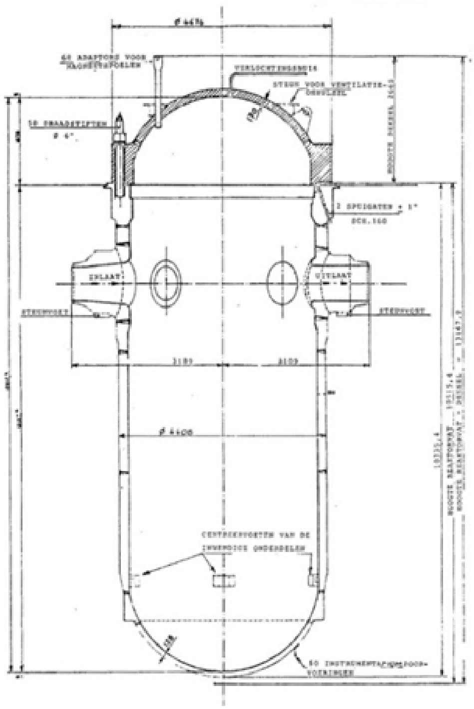

2015

Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2

Final Evaluation Report 2015

FANC

federal agency for nuclear control

FANC-AFCN

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Content

Executive summary

During the 2012 outages of the Doel 3 and Tihange 2 nuclear reactors, specific ultrasonic in-service inspections uncovered the presence of a large number of quasi-laminar flaw indications in the lower and upper core shells of both reactor pressure vessels (RPVs). It was decided that both reactors would remain shut down until the Licensee Electrabel managed to demonstrate to the Federal Agency for Nuclear Control (FANC) that the newly uncovered flaw indications did not affect the safety of both reactors.

Electrabel safety demonstration was recorded in two safety case reports, which were submitted to the FANC in December 2012. In January 2013, the FANC issued a Provisional Evaluation Report that listed a number of short-term requirements, as well as several mid-term requirements. In order to meet these requirements, Electrabel established an action plan consisting of several additional analyses, tests and inspections.

In April 2013, the Licensee submitted two addenda to the safety case reports that provided a structured answer to each of the short-term requirements. An in-depth analysis of these documents by the Belgian nuclear safety authority confirmed that all the safety concerns that were at the origin of the short-term requirements had been solved in a satisfactory manner. In May 2013, the FANC issued a Final Evaluation Report and authorized Electrabel to restart Doel 3 and Tihange 2. Both reactors resumed their electricity production in June 2013.

After the restart, Electrabel was expected to complete its mid-term action plan before the end of the planned outages of April and May 2014. But before they could do so, two actions produced unexpected partial and preliminary outcomes that appeared to challenge the conclusions of the Licensee's safety demonstration. In February 2014, tests performed on the UT inspection device suggested that the flaw indications had not been accurately characterized. In March 2014 a test on the VB395 material (a material representative of the Doel 3 and Tihange 2 RPVs containing hydrogen flakes from a rejected Areva steam generator) showed that irradiation had a bigger impact on the embrittlement of that material than expected. Since these outcomes raised questions about the extent and the understanding of the flaking phenomenon and therefore also about the conservatisms of the safety cases, it was decided in March 2014 to anticipate the planned outages of the two reactors.

Aided by its own and by external experts, the Licensee started an investigation into the impact of the unexpected outcomes on its safety demonstration and made an analysis of whether or not the affected reactor units could safely resume operation. The results of this analysis were recorded in two new 2015 safety case reports, which were backed by a number of technical documents.

Since the scientific issues addressed in the safety demonstration required a highly specialized expertise, the FANC decided to seek the help of various experts groups. Each of these groups would provide their own independent assessment of a specific part of the Licensee's safety demonstration as a complement to the assessments provided by Bel V and AIB-Vinçotte. An International Review Board consisting of renowned experts in the field of reactor pressure vessel mechanics evaluated the methodology proposed by the Licensee to predict the irradiation embrittlement. A National Scientific Expert Group, supported by additional experts, evaluated the hypothesis of hydrogen blistering or hydrogen induced cracking.

A renowned US laboratory, the Oak Ridge National Laboratory, was requested to provide a fully independent advice. ORNL performed a complete evaluation of the material properties and structural integrity assessment, to identify possible errors and to validate the results of the Licensee Safety Cases. ORNL provided its own structural integrity calculations performed with codes and modelling tools different from the ones used by the Licensee. ORNL concluded that the structural integrity of Doel 3 and Tihange 2 is confirmed under all design transients with ample margin.

In November 2015 the FANC completed its safety assessment of the Doel 3 and Tihange 2 RPVs and came to a conclusion. This conclusion was based on the Licensee safety case reports, which were approved by the Licensee's Nuclear Safety Department, and the independent review and evaluation reports of Bel V, AIB-Vinçotte, the International Review Board, Oak Ridge National Laboratory, and the National Scientific Expert Group.

The FANC can now confirm that all the safety concerns that were at the origin of the short-term and mid-term requirements have been solved in a satisfactory manner. After a detailed evaluation of the potential impact of the unexpected outcomes from February and March 2014, the FANC has concluded that the new 2015 safety case reports provide an adequate demonstration of the structural integrity of the Doel 3 and Tihange 2 reactor pressure vessels up to 40 years of operation.

As a result, the FANC authorizes the Doel 3 and Tihange 2 reactor units to resume operation until they reach the age of 40 years.

Presented hereunder are some noteworthy conclusions of the evaluation:

- The most likely origin of the flaw indications identified in the Doel 3 and Tihange 2 reactor pressure vessels is hydrogen flaking due to the manufacturing process.
- The application of a formally qualified UT inspection procedure during the 2014 follow-up UT inspections of the RPV core shells resulted in an updated flake cartography. The number of reported indications is significantly higher than in 2012, which is mainly due to the lowered detection thresholds and to the use of a more sensitive transducer. An update of the flaw sizing procedure resulted in an increase of the flake size to be taken into account in the structural integrity assessment.
- When applying the same parameters and reporting thresholds, a comparison of the data from the 2012 and 2014 UT inspections does not provide evidence for crack growth. A significant evolution of the size of the hydrogen flakes over time due to the stress of operation of the reactor units is deemed unlikely.
- The only theoretical propagation mechanism is low cycle fatigue, which is considered to have a limited effect. Other phenomena (such as hydrogen blistering or hydrogen induced cracking) have been evaluated and ruled out as possible mechanisms of in-service crack growth.

- Considering the VB395 to be an outlier for material behaviour under irradiation, the core shells of Doel 3 and Tihange 2 are unlikely to show the same sensitivity to irradiation embrittlement. Nevertheless, as a safety provision, the Doel 3 and Tihange 2 predictive equations take into account the atypical embrittlement observed in the VB395 flaked material. Therefore the FANC deems the predictive equations for the irradiation embrittlement featured in the 2015 Licensee Safety Cases are acceptable.
- A conservative analysis shows that more than 99.75% of the flaw configurations in the Doel 3 and Tihange 2 RPV shells are harmless in normal or abnormal operating conditions. Based on a refined Licensee analysis of the remaining 0.25%, the FANC concludes that the safety margins are sufficient. These safety margins have been confirmed by the independent structural integrity calculations performed by ORNL.

The FANC requires the Licensee to perform follow-up UT-inspections, using the qualified procedure on the RPV core shells wall thickness at the end of the next cycle of Doel 3 and Tihange 2, and thereafter at least every three years.

Samenvatting

Tijdens de geplande stilstanden in 2012 van de kernreactoren Doel 3 en Tihange 2 werden tijdens ultrasone in-service inspecties een groot aantal quasi-laminaire foutindicaties in de onderste en bovenste ringen van beide reactorkuipen vastgesteld. Er werd toen beslist om beide reactoren stil te leggen tot de exploitant Electrabel kon aantonen aan het Federaal Agentschap voor Nucleaire Controle dat deze nieuw ontdekte foutindicaties de veiligheid van beide reactoren niet zal beïnvloeden.

De veiligheidsdemonstratie werd door de exploitant ontwikkeld in twee Safety Case rapporten die in december 2012 aan het FANC werden overgemaakt. In januari 2013 publiceerde het FANC een Voorlopig Evaluatieverslag waarin een aantal kortetermijnvereisten waren opgenomen. Een beperkt aantal vereisten moest op middellange termijn worden aangepakt. In reactie daarop heeft de exploitant een actieplan uitgewerkt om aan de vereisten van het FANC te voldoen. Dit actieplan bestaat uit een reeks aanvullende analyses, tests en inspecties.

In april 2013 diende de exploitant twee addenda op de Safety Case rapporten in, waarin een gestructureerd antwoord wordt gegeven op elk van de kortetermijnvereisten. Na een diepgaande analyse van deze documenten bevestigde de Belgische nucleaire veiligheidsautoriteit dat alle veiligheidsbekommernissen die aan de oorsprong lagen van de kortetermijnvereisten op een bevredigende manier waren opgelost. In mei 2013 publiceerde het FANC een Finaal Evaluatieverslag en kreeg Electrabel de toelating om beide reactoren opnieuw op te starten. Beide reactoren werden in juni 2013 opnieuw opgestart.

De voltooiing van het (middellangetermijn)actieplan door Electrabel was voorzien voor het einde van de eerstvolgende stilstand die gepland was voor april en mei 2014. Vooraleer dit kan gebeuren, gaven twee acties echter gedeeltelijke en voorlopige resultaten die niet in overeenstemming leken te zijn met de conclusies van de veiligheidsdemonstratie van de exploitant. In februari 2014 suggereerden een aantal tests, die werden uitgevoerd op het UT inspectietoestel, dat de foutindicaties niet correct waren gekarakteriseerd. In maart 2014 leek het VB395-materiaal (een staal dat waterstoffenvlokken bevat en representatief werd beschouwd voor de Doel 3 en Tihange 2 reactorvaten, en afkomstig is van een afgekeurde AREVA stoomgenerator) onder bestraling een onverwacht hogere verbrossing te vertonen dan verwacht. Aangezien deze resultaten vraagtekens plaatsten bij een correct begrip en de omvang van het fenomeen van waterstofvlokken, en dus bij het conservatisme van de Safety Case rapporten, besloot de exploitant in maart 2014 om preventief te anticiperen op de geplande stilleggingen van beide reactoren.

Met de steun van interne en externe deskundigen startte de exploitant een onderzoek naar de impact van deze onverwachte resultaten op de veiligheidsdemonstratie, en stelde een eigen analyse op om te bepalen of de reactoren in kwestie veilig konden worden heropgestart. De resultaten van deze analyse werd in 2015 opgenomen in twee nieuwe Safety Case rapporten, en werd gestaafd door een aantal technische documenten.

Gezien de wetenschappelijke problemen die werden ondervonden bij de veiligheidsdemonstratie een zeer gespecialiseerde expertise vereisten, besloot het FANC om de evaluaties van Bel V en AIB-Vinçotte te onderbouwen met onafhankelijke externe evaluaties van expertgroepen, en dit voor verschillende onderdelen van het betoog van de exploitant. Een "Internationale Review Board" met vermaarde deskundigen op het gebied van reactordrukvat-mechanica evalueerde de methodologie bij de bestralingsverbrossing. Een "National Scientific Expert Group", geholpen door extra experten, evalueerde de hypothese van hydrogen blistering of hydrogen induced cracking.

Een vermaard laboratorium uit de Verenigde Staten, Oak Ridge National Laboratory, werd verzocht om een volledig onafhankelijk advies te verlenen. ORNL voerde een volledige evaluatie uit van de materiaaleigenschappen en de structurele integriteitsberekeningen, met als doel om mogelijke fouten te identificeren en om de resultaten van de Safety Case rapporten van de exploitant te valideren. ORNL voerde eigen structurele integriteitsberekeningen uit met codes en modellen die verschillen van die van de exploitant. ORNL kwam tot de conclusie dat de structurele integriteit van Doel 3 en Tihange 2 wordt bevestigd onder alle ontwerptransiënten, en dit met een ruime marge.

In november 2015 rondde het Federaal Agentschap voor Nucleaire Controle de evaluatie af en kwam tot een conclusie. Deze conclusie was gebaseerd op de Safety Cases die door de exploitant waren ingediend en werden goedgekeurd door het departement Nucleaire Veiligheid van de exploitant, en op de onafhankelijke beoordelings- en evaluatierapporten van Bel V, AIB-Vinçotte, de International Review Board, Oak Ridge National Laboratory en de National Scientific Expert Group.

Het FANC kan nu bevestigen dat de veiligheidsbekommernissen die aan de oorsprong lagen van zowel de kortetermijn- als middellangetermijnvereisten op een bevredigende manier zijn opgelost. Daarnaast heeft het FANC de potentiële impact van de onverwachte resultaten van 2014 grondig geanalyseerd. Het concludeert dat de nieuwe Safety Case rapporten van 2015 een afdoend bewijs leveren voor de structurele integriteit van de reactorvaten van Doel 3 en Tihange 2 voor een werkingsperiode tot 40 jaar.

Als gevolg daarvan geeft het Federaal Agentschap voor Nucleaire Controle de toelating om de reactoren van Doel 3 en Tihange 2 te heropstarten en verder te exploiteren tot een levensduur van 40 jaar.

Enkele vermeldenswaardige conclusies van de evaluatie zijn de volgende:

- De meest waarschijnlijke oorzaak van de foutindicaties die in de reactordrukvaten van Doel 3 en Tihange 2 zijn vastgesteld, zijn waterstofvlokken die het gevolg zijn van het productieproces.
- De toepassing van een formeel gekwalificeerde UT-inspectieprocedure tijdens de follow-up UT-inspecties van de kuipringen van de drukvaten in 2014 resulteerde in een actualisatie van de cartografie van de waterstofvlokken. Het aantal gerapporteerde indicaties is aanzienlijk hoger dan in 2012, voornamelijk als gevolg van een verlaging van de detectiedrempels en het gebruik van een gevoeliger transducer. Een update van de procedure voor

dimensionering van indicaties resulteerde in een toename van de vlokgrootte die moet worden beschouwd in de structurele integriteitsbeoordeling.

- De vergelijking tussen de resultaten van de UT-inspecties van 2012 en 2014, waarbij dezelfde parameters en rapporteringsdrempels worden gebruikt, geeft echter geen scheurgroei aan. Een significante evolutie van de grootte van de waterstofvlokken door de werking van de reactoren in de tijd is onwaarschijnlijk.
- Het enige theoretische mechanisme voor groei is vermoeiing, wat een beperkt effect heeft. Andere verschijnselen (zoals hydrogen blistering of hydrogen induced cracking) zijn geëvalueerd en worden uitgesloten als mogelijke oorzaak van vergroting van scheurtjes in werking.
- VB395 wordt beschouwd als een “outlier” voor materiaalgedrag onder bestraling, en de kuipringen van Doel 3 en Tihange 2 hebben naar alle waarschijnlijkheid niet dezelfde gevoeligheid voor bestralingsverbrossing. Niettemin, wordt als veiligheidsvoorziening de atypische verbrossing die in het staal VB395 is waargenomen mee opgenomen in de voorspellende vergelijkingen voor Doel 3 en Tihange 2. Daarom meent het FANC dat de voorspellende vergelijkingen voor bestralingsverbrossing die werden gebruikt in de Safety Cases van 2015 van de exploitant voor het FANC aanvaardbaar zijn.
- Als resultaat van een ruwe conservatieve analyse is meer dan 99,75% van de foutindicaties in de kuipringen van de Doel 3 en Tihange 2-reactoren onschadelijk in normale of abnormale uitbatingsomstandigheden. Op basis van de verfijnde analyse die door de exploitant werd uitgevoerd op de andere 0,25% concludeert het FANC dat de veiligheidsmarges toereikend zijn. Onafhankelijke structurele integriteitsberekeningen die zijn uitgevoerd door ORNL bevestigen de marges.

Het FANC eist dat de exploitant op het einde van de volgende cyclus van Doel 3 en Tihange 2, en daarna ten minste elke drie jaar, follow-up UT-inspecties op basis van de gekwalificeerde procedure uitvoert op de kuipringen van de reactorvaten.

Résumé

En 2012, à l'occasion des arrêts planifiés des centrales nucléaires de Doel 3 et Tihange 2 exploitées par Electrabel, des inspections en service par ultrasons ont détecté un nombre élevé d'indications de défauts d'orientation quasi laminaire dans les viroles supérieure et inférieure des cuves des deux réacteurs. Il a été décidé à l'époque que les deux réacteurs resteraient à l'arrêt le temps que l'exploitant arrive à démontrer à l'Agence fédérale de Contrôle nucléaire à l'aide d'analyses approfondies que ces indications de défauts nouvellement découvertes n'affectent pas la sûreté des deux réacteurs.

La démonstration de sûreté de l'exploitant a été développée dans deux rapports de sûreté soumis à l'AFCN en décembre 2012. L'AFCN a rédigé en janvier 2013 un rapport d'évaluation intermédiaire, qui formulait plusieurs exigences à court terme ainsi qu'un nombre limité d'exigences devant être mises en œuvre à moyen terme. L'exploitant a réagi à ce rapport en établissant un plan d'action destiné à satisfaire à ces exigences, consistant en une série d'analyses, de tests et d'inspections complémentaires.

En avril 2013, l'exploitant a soumis à l'AFCN deux addendas à son dossier de justification de la sûreté des unités de Doel 3 et Tihange 2, lesquels apportent une réponse structurée à chacune des exigences à court-terme. Une analyse approfondie de ces documents réalisée par l'Autorité belge de sûreté nucléaire a confirmé qu'une réponse satisfaisante avait été apportée à toutes les préoccupations de sûreté à l'origine des exigences à court-terme. En mai 2013 l'AFCN a rédigé son rapport d'évaluation final et autorisé Electrabel à redémarrer les deux réacteurs. L'exploitation des deux réacteurs a donc repris en juin 2013.

Après le redémarrage, Electrabel devait achever son plan d'action (à moyen terme) avant la fin des arrêts suivants planifiés en avril et mai 2014. Toutefois, avant d'arriver à ces dates, il s'est avéré que deux de ces actions montraient des résultats partiels et intermédiaires inattendus de nature à remettre en question la démonstration de sûreté de l'exploitant. En février 2014, les tests effectués avec la machine d'inspection par ultrasons ont indiqué une erreur de caractérisation de certains défauts, tandis qu'en mars 2014, un test mené sur le matériau VB395 (un matériau représentatif des cuves de Doel 3 et Tihange 2 affecté par des défauts dus à l'hydrogène provenant d'une virole de générateur de vapeur d'Areva rejeté suite à la présence de ces défauts) a montré que l'irradiation avait un impact plus important que prévu sur l'évolution de la fragilisation. Comme ces résultats remettaient en question la compréhension et l'étendue du phénomène de formation des défauts dus à l'hydrogène et, par corollaire, le degré de conservatisme des dossiers de justification de la sûreté, l'exploitant a décidé en mars 2014 d'avancer à titre préventif les arrêts planifiés des deux réacteurs.

Avec l'aide d'experts internes et externes, l'exploitant a entamé une étude de l'impact de ces résultats inattendus sur sa démonstration de la sûreté et a conduit sa propre analyse pour

déterminer si l'exploitation des unités concernées pourrait reprendre en toute sûreté. La démonstration de l'exploitant, étayée par de nombreux documents techniques, a fait l'objet de deux nouveaux rapports de justification de la sûreté soumis en 2015 .

En 2014 et 2015, comme la complexité des questions scientifiques soulevées par la démonstration de la sûreté des cuves nécessitait une expertise hautement spécialisée, l'AFCN a décidé de renforcer les analyses de Bel V et d'AIB-Vinçotte en chargeant des groupes d'experts d'effectuer des révisions externes indépendantes de certains chapitres de la démonstration de l'exploitant. Un « International Review Board », composé d'experts internationaux dans le domaine des propriétés mécaniques des cuves de réacteurs, a évalué le phénomène de fragilisation sous irradiation. Un National Scientific Expert group a évalué, avec l'aide de plusieurs autres experts, l'hypothèse du risque d'agrandissement des défauts induit par l'hydrogène moléculaire (hydrogen-induced cracking).

Un laboratoire renommé américain, Oak Ridge National Laboratory, a été invité à donner un avis complètement indépendant. ORNL a réalisé une évaluation complète des propriétés des matériaux et de l'évaluation de l'intégrité structurelle pour identifier de potentielles erreurs et pour valider les résultats présentés par l'exploitant dans ses Safety Cases. ORNL a fourni ses propres calculs d'intégrité structurelle réalisés à l'aide de codes et d'outils de modélisation différents de ceux employés par l'exploitant. ORNL a conclu que l'intégrité structurelle des cuves de Doel 3 et Tihange 2 était confirmée quel que soit le transitoire avec de grandes marges.

En novembre 2015, l'Agence fédérale de Contrôle nucléaire a terminé son évaluation et abouti à une conclusion sur les indications de défauts des cuves de Doel 3 et Tihange 2. Cette conclusion se base sur les dossiers de justification de la sûreté soumis par l'exploitant et avalisés par le service de sûreté nucléaire de celui-ci, des rapports d'évaluation indépendants établis par Bel V, AIB-Vinçotte, l'International Review Board, Oak Ridge National Laboratory et le National Scientific Expert Group.

L'AFCN peut maintenant confirmer que toutes les préoccupations de sûreté à l'origine des exigences à court et moyen terme ont été levées de manière satisfaisante. Après une évaluation détaillée de l'impact potentiel des résultats inattendus obtenus de février et mars 2014, l'AFCN a conclu que les dossiers de justification de la sûreté soumis en 2015 par l'exploitant démontrent que l'intégrité structurelle des cuves des réacteurs de Doel 3 et Tihange 2 est garantie jusqu'à 40 années d'exploitation.

Par voie de conséquence, l'Agence fédérale de Contrôle nucléaire autorise le retour en exploitation des unités de Doel 3 et Tihange 2 jusqu'à l'age de 40 ans.

Parmi les conclusions de l'évaluation, les principales sont :

- L'origine la plus probable des indications identifiées dans les cuves des réacteurs de Doel 3 et Tihange 2 est la formation de défauts dus à l'hydrogène liée au processus de fabrication.
- L'application de la méthode d'inspection par ultrasons qualifiée lors des inspections de suivi conduites en 2014 sur les viroles des cuves, a entraîné une mise à jour de la cartographie des défauts. Les indications détectées sont sensiblement plus nombreuses qu'en 2012 à la suite principalement de l'abaissement des seuils de détection. La mise à jour de la procédure de dimensionnement des défauts a donné lieu à une augmentation des dimensions des défauts qui doivent être pris en compte dans l'évaluation de l'intégrité structurelle.

- Cependant en appliquant les mêmes paramètres et seuils de détection, une comparaison des données obtenues lors des inspections par ultrasons de 2012 et de 2014 ne révèle pas de propagation des défauts. Une évolution significative des défauts dus à l'hydrogène en raison des efforts que l'exploitation des réacteurs entraîne au fil du temps est improbable .
- D'autres phénomènes (comme le cloquage par l'hydrogène ou la fissuration induite par l'hydrogène) ont été évalués et n'ont pas été retenus en tant que mécanismes susceptibles d'aggraver les fissures lors de l'exploitation.
- Considérant que le VB395 fait office d'exception en ce qui concerne le comportement du matériau sous irradiation, il est improbable que les viroles de Doel 3 et Tihange 2 présentent une sensibilité inattendue à la fragilisation sous irradiation. Néanmoins, par mesure de précaution, les équations de prédiction de la fragilisation des cuves de Doel 3 et Tihange 2 prennent en compte un terme supplémentaire représentant la fragilisation atypique découverte sur la VB395. Dès lors, l'AFCN juge acceptables les équations de prédiction de la fragilisation sous irradiation retenues dans les dossiers de justification de la sûreté soumis en 2015 par l'exploitant.
- Une analyse conservatrice de l'intégrité structurelle montre que plus de 99,75% des configurations de défauts affectant les viroles des cuves de Doel 3 et Tihange 2 sont inoffensives en conditions normales, anormales ou accidentelles. Sur base d'une analyse affinée de l'exploitant sur le 0,25% restant des configurations de défauts, l'AFCN conclut que les marges de sûreté sont suffisantes. Ces marges sont confirmées par les calculs d'intégrité structurelle effectués en toute indépendance par l'ORNL.

L'AFCN exige de l'exploitant qu'il conduise des inspections de suivi sur toute l'épaisseur des viroles des cuves, en appliquant la méthode par ultrasons qualifiée, à la fin du prochain cycle d'exploitation de Doel 3 et Tihange 2 et, ensuite, tous les trois ans au moins.

Zusammenfassung

Während der geplanten Betriebsunterbrechungen der Kernreaktoren Doel 3 und Tihange 2 im Jahr 2012 wurde bei Ultraschallprüfungen während des Betriebs eine große Anzahl quasi-laminarer Defektanzeigen im unteren und oberen Ring beider Reaktordruckbehälter festgestellt. Damals wurde beschlossen, beide Reaktoren stillzulegen, bis der Betreiber Electrabel der Föderalagentur für Nuklearkontrolle (FANK) gegenüber nachweisen konnte, dass diese neu festgestellten Defektanzeigen die Sicherheit der beiden Reaktoren nicht beeinflussen.

Der Sicherheitsnachweis durch den Betreiber erfolgte mithilfe von zwei Safety-Case-Berichten, die im Dezember 2012 an die FANK übermittelt wurden. Im Januar 2013 veröffentlichte die FANK einen vorläufigen Evaluierungsbericht, der mehrere kurzfristig zu erfüllende Auflagen enthielt. Eine begrenzte Zahl von Auflagen war mittelfristig zu erfüllen. In Reaktion darauf hat der Betreiber einen Aktionsplan aufgestellt, um die Auflagen der FANK zu erfüllen. Dieser Aktionsplan besteht aus einer Reihe ergänzender Analysen, Tests und Prüfungen.

Im April 2013 reichte der Betreiber zwei Nachträge zu den Safety-Case-Berichten ein, die eine strukturierte Antwort auf jede der kurzfristig zu erfüllenden Auflagen enthielten. Nach eingehender Analyse dieser Dokumente bestätigte die belgische Behörde für nukleare Sicherheit, dass alle Sicherheitsbedenken, die die Ursache für die kurzfristig zu erfüllenden Auflagen waren, auf zufriedenstellende Weise ausgeräumt worden waren. Im Mai 2013 veröffentlichte die FANK einen abschließenden Evaluierungsbericht, und Electrabel erhielt die Genehmigung, beide Reaktoren wieder hochzufahren. Die beiden Reaktoren wurden im Juni 2013 wieder hochgefahren.

Die Umsetzung des (mittelfristigen) Aktionsplans durch Electrabel war für das Ende der nächsten geplanten Betriebsunterbrechung im April und Mai 2014 vorgesehen. Bevor dies möglich war, führten jedoch zwei Maßnahmen zu partiellen und vorläufigen Ergebnissen, die nicht mit den Schlussfolgerungen des Sicherheitsnachweises des Betreibers in Übereinstimmung zu stehen schienen. Im Februar 2014 ließen am UT-Prüfgerät vorgenommene Tests darauf schließen, dass die Fehleranzeigen nicht korrekt charakterisiert wurden. Im März 2014 schien das VB395-Material (eine Wasserstoffflocken enthaltende und als repräsentativ für die Reaktorbehälter des Doel 3 und des Tihange 2 geltende Probe, die aus einem für unbrauchbar erklärten AREVA-Dampfgenerator stammt) unter Strahleneinwirkung eine höhere Versprödung zu zeigen als erwartet. Da diese Ergebnisse Fragen hinsichtlich des korrekten Verständnisses und des Umfangs des Phänomens der Wasserstoffflocken, und damit hinsichtlich des Konservatismus der Safety-Case-Berichte, aufwarfen, beschloss der Betreiber im März 2014, die geplanten Betriebsunterbrechungen beider Reaktoren präventiv vorzuziehen.

Mit Unterstützung interner und externer Fachleute begann der Betreiber eine Untersuchung der Auswirkungen dieser unerwarteten Ergebnisse auf den Sicherheitsnachweis und nahm eine Analyse vor um zu ermitteln, ob die betreffenden Reaktoren gefahrlos wieder in Betrieb gehen konnten. Die Ergebnisse dieser Analyse gingen im Jahr 2015 in zwei neue Safety-Case-Berichte ein, die durch mehrere technische Dokumente erhärtet wurden.

In Anbetracht der wissenschaftlichen Probleme, die bei dem Sicherheitsnachweis auftraten und hoch spezialisiertes Know-how erforderten, beschloss die FANK, in Bezug auf verschiedene Teile des Sicherheitsnachweises des Betreibers die Evaluierungen von Bel V und AIB-Vinçotte durch unabhängige, externe Evaluierungen von Sachverständigengruppen zu untermauern. Ein mit anerkannten Fachleuten auf dem Gebiet der Reaktordruckbehältermechanik besetztes „International Review Board“ evaluierte die Methodik bei der Strahlenversprödung. Eine „National Scientific Expert Group“, der weitere Sachverständige zur Seite standen, evaluierte die Hypothese der Wasserstoffblasenbildung („hydrogen blistering“) bzw. der wasserstoffinduzierten Rissbildung („hydrogen induced cracking“).

Ein anerkanntes Laboratorium aus den Vereinigten Staaten, das Oak Ridge National Laboratory (ORNL), wurde um ein vollständig unabhängiges Gutachten ersucht. Das ORNL nahm eine vollständige Evaluierung der Materialeigenschaften und der Berechnungen der strukturellen Integrität vor, mit dem Ziel, eventuelle Fehler zu ermitteln und die Ergebnisse der Safety-Case-Berichte des Betreibers zu validieren. Das ORNL nahm mit von denjenigen des Betreibers abweichenden Codes und Modellen eigene Berechnungen der strukturellen Integrität vor. Das ORNL gelangte zu der Schlussfolgerung, dass die strukturelle Integrität der Druckbehälter von Doel 3 und Tihange 2 unter allen Auslegungstransienten mit großer Sicherheitsmarge bestätigt wird.
Im November 2015 brachte die Föderalagentur für Nuklearkontrolle die Evaluierung zum Abschluss und gelangte zu einer Schlussfolgerung. Diese Schlussfolgerung basierte auf den durch den Betreiber eingereichten und durch die Abteilung für nukleare Sicherheit des Betreibers genehmigten Sicherheitsnachweisen, sowie auf den unabhängigen Beurteilungs- und Evaluierungsberichten von Bel V, AIB-Vinçotte, dem International Review Board, dem Oak Ridge National Laboratory und der National Scientific Expert Group.

Die FANK kann nun bestätigen, dass die Sicherheitsbedenken, die die Ursache für sowohl die kurzfristig als auch die mittelfristig zu erfüllenden Auflagen waren, auf zufriedenstellende Weise ausgeräumt wurden. Daneben hat die FANK die potenziellen Auswirkungen der unerwarteten Ergebnisse aus dem Jahr 2014 eingehend analysiert. Sie gelangt zu dem Schluss, dass die neuen Safety-Case-Berichte von 2015 die strukturelle Integrität der Reaktorbehälter von Doel 3 und Tihange 2 für eine Betriebsdauer von bis zu 40 Jahren mit hinreichender Sicherheit belegen.

Infolgedessen erteilt die Föderalagentur für Nuklearkontrolle die Genehmigung, die Reaktoren von Doel 3 und Tihange 2 wieder hochzufahren und bis zu einer Lebensdauer von 40 Jahren weiter zu betreiben.

Erwähnenswerte Schlussfolgerungen der Evaluierung sind unter anderem:

- Die wahrscheinlichste Ursache der an den Reaktordruckbehältern von Doel 3 und Tihange 2 festgestellten Defektanzeigen sind aus dem Produktionsprozess resultierende Wasserstoffflocken.
- Die Anwendung eines formal qualifizierten UT-Prüfverfahrens während der UT-Folgeprüfungen der Druckbehälterringe im Jahr 2014 führte zu einer Aktualisierung der Kartografie der Wasserstoffflocken. Die Anzahl der gemeldeten Anzeigen ist erheblich höher als im Jahr 2012, was vorwiegend auf eine Herabsetzung der Nachweisgrenzen und den Einsatz eines empfindlicheren Transducers zurückzuführen ist. Eine Aktualisierung des Defektbemessungsverfahrens führte zu einer Zunahme der Flockengröße, die im Rahmen der Beurteilung der strukturellen Integrität berücksichtigt werden muss.

- Bei Verwendung derselben Parameter und Meldeschwellen ergibt ein Vergleich zwischen den Ergebnissen der UT-Prüfungen von 2012 und 2014 jedoch keine Belege für ein Risswachstum. Eine signifikante Größenzunahme der Wasserstoffflocken durch den Betrieb der Reaktoren in dem Zeitraum ist unwahrscheinlich.
- Der einzige theoretische Mechanismus für ein Wachstum ist Materialermüdung, die begrenzte Auswirkungen hat. Andere Phänomene (wie „hydrogen blistering“ oder „hydrogen induced cracking“) wurden evaluiert und können als mögliche Ursache einer Vergrößerung von Rissen im Betrieb ausgeschlossen werden.
- VB395 wird als „Sonderfall“ in Sachen Materialverhalten unter Strahleneinwirkung betrachtet, und die Ringe der Druckbehälter von Doel 3 und Tihange 2 weisen aller Wahrscheinlichkeit nach nicht dieselbe Empfindlichkeit für Strahlenversprödung auf. Dennoch wird als Sicherheitsvorkehrung die an der VB395-Probe festgestellte atypische Versprödung mit in die prädiktiven Gleichungen für Doel 3 und Tihange 2 aufgenommen. Daher ist die FANK der Ansicht, dass die prädiktiven Gleichungen für Strahlenversprödung, die durch den Betreiber in den Sicherheitsnachweisen von 2015 verwendet wurden, für die FANK akzeptabel sind.
- Eine grobe konservative Analyse der strukturellen Integrität zeigt, dass mehr als 99,75 % der Defektanzeigen in den Druckbehälterringen von Doel 3 und Tihange 2 unter normalen und abnormalen Betriebsbedingungen unschädlich sind. Auf der Grundlage einer genaueren Analyse der verbleibenden 0,25 %, die durch den Betreiber vorgenommen wurde, gelangt die FANK zu dem Schluss, dass die Sicherheitsmargen ausreichend sind. Durch das ORNL durchgeführte unabhängige Berechnungen der strukturellen Integrität bestätigen die Margen.

Die FANK schreibt dem Betreiber vor, die Ringe der Reaktordruckbehälter UT-Folgeprüfungen auf der Grundlage des qualifizierten Verfahrens zu unterziehen, und zwar am Ende des nächsten Zyklus von Doel 3 und Tihange 2 und in der Folge mindestens alle drei Jahre.

Disclaimer

This FANC evaluation report provides a synthesis of the different opinions and evaluations that have been issued on this topic by different expert groups as part of the regulatory assessment.

In order to ensure transparency and to further explain the basis of the final evaluation by the FANC, many paragraphs of this report are complete or partial extracts of paragraphs from the documents cited in references. For more information, it is recommended to read the full text of the documents cited in references.

This evaluation report is limited in its scope to the safety evaluation of the Doel 3 and Tihange 2 reactor pressure vessels. The conclusions of this report cannot be used or extrapolated without further examination to other reactors which have similar flaw indications.

Part I – Introduction

1 Safety Concern

1.1 Context

Doel 3 and Tihange 2 are two of the seven Belgian nuclear reactors operated by Electrabel - a company of the ENGIE Group. Table 1 gives the dates of the main phases of the lifecycle of the two units:

Phases of the reactor units lifecycle	Doel 3	Tihange 2
Start of construction	1975	1975
First connection to the national grid	1982	1983
Replacement of steam generators and power increase	1993	2001
1st Long shutdown	June/September 2012 - June 2013	
2nd Long shutdown	February 2014 – …	
Scheduled date for end of operation[1]	2022	2023

Table 1 - Dates of the main phases of the lifecycle of Doel 3 and Tihange 2

In June 2012 during the 3rd ten-years outage at the Doel 3 reactor unit specific ultrasonic (UT) in-service inspections were performed to check for underclad cracking in the reactor pressure vessel (RPV), as a result of lessons learned from Tricastin[2]. No underclad defects were found but several thousands of quasi-laminar flaw indications[3] were detected in the base metal of the Doel 3 reactor pressure vessel, located mainly in the upper and lower core shells. A second inspection was performed in July 2012 with UT probes able to inspect the whole thickness of the vessel. This inspection confirmed the presence of a large number of the same type of indications deeper in the material.

[1] Nuclear Phase-out Law of 31 January 2003

[2] Tricastin is a French Nuclear Power Plant. The Tricastin RPV is affected by underclad defects. These defects appeared during the welding of the cladding, due to inadequate heat treatment.

[3] The ASME (American Society of Mechanical Engineers) code, a construction code used for the manufacturing and inspection of mechanical equipment, uses the following definitions:

- Indication: The response or evidence from the application of a non-destructive examination. An indication is an elementary record or set of records indicating the possible presence of a flaw. The definition of an indication is directly linked to the type of flaw (nature and size) which is aimed at in a given examination.
- Flaw: An imperfection or unintentional discontinuity which is detectable by a non-destructive examination.
- Defect: A flaw (imperfection or unintentional discontinuity) of such size, shape, orientation, location, or properties as to be rejectable. A defect is a flaw that is defined as rejectable by a code or specification. While all defects are flaws, not all flaws are defects.

Similar inspections were planned on the Tihange 2 unit, whose reactor pressure vessel is of identical design and construction, and were conducted in September 2012. Similar quasi-laminar flaw indications were detected as well, but to a lesser extent.

1.1.1 Licensee Safety Case and FANC Provisional Evaluation Report (January 2013)

Following those inspection results that indicated a potential safety concern, the Doel 3 and Tihange 2 reactor units remained in cold shutdown (with the core unloaded). With the support of internal and external experts, the Licensee Electrabel started an investigation of the precise nature and origin of these indications, and built its analysis to determine whether or not the reactor units could safely resume operation in spite of the detected flaws. The safety demonstration of the Licensee was documented in two Safety Case Reports which were submitted for review to the Federal Agency for Nuclear Control in December 2012, one for Doel 3 and one for Tihange 2 [1] [2]. In addition the Licensee internal Nuclear Safety Department ("Service de Contrôle Physique – Dienst voor Fysische Controle") established two independent review reports [3] [4].

The FANC made its safety evaluation with the support of its technical support Bel V, the AIA (Authorized Inspection Agency[4]) AIB-Vinçotte and relevant international expert groups (IERB and Foreign Regulatory Body workshops). Based on their reports, the FANC issued in January 2013 its Provisional Evaluation Report on the issue [5]. This report identified some remaining open issues about the in-service ultrasonic inspection technique, the origin and evolution of the flaws, the characterization of the material properties, and the structural integrity of the reactor pressure vessels under penalizing loadings. As a consequence, the Federal Agency for Nuclear Control considered in January 2013 that fulfilling the short-term requirements was a prerequisite to the restart of the Doel 3 and Tihange 2 units. A limited number of requirements had to be addressed on a mid-term basis (before restart after the next scheduled outage for refuelling).

1.1.2 Licensee Addenda to Safety Cases and FANC Final Evaluation Report (May 2013)

In response, the Licensee elaborated an action plan to fulfil those FANC requirements. This action plan consists of a series of additional analyses, tests and inspections. The action plan (see Annex 1) was submitted by the Licensee on 4 February 2013 and was approved by the FANC on 7 February 2013.

During the first months of 2013, the implementation of the different actions was followed up by Bel V and AIB Vinçotte. The FANC also requested an independent evaluation of the results of the material testing program by the Belgian experts of the National Scientific Expert Group (NSEG). In addition, a specialized consultant evaluated the results of the acoustic emission testing performed during the load tests of Doel 3 and Tihange 2.

In April 2013 the Licensee submitted to the FANC two Addenda to the Safety Case Reports for the Tihange 2 and Doel 3 reactor units that gave a structured answer to each of the short-term requirements [6] [7]. They provided the results and conclusions of additional analyses, tests, and inspections performed in this framework. These Addenda were reviewed by the internal Nuclear Safety Department of Electrabel which gave an overall positive advice regarding the restart of both reactor units [8].

The FANC, together with Bel V and AIB-Vinçotte, evaluated whether the safety concerns at the origin of the requirements were solved and whether the related concerns could be lifted in its Final Evaluation Report on the Doel 3 and Tihange 2 RPV Flaw Indications Issue [9]. After analysis of these

[4] According to the ASME definition

documents, the Belgian Nuclear Safety Authority confirmed that all the safety concerns at the origin of the short-term requirements had been solved in a satisfactory manner and Electrabel was authorized in May 2013 to restart both reactors.

However, additional follow-up actions were requested on some short-term requirements by the Belgian Nuclear Safety Authority. These additional follow-up actions had to be achieved within the same deadline as the mid-term actions.

1.1.3 Licensee Safety Case 2015 and FANC 2015 Final Evaluation Report

Both reactors restarted in June 2013. The completion of the Action Plan was due for the end of the forthcoming outages planned in April and May 2014.

However, in February 2014 and March 2014, partial and preliminary unexpected outcomes of two of the mid-term requirements appeared to potentially challenge some of the inputs and conclusions of the Licensee Safety Cases. In February 2014, some tests performed in the framework of the UT inspection procedure highlighted a potential mischaracterization of the flaw. In March 2014 a specimen containing hydrogen flakes, considered as a representative of the Doel 3 and Tihange 2 reactor pressure vessels, appeared to show an unexpectedly high embrittlement under irradiation. Since these outcomes were questioning the extent and the understanding of the flaking phenomenon and of its impact on the structural integrity of the reactor pressure vessels, and hence the conservatisms of the Safety Cases, the Licensee decided in March 2014 to preventively anticipate the outages of the two reactors.

Whilst both the reactor units were at safe shutdown, the Licensee evaluated the new results and integrated them in a complete revision of its safety demonstration. In parallel, the Licensee continued the implementation of its mid-term action plan[5]. On 17 July 2015 the Licensee submitted to the FANC the first versions of two 2015 Safety Case Reports that provide the safety demonstration of the two reactors taking into account the developments of 2014-2015. These reports provide the results and conclusions of additional analyses, tests, and inspections that were performed and give a structured answer to the FANC mid-term requirements for the Tihange 2 and Doel 3 reactor units. On 28 October the Licensee submitted the final version of these two 2015 Safety Case Reports [10] [11] taking into account some additional comments of the Safety Authority. On 4 November 2015 the internal Nuclear Safety Department of Electrabel submitted the independent reviews which give an overall positive advice regarding the restart of both reactor units [12] [13].

The present 2015 Final Evaluation Report presents the FANC evaluation of the Licensee safety demonstration taking into account the evaluations of Bel V, AIB-Vinçotte, and the different national and international expert groups which were consulted (IRB, ORNL and NSEG). Based on this evaluation, the FANC also presents its conclusions and its decision concerning the restart of the two reactors.

[5] Annex 1 presents the closure dates of the amended action plan at the date of the present report (November 12th, 2015).

2 Safety Assessment Process

2.1 Actors involved in the safety assessment

2.1.1 Licensee, associated technical support and review by international experts

To evaluate this complex issue, the Licensee took the decision to set up a multidisciplinary and multiorganization project team. This team is composed of experts from:

- Electrabel (ENGIE): Licensee of Doel 3 and Tihange 2, with expertise in nuclear operation and safety,
- Laborelec (ENGIE): technical competence centre in electrical power and energy technology, with extensive know-how in non-destructive testing techniques and material properties,
- Tractebel Engineering (ENGIE): engineering company, with specialized knowledge of nuclear design as well as structural integrity, materials, and safety.

supported by external expert entities from SCK.CEN, University of Ghent, CRM (Belgium), AREVA, INTERCONTROL, CEA (France), VTT (Finland) and Tohoku University (Japan).

In addition, the Licensee project team made its work reviewed by a team of international experts, in order to ensure the quality, completeness and soundness of the safety case.

As required by the Belgian nuclear safety regulations[6], an independent analysis and review of the Safety Case reports [10] [11] was also performed by the Electrabel Nuclear Safety Department [12] [13].

2.1.2 Belgian Nuclear Safety Authority

The Federal Agency for Nuclear Control (FANC) ensures close monitoring of the Doel 3 / Tihange 2 reactor pressure vessels issue in cooperation with Bel V, its technical subsidiary, and the company AIB-Vinçotte, the AIA.

The FANC is a public interest agency acting as an independent watchdog in charge of nuclear safety, protection against ionising radiation, physical protection and nuclear non-proliferation. Its activities include regulations, licencing, inspections and monitoring of the radioactivity throughout the country.

Bel V is the technical subsidiary of the FANC. Bel V is tasked with conducting continual and periodic inspections in the major Belgian nuclear facilities. Bel V is also involved in the safety assessment of nuclear projects, periodic safety reviews or installation modifications.

AIB-Vinçotte is the authorized inspection agency (AIA) appointed for reviewing the tests required in application of Sections III and XI of the ASME Boiler and Pressure Vessel Code transposed to the Belgian context. AIB-Vinçotte is responsible for the follow-up of in-service inspections and the review of the results. AIB-Vinçotte is also in charge of the verification of the non-destructive examination procedures and the review and follow-up of their qualification programs.

The Scientific Council for ionizing radiation is established by the Belgian regulation[7] to advise the Federal Agency for Nuclear Control on the authorization, regulation, control and the evolution of the

[6] Royal Decree of 20 July 2001
[7] Royal Decree of 18 December 2002

knowledge in regards to nuclear safety, security and radioprotection. The Scientific Council has been periodically informed by the FANC of the latest developments on the RPV issue. To ensure a thorough understanding of the issue, the Scientific Council also appointed some of its members as observers to the meetings of the external independent expert groups (see §2.1.3.1 and §2.1.3.3).

2.1.3 External and independent review

Given the complexity of the scientific and technical issues encountered in the RPV safety demonstration requiring highly specialized expertise, the FANC decided to strengthen the assessments provided by Bel V and AIB-Vinçotte with on one hand independent external assessments by some expert groups for various parts of the Licensee demonstration and on the other hand by commissioning an independent organization for performing independent calculations of the structural integrity of the two RPVs. The first part is similar to what was done for the previous assessments in 2012-2013 while the second part is an additional stage of the review process compared to the previous assessment.

2.1.3.1 International Review Board – IRB

After the unexpectedly high embrittlement of a flaked material under irradiation was discovered in 2014, the FANC decided to consult international experts on irradiation embrittlement and fracture mechanics.

The candidates for this International Review Board were selected by the Federal Agency for Nuclear Control on the grounds of their expertise in reactor pressure vessel technology, fracture mechanics and the ASME Boiler and Pressure Vessel Code together with an emphasis on irradiation embrittlement. These members are active in, or retired from, the following international organisations:

Name	Organism	Country
Thomas Pardoen	Université catholique de Louvain (UCL)	Belgium
Kim Wallin	Technical Research Centre of Finland (VTT)	Finland
Isabelle Delvallée-Nunio	Institut de Radioprotection et de Sûreté Nucléaire (IRSN)	France
Helmut Schultz	Ex - Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)	Germany
Naoki Soneda	Central Research Institute of Electric Power Industry (CRIEPI)	Japan
Tim Williams	Ex - Rolls Royce	United Kingdom
William Server	ATI Consulting	United States of America
Mark Kirk	Nuclear Regulatory Commission (US-NRC)	United States of America
Randy Nanstad	Oak Ridge National Laboratory (ORNL)	United States of America

Table 2 : Members of the IRB expert group

All these members were independent and had no connection with the Licensee[8].

This expert group was chaired by Tim Williams, while the scientific secretary was an appointed expert from the FANC. The work of the International Review Board was observed by experts from the Belgian Nuclear Safety Authority and members from the Scientific Council.

The IRB held two workshops in November 2014 and April 2015. A preliminary version of the IRB report was submitted to the FANC end of May 2015. The final version of the IRB report was released on 28 August 2015 [14].

2.1.3.2 Oak Ridge National Laboratory[9]

The FANC decided to request Oak Ridge National Laboratory (ORNL), a US laboratory, to perform a complete independent evaluation of the structural integrity assessment, including carrying out independent structural integrity calculations. Oak Ridge National Laboratory has extensive theoretical and experimental knowledge on the topic of the evolution of reactor materials under irradiation. As a member of the two expert groups, Mr. Nanstad made the bridge between the IRB and ORNL.

FANC selected ORNL because the ORNL expertise is worldly recognized in the domain of nuclear materials and their behaviour under operation. The scientific contribution of ORNL on the domain of material damage under irradiation is particularly important as well as their expertise and knowledge on structural integrity assessment.

ORNL is a multidisciplinary well-structured laboratory of thousands of scientists with an important Management and Quality System.

The FANC requested ORNL to provide a critical review of the safety case for the Doel 3 and Tihange 2 reactors, i.e. a thorough assessment of the existing safety margins against cracking in the RPVs, as a result of deterioration due to the presence of laminar flaws in the wall of each RPV. Every step of the safety demonstration submitted by the Licensee Electrabel is covered by this project, except for the qualification of the ultrasonic instrument and the non-destructive examinations.

In particular the FANC explicitly expects ORNL to perform the technical review with the following objectives

- Assess the acceptability of each assumption considered by the Licensee in the safety case except for the qualification of the ultrasonic instrument and the non-destructive examinations.
- Assess the safety margins and the level of conservatism for the successive steps of the approach submitted by the Licensee.
- Identify any non-standard aspects for a safety justification of a nuclear RPV.
- Identify the new techniques developed by the Licensee.

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[8] Pr. Kim Wallin is working for VTT, an organisation that has been charged by the Licensee Electrabel to perform some mechanical tests and evaluations. The FANC ensured that the IRB expert was not involved in the work requested by Electrabel.

[9] In 2012-2013, Electrabel requested ORNL to perform some probabilistic calculations in the framework of their Safety Cases. ORNL was charged at that time to perform the calculations of a complementary Probabilistic Structural Integrity Assessment, which was complementary to the deterministic assessment performed by Electrabel which formed the basis of the 2012 Safety case. However such a probabilistic approach is not usually taken into account by the Belgian Nuclear Safety Authority.
In 2015, the FANC requested ORNL to perform independent deterministic calculations, which differ significantly from the work done in 2012.

- Assess the acceptability of these non-standard aspects and new techniques in the successive steps of the justification of the structural integrity of the RPVs.
- Identify the mistakes, the questionable and unjustified aspects, the questionable and justifiable – though lightly justified and documented – aspects in the safety case

ORNL started its technical review work in September 2015 and issued its review report in November 2015 [15].

2.1.3.3 National Scientific Expert Group

In parallel to the evaluation of the latest developments of the RPV case in 2014-2015, some public statements by university professors challenged the previous Licensee conclusions on the potential in-service evolution of the flaws. A hypothesis of hydrogen blistering or hydrogen induced cracking was put forward by prof. W. Bogaerts (KU Leuven) and prof. D.D. MacDonald (UC Berkeley) who stated that the exposure of the reactor pressure vessels to the primary water during operation could result in a molecular hydrogen accumulation and consequently a pressure increase in the (hydrogen-induced) flakes and lead to their growth during the future operation of the RPV [16]. They considered that the issue was not conveniently handled in the 2012-2013 Safety Case evaluation.

The Scientific Council treated this subject during its meeting on 27 February 2015 and advised the FANC to start a process to investigate this topic.

This process led to the (re)-assembly of the NSEG - National Scientific Expert Group. The members of this working group were selected by the FANC in 2012-2013 with regards to their expertise on the subject of material degradation. These members are:

Name	Organism
Rudi Denys	University of Ghent (UGent)
Ludovic Noels	Université de Liège (ULg)
Thomas Pardoen	Université catholique de Louvain (UCL)
Dirk Vandepitte	Katholieke Universiteit Leuven (KUL)

Table 3 : Members of the NSEG expert group

All these members are independent and have no connection with the Licensee or the aforementioned professors. As a member of the two expert groups, Professor Pardoen made the bridge between the NSEG and the IRB expert group.

Several expert meetings and hearings with prof. Bogaerts, prof. MacDonald and the Licensee experts were held by the NSEG, which also received reports from three experts on hydrogen-blistering and corrosion related RPV issues, two of them were recommended by prof. Bogaerts:

Name	Organism
Peter Scott	Ex – Framatome/Areva
Liane Smith	WG Intetech
Joris Proost	Université catholique de Louvain (UCL)

Table 4 : International experts consulted by the NSEG

In September 2015, the NSEG issued their Final Report on the hydrogen induced cracking hypothesis [17]. This report was submitted by the FANC to the Scientific Council in November 2015, together with the FANC Synthesis Report on the “HIC hypothesis” [18] .

2.2 Evaluation Process

2.2.1 General Approach

Considering the significant developments of the RPV issue in early 2014 and their impact on the 2013 Safety Cases, the Licensee decided to submit new Safety Cases for the reactor pressure vessels of Doel 3 and Tihange 2.

To evaluate this complex issue, the Belgian nuclear Safety Authority decided in September 2014 to adopt a two-step review process:

> "The Regulatory Body the FANC and Bel V) will first review the relevance of the methodology proposed by the Licensee. Depending on the conclusions of this first review, the Regulatory Body will then communicate to the Licensee whether its safety case report (for the restart of both Doel 3 and Tihange 2 units) is eligible for review." *[FANC Website communication – October 24th 2014]*

- Step 1: Evaluation of the relevance of the methodology proposed by the Licensee to demonstrate the serviceability of the two reactors.
- Step 2: Evaluation of the application of this methodology – i.e. calculation results based on the new models developed for the methodology.

2.2.2 Step 1 : Relevance of the methodology

The review process of step 1 – i.e. the relevance of the methodology proposed by the Licensee – involved various actors (see 2.1.2 and 2.1.3.1):

- The FANC,
- Bel V,
- AIB-Vinçotte,
- International Review Board (IRB)[10].

The IRB was established to advise the FANC on a very limited and specific part of the overall methodology. After the unexpectedly high embrittlement of a flaked material under irradiation was discovered in 2014, the FANC requested the IRB to evaluate whether or not this phenomenon is related to the presence of hydrogen flakes and if a similar phenomenon could potentially affect the RPV's of Doel 3 and Tihange 2. In practice the FANC requested the IRB to comment on the acceptability of the embrittlement predictive equations used in the Licensee safety demonstration. The work of the IRB was therefore limited to Step 1 of the review process.

On the basis of the assessments provided by Bel V, AIB-Vinçotte and the IRB, the FANC decided in July 2015 that the Electrabel methodology was acceptable and the Safety Cases could be submitted for review.

[10] The IRB must be clearly distinguished from the IERB established for the assessment of the 2012-2013 Safety Cases. Even if some experts were inter alia invited to the IRB in order to make a bridge with the previous work of the IERB, the scope of the review requested to the IRB greatly differs from the IERB scope that consists in 2012-2013 in an assessment of the whole 2012 Safety Cases.

2.2.3 Step 2: Application of the methodology

The review process for step 2 – i.e. the application of the methodology – involves various actors (see 2.1.2, 2.1.3.2 and 2.1.3.3):

- The FANC,
- Bel V,
- AIB-Vinçotte,
- ORNL,
- NSEG.

The final evaluation reports of Bel V [19] and AIB-Vinçotte [20] [21] on the Safety Case were issued in November 2015.

Oak Ridge National Laboratory (ORNL) had to provide a critical review of the 2015 safety case and perform a completely independent evaluation of the structural integrity assessment, where needed by performing independent calculations. ORNL issued its final Report on 11 November 2015.

NSEG had to evaluate the relevance of the hydrogen induced cracking hypothesis and issued its report in September 2015. On the basis of their conclusions and recommendations and the Licensee replies, the FANC issued its "HIC hypothesis" Synthesis Report in November 2015 to the Scientific Council.

On the basis of the assessments provided by Bel V, AIB-Vinçotte, ORNL and NSEG, the FANC has performed its own evaluation, has drawn its conclusions and has taken the final decision.

2.3 Structure of the safety assessment report

The present Final Evaluation Report discusses the following main topics:

- Chapter 3: Detection, location and characterization of the indications,
- Chapter 4: Origin and evolution of the indications,
- Chapter 5: Material properties,
- Chapter 6: Structural integrity of the reactor pressure vessels,

In order to provide a self-standing report, each chapter contains the following information:

- A reminder of the conclusions and related requirements of the FANC Provisional Evaluation Report of January 2013 [5] and of the FANC Final Evaluation Report of May 2013 [9];
- An evaluation of the related additional Licensee analyses, tests and inspections performed by the Licensee, based on the reviews done by AIB-Vinçotte [20] [21], Bel V [19] and the external expert groups [14] [15] [17]. More details on the technical contents and results can be found in the Licensee Safety Cases.
- A final conclusion of the FANC on the topic of the chapter.

The final conclusions of the FANC and its decision on the restart of the Doel 3 and Tihange 2 reactor units are detailed in a final Chapter 7.

Part II – Technical assessment

3 Detection, location and characterization of the indications

3.1 Context

The detection, location and characterization of the nearly laminar indications in the Doel 3 and Tihange 2 reactor pressure vessels is a key issue of the Safety Case. Indeed the characterization – i.e. size, orientation… - of the flake population is the basic input for the Structural Integrity Assessment (SIA) of the Doel 3 and Tihange 2 RPVs.

In this framework, the FANC issued in 2013 the Requirement 7 consisting in demonstrating the full qualification of the UT device inspection procedure for the detection, the location and the characterization of the flaw indications found in the RPV core shells of Doel 3 and Tihange 2. The Licensee provides a qualification synthesis linking all the evaluated parameters enabling to establish the level of performance of the inspection procedures for detection, localization and characterization of hydrogen flakes. [20]

3.2 Situation in 2012-2013

3.2.1 FANC Provisional Evaluation Report – January 2013

Based on the data provided by the Licensee and the conclusions released by Bel V, AIB-Vinçotte and the expert groups about the in-service inspections, the FANC drew the following conclusions in its Provisional Evaluation Report [5].

> *"The in-service inspection techniques used to examine the Doel 3 and Tihange 2 reactor pressure vessels provide a high level of confidence in the reality of the indications detected. In other words, the actual presence of great numbers of flaw indications in both pressure vessels is confirmed.*
>
> *Some uncertainty still exists regarding the capability to properly detect and characterize all present flaws in the reactor pressure vessels. In particular, tilted flaws, hidden flaws, flaws nearby the interface cladding/base metal and smaller flaws may not be completely identified or fully described, implying a possible underestimation of the number and significance for safety of the flaw indications reported to date. Additional studies and/or examinations may be needed to resolve these questions.*
>
> *Besides, the opportunities to experimentally qualify the ultrasonic inspection techniques used so far are limited: only one component (belonging to AREVA) containing hydrogen flakes is available and this component is not fully representative of the reactor pressure vessel shells in question (no internal cladding, no heat treatment). The experimental qualification of the ultrasonic inspection technique using more representative specimens is pending."*

The FANC issued seven requirements concerning the topic of the detection, location and sizing of the flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2: six short-term actions (Requirement 1 to 6) and 1 mid-term action (Requirement 7) (see Annex 1).

3.2.2 FANC Final Evaluation Report – May 2013

Based on the data provided by the Licensee and the review and assessment of AIB-Vinçotte on the in-service inspections, the FANC concluded in its Final Evaluation Report [9] that all the identified short term open issues on this topic had been resolved.

> *"The capability to properly detect and characterize all present flaws in the reactor pressure vessel has been further evaluated. In particular, the additional simulations and tests by the Licensee have shown that hidden flaws and higher tilted flaws of critical size can be detected and characterized by the actually applied UT-techniques. No critical hydrogen flake type defects are expected in the areas non-inspectable by UT. A re-analysis of the Tihange 2 UT inspection data confirms that the small number of clad interface imperfections should not be considered as hydrogen flakes[11].*
>
> *As already mentioned in the FANC Provisional Evaluation Report* [5]*, as soon as possible after the restart of the reactor unit, the Licensee shall achieve a full qualification program to demonstrate the suitability of the in-service inspection technique for the present case. The full qualification program shall be achieved before the next planned outage for refuelling."*

The FANC concluded that the six identified short-term issues had been satisfactorily resolved for restart. Nevertheless, on the basis of the AIB-Vinçotte conclusions [14], some complementary information was requested on two topics as additional Mid-term Requirements (Requirements 2b and 3b).

3.2.3 Licensee Mid-term Action Plan (see Annex 1)

2b	The Licensee shall demonstrate that no critical hydrogen flake type defects are expected in the non-inspectable areas.
3b	The Licensee shall provide additional validation of the UT simulations to 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.
7	The Licensee shall achieve a full qualification program to demonstrate the suitability of the in-service inspection technique for this 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 outage for refuelling.

In summary, the Licensee had to carry out additional work concerning three Mid-term requirements. The Licensee performed the relevant studies from 2013 on.

[11] This position has been revaluated by the Licensee in its 2015 Safety demonstration following extensive discussions on this topic with the Belgian Safety Authority. Indeed it was decided to consider DTR (Défaut(s) Technologique(s) du Revêtement) in the structural integrity assessment as if they were additional hydrogen flakes.

3.3 Extension of MIS-B qualification (Requirement 7)

In February 2014, the implementation of the Mid-term action 7 concerning the full qualification of the UT device (MIS-B) inspection procedure for the detection, the location and the characterization of the flaw indications resulted in a significant and unexpected outcome.

3.3.1 Context

The objective of the full qualification is to ensure that the inspection procedure correctly and accurately detects, locates and sizes hydrogen flakes. In other words, the objective is to reach a very high confidence level in the inspection capabilities, even for flakes inclined up to 16°, which is more than the maximum predicted inclination of the flakes. The qualification methodology followed by the Licensee in the frame of Action 7 consisted in performing practical trials on a test block containing real hydrogen flakes, and comparing the measured sizes of the flakes with the actual ones determined from a destructive testing of the corresponding flakes. The test block was a piece of the VB395 shell, see 5.3.4.1. Also, numerical simulations were used to estimate the influence of certain parameters (as for example the faceting of the flakes) on the inspection capabilities.

In February 2014, the Licensee informed the Safety Authority that the comparison between the UT inspection results on the test block and the actual sizes obtained by destructive tests highlighted an undersizing of a significant number of flaw indications when applying the inspection procedure which was used in 2012 on the RPVs of Doel 3 and Tihange 2. The consequence was that the flaw indications reported from the UT inspections carried out in 2012 on the Doel 3 and Tihange 2 RPV core shells and considered in the structural integrity assessment of the 2013 Safety Cases were potentially also undersized. As a consequence, the Licensee has achieved several improvements, corrections and an upgrading of the data processing in order to fully qualify the UT inspection procedure for the detection, localization and characterization of the quasi-laminar flaw indications.

The reanalysis of the UT inspection rough data of 2012 using this new, more accurate procedure, combined with a lowering of the detection thresholds in order to guarantee the full detection of the indications, resulted in the detection and sizing of more flaw indications than previously detected with the former procedure and in an increase of the reported sizes of these indications.

3.3.2 Indications in Doel 3 and Tihange 2 RPVs – 2014 results

An updated flake cartography was established in 2014 using the qualified UT inspection procedure.

As a consequence of the enhanced sensitivity of the qualified inspection procedure, the 2014 inspection using the updated parameters of the qualified inspection procedure reported approximately 60% more indications compared to the 2012 data.

Number of indications	Tihange 2 Upper Core Shell	Tihange 2 Lower Core Shell
2012 inspection	1931	80
2014 inspection	3064	85

Table 4.7: Number of indications reported in the Tihange 2 core shells.

Number of indications	Doel 3 Upper Core Shell	Doel 3 Lower Core Shell
2012 inspection	857	7205
2014 inspection	1440	11607

Table 4.7: Number of indications reported in the Doel 3 core shells.

Figure 1: Number of indications reported by Electrabel in their 2015 Safety Case [10] [11]

The average and maximum dimensions of the indications are also larger than the ones reported in the 2012 Safety Cases [1] [2], as a result of (i) the conservativeness introduced by the updated UT inspection procedure and (ii) the merger of some neighbouring indications which could not be discriminated anymore by the updated UT inspection procedure and which are now detected as single larger indications.

Dimensions (mm)	Tihange 2 Upper Core Shell		Tihange 2 Lower Core Shell	
Examination*	2012	2014	2012	2014
Average X-Y dimensions	9.8-7.9	14.8-13.8	10.2-9.3	15.5-15.4
Maximum X-Y dimensions	38.0-25.4	154.5-70.9	27.4-19.1	33.1-27.6

Table 4.10: Dimensions of indications reported in the Tihange 2 core shells.

Dimensions (mm)	Doel 3 Upper Core Shell		Doel 3 Lower Core Shell	
Examination	2012	2014	2012	2014
Average X-Y dimensions	8.8-7.6	13.7-12.3	9.6-7.6	16.0-12.7
Maximum X-Y dimensions	31.0-26.4	56.4-45.3	67.9-38.4	179.0-72.3

Table 4.10: Dimensions of indications reported in the Doel 3 core shells.

Figure 2 : Dimensions of indications reported by Electrabel in their 2015 Safety Cases [10] [11]

3.3.3 Licensee Conclusions on UT qualification

As a conclusion about ultrasonic testing qualification, the Licensee states in its safety case reports [10] [11] that :

> *"The qualification process led to an inspection procedure that achieves a very high level of confidence for the detection, localization and sizing of the flakes:*
>
> *A robust qualification methodology was applied:*
>
> - *Practical trials were executed on test blocks containing real flakes.*
> - *Destructive tests were performed on approximately 100 flakes.*

- *Simulations were performed to calculate the influence of a multitude of parameters on inspection capability.*
- *Comparisons were made between UT and destructive testing results.*

The qualification process resulted in upgrading the inspection procedure to ensure its compliance with inspection objectives in terms of flaw detection and characterization. A very high confidence level is achieved for detecting flakes. Flake sizing was shown to be conservative.

The straight beam technique used in 2012 and 2013 is adequate to detect the presence, if any, of hydrogen flaking in the RPV shells."

3.3.4 Safety Authority Conclusions

3.3.4.1 Efficiency of the detection performance

In its Safety Evaluation Report [19], Bel V concludes that:

"… the satisfactory efficiency of the qualified UT inspection procedure for detecting hydrogen flakes was ensured."

"Confidence in RPV assessment requires confidence in the capability of the UT examination procedure to detect and characterize the flakes. Bel V monitored the survey activities of AIB-Vinçotte related to the qualification of the procedure but also performed an in-depth review of the results of the UT inspection performed in 2014. Bel V did not find anything that could put into question the high efficiency of the UT examination procedure as demonstrated by the qualification."

In its Synthesis Report [20] [21], AIB-Vinçotte agrees with the following Licensee conclusions:

"The main objective of the qualification was to confirm the performances in detection, localization and sizing of the "historical" inspection procedure. Related to this :

- *The performance in localization of the indications is confirmed through the different parts of the qualification process*
- *Concerning the sizing performance in X and Y, the qualification showed that 6dB drop sizing technique as initially performed through the automatic sizing procedure in the Civacuve software may lead to inaccurate dimensions, mainly due to the fact that less reflective parts of a flaw may not be taken into account by the software. A modification of the sizing methodology within the analysis software (Civacuve) was implemented to allow a correct sizing based on the 6 dB amplitude drop using the echodynamics of the UT response of a flaw. The examination procedure was modified to take this into account and the acquisitions of Doel 3 and Tihange 2 reactor vessels were re-analyzed.*
- *During the qualification tests appeared that the application of the historical procedure does not allow the detection of indications inclined up to 16° in the shell rings, with the desired confidence level, more specifically in the deepest working range of each transducer. The consolidated sets of curves for the detection performance on real flaws with a diameter of 6 mm showed that lowering the reporting thresholds and changing the transducer for the first depth range, could be an answer to the lack of sensitivity of the "historical" procedure. The examination procedure was modified accordingly and its performances were reassessed in the new revision of the qualification synthesis.*

- *The detection sensitivity of the "historical" procedure was confirmed to be sufficient for the detection of the presence of the hydrogen flaking.*
- *Due to the nature of the applied sizing methodology, the indications are conservatively sized.*

When all the aspects are combined, one can reliably state that the detection and sizing performance of the finally qualified Ultrasonic Examination Procedure has been demonstrated under representative conditions, and results in a high degree of confidence for all aspects of the inspection performance (detection, localization and characterization)."

Based on the documents provided by the Licensee and the evaluations performed by Bel V and AIB-Vinçotte, the FANC concludes that:

The capability to properly detect, locate and characterize the flaws present in the reactor pressure vessels of Doel 3 and Tihange 2 has been extensively evaluated. The UT inspection procedure has been formally qualified.

3.3.4.2 Absence of radial connection between flakes

In its Safety Evaluation Report [19], Bel V concludes that:

> *"The UT inspection of the RPV core shells with straight beam transducers does not allow to identify any hypothetical radial connection between flakes located at slightly different depths. In order to reject that assumption, the data recorded by the eight 45° transducers installed on the UT inspection tool were analysed in order to detect any such connections."*
>
> *"no radial connections between flakes were detected. That conclusion is of prime importance in particular for the assessment of the prevention of the instantaneous failure under single load application."*

In its Synthesis Report [20] [21], AIB-Vinçotte agrees with the following Licensee conclusions:

> "*The examination conducted with 45° transducers evidenced the absence of significant radial connections between hydrogen flakes;"*

Based on the documents provided by the Licensee and the evaluations performed by Bel V and AIB-Vinçotte, the FANC concludes that:

No significant radial connections between hydrogen flakes are detected in the RPV core shells of Doel 3 and Tihange 2.

3.3.4.3 Increased number of reported flaw indications

In its Safety Evaluation Report [19], Bel V concludes that:

> *"The core shells of the Doel 3 and the Tihange 2 Reactor Pressure Vessels have been subjected in 2014 to ultrasonic examination in view of characterizing the population of embedded hydrogen flakes with the qualified procedure and assessing any flaw evolution. The following observations were drawn from the data records:*

In its Synthesis Report [20] [21], AIB-Vinçotte agrees with the following Licensee conclusions:

> *"The core shells of the Doel 3 and the Tihange 2 Reactor Pressure Vessels have been subjected in 2014 to ultrasonic examination in view of characterizing the population of*

embedded hydrogen flakes with the qualified procedure. The following observations could be drawn from the data records:

- *As a consequence of the examination procedure evolution, the number of reported indications is higher than in 2012;*
- *The shell material volume affected by flaking is essentially unchanged with reference to 2012, but the associated flaw indication density is increased;*
- *Amplitude distribution indicates that flaw detection was effective in 2014;*
- *Most flakes are located in the inner half of the shell thickness;*
- *Hydrogen flakes feature typical dimensions ranging from 10 to 15 mm;*
- *An expertise conducted by Areva Intercontrôle with a 15° transducer allowed concluding to the absence of flakes oriented along the ghost lines with inclinations beyond the qualified range (16°)."*

Based on the documents provided by the Licensee and the evaluations performed by Bel V and AIB-Vinçotte, the FANC concludes that:

The application of a formally qualified UT inspection procedure during the 2014 follow-up UT inspections of the RPV core shells of Doel 3 and Tihange 2 resulted in an updated flake cartography.

The number of reported indications is significantly higher than in 2012, which is mainly due to the lowered detection thresholds and the use of a more sensitive transducer.

3.3.4.4 Large flaw indications

In its Safety Evaluation Report [19], Bel V concludes that:

> *"Bel V found satisfactory the analysis of the large flaw indications by Electrabel and agreed with him that the larger maximum dimensions of the flaw indications reported in 2014 resulted from the merging of small neighbouring indications that could not be discriminated when using the qualified inspection procedure.*
>
> *To Bel V opinion, the fact that the large indications are clusters of small indications with sound material between them is of prime importance since, as mentioned above, individual flakes of large size are practically excluded due to metallurgical considerations. Moreover, the methodology for evaluating the crack growth analysis of the flaw indications with large size (see section 10) has therefore an inherent conservatism."*

In its Synthesis Report [20] [21], AIB-Vinçotte agrees with the following Licensee conclusions:

> *"Due to the nature of the applied sizing methodology, the indications are conservatively sized."*

Based on the documents provided by the Licensee and the evaluations performed by Bel V and AIB-Vinçotte, the FANC concludes that:

The application of a formally qualified UT inspection procedure during the 2014 follow-up UT inspections of the RPV core shells of Doel 3 and Tihange 2 resulted in an updated flake cartography.

An update of the flaw sizing procedure resulted in an increase of the flake size to be taken into account in the structural integrity assessment. The tendency of the updated flaw sizing procedure

to report clusters of indications as large individual flakes leads also to the reporting of larger average dimensions and much larger maximum dimensions in 2014.

The newly reported indications are located in the same zones as the indications reported in 2012.

3.4 Other FANC requirements : 2b/3b/7

3.4.1 Non-inspectable areas (Action 2/2b)

3.4.1.1 Context

In January 2013, on the basis of the conclusions from AIB-Vinçotte, the FANC issued the following short-term requirement in its Provisional Evaluation Report [5]:

> *"The Licensee shall demonstrate that no critical hydrogen flake type defects are expected in the non-inspectable areas."*

In May 2013, in its Final Evaluation Report [9], based on the data provided by the Licensee and the conclusions from the various expert groups, the FANC concluded that the Licensee reply to this topic was satisfactory for restart.

However AIB-Vinçotte was concluding in [22] [23] that:

> *"AIB-Vinçotte considers the Licensee reply to the Action 2 requirement satisfactory but asks the Licensee to apply an appropriate visual examination of the concerned bracket zones at the next outage."*

Indeed, as stated in the Licensee 2015 Safety Cases [10] [11]:

> *"Previous analysis showed that the presence of hydrogen flakes in the few non-inspectable areas could be excluded, except behind and in the vicinity of the four welded brackets of the Doel 3 RPV. The function of those brackets – above the weld to the transition ring, on the inner surface of the lower core shell – is to guide the insertion of the lower internal structures in the RPV. It was considered that these potential flaws could never be critical to the RPV's structural integrity since the brackets would protect them in terms of stress and toughness."*

In consequence, the FANC requested a follow-up on this topic as the mid-term action 2b.

3.4.1.2 Licensee Conclusions

In the 2015 Safety Cases [10] [11], the Licensee concludes on this topic that:

> *"A visual examination of the bracket zones (action 2b) was carried out in May 2014. No imperfection was found during the examination."*

3.4.1.3 Safety Authority Conclusions

Based on the visual examinations performed by the Licensee and the data provided, AIB-Vinçotte concludes in its Synthesis Report [20] [21] that :

> *''The Licensee performed a visual examination during the 2014 outage of Doel 3 and Tihange 2. Particular attention was paid to detect any possible damage of the austenitic stainless steel cladding around the four brackets that are welded onto the inner surface of the lower*

core shell of the Doel 3 and Tihange 2 Reactor Pressure Vessels. No degradation was reported. The visual examination was carried out in the presence of the MO/AIA.

The MO/AIA considers the Licensee reply to the Action 2 requirement satisfactory and has no more comments related to Action 2."

On this basis, the FANC concludes that :

No critical hydrogen flake type defects are expected in the areas non-inspectable by UT.

The action 2b was satisfactorily replied to and closed by the Safety Authority in September 2014.

3.4.2 Potentially unreported higher tilted flaws (Action 3/3b)

3.4.2.1 Context

In its Provisional Evaluation Report [5], the FANC issued the following requirement in order to investigate the potentially unreported higher tilted flaws :

"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."

In May 2013, AIB-Vinçotte concluded that :

" … the Licensee reply to the Action 3 requirement satisfactory. However, as Medium Term Action, the Licensee shall provide additional validation of the UT simulations." [22] [23]

Consequently the FANC concluded in its Final Evaluation Report that the Licensee reply to Requirement 3 was satisfactory for restart [9]. However, the FANC requested the Licensee to provide additional validation of the UT simulations. Therefore the FANC requested the Licensee to deepen the Action 3 in a new Mid-Term Action 3b.

3.4.2.2 Licensee Conclusions

In the 2015 Safety Cases [10] [11], the Licensee concludes on this topic that: "

- *The observations confirmed that the flakes are located in ghost lines, primarily in those with the highest level of segregation.*
- *…*
- *The flakes were globally less inclined than the maximum angle of the ghost lines. They tend to remain laminar due to the influence of the forging's residual stresses.*
- *The maximum inclination of the ghost lines susceptible for flaking did not exceed 16° in both axial and circumferential directions.*
- *15° is the maximum value expected for the flake inclination."*

And :

- *"UT signal reporting thresholds of 0° transducers were lowered to ensure the detection of flakes inclined up to 16°."*

3.4.2.3 Safety Authority Conclusions

In its Synthesis Report [20] [21], AIB-Vinçotte agrees with the following Licensee conclusions:

" To further demonstrate the reliability of the simulations, a cross-check was requested to be performed between the reflectivity on real flakes in VB395/1 and the results obtained with Phased Array laws with non-perpendicular insonification. Specifically relative amplitude drops with UT desorientations between 15 and 20 degrees were looked for. The results of the cross-check presented by the Licensee showed that :

- *The values obtained by simulation are conservative compared to the experimental UT measurements on the cut indications;*
- *The difference between simulation and experimental measurements is the lowest when the flaw is inclined along one plane only;*
- *For flaws having a double inclination along X- and Y-axes, the simulation is shown to be substantially conservative.*

The general conclusion of the Action 3 investigations was that the inspection techniques using a straight UT beam can result in a correct detection and sizing of hydrogen flake flaws.

The MO/AIA considers the Licensee reply to the Action 3 requirement satisfactory and has no more comments related to Action 3. "

On this basis, the FANC concludes that:

Additional simulations and reconciliation with destructive tests by the Licensee have shown that hidden flaws and higher tilted flaws of critical size can be detected and characterized by the actually applied UT-techniques.

The FANC considers that the Action 3b is satisfactorily replied to and closes this requirement.

3.4.3 Additional questions on load test (Action 16/16b)

3.4.3.1 Context

In conclusion of its Provisional Evaluation Report [5], the FANC issued the requirement 16 in order to demonstrate that the pressure vessel still has sufficient strength to bear the design pressure under hydrostatic conditions, whilst ensuring by non-destructive means that existing flaws remain stable under these conditions:

"*… the Licensee shall, as a prerequisite to the 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 acceptance criterion will be that no crack initiation and no crack propagation are recorded under the pressure loading".*

In May 2013, the AIB-Vinçotte concluded that :

" … the Licensee reply to the Action 16 requirement satisfactory. However, as Medium Term Action, further evidence of the efficiency of the applied Acoustic Emission Technique shall be provided." [22] [23]

Consequently the FANC concluded in its Final Evaluation Report that :

"Based on the data provided by the Licensee and the review and assessment of AIB-Vinçotte, Bel V and MISTRAS Group, the FANC considers that the requirement on the load test has been resolved.

The load tests performed on the Tihange 2 and Doel 3 reactor pressure vessel did not reveal any unexpected conditions. The results from the acoustic emission measurements performed did not reveal any critical source of area where supplementary investigations are mandatory.

The post-load test ultrasonic testing inspections in 2013 on the upper core shell of Tihange 2 and upper and lower core shells of Doel 3 confirmed that there was no evolution of the flaws induced by the load test. The number of indications, the UT amplitude and the dimensions of each indication are consistent with the results of the ultrasonic inspection testing in 2012." [9]

The FANC additionally requested the Licensee to provide additional validation of the Acoustic Emission Measurements. Therefore the FANC requested the Licensee to deepen the Action 16 in a new Mid-Term Action 16b.

3.4.3.2 Licensee Conclusions

In its 2015 Safety Cases, the Licensee concludes on this topic:

"All questions have been successfully addressed, confirming the validity of the Acoustic Emission (AE) measurements performed during the load tests."

3.4.3.3 Safety Authority Conclusions

Based on the answers provided by the Licensee, AIB-Vinçotte concludes from its evaluation in its Synthesis Report [20] that:

''Information was received about an additional detailed analysis of the acoustic activity that was recorded by the sensors placed in the In-Core Instrumentation room.

The Licensee submitted a supplementary test report to justify the equivalency between the auto-calibration and the Hsu-Nielsen calibration.

The MO/AIA considers the Licensee reply to the Action 16 requirement satisfactory and has no more comments related to Action 16. "

On this basis, the FANC concludes that **:**

The action 16b was satisfactorily replied to and closed the action in April 2014.

3.5 FANC Conclusions on the detection, location and characterization of the indications

The suggestions, observations and conclusions of the different organisations and working groups were evaluated by the Federal Agency for Nuclear Control. Wherever appropriate and relevant, the FANC decided to use this input in the formulation of the FANC final conclusions.

The Licensee performed an extensive qualification of the UT inspection procedure for the detection, the location and the characterization of the flaw indications found in the core shells of the reactor pressure vessels of Doel 3 and Tihange 2. From the evaluation of this UT inspection procedure, the FANC concludes:

The capability to properly detect, locate and characterize the flaws present in the reactor pressure vessels of Doel 3 and Tihange 2 has been extensively evaluated. The UT inspection procedure has been formally qualified.

The application of a formally qualified UT inspection procedure during the 2014 follow-up UT inspections of the RPV core shells of Doel 3 and Tihange 2 resulted in an updated flake cartography.

- The number of reported indications is significantly higher than in 2012, which is mainly due to the lowered detection thresholds and the use of a more sensitive transducer.
- An update of the flaw sizing procedure resulted in an increase of the flake size to be taken into account in the structural integrity assessment. The tendency of the updated flaw sizing procedure to report clusters of indications as large individual flakes leads also to the reporting of larger average dimensions and much larger maximum dimensions in 2014.
- The newly reported indications are located in the same zones as the indications reported in 2012.
- No significant radial connections between hydrogen flakes are detected in the RPV core shells.

Additional simulations and reconciliation with destructive tests by the Licensee have shown that hidden flaws and higher tilted flaws of critical size can be detected and characterized by the actually applied UT-techniques. No critical hydrogen flake type defects are expected in the areas non-inspectable by UT.

All mid-term requirements concerning the detection, the location and the characterization of the flaw indications found in the core shells of the reactor pressure vessels of Doel 3 and Tihange 2 have been satisfactory replied and have been closed by the Safety Authority.

4 Origin and evolution of the indications

4.1 Context

Determining the origin of the indications was overriding for this issue because it provides a better understanding of the impact of these indications on the RPV properties and of their potential evolution, which is a prerequisite to the fitness for service assessment of Doel 3 and Tihange 2.

The metallurgical origin and the evolution of the indications were extensively studied in 2012-2013 by the Licensee. The Licensee concluded

> "Based on the indications' morphology (elliptical and flat), their number and position in relation to the residual metallurgical features in the original ingot (positive macro-segregations) and the associated detrimental elements (e.g. relatively high carbon content, small piercing diameter of the ingot), that the indications found are caused by hydrogen flaking. The full screening of all potential forming mechanisms confirms the hydrogen flaking as the most likely origin of the indications " [1] [2]. The Licensee also concluded that "The only possible propagation mechanism is fatigue crack growth, which is calculated to be insignificant over 40 years of operation and concluded that there is no risk of ligament cracking between the flakes" [1] [2].

4.2 Situation in 2012-2013

4.2.1 FANC Provisional Evaluation Report – January 2013

Based on the data provided by the Licensee and the conclusions released by Bel V, AIB-Vinçotte and the expert groups about the material properties, the FANC drew the following conclusions in its Provisional Evaluation Report [5]:

> *"The most likely origin of the indications identified in the Doel 3 and Tihange 2 reactor pressure vessels is hydrogen flaking due to the manufacturing process. This assumption is supported by the number of flaws, their shape, orientation, and location in zones of suspected macro-segregation. No other plausible origin was identified. However, it is not possible to guarantee this assumption with absolute certainty without performing destructive testing on the reactor pressure vessels, which is not an option.*
>
> *Meanwhile, the exact root cause of the hydrogen flaking could not be precisely defined so far. The formation of hydrogen flakes is probably due to different contributing factors, such as the hydrogen concentration in ingots, the absence of or inadequate heat treatment, or the ingot size. The fact that only these vessel shells were affected (and not other similar parts manufactured by RDM) also remains an open issue to date.*
>
> *Besides, significant evolution over time of hydrogen flakes due to the operation of the reactor units is unlikely. Indeed, the indications identified are still characteristic of hydrogen flakes even after 30 years of operation. Furthermore, the only theoretical propagation mechanism is low cycle fatigue, which is considered to have a limited effect. However, there is little literature or experience about the influence of irradiation on flaw propagation in zones with hydrogen flakes. Hence, the potential evolution of the flaws under irradiation cannot be completely ruled out at this stage."*

The FANC issued one mid-term requirement concerning the topic of the origin and the evolution of the indication in its provisional evaluation report (Requirement 8).

4.2.2 FANC Final Evaluation Report – May 2013

In May 2013 based on the data and analysis provided by the Licensee and the conclusions released by Bel V, AIB-Vinçotte and the experts about the metallurgical origin and evolution of the indications, the FANC drew the following conclusions in its Final Evaluation Report [9].

> *"The most likely origin of the indications identified in the Doel 3 and Tihange 2 reactor pressure vessels is hydrogen flaking due to the manufacturing process. This assumption is supported by the number of flaws, their shape, orientation, and location in zones of suspected macro-segregation.*
>
> *Additional information was provided to explain why the hydrogen-induced flaking did not evenly affect all the forged components of the Doel 3 and Tihange 2 reactor pressure vessels (RPVs). Some of the contributing factors are the size of the ingots and the combined sulphur and hydrogen contents. New tests on samples from the reference block VB395 confirmed that the hydrogen flakes are located in macro-segregated areas, more specifically in ghost lines within these macro-segregated areas.*
>
> *Significant evolution over time of hydrogen flakes due to the operation of the reactor units is unlikely. Indeed, the indications identified are still characteristic of hydrogen flakes even after 30 years of operation. Furthermore, the only theoretical propagation mechanism is low cycle fatigue, which is considered to have a limited effect. However, there is little literature or experience about the influence of irradiation on flaw propagation in zones with hydrogen flakes. Hence, the potential evolution of the flaws under irradiation cannot be completely ruled out at this stage. "*

4.2.3 Mid-term Action Plan

The FANC issued the Requirement 8 about the metallurgical origin and evolution of the indications in its Provisional Evaluation Report [5].

8 After the restart of both reactor units, 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.

4.3 Origin of the flaw indications

Concerning the origin of the indications, the hydrogen flaking has been recognized by far as the most likely origin of the flaw indications identified in the Doel 3 and Tihange 2 reactor pressure vessels by all organisms and expert groups consulted by the FANC [24] [25] [25]. In May 2013, the FANC was satisfied by the arguments and the information provided by the Licensee to demonstrate the origin of the flaws and concluded that no open issues were remaining on this topic [9]. Consequently no additional investigations were carried out by the Licensee on this topic.

Thus, the conclusions issued by the FANC in May 2013 remain unchanged in 2015: the most likely origin of the indications identified in the Doel 3 and Tihange 2 reactor pressure vessels is hydrogen flaking due to the manufacturing and heat treatment processes.

4.4 Evolution of the flaw indications - 2014 Follow-up inspection (Requirement 8)

4.4.1 Introduction

Concerning the crack propagation of the hydrogen flakes during operation of the reactor units, each of the organisms and working groups consulted agreed with the Licensee conclusions for limiting the plausible mechanisms for a potential evolution of the flaws to the fatigue crack growth only. The experts recognized the Licensee arguments as appropriate but nevertheless recommended to perform new follow-up inspections during the next planned outage.

4.4.2 2014 outcomes

In order to answer the mid-term requirement 8, Electrabel performed follow-up UT inspections of the Doel 3 and Tihange 2 RPV core shells during the 2013 and 2014 outages, in order to rule out the evolution of the flakes.

However, in the framework of the full qualification of the UT device inspection procedure, the Licensee modified several parameters of the inspection procedure between the first UT inspection of 2012 and the latest of 2014. Indeed the Licensee lowered the detection threshold of the transducers, adapted the detection depth ranges of the transducers, changed one of the transducers to use a more sensitive one and improved the detection procedure. This consequently lead to an increase of both average and maximum flake sizes as well as the number of flakes reported, and therefore made a direct comparison of the results with the ones obtained in 2012 not evident.

To perform a meaningful comparison as a reply to requirement 8, the Licensee applied the optimized parameters achieved in 2014 on the 2012 and 2014 rough data, with the 2012 detection thresholds of the transducers.

4.4.3 Licensee conclusions

In its 2015 Safety Cases [10] [11], the Licensee concludes that:

> *"The hypothetical in-service growth of the flakes between the restart in 2013 and the shutdown in 2014 was investigated. For this purpose, the data collected during the 2014 UT inspection were analysed in accordance with the 2012 inspection procedure, applying the same parameters and reporting thresholds. The optimized sizing procedure resulting from the qualification was implemented on both data sets.*
>
> *The ultrasonic amplitude and dimensions associated to each indication of both the 2012 and 2014 datasets were compared (using criteria derived from the French RSE-M code) to verify any hypothetical occurrence of in-service growth of the flakes between 2012 and 2014. This comparison revealed no evolution. None of the indications showed any sign of modification between the two inspections."*

4.4.4 Safety Authority Conclusions

In its Safety Evaluation Report [19], Bel V concludes that:

> *"The UT inspection of the Doel 3 and Tihange 2 core shells performed in 2014 also allowed to investigate whether flakes had experienced in-service growth since the first inspection in*

2012 (less than one operating cycle). To allow the comparison with the 2012 inspection, the data acquired during the 2014 inspection were analysed using the same settings as those used in 2012. For each of the indications, the amplitude and size were compared according to the criteria set forth in the (French) RSE-M Code.

According to Electrabel, the comparison led to conclude that no new indication was detected in 2014 and no in-service growth of the indication was identified.

To Bel V opinion, considering that the time elapsed between the restart in 2013 and the shutdown in 2014 is less than one year, the results of the comparison do not allow to claim that there is an experimental evidence of no in-service growth. However, they should be considered as positive results."

In its Synthesis Report [20] [21], AIB-Vinçotte agrees with the following Licensee conclusions:

"To assess the flaw evolution, acquisition data from 2012 and 2014 were compared for flaw detection and sizing. Therefore 2014 indications were paired with those of 2012 and for the unpaired indications the under-threshold counterparts were identified.

From the comparison could be concluded that the flaw amplitude and the size variations observed between 2012 and 2014 data remain within the pre-set acceptable tolerances.

The MO/AIA considers the Licensee reply to the Action 8 requirement satisfactory and has no more comments related to Action 8."

On this basis, the FANC concludes that:

When applying the same parameters and reporting thresholds, a comparison of the data from the 2012 and 2014 UT inspections does not provide evidence for crack growth. A significant evolution of the size of the hydrogen flakes over time due to the stress of operation of the reactor units is deemed unlikely. However, the time elapsed between the restart in 2013 and the shutdown in 2014 is too short to claim that there is a definitive experimental evidence of no in-service fatigue crack growth.

4.5 Crack propagation due to hydrogen accumulation

4.5.1 Context

As part of the 2012 Safety Cases [1] [2], the Licensee made an assessment of the potential growth over time of hydrogen flakes. Based on this thorough analysis, fatigue crack growth had been identified as the only possible propagation mechanism in the specific situation of the Doel 3 and the Tihange 2 RPVs. Other propagation mechanisms (such as crack growth by a mechanism similar to flake formulation due to hydrogen intake from the primary side, and hydrogen induced cracking) were ruled out.

However in the beginning of 2015, some public statements challenged this conclusion. A hypothesis of hydrogen blistering or hydrogen-induced cracking was put forward by prof. W. Bogaerts (KU Leuven) and prof. D.D. Macdonald (UC Berkeley) who state that the exposure of the reactor pressure vessels to the primary water during operation could result in a molecular hydrogen accumulation and consequently a pressure increase in the (hydrogen-induced) flakes, and lead to their growth during the operation of the RPV. They considered that the issue was not conveniently handled in the 2012-2013 Safety Case evaluation.

Following these public statements, the FANC decided to examine the technical arguments behind this hydrogen-induced cracking (HIC) hypothesis and asked the Licensee to deepen its position on this topic. In response the Licensee performed several additional studies summarized in its 2015 Safety Cases.

In parallel, on the request of the Scientific Council for Ionizing Radiations (see 2.1.2), the FANC re-established in March 2015 the scientific group of Belgian university professors NSEG in order to evaluate the relevance of this HIC hypothesis. Several expert meetings and hearings with prof. Bogaerts, prof. MacDonald and the Licensee were held by this National Scientific Expert Group (NSEG) (see 2.1.3.3), which also received reports from three international experts on hydrogen-induced corrosion issues, some of whom were recommended by prof. Bogaerts himself.

Based on the NSEG outputs and its analysis of the experts statements, the FANC presented its HIC synthesis report and its conclusions to the Scientific Council for Ionizing Radiations [18]. The conclusions of the Licensee and the Safety Authority, detailed in this report, are summarized in the following sections.

4.5.2 Licensee conclusions

In its 2015 Safety Cases [10] [11], the Licensee concludes that:

> *"Based on an extensive study, it can be concluded that the hydrogen uptake during operation is too low to induce propagation of the existing hydrogen flakes in the D3T2 RPVs by a hydrogen-related mechanism.*
>
> *…*
>
> *As the hydrogen content and pressure in the flakes is too low, no primary side hydrogen impact is expected on the material properties and no hydrogen-related propagation mechanism is possible.*
>
> *The approach and calculation hypotheses have been validated by measurements of residual H content in flakes (showing no significant H content), through literature review and advice from international experts.*
>
> *The absence of H-induced flake propagation is also confirmed by the absence of evolution of the flakes after one complete cycle and shutdown. "*

4.5.3 Safety Authority Conclusions

In its 2015 Safety Evaluation Report [19], Bel V concludes that:

> *"The arguments presented by the protagonists of the molecular hydrogen accumulation hypothesis did not convince Bel V, neither did they convince the international experts invited by the NSEG. On the contrary, it was concluded that the Doel 3 and Tihange 2 reactor pressure vessels are unlikely to suffer hydrogen induced cracking."*

Based on the documents available and the discussions held during the two NSEG meetings , the NSEG issued in September 2015 two additional recommendations to the Licensee:

1. *"that the Licensee should confidently justify that the predicted hydrogen pressures in the existing flakes during cooling are conservative. …;*
2. *that the Licensee should also consolidate its calculation of stress intensity factors in case of an unplanned emergency cooling down by combining the thermo-mechanical loading and the internal pressure evolution.*

In October 2015 the Licensee submitted additional reports and calculation notes to the FANC to take into account these recommendations. The FANC and Bel V have evaluated the documents and results provided by the Licensee in order to fulfil the NSEG recommendations. The FANC remarks that the Licensee's additional studies meet the justifications and demonstrations suggested by the NSEG group and strengthen their arguments considering the relevance of this hydrogen induced cracking hypothesis. In consequence, the FANC concludes that the Licensee adequately replied to these recommendations.

Taking into account

- the initial arguments from the Licensee and the two professors Bogaerts and Macdonald ;
- the comments from the NSEG group;
- the additional studies and calculations provided by the Licensee to fulfil the NSEG recommendations ;
- the evaluation by Bel V;
- the comments stated by three international experts which are worldly recognized as specialists in hydrogen induced corrosion issues,

The FANC draws the following conclusions in its HIC Synthesis Report [18]:

The only theoretical propagation mechanism for the flakes detected in the Doel 3 and Tihange 2 reactor pressure vessels is low cycle fatigue, which is considered to have a limited effect. Other phenomena (such as hydrogen blistering or hydrogen induced cracking) have been evaluated and ruled out as possible mechanisms of in-service crack growth.

4.6 FANC final conclusions on the origin and evolution of the indications

The suggestions, observations and conclusions of the different organisations and 2015 working groups were evaluated by the Federal Agency for Nuclear Control. Wherever appropriate and relevant, the FANC decided to use this input in the formulation of the FANC final conclusions.

Concerning the origin of the indications, the conclusions issued by the FANC in May 2013 remains unchanged.

The most likely origin of the flaw indications identified in the Doel 3 and Tihange 2 reactor pressure vessels is hydrogen flaking due to the manufacturing process.

Concerning the evolution of the indications, when applying the same parameters and reporting thresholds, a comparison of the data from the 2012 and 2014 UT inspections does not provide evidence for crack growth. A significant evolution of the size of the hydrogen flakes over time due to the stress of operation of the reactor units is deemed unlikely. However, the time elapsed between the restart in 2013 and the shutdown in 2014 is too short to claim that there is a definitive experimental evidence of no in-service fatigue crack growth.

The only theoretical propagation mechanism for the flakes detected in the Doel 3 and Tihange 2 reactor pressure vessels is low cycle fatigue, which is considered to have a limited effect. Other phenomena (such as hydrogen blistering or hydrogen induced cracking) have been evaluated and ruled out as possible mechanisms of in-service crack growth.

All mid-term requirements concerning the origin and evolution of the flaw indications found in the core shells of the reactor pressure vessels of Doel 3 and Tihange 2 have been satisfactorily replied to and closed by the Safety Authority.

The FANC requires the Licensee to perform the following Requirement:

> **REQUIREMENT 2015/1 - FOLLOW-UP IN-SERVICE INSPECTIONS: The Licensee will perform follow-up UT-inspections, using the qualified procedure on the upper and lower core shells wall thickness of the reactor pressure vessels at the end of the next cycle of Doel 3 and Tihange 2, and thereafter at least every three years.**

5 Material Properties

5.1 Context

The characterization of the material properties is an important topic of the Safety Case. Indeed the initial material properties and their time evolution are one of the key inputs for the Structural Integrity Assessment (SIA) of the D3T2 RPV core shells.

It is well known that the RPV steel mechanical properties evolve under irradiation, i.e. the steel becomes harder and brittle over the time, which gradually brings the RPV steel from the ductile domain to the brittle domain. In this context, it is of utmost importance to be able to predict the evolution of the material properties of the RPV forgings all over the lifetime of a nuclear reactor.

In this framework, the FANC issued in 2013 the Requirement 11 consisting in evaluating the material properties of an irradiated flaked material. However the unexpected outcomes obtained in 2014 on this topic gave rise to an extension of the material testing program. A significant part of the activities performed by the Licensee for the 2015 Safety Case is thus related to the evaluation of the evolution of the material properties in operation. In order to fully address this concern, the initial action plan was gradually extended taking full benefit of the available materials. No flaked specimens from Doel 3 and Tihange 2 are available as the surveillance specimens were taken far from the macrosegregated areas in which the hydrogen flakes form. Most test materials were thus performed on representative flaked material such as theVB395, KS02 or unflaked materials such as the nozzle cuts of Doel 3 and Tihange 2 and some reference materials. The Licensee finally carried out more than 1500 material tests in different laboratories (AREVA, Laborelec, SCK●CEN, VTT) for determining the material properties for the structural integrity assessment.

5.2 Situation in 2012-2013

5.2.1 FANC provisional evaluation report – January 2013

Based on the data provided by the Licensee and the conclusions released by Bel V, AIB-Vinçotte and the expert groups about the material properties, the FANC drew the following conclusions in its Provisional Evaluation Report [5]:

> "*Within a limited timeframe, a material testing program was performed by the Licensee on the available specimens. However, no test sample or specimen containing hydrogen flakes is available from the Doel 3 and Tihange 2 reactor pressure vessel shells. Therefore, some uncertainty about the representativeness of the test program exists.*
>
> *Furthermore, there is at present little experimental data available about the (local) mechanical properties of materials in zones with macro-segregations containing hydrogen flakes. This applies even more to irradiated materials containing hydrogen flakes. Hence more experimental data on tensile and toughness properties of the materials are needed to validate the approach followed in the structural integrity assessment for both reactor pressure vessels and especially to confirm that the additional 50° shift in RTNDT proposed by the Licensee is conservative.*"

The FANC issued five requirements concerning the topic of the material properties in its provisional evaluation report: two short-term actions (Requirement 9 and 10) and three mid-term actions (Requirements 11, 12 and 13) (see Annex 1).

5.2.2 FANC final evaluation report – May 2013

Based on the data provided by the Licensee and the review and assessment of AIB-Vinçotte, Bel V and the National Scientific Expert Group on the topic "Material properties", **the FANC concluded in its Final Evaluation Report in 2013** [9] **that all the identified short-term open issues on this topic had been resolved:**

> *"The Licensee performed additional material tests on H1 nozzle cut-out material from Doel 3 and on materials, with and without flakes, from the AREVA steam generator shell VB395.*
>
> *The results of the additional characterization tests on the H1 nozzle cut-out from Doel 3 has shown that the ghost lines do not affect significantly the mechanical (tensile and fracture toughness) properties of the material.*
>
> *The results of the additional characterization of the AREVA shell VB395 have shown that the hydrogen flaking affects the mechanical (tensile and fracture toughness) properties of the material by reducing its ductility and increasing its brittleness. However the degradation of the material properties as evidenced by the tensile and fracture toughness tests are considered to be limited.*
>
> *From additional experimental fracture toughness tests on VB395 specimens, the 50°C margin on RTNDT considered in the Safety Case is deemed to be conservative.*
>
> *Additional tests also confirmed that there is no significant amount of residual hydrogen present inside the flakes."*

The FANC concluded that the two identified short term issues (Requirements 9 and 10) had been satisfactorily resolved for the restart. Nevertheless some complementary information was requested on these two topics as additional Mid-term Requirements (Requirements 9b and 10b) to be performed before the first reactor restart following the next planned outage of the two reactors.

5.2.3 Mid-term Action Plan

9/9b	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
10/10b	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.
11	A further experimental study program on the material properties of irradiated specimens containing hydrogen flakes shall be elaborated by the Licensee.

12 The Licensee shall further experimentally investigate 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.

13 The Licensee shall further evaluate the effect of thermal ageing in the zone of macro-segregation

In summary, the Licensee had to carry out additional studies concerning five Mid-term requirements on the flaked material properties. The Licensee performed the relevant studies from 2013 on.

5.3 Material properties of flaked materials under irradiated conditions (Requirement 11)

In March 2014 the realization of Action 11 concerning the experimental validation of the assumed evolution of the mechanical properties of a flaked material under irradiation resulted in significant outputs that could challenge the assessment provided in the 2012 Safety Case.

As a consequence, the Licensee decided to immediately anticipate the planned outages for both reactors, and to maintain them shut down (with core unloaded) until proven that they can be safely operated, i.e. by demonstrating that these unexpected results do not raise safety concerns for the integrity of the RPVs of Doel 3 and Tihange 2.

5.3.1 Context

Existing formula are commonly used to predict the irradiation embrittlement of the RPVs during operation. For Doel 3 and Tihange 2, the Licensee was using the French FIS formula as it was best fitting the data obtained from the surveillance specimens. In its 2012 Safety Case, the Licensee based its prediction of the embrittlement on the French FIS formula, adding some additional terms to the equation for considering potential effects of the flakes on the material fracture toughness.

In its evaluation of the Licensee Safety Cases of 2012, the FANC concluded from experimental unirradiated fracture toughness tests and from theoretical considerations that the additional terms were deemed to be conservative for addressing the behaviour of a flaked material under irradiation but nevertheless requested the Licensee to perform an experimental program to confirm this assumption (Requirement 11).

In order to reply to this open mid-term issue, the Licensee planned for 2014 fracture toughness tests on specimens taken from a representative flaked material (VB395) and irradiated in the BR2 test reactor from the SCK•CEN research centre (Belgium). These specimens were irradiated during an irradiation campaign (referenced as Chivas 9) of the BR2 reactor in February 2014, at a level of fluence corresponding to more than 40 years of reactor operation.

In March 2014, the preliminary results of the destructive tests (fracture toughness tests) conducted on these irradiated specimens gave an embrittlement of these specimens significantly higher than the values predicted by the dedicated D3T2 formula, questioning the conservatism of the proposed additional terms. So the experimental program evidenced an unexpected enhanced irradiation embrittlement.

In view of assessing these unexpected test results, the FANC therefore requested Electrabel to investigate the root causes of these unexpected outcomes and to justify the adequacy of the predictive equations for the irradiation embrittlement, by demonstrating its conservativeness. A significant part of the activities performed by the Licensee for the 2015 Safety Case is thus related to the assessment of this unexpected irradiation embrittlement of the VB395 shell material. That assessment was indeed a prerequisite for determining whether or not a similar behaviour was expected for the Doel 3 and Tihange 2 RPV core shells.

5.3.2 Unexpected enhanced irradiation embrittlement

During the Chivas 9 test campaign, the Licensee made use of the VB395 material to characterize the behaviour of a flaked material under irradiation. Indeed this particular material, already used by the Licensee in the framework of the 2013 Safety Case for the characterization of the unirradiated mechanical properties of a flaked material and for validating UT investigations, was the only available flaked material at that time. In addition, the VB395 material has a similar chemical composition as the Doel 3 and Tihange 2 RPVs. This piece was originally forged for a French steam generator, but rejected during the manufacturing process due to the presence of hydrogen flaking. Indeed a high density of hydrogen flakes was found in the macro-segregated zones of this material.

Some fracture toughness test specimens taken from the flaked region of the VB395 shell material were irradiated under high flux in the BR2 in a loop simulating PWR conditions. The preliminary results of the destructive tests in March 2014 suggested the presence of an atypical and unknown phenomenon as most mechanical properties (hardening, yield stress ,…) behave as predicted at the exception of an embrittlement significantly greater than expected.

In this context, investigations on another flaked material KS02 from a German research program from the 70's and 80's were resumed, after discovery of the existence of remaining block of this vessel material. The Licensee demonstrated that the flaws detected in this KS02 material, which is made of a steel of a slightly different composition than the VB395 and the RPV forgings of Doel 3 and Tihange 2, were actually hydrogen flakes.

The Licensee initial action plan was therefore gradually extended taking full benefit of the available materials. Indeed since the Chivas 9 irradiation test campaign, the Licensee has irradiated test samples from some representative materials, in various conditions, during the three consecutive irradiation campaigns of the BR2 research reactor (Chivas 10, Chivas 11 and Chivas 12):

- New irradiation campaigns were performed and microstructural material investigations were launched in order to assess the atypical embrittlement of the flake-affected material VB395.
- Irradiation and investigations on the flaked KS02 material.
- Irradiation of material from the nozzle cuts of Doel 3
- Validation on reference JRQ material for irradiation damage studies ("introduced by the IAEA in the Co-ordinated Research Project on "Optimizing Reactor Pressure Vessel Surveillance Programmes and their Analysis", which began in 1983. The use of JRQ material has since then been internationally recognized and explored by a number of IAEA Member States." [26])

5.3.3 Evaluation Process

5.3.3.1 Two-step approach

In the framework of the two-steps approach defined in 2014, the Safety Authority focused first on the methodology proposed by the Licensee to consider the unexpected test results in the evaluation of the material properties of the D3T2 RPV forgings in irradiated conditions. This methodology gives rise to an adapted predictive fracture toughness equation for use in the structural integrity assessment.

In the second step of the Safety Case review, the Safety Authority reviewed the application of this predictive equation for the irradiation embrittlement of the RPV's core shells and validated the values considered by the Licensee in the 2015 Safety Cases. Although SIA of Doel 3 and Tihange 2 RPVs was the primary focus of the review performed by ORNL, FANC also requested ORNL to discuss the material properties of the reactor vessels as they are parameters directly used in the SIA.

5.3.3.2 International Review Board

The results of the mechanical tests following the first irradiation campaigns were unexpected and were suggesting the presence of an atypical embrittlement phenomenon. Considering that these results were within the current limits of material science, the FANC decided to establish a group of international experts in order to consolidate its analysis: the International Review Board (see paragraph 2.1.3.1 for more details).

The FANC charged the International Review Board to conduct an independent review and to address two specific, limited topics. The implication of the IRB is therefore limited to the first step of the review process, the evaluation of the methodology proposed by the Licensee [14]:

> **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) VB395 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:*
>
> **"**P*recise mechanism of non-hardening embrittlement and precise root cause of non-hardening embrittlement of VB395 remain unidentified but hydrogen-related and hydrogen-flaking related mechanisms are excluded."*

5.3.3.3 Evaluation timing

Following the first irradiation campaign of February 2014, the Licensee decided to perform a second irradiation campaign in order to confirm the unexpected outcome and evaluate the plausibility of the various potential explanations, in particular the effects of the irradiation or test conditions.

This second campaign (Chivas 10) took place in April-May 2014, in the same reactor BR2 in similar PWR conditions (fluence, pressure, temperature,…). Investigations were planned on a wide selection of materials and test conditions. This second irradiation campaign confirmed the unexpected enhanced embrittlement within the macro-segregation zones of the VB395, where the flakes are located, and allowed to eliminate the most possible explanations, in particular an effect of test conditions in BR2 reactor.

In July-August 2014, a third irradiation campaign (Chivas 11) took place with reduced fluence compared to the two first irradiation campaigns in order to investigate the evolution of the unknown phenomenon over time, so as a function of the fluence.

On the basis of these new results, the Licensee drafted a predictive equation for the embrittlement of the VB395 under irradiation, based on the new R-SEM French predictive formula, aiming to replace the FIS formula.

A first meeting of the IRB was held in the beginning of November 2014, leading to a first evaluation on the acceptability of the methodology proposed by the Licensee to incorporate the unexpected outcomes of the material properties within the inputs of the structural integrity assessment. The IRB concluded that the case was not mature enough to reach firm judgments on this topic. In parallel, the Safety Authority reached similar conclusions.

In December 2014 the FANC formulated several requests summarizing the IRB and the Safety Authority concerns on this topic. Their fulfilment was a prerequisite for a revaluation of the acceptability of the methodology.

The Licensee answered these demands from December 2014 to April 2015 by performing additional material investigations, including a fourth irradiation campaign in February 2015 with another material affected by hydrogen flaking, namely the German KS02 material. The Licensee therefore significantly improved and justified his method for estimating the fracture toughness bounds for a flaked material, i.e. by improving their predictive equation taking into account the new test results.

By the end of April 2015, a second meeting of the IRB was held. The IRB concluded that [14]:

> *"In the judgement of the majority of IRB members, and based on the information available to it on 24 April 2015, there are no major concerns with the methods proposed for estimating the fracture toughness bounds for the Doel 3 and Tihange 2 RPV core shells to a 40 year plant life. One member, however, remains concerned that the overall margins in the safety case may be inadequate for reasons given in the Final IRB Report* [14]*"*

In fact eight of nine experts share the conclusions that the predictive equation for the irradiation embrittlement proposed by the Licensee is adequate to evaluate the behaviour of the D3T2 RPV core shells under irradiation. The 9th expert presented his concern to the Safety Authority, based on the documents available during the second IRB meeting on the irradiation concern.

IRB provided its draft report by the end of May 2015. However the final report has been provided to the FANC by 28 August 2015. In this final report, the IRB conclusions of the draft report remain unchanged. During this time the IRB was able to discuss in depth the formulation of their arguments and the 9th expert reviewed the Licensee replies to his concerns.

By the end of May 2015, the Safety Authority performed its revaluation of the detailed approach for achieving these predictive equations and shared partly the concern of the 9th expert from the IRB. In consequence, the FANC announced to the Licensee that its predictive equations for the embrittlement under irradiation were therefore not yet acceptable and required some additional justification and modifications.

By the end of June 2015, the Licensee provided an adapted predictive equation based on test results, sensitivity studies and justifications from additional studies replying to the concern expressed by the Safety Authority. On the basis of those new elements, the Safety Authority considered the concern as resolved and accepted the adapted predictive equations to evaluate the embrittlement under irradiation.

The FANC provided the final documents concerning the material properties of the reactor vessels directly used in the SIA to ORNL for evaluation.

5.3.4 Mechanical behaviour of a flaked material

5.3.4.1 Available material

In its extensive material testing program, the Licensee made mainly use of three materials: samples from the D3T2 RPV forgings, VB395 shells and a KS02 flange. These are the three materials that have large numbers of hydrogen flakes in their macro-segregated areas.

Although the three materials have slightly different chemical compositions, they all belong to the RPV steel type families. These materials have been subjected to different anomalies during their manufacturing process:

- D3T2 RPV forgings : The Licensee made use of the specimens from the RPV surveillance programme from both upper core shells of Doel 3 and Tihange 2 and of specimens from the nozzle shell cut-outs from Doel 3 and Tihange 2.
- VB395 : VB395 is a steam generator forged shell in 18MND5 steel, rejected during manufacturing in the beginning of 2012 due to the presence of a large number of flakes. It was partially characterized in non-irradiated conditions in the framework of the first Safety Case addendum, and more extensively in support of the irradiation program [20].
- KS02 : The KS02 component is a forging for a vessel flange of a 1300 MW PWR in steel 22NiMoCr37 which was rejected in fabrication in 1971 due to the presence of numerous indications, identified recently as hydrogen flakes [20].

5.3.4.2 Licensee Conclusions

On the basis of the results of its extensive research program, the Licensee states in its 2015 Safety Case reports [10] [11] that:

"Tests performed under non-irradiated and irradiated conditions on flaked material from VB395 and KS02 confirm that the presence of hydrogen flakes does not have any effect on the evolution of fracture toughness under irradiation.

The D3T2 RPV forgings and the German KS02 flange behave as expected under irradiation conditions, as shown by:

- *Very similar material properties in their different zones*
- *An embrittlement that is in line with the predictions*
- *The expected hardening embrittlement*
- *Almost no variation of micro-cleavage fracture stress when fluence increases*

Contrary to the D3T2 RPV forgings and KS02, the VB395 shell does not behave as expected under irradiation, and is to be considered as an outlier because of:

- *Very different properties in different zones*
- *An embrittlement that is far beyond predictions as evidenced by detailed comparison to embrittlement data from the ASTM E-900 database and to the French database used to develop the RSE-M trend curve*
- *Atypical embrittlement characterized by a high shift of the fracture toughness curve while the hardening is as expected for this type of material*
- *A substantial decrease in micro-cleavage fracture stress with fluence in all zones and a shift in fracture"*

"In comparison with the D3T2 RPV forgings and the KS02, it can thus be concluded that the VB395 demonstrates the behaviour of an outlier. Its embrittlement under irradiation is characterized by a substantial decrease in micro-cleavage fracture stress in Blocks 5 and 6, and a shift in fracture toughness T0 that is considerably higher than predicted in all zones of Block 6. This outlier behaviour only affects the irradiation embrittlement, while the non-irradiated properties are representative for this type of material."

"Results obtained under irradiated conditions confirm that the presence of hydrogen flakes does not induce a specific sensitivity of the material to irradiation embrittlement".

<u>On the enhanced irradiation embrittlement of the VB395</u>, the Licensee states in its 2015 Safety Case reports [10] [11] that :

- *"The root cause analysis of the atypical VB395 embrittlement concludes that several mechanisms can be excluded. In particular, hydrogen flaking or any other hydrogen-related mechanism can be excluded as the cause of the unexpected behaviour. This conclusion is also further supported by the results on the German KS02 material, which shows an important amount of hydrogen flakes and is not affected by atypical embrittlement under irradiation.*
- *No mechanisms that are likely to be responsible for atypical embrittlement were identified. However, two mechanisms are considered as possible: segregation of impurities to carbide or precipitate interface with matrix, and loss of strength of the segregation network due to atypical embrittlement of martensite.*
- *Both mechanisms might be linked to specific aspects of the manufacturing history of the rejected VB395 shell that were evaluated as being possible root causes. These aspects are related to chemical composition, casting technique and thermal treatment.*
- *Since the larger than predicted shift in transition temperature after irradiation of VB395 is not linked with the hydrogen flaking and since none of the above-mentioned manufacturing specificities are reported for the D3T2 RPVs, it is expected that the D3T2 RPV shells do not suffer from the atypical embrittlement observed on VB395."*

5.3.4.3 Safety Authority Conclusions

The IRB concludes [14] that :

"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. <u>The IRB accepts this conclusion</u>. 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. "

In its Safety Evaluation Report [19], Bel V concludes that

"Bel V concludes that the hydrogen flaking as a damage has no effect on the fracture toughness of the material and the fracture resistance of the flakes is governed by the fracture toughness of the macro-segregated material where the flakes are located. The flakes may therefore be evaluated as any other crack in a sound material, the latter being in the present case the macro-segregated material where the flakes are located. This conclusion assumes that the stability of the flakes under single loading and their growth under repeated loadings may be assessed using the same methods as those currently used for mechanically-induced cracks (e.g., fatigue cracks).

…

there is likely no link between enhanced irradiation embrittlement and hydrogen flaking but the demonstration might appear as exhibiting certain weaknesses.

Bel V has no fundamental objection against the identification of two mechanisms as mechanisms that contribute to the occurrence of the enhanced irradiation embrittlement. Bel V also shares the cautiousness shown by Electrabel when establishing the possible link between both mechanisms and specific aspects of the manufacturing history of the VB395 shell."

…

Those results suggest that a second embrittlement mechanism is acting in addition to the irradiation hardening mechanism in the VB395 material.

…

To Bel V opinion, there are arguments to support the statement that the material of Doel 3 and Tihange 2 RPV core shells is likely not affected by the enhanced irradiation embrittlement. However Bel V considers that the statement does not rely on a sound and well-reasoned demonstration… The fact that enhanced irradiation embrittlement has not been identified in the Doel 3 nozzle shell and upper core shell does not allow to conclude that the occurrence of enhanced irradiation embrittlement may be excluded for the Doel 3 lower core shell and Tihange 2 upper core shells (which are the most affected by hydrogen flaking)."

In its Synthesis Report [20] [21], AIB-Vinçotte agrees with the following Licensee conclusions:

"The main objective of action 11 was to demonstrate the conservatism of the 50°C margin on the RT_{NDT} shift considered in the Safety Case of 2012-2013. This would have been straightforward if the VB395 material had shown the behavior that could be expected based on its chemical composition and the absence of an important effect of flakes in non-irradiated condition.
Out of two materials affected by hydrogen flakes in fabrication that were available for testing, the German KS02 material behaved normally, while the other material (VB395) showed an atypical embrittlement.
…
The fact that the fracture toughness in the ligament between flakes or at the tip of real flakes is practically identical shows that the flakes themselves are not responsible for the high embrittlement of the VB395 material.
…
From the presented test results followed that the only material exhibiting an atypical embrittlement is the VB395 material and there is no reason to conclude that the material properties in the flaked RPV shells of Doel 3 and Tihange 2 are necessarily worse than in a shell without flakes like the Doel 3 H1 cut-out."

In its final report [15] ORNL concludes that:

- *"Tests performed on flaked material (VB395 and KS02 forgings) show that the presence of flakes has no substantial impact on the mechanical properties as very similar results were obtained for specimens with flakes, for specimens taken between flakes, and for specimens taken outside the flaked area.*
- *Overall, the differences between fracture toughness T0 and Charpy V-notch T41J measured on all tested materials in the unirradiated condition are within the scatter band observed on various RPV steels.*

- *The surveillance data from D3 and T2 demonstrate very good correspondence between the measured T41J shifts and the predictions by the French RSE-M predictive equation.*
- *Regarding the VB395 forging, very disparate results point to an extremely inhomogeneous material leading to the observation that the primary benefit from the testing of this material is that the hydrogen flakes did not substantially affect the fracture toughness of the material*
- *The root cause for the abnormal and excessive embrittlement of the VB395 forging is not thoroughly known at this time. Although not necessary for application to D3/T2, ORNL suggests that further research be conducted to discern the exact mechanism(s) of the abnormal embrittlement to provide additional knowledge regarding behavior of forgings with hydrogen flakes."*

The FANC concludes on the basis of the previous conclusions that:

- **The tested materials have exhibited different behaviour under irradiation :**
    - **The unflaked test specimens from the surveillance program of Doel 3 and Tihange 2 and from the nozzle cuts of Doel 3 exhibit a behaviour under irradiation consistent with the predictions.**
    - **The test specimens, with or without flakes, from the macrosegregation zone of the VB395 exhibit an enhanced irradiation embrittlement inconsistent with the predictions, but a hardening consistent with the predictions.**
    - **The test specimens from the KS02, flaked or unflaked, from any zones, exhibit a behaviour consistent with the predictions. Due to the chemical composition of this material, the predicted embrittlement is nevertheless higher than for VB395 and reactor pressure vessels material.**
- **An unknown phenomenon affects the VB395 material inducing an enhanced embrittlement without a hardening of the test specimens from the macrosegregation zones of the VB395 material.**
- **Hydrogen flaking is likely to be excluded as the root cause of this enhanced irradiation embrittlement, as the existence of KS02 shows that hydrogen flaking does not necessarily imply enhanced irradiation embrittlement.**
- **Complementary investigations on the flaked materials available (VB395 and KS02) show that the presence of flakes has no direct effect on the fracture toughness of the RPV material (in unirradiated or irradiated conditions).** [12]
- **The VB395 can be considered as an outlier. Therefore it can be assumed that the irradiation embrittlement of the VB395 is likely to be not representative and significantly higher than the expected embrittlement of Doel 3 and Tihange 2 core shells.**

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[12] This conclusion is a revaluation of one of the conclusion of the 2013 Final Evaluation Report:

"The results of the additional characterization of the AREVA shell VB395 have shown that the hydrogen flaking affects the mechanical (tensile and fracture toughness) properties of the material by reducing its ductility and increasing its brittleness. However the degradation of the material properties as evidenced by the tensile and fracture toughness tests are considered to be limited.

5.3.5 Predictive formula for the irradiation embrittlement

5.3.5.1 Description

In the 2015 Safety Cases [10] [11], the Licensee described the predictive formula for the irradiation embrittlement used in the structural integrity assessment : "The first mechanical tests performed on VB395 specimens under irradiated conditions indicated that the 2012 Safety Case trend curve was not enveloping the behaviour of VB395 under irradiation at high fluence values. On the basis of those test results modified trend curves were built", as follows:

$RT_{NDT} = RT_{NDT,init} + \Delta RT_{NDT,init,segr} + \Delta RT_{NDT,RSE\text{-}M} + \Delta RT_{NDT,VB395} + M$

- $RT_{NDT,init}$ corresponds to the initial RT_{NDT} of the core shells as determined by RDM
- *$\Delta RT_{NDT,init,segr}$ covers the potential effect of the macro-segregation on the initial RT_{NDT}. On the basis of material representative of the D3T2 core shells, this effect was estimated as 10°C*
- *$\Delta RT_{NDT,RSE\text{-}M}$ corresponds to the shift in RT_{NDT} as a function of fluence, as given by the French RSE-M (Ed.2010) embrittlement trend curve evaluated for the D3T2 core shell chemical composition …*
- *$\Delta RT_{NDT,VB395}$ is an additional fluence dependent shift as observed on the VB395 material. It is taken as the difference between the observed atypical embrittlement of the material between hydrogen flakes and the embrittlement that can be expected for this material on the basis of the RSE-M trend curve*
- *M is a margin based on the uncertainties of the different terms …"*

5.3.5.2 Safety Authority Conclusions

The different terms of the predictive formula have been evaluated by the Safety Authority as described below.

<u>On the beginning of life toughness </u>: $RT_{NDT,init}$

Based on the documents available in April 2015, the majority of the IRB experts concluded:

> *"The method proposed by Electrabel to estimate the 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..."*

The IRB 9th expert concludes that :

> *"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."*

On the basis of the two above comments and the first evaluations of the Safety Authority of May 2015, the Licensee added the specific term $\Delta RT_{NDT\ init\ (segregation)}$ to additionally taking into account a potential effect of the degree of segregation on the beginning-of-life toughness.

Based on his own analysis of the available data [19], Bel V concludes on this updated term for the beginning-of-life toughness that:

"The estimated difference in RT_{NDT} between the non-segregated and the segregated zones of the Doel 3 and Tihange 2 core shells was in the range of 0°C to 20°C. That is to say that those values of 0°C and 20°C are to be considered respectively as the estimated lower bound and the upper values of the difference in RT_{NDT}. Then, there are some unpublished experimental data which show that the segregation effect increases by about 10°C the RT_{NDT} temperature in the zones with positive segregation when compared to the zones with a carbon segregation equal to zero. So, Bel V concluded that a value of 10°C for $\Delta RT_{NDT\ init\ (segregation)}$ and a value of 5°C for the associated uncertainty (1σ) were acceptable. Those values are identical to the values proposed by Electrabel to solve the issue but they were obtained in a different way."

<u>On the shift of fracture toughness due to irradiation</u> : $\Delta RT_{NDT,RSE-M} + \Delta RT_{NDT,VB395}$

All the experts of the IRB consider 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. "

In its Safety Evaluation Report [19], Bel V concludes that:

"$\Delta RT_{NDT}(VB\ 395)$ is an additional term that accounts for the anomalous irradiation embrittlement affecting the VB395 material in addition to the hardening embrittlement. It is expressed as:

$$\Delta RT_{NDT}(VB\ 395) = factor_{VB\ 395} * \Phi^{0.59}$$

… Electrabel assumes that the irradiation embrittlement is the sum of two components, i.e., the (usual) hardening component and an additional component responsible for the enhanced irradiation.

Bel V agrees with that assumption… Those results suggest that a second embrittlement mechanism is acting in addition to the irradiation hardening mechanism in the VB395 material.

To Bel V opinion, the only possible way to define a value to $factor_{VB\ 395}$ is to consider the value calculated from the experimental data obtained in the flaked region of the VB395 shell as an estimate of the upper bound and to associate therefore no uncertainty to it. Bel V considers that approach as satisfactory for providing an acceptable value to the safety provision $factor_{VB\ 395}$."

<u>On the Margins :</u>

All the experts of the IRB consider that :

"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… 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. "

In its Safety Evaluation Report [19], Bel V concludes that the evaluation of the Margin term M by combining the uncertainties associated to $RT_{NDT,init}$, $\Delta RT_{NDT,init,segr}$ and $\Delta RT_{NDT,RSE-M}$: without taking any uncertainty on $\Delta RT_{NDT,VB395}$ was acceptable.

<u>Overall validity of the predictive equations for the irradiation embrittlement</u>

On the acceptability of the predictive equations for the irradiation embrittlement the IRB [14] concludes that:

> *"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."*

In its Safety Evaluation Report [19], Bel V concludes that

> *"The modified predictive equation was adopted Electrabel in the Safety Case. … That was accepted by Bel V."*

In its Synthesis Report AIB-Vinçotte [20], agrees with the following Licensee conclusions:

> *"From the presented test results followed that the only material exhibiting an atypical embrittlement is the VB395 material and there is no reason to conclude that the material properties in the flaked RPV shell of Doel 3 are necessarily worse than in a shell without flakes like the Doel 3 H1 cut-out.*
> *In view of ensuring a conservatism of the structural integrity analysis, the Licensee considered a fracture toughness in the analysis that was based on the assumption that the Doel 3 and Tihange 2 vessel shells have an additional sensitivity to irradiation embrittlement of the same magnitude as the VB395 material."*

The MO/AIA considers the Licensee reply to the Action 11 requirement satisfactory and has no more comments related to Action 11.

In its final report [15] ORNL concludes that:

- *"The VB395 and KS02 materials are only relevant to D3/T2 primarily with regard to the fact that they each contain a high density of hydrogen flakes that is valuable in assessing if the hydrogen flakes have significant effects on the mechanical properties and fracture toughness of the D3/T2 forgings as a consequence of exposure to irradiation. The fact that Electrabel has applied an additional margin based on the behavior of the irradiated VB395 material is considered an additional conservatism.*
- *A concern expressed by the International Review Board regarding the margin applied to the unirradiated RT_{NDT} for the D3/T2 materials resulted in Electrabel using a new approach to the overall margin with recent calculations showing that the current method has other built-in margins that compensate for this area of concern. ORNL is in agreement with the appropriately conservative margin applied by Electrabel in the Safety Cases. "*

The FANC concludes on the basis of the previous conclusions that :

> **New predictive equations for the irradiation embrittlement have been proposed by the Licensee for the structural integrity assessment of the Doel 3 and Tihange 2 reactor pressure vessels.**
>
> **The 50°C margin on RT_{NDT} considered in the 2013 Safety Case is discarded and replaced by predictive equations depending on the material properties. Considering the VB395 to be an outlier for material behaviour under irradiation, the core shells of Doel 3 and Tihange 2 are unlikely to be more sensitive to irradiation. Nevertheless, as a safety provision, the Doel 3 and Tihange 2 predictive equations take into account the atypical embrittlement observed in the VB395 flaked material. Therefore the FANC deems the predictive equations for the irradiation embrittlement featured in the 2015 Licensee Safety Cases are acceptable.**

5.4 Other FANC requirements on material properties

The Licensee had to resolve Actions 9 to 13 in the framework of the topic on the material properties.

5.4.1 Additional tensile tests of specimens with a ghost line (Requirement 9/9b)

5.4.1.1 Context

Following comments and requests from Bel V and AIB-Vinçotte in January 2013 on the need to perform mechanical tests on flaked specimens from the macro-segregated areas [5], the Licensee had to answer to Requirement 9 as a prerequisite to a restart of the two reactors in 2013 [5].

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.

In May 2013, the Safety Authority reviewed the Licensee conclusions and concluded that the Requirement was replied to satisfactory and closed the Action 9. However AIB-Vinçotte required additional investigations as a mid-term Requirement

9b The Licensee shall provide data about the tensile properties at ambient temperature of specimens with T orientation and taken in ghost lines (ghost line along the specimen axis).

5.4.1.2 Licensee Conclusions

The Licensee concludes in its 2015 Safety Cases [10] [11] that :

> *"Three additional tensile tests on specimens with a ghost line along the specimen axis were performed at room temperature at the request of the AIA (Action 9b). They confirmed the results obtained previously on similar specimens at operating temperature, thereby confirming the good ductility of the material."*

5.4.1.3 Safety Authority Conclusions

Bel V concludes in its Safety Evaluation Report [19] that:

> *"In the 2012 Safety Case, the issue of the possible impact of the hydrogen flaking on the material properties was raised and investigated. To Bel V opinion, this issue was of prime importance. Indeed if this impact was confirmed, this would mean that the hydrogen flaking would have a double detrimental effect on the structural behaviour of the RPVs: (i) on one side, the flakes are crack-like flaws which could potentially grow and lead to RPV failure, particularly when the vessel is subjected to large thermal transients and (ii) on the other side, the deterioration of the mechanical properties of the flaked material could compromise the required ductile behaviour of the material but also decrease the crack initiation fracture toughness for the flakes well below the fracture toughness of the material in the non-affected regions. In 2013, tensile tests performed on specimens taken from the VB395 shell in the ligaments between the flakes showed that the ductility of the material was not affected."*

In its Synthesis Report [20] [21], AIB-Vinçotte agrees with the following Licensee conclusions:

“Three additional tensile tests at room temperature were performed on specimens with ghost lines along the specimen axis. The test results presented by the Licensee were found to be comparable to those obtained for a specimen taken in the macro-segregation but not specifically in a ghost line. It was observed that the ductility of the specimens with a ghost line is slightly reduced but the absolute value remains high.”

The MO/AIA considers the Licensee reply to the Action 9 requirement satisfactory and has no more comments related to Action 9.

The FANC concludes that:

The ductility of a flaked material is not affected by the presence of flakes.

The FANC concluded in April 2014 that the **Licensee reply to this requirement 10b is satisfactory** and closed the Action 9b.

5.4.2 Residual hydrogen content (Requirement 10/10b)

5.4.2.1 Context

Following a comment from AIB-Vinçotte in January 2013 on the residual hydrogen content in the base material from fabrication [5], the Licensee had to answer to Requirement 10 as a prerequisite to a restart of the two reactors in 2013 [5].

10/10b 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...

The FANC concluded that this was done satisfactory for restart in May 2013 in its Final Evaluation Report [9] but nevertheless, following a recommendation from AIB-Vinçotte [22] [23], requested the Licensee to perform a follow-up of the requirement as a mid-term action in order to consolidate and confirm the results.

" … the Licensee reply to the Action 10 requirement satisfactory. However, as Medium Term Action, the Licensee shall inform about the results of the melt extraction tests that are ongoing in order to confirm the results found with the hot extraction tests at 1100°C.”

5.4.2.2 Licensee Conclusions

The Licensee concludes in its 2015 Safety Cases [10] [11] that :

“As shown by the investigations performed under Action 10b, only a very low amount of hydrogen is measured, and most of it is trapped at high-energy traps.”

5.4.2.3 Safety Authority Conclusions

In its Synthesis Report [20] [21], AIB-Vinçotte agrees with the following Licensee conclusions:

“The Licensee performed melt extraction tests on the samples that already underwent the 1100°C hot extraction in order to check the amount of hydrogen that is not detected with hot extraction measurements at 1100°C. The additional measurements showed that the amount of hydrogen left inside a material after hot extraction at 1100°C is very small (0.1 ppm).”

The MO/AIA considers the Licensee reply to the Action 10 requirement satisfactory and has no more comments related to Action 10.

The FANC concluded that the tests were performed as required by the Safety Authority. The FANC remarks that the results of these tests did not raise any specific issue and had no more comments related to this Action.

The FANC concluded in April 2014 that the **Licensee reply to this requirement 10b is satisfactory** and closed the Action 10b.

5.4.3 Local micro-scale properties of specimens with macro-segregations, ghost lines and hydrogen flakes (Requirement 12)

5.4.3.1 Context

Following a comment from the IERB in January 2013 on the unresolved issues regarding the representativeness of the materials used in the mechanical tests [5], the Licensee had to answer to Requirement 12 as a mid-term requirement [5].

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.

5.4.3.2 Licensee Conclusions

The Licensee concludes in its 2015 Safety Cases [10] [11] that :

> *"This requirement was further completed with KS02 investigations and by complementary detailed investigations, performed in the context of the assessment of the root cause of the atypical VB395 embrittlement under irradiation."*

5.4.3.3 Safety Authority Conclusions

The Bel V evaluation of this requirement is fully integrated in its evaluation of the unexpected mechanical behaviour of the VB395 under irradiation in the context of improving the understanding of the mechanical behaviour of flaked material.

In its Synthesis Report [20] [21], AIB-Vinçotte agrees with the following Licensee conclusions:

> *"The Licensee performed investigations with the main objective to identify the potential correlation between local material mechanical properties and local structural and chemical material characteristics (local microstructure, grain sizes, chemical composition of the ghost lines and on grain boundaries, fracture mode …). A secondary objective was to confirm the representativeness at local scale of the test materials VB395 and D3H1.*
>
> *No obvious correlation between local material characteristics and some specific local mechanical properties could be evidenced so that no quantification (model) could be proposed.*
>
> *Small differences were observed in the local characteristics between D3H1 and VB395 materials but were judged being not statistically significant. The materials are considered as globally representative for flaking and mechanical behaviour in the as received condition."*
>
> The MO/AIA considers the Licensee reply to the Action 12 requirement satisfactory and has no more comments related to Action 12.

Based on the data provided by the Licensee and the evaluations performed by AIB-Vinçotte and Bel V the FANC concludes that :

The materials VB395, KS02 and D3H1 are considered as globally representative for flaking and mechanical behaviour in the 'as-received' condition.

The **Licensee reply to the Action 12 requirement is satisfactory**. In consequence the FANC closes Action 12.

5.4.4 Effect of thermal ageing of the zone of macro-segregation (Requirement 13)

5.4.4.1 Context

In January 2013, on the basis of the comments from the IERB and in order to evaluate the effect of thermal ageing on a flaked material, the FANC issued the following mid-term requirement (Requirement 13):

13 The Licensee shall further evaluate the effect of thermal ageing in the zone of macro-segregation

5.4.4.2 Licensee Conclusions

As a conclusion about the effect of thermal ageing on zones of macrosegregation, the Licensee states in its 2015 safety case reports [10] [11] that :

> *"A literature survey showed that thermal ageing is not to be expected for the Doel 3 and Tihange 2 RPV forgings. The limited evolution of the mechanical properties and the small proportion of intergranular fracture after irradiation and/or accelerated ageing tests confirmed that thermal ageing has no significant effect in the D3T2 RPV materials. "*

5.4.4.3 Safety Authority Conclusions

In its Synthesis Report [20] [21], AIB-Vinçotte agrees with the following Licensee conclusions:

> *"The MO/AIA agrees with the licensee conclusion that almost no thermal ageing effect on the mechanical properties is expected for the Doel 3 – Tihange 2 materials (fine grained material, with relatively low P content).*
>
> *In addition to the initial action plan, additional thermal ageing experiments were performed on the VB395 materials in order to identify a possible thermal ageing contribution in the atypical embrittlement of this material seen in the irradiation campaigns in BR2. The behavior of the VB395 materials was found to be comparable to other RPV steels from the point of view of sensitivity to thermal ageing."*
>
> The MO/AIA considers the Licensee reply to the Action 13 requirement satisfactory and has no more comments related to Action 13.

Consequently the FANC concludes that:

The test results are in line with the expectations. Based on the data provided by the Licensee, the final evaluation of AIB-Vinçotte, the evaluation of Bel V and the discussions with the international experts of the IRB on this topic, the FANC concludes that the **Licensee reply to the Action 13 requirement is satisfactory**, has no more comments and closed Action 13 in November 2015.

5.5 FANC Conclusions on the material properties

The suggestions, observations and conclusions of the different organisations and working groups were evaluated by the Federal Agency for Nuclear Control. Wherever appropriate and relevant, the FANC decided to use this input in the formulation of the FANC final conclusions.

The Licensee performed an extensive material testing program in order to characterize the mechanical properties of some flaked and unflaked materials (VB395, KS02, nozzle cut-out materials from Doel 3 and Tihange 2, world reference materials…). From the evaluation of the results of these investigations, the FANC concludes:

- The tested materials have exhibited different behaviour under irradiation :
    - The unflaked test specimens from the surveillance program of Doel 3 and Tihange 2 and from the nozzle cuts of Doel 3 and Tihange 2 exhibit a behaviour under irradiation consistent with the predictions.
    - The test specimens, with or without flakes, from the macrosegregation zone of the VB395 exhibit an enhanced irradiation embrittlement inconsistent with the predictions, but a hardening consistent with the predictions.
    - The test specimens from the KS02, flaked or unflaked, from any zones, exhibit a behaviour consistent with the predictions. Due to the chemical composition of this material, the predicted embrittlement is nevertheless higher than for VB395 and reactor pressure vessels material.
- An unknown phenomenon affects the VB395 material inducing an enhanced embrittlement without a hardening of the test specimens from the macrosegregation zones of the VB395 material.
- Hydrogen flaking is likely to be excluded as the root cause of this enhanced irradiation embrittlement, as the existence of KS02 shows that hydrogen flaking does not necessarily imply enhanced irradiation embrittlement.
- Complementary investigations on the flaked materials available (VB395 and KS02) show that the presence of flakes has no direct effect on the fracture toughness of the RPV material (in unirradiated or irradiated conditions).
- The VB395 can be considered as an outlier. Therefore it can be assumed that the irradiation embrittlement of the VB395 is likely to be not representative and significantly higher than the expected embrittlement of the Doel 3 and Tihange 2 core shells
- New predictive equations for the irradiation embrittlement have been achieved for the structural integrity assessment of the Doel 3 and Tihange 2 reactor pressure vessels.

  The 50°C margin on RT_{NDT} considered in the 2013 Safety Case is discarded and replaced by predictive equations depending on the material properties. Considering the VB395 to be an outlier for material behaviour under irradiation, the core shells of Doel 3 and Tihange 2 are unlikely to show the same sensitivity to irradiation embrittlement. Nevertheless, as a safety provision, the Doel 3 and Tihange 2 predictive equations take into account the atypical embrittlement observed in the VB395 flaked material. Therefore the FANC deems the predictive equations for the irradiation embrittlement featured in the 2015 Licensee Safety Cases are acceptable.

All mid-term requirements concerning the material properties of a flaked steel have been satisfactorily replied to and closed by the Safety Authority.

6 Structural integrity assessment

6.1 Context

The structural integrity assessment aims at demonstrating that the structural integrity of the reactor pressure vessels either under operating or accidental conditions is maintained given the presence of thousands of quasi-laminar crack-like defects.

The Licensee Electrabel performed this structural integrity assessment according to the applicable rules of Section XI of the ASME Boiler and Pressure Vessel Code [10] [11]. In this framework, this assessment includes :

- the assessment of the absence of crack initiation for all individual flaws with adequate safety margins,
- the assessment of fatigue crack growth,
- the assessment of the satisfaction of the primary stress intensity acceptance criteria.

6.2 Situation in 2012-2013

6.2.1 FANC Provisional Evaluation Report – January 2013

Based on the data provided by the Licensee and the conclusions released by Bel V, AIB-Vinçotte and the expert groups about the structural integrity of the reactor pressure vessels, the FANC drew the following conclusions in its Provisional Evaluation Report [5]:

> *"The fracture mechanics evaluation procedures need an appropriate level of conservatism backed by experimental validations where appropriate. Indeed, a high level of confidence is required in fracture mechanics evaluations as the failure of the reactor pressure vessels is to be excluded.*
>
> *A deterministic flaw evaluation of each detected indication in accordance with the basic principles of Section XI of the ASME Code was performed by the Licensee. However, the approach described in this ASME code is in principle applicable for the justification of indications originating from in-service degradation mechanisms and not for the justification of large numbers of interacting flaws in base materials. Therefore, though the philosophy and background of the ASME code can be used for reference, the suitability of the approach adopted by the Licensee to justify the structural integrity of the reactor pressure vessels needed to be validated on some topics. Several issues in the fracture mechanics evaluation were therefore studied more in detail to ensure that sufficient conservatism was included in the analytical flaw calculations: modelling of flaws, grouping criteria used for flaw interactions, use of most penalizing transients,…*
>
> *The development of a "screening criterion" for the analytical flaw evaluation was in this way also useful to clearly identify the flaws that are most detrimental for the safety of the reactor pressure vessels and focus attention on these flaws. The Licensee's calculations show that a very large majority of indications has no safety impact.*

Deterministic calculations also demonstrated that the primary stress limits of Section III of the ASME B&PV [27] *code are satisfied and that fatigue crack growth over the remaining service lifetime of the reactor pressure vessels is very small.*

The probabilistic assessment approach provided by the Licensee can be considered as complementary, and does not represent a determining input for the final evaluation of the safe operability of both reactor pressure vessels."

The FANC issued two short-term requirements concerning the topic of the structural integrity assessment in its provisional evaluation report: Actions 14 and 15.

6.2.2 FANC Final Evaluation Report – June 2013

Based on the data provided by the Licensee and the review and assessment of AIB-Vinçotte, Bel V and the National Scientific Expert Group on the topic "Structural Integrity of the Reactor Pressure Vessel", the FANC concluded that all the identified short term open issues on this topic (Requirements 14 and 15) had been resolved in its Final Evaluation Report [9].

"The use of a screening criterion procedure allows to conclude that the presence of hydrogen-induced flaws in the Tihange 2 and Doel 3 RPV shells has not a significant impact.

The potential presence of non-reported highly-tilted hydrogen flakes in the upper core shell of the Tihange 2 RPV and the lower core shell of the Doel 3 RPV does not affect significantly its structural integrity.

Large Scale tensile test specimens from the VB395 shell were taken with inclined flakes at a tilt angle of 20° to the specimen axis. Two specimens were tested at –80°C and two at room temperature. The tests confirmed that the requirement for sufficient ductility and sufficient load carrying capacity is satisfied.

The initially available experimental results of the large scale tensile tests allowed to confirm that the material affected by flaking is in the transition zone at 20°C, but could not confirm with certainty that it is the upper shelf region. The Licensee has therefore performed additional tests to demonstrate that the material is in the upper shelf region under test conditions at 20°C.

Two large-scale bend tests on specimens from the VB395 shell were also performed to confirm the conservatism of the 3D finite element calculations. The test results confirmed the conservatism of the predictions with a failure load well above the predicted load."

Nevertheless some complementary information was requested on Action 15 as an additional Mid-term Requirement to be performed before the first reactor restart following the next planned outages of the two reactors.

6.2.3 Mid-Term Action Plan

15b The Licensee shall complete the ongoing test program by testing larger specimens containing hydrogen flakes.

6.3 Technical evaluation of structural integrity calculations

6.3.1 Introduction

As pointed out by AIB-Vinçotte [20], for the SIA "basically the same methodology was applied as in the anterior Safety Case and its addendum presented by the Licensee in 2012-2013.

The Licensee established a new Safety Case to take into account the following updated input data:

- The updated predictive equation for the RT_{NDT} as a function of fluence;
- The updated RPV fluence distribution after 38 years of operation (40 years of lifetime);
- The increased Safety Injection (SI) water temperature implemented in Doel 3 NPP;
- The updated UT indications cartography, obtained by application of the qualified inspection procedure. "

The methodology applied by the Licensee and approved by the Safety Authority is extensively described in the Licensee Safety Cases [10] [11].

6.3.2 Flaw Acceptability Assessment - Prevention against crack initiation

6.3.2.1 Context

Electrabel aims at demonstrating "the absence of crack initiation for all individual flaws with adequate safety margins" [10] [11]. In this framework, "a Flaw Acceptability Assessment was performed in accordance with 'ASME Section XI (1992) – Rules for In-service Inspection of Nuclear Power Plant Components'. The assessment was conducted on all flaws using the dimensional data gathered through ultrasound measurements and the loads from the design transients." [10] [11].

In this framework the Licensee updated the grouping method and the proximity rules presented in its 2013 Safety Cases [1] [2]. "Proximity rules suited to quasi-laminar flaws and the associated flaw grouping method are used by Electrabel to determine the flaws that need to be grouped for the flaw acceptability assessment" [19]. The revision of these proximity rules and the flaw grouping method gave rise to extensive discussions between the Licensee and the Safety Authority. What came out from these discussions is detailed in the Safety Evaluation Report of Bel V [19] that finally concludes:

> *"The use of the revised proximity rules for quasi-laminar flaws is acceptable, but [Bel V] also emphasizes that the conclusion only applied to the flaw configurations detected in the Doel 3 and Tihange 2 RPV core shells."*

6.3.2.2 Licensee conclusions

The Licensee states in its 2015 safety case reports [10] [11] that :

> *"The SIA of the Doel 3 RPV was performed considering all indications that were revealed by the qualified UT inspection procedure. As such, it covers the indications that were classified as hydrogen flakes as well as the indications that were classified as clad interface imperfections but that are conservatively considered and treated as hydrogen flakes.*
>
> *The Flaw Acceptability Assessment with its refined analysis was based on conservative data and calculation methodologies. More than 99.75% (Doel 3) of the flaw configurations meet the screening criterion $2a < 0.5\ 2a_{acc}$. This means that most of the flaws affecting the Doel 3*

RPV shells are harmless in the event of a transient. This is a consequence of their quasi-laminar character.

The remaining 0.25% (Doel 3) flaw configurations that were subjected to a refined 3D XFEM analysis meet the acceptance criterion $2a < 2a_{acc}$ by a considerable margin (maximum ratio of 0.32 in the Doel 3 RPV).

The refined analyses clearly highlighted the very low level of the crack driving forces K_{MAX} of the quasi-laminar hydrogen flakes: K_{MAX} for all flaw configurations is well below the fracture toughness lower shelf $K_{IR,lower\ shelf}$ demonstrating that the quasi-laminar hydrogen flakes are acceptable with respect to the structural integrity of the Doel 3 RPV.

The majority of the flaws even have a K_{MAX} value below the lower shelf considering the safety factor $K_{IR,lower\ shelf}/SF$ which means that their acceptability is independent from the RT_{NDT}.

For the few flaws of which KMAX exceeds $K_{IR,lower\ shelf}/SF$, the margin in terms of RT_{NDT} is calculated based on the conservative transposition of the VB395 properties. The calculated margin is very large (80°C and more).”

6.3.2.3 Safety Authority Conclusions

In its Safety Evaluation Report [20], Bel V concludes that :

“Bel V had no objection against the approach used by Electrabel for flaw acceptability assessment.”

“The calculation of the driving forces of the flaws is, to Bel V opinion, a key element in the demonstration of the acceptable impact of the flaking damage on the serviceability of the Doel 3 and Tihange 2 RPVs. While recognizing that the presence of flakes increases the risk of RPV failure from pre-existing crack-like defects, Bel V also considers that the low value of the stress intensity factors provides a convincing evidence of the low potential of RPV fracture from those defects.”

In its Synthesis Report [20] [21], AIB-Vinçotte agrees with the following Licensee conclusions:

“In order to consider the interactions of the flaws, the licensee applied a grouping process. After that a screening analysis showed that nearly all flaws indications could be considered as harmless while only a limited number of flaws required a more in-depth analytical evaluation.

The flaw configurations resulting from the grouping process were compared to the acceptable size calculated by 3D finite element calculations. The grouped flaws exceeding the acceptable size were reanalyzed using 3D multi-flaws and refined analyses to show their acceptability and to assess the actual margins. It was found that all flaws fall finally below the screening criterion threshold $2a/2a_{acc} = 0.5$.

Also it was noted that considering the DTR in the flaw acceptability analysis, did not impact the structural integrity assessment conclusion.”

In its final report [15] ORNL concludes that:

“Specific findings of the ORNL evaluation of that part of the ELECTRABEL SIA focusing on stability of the flaw population subjected to primary design transients include the following results and conclusions derived from screening assessments and refined analyses.

<u>Screening assessments:</u>

• ELECTRABEL screening assessments found that few characterized flaws in D3T2 were not compliant with ASME (1992) acceptance criterion

• ORNL screening analyses identified fewer non-compliant flaws than ELECTRABEL; furthermore, ORNL applications of the more recent ASME Section XI (2004) produced only four non-compliant flaws, all due to LOCAs; when a warm-prestress model is invoked, only one characterized flaw remains non-compliant

• The finding of a greater number of non-compliant flaws in the ELECTRABEL screening assessment is due principally to a significantly more restrictive (i.e. more conservative) criterion for flaw size acceptance used by ELECTRABEL

***Conclusion**: ORNL screening assessment results for D3T2 (obtained using different a analysis methodology) are interpreted herein as confirming the more conservative ELECTRABEL screening results*

Refined analyses:

• ELECTRABEL showed that all characterized flaws not compliant in the screening assessment meet the acceptance criterion with ample margin when subjected to refined analyses using 3-D XFEM models

• ORNL demonstrated that the ELECTRABEL-characterized flaw #16603, which is non-compliant in both the ORNL and ELECTRABEL screening assessments, is rendered compliant when modelled as a more realistic individual flaw using 3-D XFEM

• ORNL and ELECTRABEL refined analysis results are in good agreement for the individual flaw #1660 close to the clad/base metal interface; ORNL is not persuaded that repeating that exercise for more than one non-compliant flaw is necessary to accept ELECTRABEL conclusions derived from the aggregate of ELECTRABEL refined analysis results

***Conclusion**: ORNL interprets the refined analysis results provided by ELECTRABEL for all originally noncompliant flaws, combined with the limited refined analysis results generated by ORNL, as being sufficient to declare the detected D3T2 flaw population in compliance with the ASME Section XI acceptance criterion."*

On this basis the FANC concludes that:

The latest developments of the case resulted in a complete revaluation of the structural integrity assessment. Although the overall general conclusions remains valid, these developments lead to a more detailed and refined analysis.

A conservative analysis by the Licensee shows that more than 99.75% of the flaw configurations in the Doel 3 and Tihange 2 RPV shells are harmless in normal or abnormal operating conditions.

An independent conservative analysis by ORNL (obtained using different analysis methodologies) shows that 99.97% of the flaw configurations in the Doel 3 and Tihange 2 RPV shells are harmless in normal or abnormal operating conditions, confirming the more conservative Licensee screening results.

All characterized flaws not compliant in the Licensee screening assessment meet the acceptance criterion with ample margin when subjected to refined analyses. The Licensee refined analysis of the remaining 0.25% shows the low level of the crack driving forces K_{MAX} of the quasi-laminar hydrogen flakes. The detected Doel 3 and Tihange 2 flaw population is in compliance with the ASME Section XI acceptance criterion.

6.3.3 Primary Stress Revaluation

6.3.3.1 Context

"The assessment of the structural integrity of the Doel 3 and Tihange 2 RPVs shall not be limited to the prevention of fracture from the flakes. It should also be verified that the degraded condition of the RPVs does not put into question the prevention of the other failure modes (with the safety coefficients required by the ASME B&PV Code). Recognizing that the flaking degradation only affects the core shells that have a simple geometry with no structural discontinuities, the required effort shall be limited to the assessment of the prevention of the (instantaneous) collapse failure under single load application... Protection against those failure modes is ensured in Section III of the ASME B&PV code (Subsection NB) by limiting the primary stresses and primary plus secondary stress ranges. For assessing the prevention of those failure modes with consideration of the degradation, plastic analysis was found by Bel V to be the most adequate method. " [19]

According to ASME III a primary stress re-evaluation had to be performed in order to check that the acceptance criterion from ASME III NB-3228.3 is met despite the presence of thousands of flaws in the RPVs core shells. This acceptance criterion justifies the primary stress limits by verifying that the calculated collapse pressure of the worst flaw configuration remains higher than 1.5 times the design pressure.

6.3.3.2 Licensee Conclusions

The Licensee states in its 2015 safety case reports [10] [11] that :

> *"A Primary Stress Re-evaluation was performed in accordance with 'ASME, Section III – Rules for Construction of Nuclear Facility Components'. This evaluation takes into account the presence of flaws in the Doel 3 and Tihange 2 RPV shells. The re-evaluation was performed on all flaws using the dimensional data gathered through ultrasound measurements and starting from the flaw modelling as in ASME XI. The acceptance criterion that needed to be verified is that the calculated collapse pressure should be more than 1.5 times the design pressure."*
>
> *"The elasto-plastic analysis was updated using all of the reported indications from the qualified UT inspection that was performed during the 2014 outage."*
>
> *"The re-evaluation made clear that the collapse pressure is more than 1.5 times the design pressure, confirming the criterion is met."*
>
> *The results confirmed that the collapse load for the most penalizing flaw configuration meets the ASME III NB-3228.3 acceptance criterion."*

6.3.3.3 Safety Authority Conclusions

In its Safety Evaluation Report [19], Bel V concludes that :

> *"From those analyses, Bel V concludes that, although some part of the available margin is being consumed by the presence of flakes, hydrogen flaking has a low impact on the capacity of the RPV to prevent instantaneous failure under a single application of load and that the prevention is ensured with the safety coefficient required by Section III of the ASME B&PV Code."*

In its Synthesis Report [20] [21], AIB-Vinçotte agrees with the following Licensee conclusions:

"The presented ASME III elastic-plastic analysis showed that the primary stress criteria are met and that no progressive deformation is expected to occur under cyclic loading. The calculations demonstrated that the collapse load is only slightly reduced in comparison with a model without flaws."

In its final report [15] ORNL concludes that:

"ELECTRABEL performed an ASME Section III primary stress re-evaluation that accounted for the existing flaw population in D3/T2 and verified that the calculated collapse pressure is more than 1.5 times the design pressure as required by code

Although ORNL did not perform verification calculations for this assessment, the process and illustrated results appear reasonable and conservative. Thus, ORNL is in agreement with the conclusions reported by ELECTRABEL for the foregoing elements of the SIA."

On this basis the FANC concludes that:

The elastic-plastic analysis was performed according to ASME III primary stress re-evaluation. The calculations demonstrated that the collapse load is only slightly reduced in comparison with a model without flaws. The primary stress criteria are met – i.e. the calculated collapse pressure is more than 1.5 times the design pressure as required by code.

6.3.4 Fatigue crack growth analysis

6.3.4.1 Context

"Usual flaw assessment requires also to demonstrate that the potential in-service crack growth by any mechanism does not increase the size of the pre-existing crack up to its critical size. The only suspected mechanism for in-service growth of the flakes is fatigue crack growth." [19] The evaluation of the Fatigue Crack Growth had been evaluated by the Licensee following ASME XI.

6.3.4.2 Licensee Conclusions

The Licensee states in its 2015 safety case reports [10] [11] that :

"As requested by ASME XI IWB-3610(a), the Fatigue Crack Growth was evaluated by the analytical procedures described in ASME XI Appendix A 'Analysis of Flaws', based on linear elastic fracture mechanics. The objective was to assess the stability of the flakes, i.e. the possible growth of the quasi-laminar flaws until the end of service lifetime."

"The Fatigue Crack Growth analysis shows that the maximum potential growth of the flaws in the forgings over the entire service lifetime of the RPV, assessed by a conservative methodology, is limited to 3.19% of their size in the Doel 3 RPV [and to 1.66% of their size in the Tihange 2 RPV]. This confirms the results of the Safety Case. Fatigue crack growth is not a concern and does not need to be considered further in the Flaw Acceptability Analysis."

6.3.4.3 Safety Authority Conclusions

In its Safety Evaluation Report [19], Bel V concludes that :

"Bel V concludes that the ranges of applied stress intensity factors must be sufficiently low to practically exclude potential fatigue growth of those flaws. The crack growth analysis should therefore show not only that the calculated crack growth is low but also not significant.

…

The analysis shows that the calculated maximum crack growth for a lifetime of 40 years is 3.2% for the Doel 3 RPV core shells and 1.2% for the Tihange 2 RPV core shells, which is considered by Bel V as low but still significant. However, the crack growth analysis includes some identified conservatisms that lead to overestimations of the growth. By eliminating one of those, i.e., the use of the equivalent stress intensity factor of the quasi-laminar flaw instead of that of its axial projection, Electrabel showed that the growth of the flaw having the largest (calculated) growth decreased from 3.2% to 0.2%. This confirms the conclusions drawn in 2012 for the former flaw cartography that the fatigue crack growth under the service loadings for a service life of 40 years is not significant. "

"It should also be emphasized that the highest values of the calculated fatigue growth were obtained for the flakes of large size and it is known … that those large flakes are sets of individual smaller neighbouring flakes either grouped by application of the proximity rules or merged because they could not be discriminated when using the qualified UT procedure. To Bel V opinion, that provides additional confidence in the non-significant fatigue growth of the flakes."

In its Synthesis Report [20] [21], AIB-Vinçotte agrees with the following Licensee conclusions:

"The fatigue crack growth analysis was performed according to Appendix A of ASME XI.

It was shown that the flaw indications will not grow significantly by fatigue for the remaining time of operation (~10 years). It was also shown that flaw indications at the beginning of lifetime could not have grown significantly by fatigue during 30 years of operation."

In its final report [15] ORNL concludes that:

"ELECTRABEL assessments of the stability of the quasi-laminar flaws with respect to fatigue crack growth through end of service life predicted maximum flaw growth of 3.19% for Doel 3 and 1.66% for Tihange 2

Although ORNL did not perform verification calculations for this assessment, the process and illustrated results appear reasonable and conservative. Thus, ORNL is in agreement with the conclusions reported by ELECTRABEL for the foregoing elements of the SIA."

On this basis the FANC endorses the previous conclusions:

The fatigue crack growth analysis was performed according to Appendix A of ASME XI. It was shown that the flaw indications will not grow significantly by fatigue for the remaining time of operation. It was also shown that flaw indications at the beginning of lifetime could not have grown significantly by fatigue during 30 years of operation.

6.3.5 Prevention against brittle fracture – P-T limits and PTS analyses

6.3.5.1 Context

The Licensee describes in its 2015 safety case reports [10] [11] the fracture toughness requirements imposed by the Appendix G of 10CFR50, the US-NRC regulations for licensing and utilisation of nuclear facilities, applicable to Doel 3 and Tihange 2 [28]:

"Appendix G of 10CFR50, which is applicable to the Doel 3 and Tihange 2 RPV, defines the fracture toughness requirements for ferritic materials of pressure-retaining components of the reactor coolant pressure boundary of light water nuclear power reactors. The goal is to provide sufficient safety margins in any conditions of normal operation, as well as anticipated transient and accident

conditions, to which the pressure boundary may be subjected over its service lifetime. As such, 10CFR50 Appendix G refers to the analysis method included in ASME XI Appendix G, which covers the requirements regarding Pressure-Temperature Operating Limits and Low-Temperature Overpressure Protection."

In addition, this 10CFR50.61 [29] prescribes that 'Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock Events' aims to verify that the (irradiated) RT_{NDT} of the base metal of the Doel 3 RPV forged components will remain below 132 °C at the end of its service lifetime, and that the RT_{NDT} of the circumferential welds at the end of the RPV's service lifetime will remain below 149 °C.

6.3.5.2 Licensee Conclusions

The Licensee states in its 2015 safety case reports [10] [11] that :

> *"The p-T curves integrated into the plant's Technical Specifications in the framework of the 2012 Safety Case remain valid and do not have to be updated. The Deterministic PTS Analysis of the RPV core shells shows that the RTNDT of the base metal will remain below 132 °C at the end of its service lifetime."*

6.3.5.3 Safety Authority Conclusions

In its Safety Evaluation Report [19], Bel V concludes that :

> *"According to Electrabel, the current pressure-temperature limits defined for Doel 3 and Tihange 2 from the RT_{NDT} values determined in 2012 as a part of the former Safety Case are not to be updated, and a result thereof, the overpressure protection reports also remain valid. That conclusion is supported by the fact that the end-of-life RT_{NDT} values calculated at 1/4T and 3/4T in the core shells with the assumptions used in the 2015 Safety Case are lower than the values used in 2012 for the verification of the fracture toughness requirements of Appendix G to 10CFR50. The lower end-of-life RT_{NDT} values obtained in 2015 at the tip of the postulated flaws are lower than to the values used in 2012 due to the lower values of the end-of-life fluence (38 years of operation instead of 40 years) but also to the fact that because of the additional shift of 50°C independent of the fluence, the predictive equations used in 2012 provide values of the RT_{NDT} shift higher than the ones obtained by the 2015 predictive equations for fluences lower than about 4 10^{19}n/cm² for Doel 3 and about 4.5 10^{19}n/cm² for Tihange 2.*
>
> *Bel V agreed with the non-necessity of updating the current pressure-temperature limits.*
>
> *According to paragraph 50.61 of 10 CFR "Fracture toughness requirements for protection against pressurized thermal shock events" applicable to the Doel 3 and Tihange 2 nuclear power reactors, no assessment is to be performed if the RTNDT evaluated at the end-of-life fluence for the RPV beltline materials does not exceed the PTS screening criterion. The PTS screening criterion is 132°C (270°F) for the forgings. For the Doel 3 RPV, the highest end-of-life RT_{NDT} as calculated by the predictive equation proposed by Electrabel is the one for the*

upper core shell and is equal to 115.2°C. For the Tihange 2 RPV, the highest end-of-life RT_{NDT} is equal to 116.3°C (upper core shell). As the highest end-of-life RT_{NDT} does not exceed the screening criterion as well for the Doel 3 RPV as for the Tihange 2 RPV, Electrabel concluded that the protection against pressurized thermal shock was satisfied.

Bel V agreed with that conclusion."

On this basis the FANC concludes that:

The p-T curves integrated into the plant's Technical Specifications in the framework of the 2012 Safety Case remain valid and do not have to be updated.

A PTS Analysis of the RPV core shells shows that the RT_{NDT} of the base metal will remain below 132°C at 40 years of lifetime.

6.3.6 Overall Safety Authority Conclusions on SIA

AIB-Vinçotte concludes in its Synthesis Report [20] [21] that:

"The MO/AIA reviewed the Safety Case submitted by the Licensee to justify the structural integrity of the Doel 3 and Tihange 2 Reactor Pressure Vessels. Our review concerned the verification of the submitted analyses for their compliance with the requirements of the Code ASME XI ed.1992. It shall be noted that the Licensee made use of the Article IWB-3132.4 : Acceptance by Analytical Evaluation.

Taking into account the loading conditions specified by the Licensee and the material properties considered in the analyses, the presented structural integrity assessment shows that the Doel 3 Reactor Pressure Vessel core shells with hydrogen flakes meet the ASME XI requirements for 'Acceptance by Analytical Evaluation'."

In its Safety Evaluation Report [19], Bel V concludes that the Licensee reports provide a convincing evidence of the low potential of RPV failure from the detected flakes and that the in-service fatigue growth of the flakes was not significant:

"Confidence in those conclusions requires also that each step of the assessment includes conservatism. Although it may not be quantified, Bel V recognizes that the analysis procedures include inherent conservatism even if some potential lacks of conservatism have been identified. Moreover the input data also include conservatism or at least consider satisfactory the uncertainties associated to them or the necessary provisions to account for the limited knowledge of some phenomena.

Ensuring the serviceability of the RPV also requires the prevention of other basic failure modes under tensile stress, i.e., the instantaneous failure by single load application and the incremental failure by repeated loadings. When designing a pressure component assumed to be made from a defect-free material, prevention of those modes is ensured by the requirements of the design code. To Bel V opinion, prevention of those failure modes for a degraded component may only be ensured by performing plastic analyses. The analyses performed by Electrabel showed that, although some part of the available margin is consumed by the presence of flakes, the prevention of the instantaneous failure mode was ensured with the safety coefficient required by Section III of the ASME B&PV Code. It was also shown that the elastic shakedown behaviour of the RPV core shells, and so the prevention of the incremental failure mode, was not affected by the presence of flakes.

Finally it was shown by Electrabel for both the Doel 3 and Tihange 2 RPVs that it was not necessary to update the current pressure-temperature limits and also that the updated *predictive equation for the irradiation embrittlement did not lead to exceed the Pressurized Thermal Shock screening criterion of 10 CFR 50.61. "*

In its final report [15] ORNL concludes that:

"Bases on comparative evaluations of ORNL and ELECTRABEL SIA calculations summarized herein and on consideration of other results, ORNL is in agreement with the general conclusions reported [by the Licensee]… Specifically,

• more than 99 percent of flaws in D3T2 meet the defined screening criterion, rendering them benign with respect to initiation in the event of a design transient

• refined analyses of flaws that were non-compliant in that screening assessment indicate that 11 of the 18,000 detected flaws have $K_{MAX} > K_{IR,\ lower\ shelf}/SF$; for those 11 flaws, the calculated margin in $RT_{NDT} > 80°C$

• Fatigue crack growth is not a concern in the flaw acceptability analyses

• Primary stress re-evaluation confirms that the collapse pressure is more than 1.5 times the design pressure in the presence of defects detected in D3/T2

• Sufficient conservatisms are built into the input data and into the different steps of the SIA; in some cases, those conservatisms are quantified and imply that additional margins exist in the SIA

***Conclusion:** Taken as a whole, the foregoing results and conclusions confirm the structural integrity of Doel 3 and Tihange 2 under all design transients with ample margin in the presence of the 18,000 detected flaws"*

In addition in its final report [15] ORNL provides the following answers to the specific FANC requests on the Structural Integrity Assessment :

1. "***FANC**: Assess the acceptability of each assumption considered by the licensee in the safety case except for the qualification of the ultrasonic instrument and the non-destructive examinations.*

   ***ORNL**: Assumptions employed by the licensee that are considered by ORNL for comment include the following:*

   • ELECTRABEL flaw acceptance criterion was one-half of the ASME Section XI criterion, a very conservative assumption that resulted in a total of 37 non-compliant flaws. ORNL applied the ASME Section XI criterion without any modification and identified only four flaws that did not satisfy ASME Section XI. ORNL agrees with the ELECTRABEL application of the ASME criterion.

   • ELECTRABEL binned the design transients and boxed flaw ligaments according to a scheme depicted herein in Fig. 5.4 [see ORNL report [15]*]. As a check on that scheme, ORNL performed analyses in which the transient / flaw binning illustrated in Fig. 5.4 was removed, i.e., all flaws were subjected to all design transients. While the latter action did increase the number of flaws for which a value of $RT_{NDTCRI}T$ exists, it did NOT increase the number of flaws that were non-compliant with respect to the ASME screening criteria.*

   • ELECTRABEL identifies a list of conservatisms that are built into the input data and into the different steps of the SIA. In some cases, those conservatisms are quantified and imply that additional margins exist in the SIA; ORNL agrees with the assumptions in Section 6.5 of 2015 Doel 3 Safety Case.

   • ELECTRABEL's representation of flaw size for screening assessments defines the largest circular flaw that fits into each 3-D flaw box. The latter procedure is recognized as a very

conservative representation of a characterized flaw. Using that population of characterized flaws, ORNL assessments identified only four non-compliant flaws with respect to ASME Section XI.

• ELECTRABEL assumes the embrittlement shifts for D3 and T2 to be the same as those measured in the VB395 material. While that assumption has not been substantiated, it is considered to be very conservative.

2. ***FANC**: Assess the safety margins and the level of conservatism for the successive steps of the approach submitted by the licensee.*

   ORNL:

   • ELECTRABEL presents a quantification of safety margins for the detected flaw populations of D3/T2;

   • ELECTRABEL describes the levels of conservatism in the successive steps of the SIA for D3/T2;

   • Based on comparative evaluations of ORNL and ELECTRABEL calculations for the SIA and on consideration of other results, ORNL is in agreement with the ELECTRABEL conclusions that the safety margins and levels of conservatism are adequate to confirm structural integrity with respect to the entire population of defects.

3. ***FANC**: Identify any non-standard aspects for a safety justification of a nuclear RPV.*

   ***ORNL**:*

   • ELECTRABEL engaged in a major effort to develop suitable methodology to confirm structural integrity of D3/T2 in the presence of large, dense populations of hydrogen flakes. Thus, ELECTRABEL developed a methodology to account for interaction of closely-space flaws, i.e., proximity rules. For the ELECTRABEL screening assessments, the flaws are characterized either as individual or as grouped flaws and are placed in 3-D rectangular boxes that completely contain the flaws. A single circular flaw is then defined for screening assessment that fits totally into that box with an appropriate tilt based on the box dimensions.

   • ELECTRABEL binned the design transients and boxed flaw ligaments according to a scheme depicted herein in Fig. 5.4 [see ORNL report [15]*]; flaws are then analysed with cool-down, heat-up or LOCA design transients depending on ligament distance from the clad/base interface. However, ORNL analyses indicate that whether or not the flaws are binned had no influence on the outcome of the SIA*

4. ***FANC**: Identify the new techniques developed by the licensee.*

   ***ORNL**: Non-standard aspects of the ELECTRABEL SIA effort to confirm structural integrity of D3/T2 … involved at least some development of new techniques.*

   No additional elaboration is necessary here.

5. ***FANC**: Assess the acceptability of these non-standard aspects and new techniques in the successive steps of the justification of the structural integrity of the RPVs.*

   ***ORNL**: Much of the ELECTRABEL methodology used to analyse the non-standard quasi-laminar flaw populations in D3/T2 is incorporated into the ASME Code Case N-848, "Alternative Characterization Rules for Quasi-Laminar Flaws". Thus, the ELECTRABEL methodology for assessing quasi-laminar flaws is backed by the ASME Boiler & Pressure*

Vessel Code. That same methodology was the basis for ORNL's evaluation of the ELECTRABEL SIA.

6. ***FANC**: (a) Identify the mistakes.*

   ***ORNL**: None identified*

   ***FANC**: (b) Identify the questionable and unjustified aspects.*

   ***ORNL**: None identified*

   ***FANC**: (c) Identify the questionable and justifiable – though lightly justified and documented – aspects in the safety case.*

   ***ORNL**: None identified*

On this basis the FANC concludes that:

The presented structural analysis shows that the Doel 3 and Tihange 2 RPVs with hydrogen flakes meet the ASME XI requirements for 'Acceptance by Analytical Evaluation' for the specified loading and material properties.

The foregoing results and conclusions confirm the structural integrity of Doel 3 and Tihange 2 under all design transients with ample margins.

6.4 Large-scale tensile testing on flaked materials (Requirement 15/15b)

6.4.1 Context

Following comments and requests from Bel V and AIB-Vinçotte in January 2013 on the need for experimental verification that the presence of hydrogen-induced flaws does not lower ductility of the material to an unacceptable level and for experimental confirmation of the conservatism of the 3D finite element analysis for flaw evaluation [5], the Licensee had to answer to the Requirement 15 as a prerequisite to a restart of the two reactors in 2013 [5].

15 The Licensee shall complete the ongoing test program by testing larger specimens containing hydrogen flakes , with the following 2 objectives:

o 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.

o Objective 2: An experimental confirmation of the suitability and conservatism of the 3D finite elements analysis.

In May 2013, the Safety Authority reviewed the Licensee conclusions and concluded that the Requirement was replied to satisfactory and closed Action 15. However Bel V required additional investigations as a mid-term Requirement 15b.

15b Bel V considers that it would have been a significant contribution to the demonstration to perform tensile testing of large-scale specimen(s) taken from the AREVA shell VB395 in the ligament between the flakes and provided with a notch made by electro-erosion and representative of a flake with a 20° tilt angle. Comparing the results of these tests with the results of the tests performed on specimens with tilted flakes would allow to discriminate between the effects of a flake configuration and the effects of a notch configuration on the fracture behaviour.

Without putting into question this conclusion, Bel V reminds its reservations about the fracture process of the large scale tensile specimens tested at 20°C. These reservations would be withdrawn if tensile testing at a temperature of about 100°C of a specimen with 20° tilted flakes showed mostly ductile fracture.

6.4.1.1 Licensee Conclusions

The Licensee concludes in its 2015 Safety Cases [10] [11] that :

"Fracture mechanics tests were performed at different temperatures by tensioning 25 mm diameter tensile type specimens with flakes or machined notches inclined at 20° with respect to the specimen axis.

The tests confirmed the load bearing capacity of the flaked and notched specimens.

The fracture modes of the different types of specimens were as expected and were well predicted by the simulations using the Extended Finite Element Method."

6.4.2 Safety Authority Conclusions

In its Safety Evaluation Report [19], Bel V concludes that :

"… Bel V concluded that the large-scale tests performed at 20°C on dia 25mm specimens taken from the VB395 shell did not allow to evidence a fracture behaviour that could be affected by the flaking damage."

In its Synthesis Report [20] [21], AIB-Vinçotte agrees with the following Licensee conclusions:

"The Licensee performed an additional tensile test at 100°C on specimens with flakes oriented at 20° with respect to the specimen axis. The objective was to show a mostly ductile behavior at this temperature.

Additional tests were also performed on specimens with machined notches. Finite element analyses of specimens with flakes supported the interpretation of the results. The tests confirm the load bearing capacity of specimens with hydrogen flakes."

The MO/AIA considers the Licensee reply to the Action 15 requirement satisfactory and has no more comments related to Action 15.

On this basis the FANC concludes that:

The tests performed confirmed the expectations.

The **Licensee reply to the Action 15 requirement is satisfactory**. In consequence the FANC closed the Action 15b in August 2015.

6.5 FANC Conclusions on the SIA

The suggestions, observations and conclusions of the different organisations and working groups were evaluated by the Federal Agency for Nuclear Control. Wherever appropriate and relevant, the FANC decided to use this input in the formulation of the FANC final conclusions.

The latest developments of the case resulted in a complete revaluation of the structural integrity assessment. Although the overall general conclusions remain valid, these developments lead to a more detailed and refined analysis.

> **A conservative analysis by the Licensee shows that more than 99.75% of the flaw configurations in the Doel 3 and Tihange 2 RPV shells are harmless in normal or abnormal operating conditions.**
>
> **An independent conservative analysis by ORNL (obtained using different analysis methodologies) shows that 99.97% of the flaw configurations in the Doel 3 and Tihange 2 RPV shells are harmless in normal or abnormal operating conditions, confirming the more conservative Licensee screening results.**
>
> **All characterized flaws not compliant in the Licensee screening assessment meet the acceptance criterion with ample margin when subjected to refined analyses. The Licensee refined analysis of the remaining 0.25% shows the low level of the crack driving forces K_{MAX} of the quasi-laminar hydrogen flakes. The detected Doel 3 and Tihange 2 flaw population is in compliance with the ASME Section XI acceptance criterion.**

The elastic-plastic analysis was performed according to ASME III primary stress re-evaluation. The calculations demonstrated that the collapse load is only slightly reduced in comparison with a model without flaws. The primary stress criteria are met – i.e. the calculated collapse pressure is more than 1.5 times the design pressure as required by code.

The fatigue crack growth analysis was performed according to Appendix A of ASME XI. It was shown that the flaw indications will not grow significantly by fatigue for the remaining time of operation. It was also shown that flaw indications at the beginning of lifetime could not have grown significantly by fatigue during 30 years of operation.

The p-T curves integrated into the plant's Technical Specifications in the framework of the 2012 Safety Case remain valid and do not have to be updated.

The presented structural analysis shows that the Doel 3 and Tihange 2 RPVs with hydrogen flakes meet the ASME XI requirements for 'Acceptance by Analytical Evaluation' for the specified loading and material properties.

The foregoing results and conclusions confirm the structural integrity of Doel 3 and Tihange 2 under all design transients with ample margins.

A PTS Analysis of the RPV core shells shows that the RT_{NDT} of the base metal will remain below 132°C at 40 years of lifetime.

Part III - Conclusions

7 FANC final conclusions

On 28 October 2015 the Licensee submitted to the FANC two final Safety Case Reports [10] [11]. The Licensee's internal Nuclear Safety Department established two independent review reports [12] [13] of these Safety Cases.

The Belgian Safety Authority performed an extensive review and evaluation of this complex issue since the detection of the flaw indications in June 2012 in the reactor pressure vessel of Doel 3.

In the general conclusions of its Synthesis Report [20] [21], AIB-Vinçotte states that:

- *Taking into account the loading conditions specified by the Licensee and the material properties considered in the analyses, the presented structural integrity assessment shows that the Doel 3 and Tihange 2 Reactor Pressure Vessel core shells with hydrogen flakes meet the ASME XI requirements for 'Acceptance by Analytical Evaluation'.*
- *The MO/AIA considers the Licensee replies to the Mid-Term Action requirements satisfactory.*
- *The MO/AIA requests re-inspection of the Doel 3 and Tihange 2 RPV core shells during the next planned outage within maximum 18 months from restart."*

In the general conclusions of its Safety Evaluation Report [19], Bel V states that:

> *"Considering the information made available, in particular the Electrabel assessment reports and the supporting analysis reports, but also the current understanding of the involved phenomena, Bel V concludes that the flaking degradation has been demonstrated satisfactory to have an acceptable impact on the serviceability of the Doel 3 and Tihange 2 RPVs during normal and abnormal service condition ."*

In November 2015, based on the Safety Cases provided by the Licensee, the independent review reports by the Licensee's Nuclear Safety Department, the assessments released by Bel V, AIB-Vinçotte, IRB, ORNL and NSEG about the flaw indications of the Doel 3 and Tihange 2 reactor pressure vessels, the Federal Agency for Nuclear Control draws the following **global conclusions :**

Regarding the In-service inspections:

The capability to properly detect, locate and characterize the flaws present in the reactor pressure vessels of Doel 3 and Tihange 2 has been extensively evaluated. The UT inspection procedure has been formally qualified.

Applying the qualified UT inspection procedure during the 2014 follow-up UT inspections of the RPV core shells wall thickness resulted in updating the flake cartography:

- The number of reported indications is significantly higher than in 2012, mainly due to a lowering of the detection thresholds and to the use of a more sensitive transducer.
- The update of the flaw sizing procedure resulted in an increase of the flake sizes to be considered in the structural integrity assessment. The tendency of the updated flaw sizing procedure to report clusters of indications as large individual flakes leads also to the reporting of larger average dimensions and much larger maximum dimensions in 2014.
- The newly reported indications are located in the same zones as the indications reported in 2012.

    - No significant radial connections between hydrogen flakes are detected in the RPV core shells.

Additional simulations and reconciliation with destructive tests by the Licensee have shown that hidden flaws and higher tilted flaws of critical size can be detected and characterized by the actually applied UT-techniques. No critical hydrogen flake type defects are expected in the areas non-inspectable by UT.

Regarding the metallurgical origin and evolution of the indications:

The conclusions issued by the FANC in May 2013 on the origin of the indications remain unchanged. The most likely origin of the indications identified in the Doel 3 and Tihange 2 reactor pressure vessels is hydrogen flaking due to the manufacturing process.

Significant evolution over time of hydrogen flakes due to the operation of the reactor units is unlikely. The comparison between the inspections data from the 2012 and 2014 UT inspections, applying the same parameters and reporting thresholds, does not evidence a crack growth. However, the time elapsed between the restart in 2013 and the shutdown in 2014 is too short to claim that there is a definitive experimental evidence of no in-service crack growth. The FANC requires that the Licensee shall perform follow-up UT-inspections, using the qualified procedure on the RPV core shells wall thickness at the end of the next cycle of Doel 3 and Tihange 2, and thereafter at least every three years.

The only theoretical propagation mechanism for the flakes detected in the Doel 3 and Tihange 2 reactor pressure vessels is low cycle fatigue, which is considered to have a limited effect. Other phenomena (such as hydrogen blistering or hydrogen induced cracking) have been evaluated and ruled out as possible mechanisms of in-service crack growth.

Regarding the material properties:

The Licensee performed an extensive material testing program in order to characterize the mechanical properties of some flaked and unflaked materials (VB395, KS02, nozzle cut-out materials from Doel 3 and JRQ reference materials…). From the evaluation of the results of these investigations, the FANC concludes:

- The tested materials have exhibited different behaviour under irradiation :
    - The unflaked test specimens from the surveillance program of Doel 3 and Tihange 2 and from the nozzle cuts of Doel 3 exhibit a behaviour under irradiation consistent with the predictions.
    - The test specimens, with or without flakes, from the macrosegregation zone of the VB395 exhibit an enhanced irradiation embrittlement inconsistent with the predictions, but an irradiation hardening consistent with the predictions.
    - The test specimens from the KS02, flaked or unflaked, from any zones, exhibit a behaviour consistent with the predictions. Due to the chemical composition of this material, the predicted embrittlement is nevertheless higher than for VB395 and the Doel 3 and Tihange 2 reactor pressure vessels material.
- An unknown phenomenon affects the VB395 material inducing an enhanced embrittlement without a hardening of the test specimens from the macrosegregation zones of the VB395 material. Hydrogen flaking is likely to be excluded as the root cause of this enhanced irradiation

embrittlement, as the existence of KS02 shows that hydrogen flaking does not necessarily imply enhanced irradiation embrittlement.

- Complementary investigations on the flaked materials available (VB395 and KS02) show that the presence of flakes has no direct effect on the fracture toughness of the RPV material (in unirradiated or irradiated conditions).

- The VB395 can be considered as an outlier. Therefore it can be assumed that the irradiation embrittlement of the VB395 is likely to be not representative and significantly higher than the expected embrittlement of Doel 3 and Tihange 2 core shells.
- New predictive equations for the irradiation embrittlement have been achieved for the structural integrity assessment of the Doel 3 and Tihange 2 reactor pressure vessels.

  The 50°C margin on RT_{NDT} considered in the 2013 Safety Case is discarded and replaced by predictive equations depending on the fluence. Considering the VB395 as an outlier for the behaviour under irradiation, the core shells of Doel 3 and Tihange 2 are unlikely to show the same sensitivity to irradiation embrittlement. The atypical embrittlement observed in VB395 in the material between flakes is included in their predictive equations to account as a safety provision.

  Therefore the predictive equations for the irradiation embrittlement used in the 2015 Licensee Safety Cases are acceptable for the FANC.

Regarding the structural integrity of the reactor pressure vessels:

The latest developments of the case resulted in a complete revaluation of the structural integrity assessment. Although the overall general conclusions remain valid, these developments lead to a more detailed and refined analysis.

A conservative analysis by the Licensee shows that more than 99.75% of the flaw configurations in the Doel 3 and Tihange 2 RPV shells are harmless in normal or abnormal operating conditions.

An independent conservative analysis by ORNL (obtained using different analysis methodologies) shows that 99.97% of the flaw configurations in the Doel 3 and Tihange 2 RPV shells are harmless in normal or abnormal operating conditions, confirming the more conservative Licensee screening results.

All characterized flaws not compliant in the Licensee screening assessment meet the acceptance criterion with ample margin when subjected to refined analyses. The Licensee refined analysis of the remaining 0.25% shows the low level of the crack driving forces K_{MAX} of the quasi-laminar hydrogen flakes. The detected Doel 3 and Tihange 2 flaw population is in compliance with the ASME Section XI acceptance criterion.

The elastic-plastic analysis was performed according to ASME III primary stress re-evaluation. The calculations demonstrated that the collapse load is only slightly reduced in comparison with a model without flaws. The primary stress criteria are met – i.e. the calculated collapse pressure is more than 1.5 times the design pressure as required by code.

The fatigue crack growth analysis was performed according to Appendix A of ASME XI. It was shown that the flaw indications will not grow significantly by fatigue for the remaining time of operation. It was also shown that flaw indications at the beginning of lifetime could not have grown significantly by fatigue during 30 years of operation.

The p-T curves integrated into the plant's Technical Specifications in the framework of the 2012 Safety Case remain valid and do not have to be updated.

A PTS Analysis of the RPV core shells shows that the RT_{NDT} of the base metal will remain below 132°C at 40 years of lifetime.

The presented structural analysis shows that the Doel 3 and Tihange 2 RPVs with hydrogen flakes meet the ASME XI requirements for 'Acceptance by Analytical Evaluation' for the specified loading and material properties.

The foregoing results and conclusions confirm the structural integrity of Doel 3 and Tihange 2 under all design transients with ample margins.

In conclusion the FANC confirms that all the safety concerns that were at the origin of the short-term and mid-term requirements have been solved in a satisfactory manner. After a detailed evaluation of the potential impact of the unexpected outcomes from February and March 2014, the FANC has concluded that the new 2015 safety case reports provide an adequate demonstration of the structural integrity of the Doel 3 and Tihange 2 reactor pressure vessels up to 40 years of operation.

As a result, the FANC authorizes the Doel 3 and Tihange 2 reactor units to resume operation until they reach the age of 40 years.

The FANC requires the Licensee to perform follow-up UT-inspections, using the qualified procedure on the RPV core shells wall thickness at the end of the next cycle of Doel 3 and Tihange 2, and thereafter at least every three years.

8 Acronyms

2a	Flaw diameter
$2a_{acc}$	Acceptable flaw diameter
(MO/)AIA	Authorized Inspection Agency (AIB Vinçotte)
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BR2	Research reactor at SCK•CEN
CEA	Commissariat à l'énergie atomique et aux énergies alternatives
CRIEPI	Central Research Institute of Electric Power Industry
D3	Doel 3
D3H1	Doel 3 nozzle shell cut-out H1
DTR	Défaut technologique de revêtement (technological cladding defect)
EAR	Examen d'Accrochage du revêtement (specific straight beam transducer)
EC	European Community
ENIQ	European Network for Inspection and Qualification
FANC	(Belgian) Federal Agency for Nuclear Control
FEM	Finite Element Modelling
XFEM	Extended Finite Element Modelling
FIS	Formule d'irradiation supérieure (French Predictive equation)
FKS	Forschungsvorhaben Komponenten Sicherheit
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit
H	Hydrogen
HIC	Hydrogen-Induced Cracking
IAEA	International Atomic Energy Agency
IERB	International Expert Review Board (2012-2013)
IRB	International Review Board (2014-2015)
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
JRQ	Reference material for fracture toughness
K_{Ia}	Crack arrest material toughness
K_{IC}	Crack initiation material toughness
KS02	Material Piece from German FKS research Program
KU Leuven	Katholieke Universiteit Leuven
LCS	Lower Core Shell

LEFM	Linear Elastic Fracture Mechanics
LOCA	Loss-Of-Coolant-Accident
MER	Mesure d'Epaisseur du Revêtement (ultrasonic transducer)
MIS-B	Machine d'Inspection en Service belge
MT	Magnetic Testing
NDE	Non-Destructive Examination
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plan
(US) NRC	Nuclear Regulatory Commission (USA)
NSEG	National Scientific Expert Group
OECD	Organisation for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory
ppm	Parts per million
PTS	Pressurized Thermal Shock
PWR	Pressurized Water Reactor
SIA	Structural Integrity Assessment
SI	Safety Injection System
SF	Safety Factor
RDM	Rotterdamsche Droogdok Maatschappij
RN	Rotterdam Nuclear
RPV	Reactor Pressure Vessel
RSE-M	Règles de Surveillance en Exploitation des Matériels Mécaniques (Predictive equation)
RT_{NDT}	Reference temperature for nil ductility transition
SI	Safety Injection
SIA	Structural integrity assessment
SCK●CEN	StudieCentrum voor Kernenergie – Centre d'étude de l'énergie nucléaire : Belgian Nuclear Research Centre
T0	Reference temperature for fracture toughness
T2	Tihange 2
T2H2	Tihange 2 nozzle shell cut-out H2
UC Berkeley	University of California, Berkeley
UCS	Upper Core Shell
UCL	Université catholique de Louvain
UGent	Universiteit Gent
ULB	Université Libre de Bruxelles

ULg	Université de Liège
UT	Ultrasonic Testing
VB395	Material Piece from the discarded French Steam Generator shell VB395
VTT	Technical Research Centre of Finland
Φ	Neutron fluence : neutron flux integrated over a certain time period

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Annex 1 – Status of action plan

Following the FANC Provisional Evaluation Report [5], the Licensee submitted an action plan to the Safety Authority. This action plan included answers to both the short term and mid-term requirements as formulated by the Federal Agency for Nuclear Control in its Provisional Evaluation Report [5].

The results of the short term requirements were analysed for the Final Evaluation Report [9] either closing the short term actions or formulating a follow-up mid-term requirement.

This section presents the amended action plan.

N°	Requirement	Status	Closure	Topic
1	The Licensee shall re-analyse 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	May 2013	In-service Inspection
2	The Licensee shall demonstrate that no critical hydrogen flake type defects are expected in the non-inspectable areas.	Short-term	May 2013	In-service Inspection
2b	Follow-up action	Mid-term	September 2014	In-service Inspection
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	May 2013	In-service Inspection
3b	Follow-up action	Mid-term	November 2015	In-service Inspection
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	May 2013	In-service Inspection
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	May 2013	In-service Inspection
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	May 2013	In-service Inspection
7	The Licensee shall achieve a full qualification program to demonstrate the suitability of the	Mid-term	November 2015	In-service

	in-service inspection technique for this 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 outage for refuelling.			Inspection
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	November 2015	Origin and evolution of the indications
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	May 2013	Material Properties
9b	Follow-up action	Mid-term	April 2014	Material Properties
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	May 2013	Material Properties
10b	Follow-up action	Mid-term	April 2014	Material Properties
11	A further experimental study program on the material properties of irradiated specimens containing hydrogen flakes shall be elaborated by the Licensee.	Mid-term	November 2015	Material Properties
12	The Licensee shall further investigate	Mid-term	November 2015	Material

	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.			Properties
13	The Licensee shall further evaluate the effect of thermal ageing in the zone of macro-segregation	Mid-term	November 2015	Material Properties
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	May 2013	Structural Integrity
15	The Licensee shall complete the ongoing test program by testing larger specimens containing hydrogen flakes.	Short-term	May 2013	Structural Integrity
15b	Follow-up action	Mid-term	August 2015	Structural Integrity
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	May 2013	Load Test
16b	Follow-up action	Mid-term	April 2014	Load Test

Table Annex 1 : 16 FANC requirements