flaked and segregated regions of the D3 and T2 core shells, by adding an allowance Δ_{VBUx} (see Eqn. 2). The acceptability of this assumption rests on the answers to four separate questions:

- Is there an intrinsic effect of hydrogen flakes on irradiation sensitivity?
- Is the irradiation sensitivity of the material surrounding the flakes significantly different from that of the material in segregated regions that do not contain flakes?
- Could the unexpected behaviour of VB395 apply to D3 and T2; if so is Δ_{VBUx} a conservative estimate of it?
- Is the evidence on the effect of irradiation valid, given the difference between the test reactor irradiations performed in Chivas and the power reactor irradiation conditions in D3 and T2?

These are discussed in the following sub-sections.

3.2.1 Is there an intrinsic effect of hydrogen flakes on irradiation sensitivity?

As discussed in Section 3.1, the IRB considers that, for unirradiated material, hydrogen flakes can be modelled in the same way as is any crack using fracture mechanics. The question addressed in this section is whether the processes involved in the formation of hydrogen flakes, or subsequently enabled by their existence, could affect the irradiation sensitivity of material surrounding the tips of the flakes. If that were the case, irradiation shifts measured using CVN or FT specimens on material between flakes could over or under-estimate the shift applicable to fracture initiating from the tip of a flake. The IRB considers that the evidence that hydrogen flakes do not, in themselves, affect irradiation sensitivity is adequate.

a) There is no significant difference in irradiation sensitivity between VB395 specimens containing flakes as pre-cracks and FT specimens with conventional pre-cracks taken from the material between flakes.
b) The formation of a flake involves initiation and rapid propagation followed by arrest, most likely in tougher material beyond the ghost-line. The formation mechanism does not provide the opportunity to change the irradiation sensitivity of surrounding material.

3.2.2 Is the irradiation sensitivity of the material surrounding flakes significantly different from that of the material in segregated regions that do not contain flakes?

Hydrogen flakes are formed in ghost lines and their crack tips (or those of other types of defects) must therefore be: either in ghost lines that did not fully crack (perhaps for reasons of loss of driving force or exhaustion of hydrogen); or in the macro-segregated regions in which the ghost-lines are formed; or, possibly, in the non-segregated material. The case of crack tips in non-segregated material is trivial since the irradiation sensitivity would be that of the bulk material, as represented by the surveillance results. For the other two cases, the IRB considers that it is reasonable to assume that the irradiation sensitivity of material surrounding flakes can be estimated from the irradiation sensitivity of adjacent segregated, but not necessarily flaked, material.

a) In VB395 Block 6, there is no difference in irradiation shift (both ΔT_0 and ΔT_{41J}) between specimens taken between flakes and those taken from adjacent macro-segregated regions. This is not inconsistent with the view that there is nothing 'special' about the macro-segregated material in the flaked region as far as FT is concerned: the flakes were formed in macro-segregated regions only where there were ghost-lines, and sufficient hydrogen and driving forces.

b) The same applies for KS02 material; this is a somewhat different steel to the others so the similarity of the result suggests that the similarity of irradiation sensitivity between MS and MS and flaked regions is not strongly dependent on composition or heat treatment.

c) Although there are no direct measurements of the irradiation sensitivity of ghost-line material, the following points may be made:

    i. The flakes are associated with ghost-lines, but it is likely that most flakes arrest outside the ghost-line in tougher and less-segregated material. Evidence for this is given by the lower average flake orientation with respect to the circumferential direction, compared with the average orientation of the ghost-lines. This suggests that the process is controlled at the time of formation more by the stresses than by the lower toughness in the ghost-lines, and this causes the cracks to deviate slightly from the ghost-lines. For any cracks following a ghost-line it is likely that arrest would occur in the tougher material beyond the end of the ghost-line.

    ii. The testing of irradiated VB395 specimens with flakes as cracks did not produce any anomalously low toughness results that might have been caused by a flake arresting in a ghost-line.

    iii. The MS, but not flaked regions in VB395 and KS02 contained ghost-lines. It is probable that some of the test specimens removed from this position would have been intercepted by fatigue pre-cracks or Charpy notches, but the results appear reasonably uniform.

3.2.3 Could the abnormal behaviour of VB395 apply to D3 and T2; if so is Δ_{VBUx} a conservative estimate of it?

The IRB considers that the behaviour of VB395 is not relevant to D3/T2. In this respect the addition of the Δ_{VBUx} bias, while cautious, is adequately conservative. The principal reasons for reaching this conclusion are:

i. The irradiation shifts for Block 6 of this material with respect to cleavage initiation (though not to crack arrest), are well beyond expectation based on previous studies on material of this type and given that it's composition is generally within the ranges over which the RSE-M trend curve used is expected to be applicable. This conclusion was reinforced by an informal crack arrest study done by a member of the IRB.

ii. The Block 5 irradiation shift is within the RSE-M predictions; no other cases are known to the IRB where part of a forging has such high shift compared with another part. However, at fluences above a 'threshold', the rate of increase in shift with fluence of Block 5 is similar to Block 6; this may be important in the context of understanding the root cause.

iii. VB395 has unusually high unirradiated yield stress compared with other examples of this class of RPV material.

iv. Other detailed characteristics of VB395 are also unusual.

    - There is a very high degree of embrittlement relative to hardening, without evidence for classical NHE such as the fracture surface dominated by grain boundary fracture.

- For both Block 6 and Block 5, cleavage fracture stress reduces with irradiation damage. Such behaviour was not observed for D3 and T2 and other materials reported in the SC. No other cases similar to VB395 are known, but the IRB is not aware of many investigations of this nature.
- The drop in cleavage facture stress in Block 5 suggests that the NHE effect is not necessarily related to the type of segregation that was clearly observable in Block 6.
- On the basis of a number of international studies, the irradiation damage of materials of the same type as VB395 would be expected to be fully recovered by Post-Irradiation Annealing (PIA) at 450°C for 150 hours, but VB395 only recovered about 35% of its irradiation embrittlement. That it was necessary to anneal VB395 material at 610°C for one hour to recover the damage suggests the existence of a hitherto unknown mechanism, potentially involving phosphorus but (from the fractographic evidence) not classical NHE.

v. The above characteristics of VB395 are not observed in the D3 and T2 materials, or in the flaked or segregated regions of KS02. KS02 shifts are predicted well by the new ASTM E900 model, which is based on a wide range of materials including those with relatively high nickel content. They are also within the scatter bound of the RSE-M model, even though its composition range is outside the limits of that model.

vi. There were fabrication difficulties with VB395, including the contamination of the ladle with a previous stainless steel melt, which increased chromium and potentially other minor elements, and the unusual heat treatment cycle. Although there is no direct evidence that these factors were responsible for the unexpected irradiation sensitivity, they can in principle affect microstructure. Differences in microstructure from the norm are implicated in the postulated root cause of the unexpected shift but the microstructural investigations to date have been limited to optical metallography and SEM, which do not have the resolution necessary to identify changes at the nano-structural level. It is well known that irradiation damage in RPV steels is caused by changes at the nanometre scale.

3.2.4 Is the available evidence on the effect of irradiation valid, given the difference between Chivas and D3 and T2 irradiation conditions?

During its meeting in November 2014, the IRB had been concerned that differences in irradiation conditions, in particular the very high fluxes in the Chivas test reactor irradiations used by Electrabel, might invalidate conclusions drawn from test specimens irradiated in that facility. This previous evidence has been strengthened by the work performed since that time. The IRB now considers the evidence to be adequate for the following main reasons:

- The KS02 irradiations show that the high irradiation shift of flaked VB395 material was not caused by the Chivas irradiation conditions.
- A concern that the Chivas results might be affected by the formation of unstable matrix defects has been alleviated by the results of PIA of material at 335°C for 5 hours.
- The results from Chivas irradiations of D3H1, which included macro-segregated material, were similar to the results of other D3 and T2 materials. This is not inconsistent with the assumption that the kinetics of any phosphorus segregation effects in the macro-segregated regions of D3 and T2 materials would be affected by Chivas irradiation conditions.

3.3 Root Cause

As described above, the IRB considers that there is adequate evidence from the testing of VB395 and KS02 materials that hydrogen flakes and the causes of hydrogen flakes were not responsible for the unexpectedly high irradiation shifts in VB395. It also considers that there is adequate evidence, from the hydrogen measurements before and after irradiation, to show that the increased irradiation sensitivity of VB395 was not related to the presence of hydrogen in the material during the irradiation.

The IRB considers that the root cause analysis reinforces the confidence that irradiation shifts in D3 and T2 would not be affected by hydrogen remaining after manufacture. Although the root cause analysis is some way from being conclusive, it is not inconsistent with the evidence from the mechanical property testing that suggests that VB395 is an anomalous material. This anomalous behavior could be related to either non-classical non-hardening embrittlement or some other mechanism.

The experimental evidence on the decrease in cleavage fracture stress and the PIA experiment on highly-irradiated VB395 materials support the idea of NHE. On the other hand, there are some results that are not necessarily consistent with NHE particularly for the materials irradiated to relatively low fluences. The IRB considers that, since the unusual heat treatment that the VB395 material received might have been a cause of the high initial yield stress of VB395, it would be necessary to investigate the contribution of hardening embrittlement directly from the view point of microstructural changes. Transmission electron microscopy and atom probe tomography are the promising techniques for such investigations, and the comparison of the results with the data in literature will allow us quantitative evaluation of the contribution of hardening embrittlement in the VB 395 material.

Nevertheless, the IRB considers that the work done to establish root cause is adequate in the context of the D3 and T2 SC. However, the unexpectedness of the VB395 result might be important in a broader context, and the IRB considers that further work should be done.

3.4 Margins

Topic 1 involves assessment of the acceptability of the method used to transfer test data to the RPVs. Because this is outside usual practice, depends on limited data, and the case itself is exceptional, the assessment requires judgement. As described in Section 2.1, the confidence required in a judgement depends on the residual safety margins, M_R, in the overall SC. For this reason (Section 2.2), the IRB has considered Topic 1 in the context of the overall margins. However, as noted in Section 2.3, the IRB has not assessed values for M_R presented by Electrabel, and judged the acceptability of the FT assumptions on the assumption that these are accurate.

The margin on K_{LB} was derived essentially as required in the ASME code, but with the addition of a bias to allow for the possibility that the additional irradiation sensitivity of VB395 applies to D3 and T2.

Although the IRB has a minor concern that the BOL FT may be underestimated due to differences between the tested and highly segregated regions of the core shells, it is likely that this is compensated for by the over-conservatism of the assumption that Δ_{VBUx} applies to D3 and T2. Furthermore, at the IRB's suggestion, Electrabel had assessed an alternative approach of assuming that the KS02 segregation effect applies to D3 and T2, but Δ_{VBUx} does not. This assessment gave a similar RT_{NDT} for 40 years operation to that used in the SC ($RT_{NDT(SC)}$). This increases confidence in the judgement that the method used to estimate BOL FT is adequate.

Confidence in K_{LB} was also re-enforced by the Electrabel studies of alternative approaches: the use of linear shift increases and the use of an RT_{T0} approach, instead of the RT_{NDT} approach, which the IRB had suggested at the previous meeting.

It is not within the IRB remit to assess the acceptability of the K_I estimates. However, the IRB notes that these are likely to contain conservatisms not reflected in M_R due to conservative assumptions about reactor transients, crack sizes and conservatism in the way in which the equivalent K_I incorporates contributions from Mode II and Mode III loadings.

However, the single most important factor contributing to the IRB's confidence that the materials aspects of the SC are acceptable is that the K_I values for the majority of flakes presented are low compared to the minimum fracture toughness for the material. With one exception they are below the Master Curve lower shelf at approximately the 1% probability level. Given that the MC lower shelf is the same for all steels and is not reduced by irradiation or other materials conditions, the M_{FT} for these defects is independent of RT_{NDT}. For the one defect in D3 where the K_I value is higher than the 1% Master Curve lower shelf, M_R is 80°C relative to the ASME K_{IC} lower shelf factored by $1/\sqrt{2}$. This is a very substantial margin relative to potential unknowns. For T2 there are two cases with higher K_I, and for these M_R is 130°C.

Another factor contributing to the IRB's confidence is a supporting analysis, performed by one of its members, based on crack arrest properties. This alternative analysis demonstrates also the conservatism of the Electrabel toughness estimates.

However, as noted above, one IRB member is not satisfied that the overall margins are adequate for the reasons developed in Appendix B.

4 IRB Conclusions and Recommendations

The IRB has considered the approach proposed by Electrabel for estimating the fracture toughness bounds for the Doel 3 and Tihange 2 RPV core shells to a 40 year plant life.

In the judgement of the majority of IRB members, and based on the information available to it on 24th April 2015, there are no major concerns with the methods proposed for estimating these bounds. One member, however, remains concerned that the overall margins in the safety case may be inadequate for reasons that are given in Appendix B.

The IRB's assessment was made by considering four separate factors; the majority IRB opinion on each of these is as follows

- The method proposed by Electrabel to estimate beginning of life toughness is consistent with the approaches used in other countries. However, the IRB has a **minor concern** that the uncertainty allowance for the values used might be too low. This could be the case if there were an unusually high systematic difference (bias) in toughness properties between the location from which test data were obtained and the regions of the vessels containing the flakes. The IRB has suggested further work that might be done to resolve this, but nevertheless believes that any plausible bias is covered by the residual safety margins, $M_{R,}$ given by the Electrabel technical documents

- The IRB considers that the proposed method of estimating the shift of fracture toughness due to irradiation is adequately conservative. The shift is estimated in a way that is consistent with the approaches used in other countries, but with the addition of a bias to take into account the possibility that the unexpectedly high irradiation shift found for the VB395 steam generator shell material might also apply to the Doel 3 and Tihange 2 RPV core shells. In the opinion of the IRB, VB395 is likely, in terms of irradiation shift, an anomalous and unrepresentative material.

- The overall margins on the estimated end of life toughness bound have also been estimated in a way that is consistent with the approach used in other countries. Alternative approaches to the prediction of the end of life toughness bound, most importantly the use of an RT_{T0} approach, produces similar margins. Given that the proposed margins also include an allowance (bias) for the extra VB395 shift, and given the very low crack driving forces, K_I, the IRB have no concerns with the proposed margins.

- Electrabel/Laborelec, in consultation with another international expert group, has concluded that the unexpectedly high shift in VB395 is not due to hydrogen-related or a hydrogen-flaking related mechanism. The IRB accepts this conclusion. The IRB is not fully convinced that the mechanism is a form of non-hardening embrittlement and considers that more work should be done to investigate the root cause. However, identification of a root cause is not an essential aspect of this analysis because of the IRB's view that the behaviour of the VB395 forging is not representative of the behaviour of the forgings in D3 and T2.

The above judgements are based on the assumption the information provided to it is correct, including that the defect distribution has been correctly, or conservatively, characterized and that the SIA calculations are also not non-conservative. The IRB judgement is only applicable in the context of the specific safety case presented to it:

- Application to SIA of the hydrogen flaking determined by UT examination of the Doel 3 and Tihange 2 upper and lower core shells.

- A maximum fluence of approximately 6 x 10^{19} n/cm^2 (E > 1MeV)
- For use in prevention of brittle failure for Type A/B and Type C/D transients, including pressurized thermal shock (PTS).

Although the IRB considers the methods used by Electrabel to derive FT values for a 40 year RPV life are acceptable, it has two recommendations that it considers would provide it additional strength:

- That the variability in toughness within forgings should be investigated by review of data already available in the open literature, or that can be made available from private sources. The purpose would be to confirm that the uncertainty allowance for start of life is sufficiently large, particularly against the possibility of systematic differences (bias) between the parts of an RPV forging that can be tested and regions in the same forging that may contain high levels of segregation, or other factors that could reduce toughness. An alternative would be to add a margin for this uncertainty.
- That the investigations to determine the root cause should continue with the aim of identifying the factors responsible for the unexpected shift in VB395so that those conditions can be avoided in future steel production.

5. Members of the International Review Board

The International Review board has been gathered by the Belgian safety authorities among scientists, experts in the field of radiation damage mechanisms and mechanical testing. These experts have been selected on the basis of scientific criteria, settled by the Belgian Regulatory Body.

The composition of the International Review Board has been presented to and approved by the Scientific Council of Ionizing radiations.

Composition

International experts

- Tim Williams (UK) – ex Rolls-Royce - **IRB Chairman**
- Isabelle Delvallée-Nunio (France) – IRSN
- Mark Kirk (USA) - USNRC
- Randy Nanstad (USA) - ORNL
- Thomas Pardoen (Belgium) – UCL
- William Server (USA) – ATI consulting
- Helmut Schulz (Germany) – ex-GRS
- Naoki Soneda (Japan) - CRIEPI
- Kim Wallin (Finland) – VTT

Scientific secretaries

- Scientific secretary (Belgium) - FANC

Observers

- William D'haeseleer, observer (Belgium) – Scientific Council
- Michel Giot, observer (Belgium) – Scientific Council
- Jean Vereecken, observer (Belgium) – Scientific Council

- Experts from the Belgian Safety Authorities

Acronyms

Acronym	Signification
AIA	Authorized Inspection Agency
APT	Atom Probe Tomography
ASME	American Society of Mechanical Engineers
ASTM	American Society For Testing and Materials (ASTM International)
Bel V	FANC Technical Support Organization
CFR	Code of Federal Regulations
CVN	Charpy V-Notch (specimen, also material test)
FANC	Federal Agency for Nuclear Control
FIS	French empirical irradiation shift correlation (Fragilisation par Irradiation Supérieure)
FT	Fracture Toughness
FTP	Fracture Transition Plastic
IG	Intergranular
J_{IC}	Plane strain of Fracture toughness as measured by the J-integral at the initiation of ductile tearing
K_{Ia}	Plain strain fracture toughness (for crack arrest) characterized by the K-factor
K_{IC}	Critical stress intensity factor for initiation of cleavage fracture under plain strain; material fracture toughness (at initiation of cleavage) as characterized by the K-factor
K_{cp}	Plastically corrected K
K_{JC}	Fracture toughness determined in a test specimen using the J-integral approach (critical J converted to the equivalent critical K) in MPa √m (as mentioned in ASTM E1921)
K_{min}	Threshold toughness, ASTM E1920 fixed K_{min} at 20 MPa √ m (18.2 ksi √in) for ferritic steels
KS02	German material with flaws potentially due to hydrogen flaking (07/11/2014)
LOCA	Loss-of-coolant Accident
MS	Macro-Segregated
MTR	Material Test Reactor
NHE	Non-hardening embrittlement
NPP	Nuclear Power Plant
RPV	Reactor Pressure Vessel
PIA	Post-Irradiation Annealing
PIE	Post-Irradiation Examination
PTS	Pressurized thermal shock
PWHT	Post Weld Heat Treatment
RSEM	French empirical correlation for irradiation shift
RT_{NDT}	Reference Temperature for Nil Ductility Transition
SC	Safety Case
SEM	Scanning Electron Microscopy
SI	Safety Injection or Structural Integrity
SIA	Structural Integrity Assessment
SINTAP	**S**tructural **INT**egrity **A**ssessment **P**rocedures for European Industry
SMD	Stable Matrix Defects (or Damage)

T_0	Reference temperature for the Master Curve
T_{41J}	Index temperature for the Charpy curve (temperature at which the absorbed energy is 41 Joules)
UMD	Unstable Matrix Defects (or Damage)
UT	Ultrasonic Testing
VB395	An AREVA steam generator shell forging that includes hydrogen flakes
WPS	Warm Pre-Stressing

Table 2: Acronyms

Appendices

A. Terms of reference (2014-04-10) for the International Working Group (IRB) in support of Belgian nuclear safety authorities

Scope

- Follow-up of the long-term action plan concerning the flaw indications found in the RPV of Doel 3 and Tihange 2.
- Evaluation of the results of the long-term actions concerning the material properties of hydrogen flaking (irradiation, fracture toughness,…).

Mission

- Give an expert opinion on the results of the long -term actions concerning the material properties. The final evaluation and decision of potential continued operation of Doel 3 and Tihange 2 remains the responsibility of the Belgian nuclear safety authorities.

Participants

- Members selected by the Federal Agency for Nuclear Control with expertise in material and mechanical properties and having participated to the precedent working groups.
- Expert members proposed by foreign nuclear safety authorities or related organisations (IAEA, NEA, IRSN).
- Technical secretary will be provided by Belgian nuclear safety authorities.

Input

- All relevant documents will be provided through the technical secretary: a complete list of available documents will be provided at the start of the working groups
- Specific presentations can be given by licensee and/or regulatory body on request of the working group

Output

- Meeting reports
- Expert opinion on the results of the long-term actions on material properties (evaluation, questions to the licensee, proposals for additional testing or studies to be performed, …)

Methodology

- Documents distributed by e-mail
- Access to a VPN server of the FANC.
- *Workshop sessions to be defined: One or more workshops can be held in Brussels, with representatives of the licensee and the Belgian nuclear safety authorities present.*

B. Minority concern about the adequacy of the margins in the beginning of life toughness and other aspects of the safety case.

One member of the board does not fully support the IRB assessment, Section 3 and the conclusion, Section 4, on the basis of the following arguments and review of documents supplied after the IRB meeting in April 2015 in response to the minority concerns by Electrabel:

a) The initial fracture toughness values may be not conservative for the zones with a high density of UT indications because these are probably correlated with a high degree of segregation.
b) The content of phosphorus in the D3 and T2 shells is higher than VB395 and KS02 taking the product analysis, which may affect the extent of segregation and the irradiation response.
c) The distribution of near surface indications of the Lower Core Shell in D3 shows a type of truncation which differs considerably from the other shells and need to be explained in conjunction with the basic hypotheses of hydrogen flaking.
d) Based on the type of distribution mentioned above the expert sees no reason why the segregations would not be present up to the surface of the D3 Lower Core Shell affecting the cladding interface material properties. Furthermore it is possible that base metal repairs were made before cladding to remove surface defects in this region and, given the manufacturing practice at the time, not documented.
e) The distribution of indications of the 2014 inspection compared to the 2012 inspection show to some extent a more densely population in the axial direction which could result in a decrease of ligament sizes indicated in and would make it difficult to exclude non-detectable small defects or weak grain boundaries in the ligaments.
f) The expert understands that the stress intensity calculation does not consider residual stresses. These may be present due to manufacturing influences including: heat treatment; the different local microstructures; the formation of the hydrogen flakes; and for the near surface indications the heat affected zone of the weldment of the cladding. It is difficult to assess the values and direction (tensile/compression) during the transient loads.
g) The tilt angle may differ in the different segregation zones and basing the tilt angle on the UT measurements may be too demanding for the UT method for which the validation does not cover the whole spectrum of flake sizes and populations.
h) To rely on the visual inspection to support the assumption of an un-cracked cladding remains as a source of debate considering operating experience.
i) The areas of high density of near surface indications in D3 with the present interpretation of flake sizes could impact the local temperature distribution in transient conditions causing non-uniform stresses in the local ligaments.
j) Some IRB members gained some additional confidence in the case from a supporting crack arrest argument, which was not part of the Electrabel case, but had been suggested by one of the IRB experts. However the use of crack arrest condition may be difficult to validate for the shell areas with a high degree of segregation and flakes. To the knowledge of the expert large scale experiments (e. g. ORNL, MPA, NESC) simulating combined thermal-mechanical loads did not covered material conditions containing similar segregations and flakes and even under less complicated conditions was the extent of crack extension and number of re-initiation not sufficiently predicted.