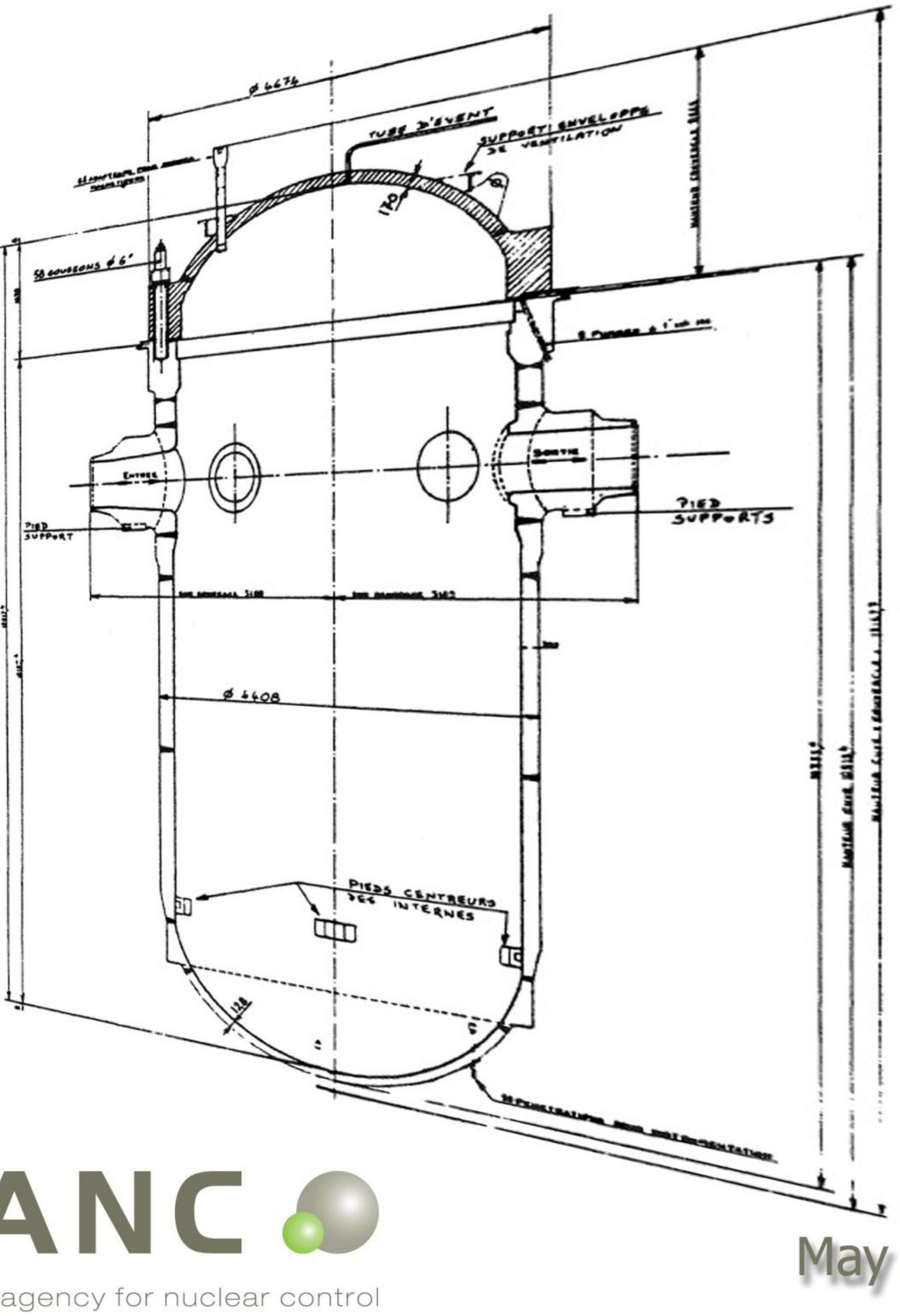
Doel 3 and Tihange 2 reactor pressure vessels

Final Evaluation Report



FANC

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1. Introduction

In June 2012, during a new type of in-service inspection conducted for the first time in Belgium, several thousands of flaw indications were detected in the base metal of the Doel 3 reactor pressure vessel, located mainly in the upper and lower core shells. As a precaution, similar inspections were conducted in September 2012 on the Tihange 2 unit, whose reactor pressure vessel is of identical design and construction. Flaw indications were detected as well, but to a lesser extent.

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 own analysis to determine whether or not the reactor units in question could safely resume operation in spite of the detected flaws. The demonstration of the licensee was recorded 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].

Taking into account the review conclusions of Bel V, AIB-Vinçotte, and the different national and international expert groups, the FANC issued in January 2013 its Provisional Evaluation Report on the issue [2]. 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 the Doel 3 and Tihange 2 reactor units should only restart after the additional requirements listed in its Provisional Evaluation Report are fulfilled by the licensee. These requirements included for example further validation of the ultrasonic inspection methods, completing the proposed material testing program (including large scale specimen tests) and the performance of a load-test on both reactor pressure vessels. A limited number of these requirements did not have to be addressed on a short term basis (= before a possible restart of the reactor unit), but could be answered on a mid-term (=before restart after the next scheduled outage for refuelling).

In response, the licensee elaborated an action plan to fulfil those FANC requirements, including a methodology and associated acceptance criteria where applicable. This action plan consists of a series of additional analyses, tests and inspections. The action plan 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 of the action plan 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 which was performed during the load tests of Doel 3 and Tihange 2.

On 15 April and 26 April 2013 the licensee submitted to the FANC two Addenda to the Safety Case Report that give a structured answer to each of the FANC's (short-term) requirements for the Tihange 2 and Doel 3 reactor units [3]. They also provide the results and conclusions of additional analyses, tests, and inspections that were performed to complement the original Safety Case Reports for Tihange 2 and Doel 3 of December 2012. These Addenda were reviewed by the internal "Service de Contrôle Physique – Dienst voor Fysische Controle " of Electrabel which gave an overall positive advice regarding the immediate and safe restart of both reactor units [4].

The FANC, together with Bel V and AIB-Vinçotte, have evaluated whether all the safety concerns at the origin of the requirements are solved and whether the related reservations can be lifted. This evaluation consisted in the review of documents, witnessing of material tests, inspections during the load test and participation to working meetings with the licensee.

The results of this evaluation can be found in this Final Evaluation Report on the Doel 3 and Tihange 2 RPV Flaw Indications issue. The other actions of the licensee action plan (which do not need to be finished before the restart of the reactor units) will be followed up by the Belgian safety authorities in the future but are not detailed in this report.

The following main topics are discussed in this Final Evaluation report:

- Chapter 2: In-service inspections,
- Chapter 3: Origin and evolution of the indications,
- Chapter 4: Material properties,
- Chapter 5: Structural integrity of the reactor pressure vessels,
- Chapter 6: Load Tests

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 [2];
- An evaluation of the related additional licensee analyses, tests and inspections performed by the licensee, based on the review done by AIB-Vinçotte [5], Bel V [6], the National Scientific Expert Group [7] and an expert consultant on Acoustic Emission Testing [8]. A more detailed description of the contents and results of each action can be found in the licensee Safety Case Addenda [3].
- A final conclusion of the FANC on the topic of the chapter.

The final conclusions of the FANC, including a proposal for a decision about the possible restart of the Doel 3 and Tihange 2 reactor units are detailed in a final chapter 7.

2. In-service inspections

2.1 Conclusions and requirements of Provisional Evaluation Report

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 [2].

> *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 the following requirements about the in-service inspections in its Provisional Evaluation Report [2].

> *As a prerequisite to the restart of both reactor units, the short-term requirements on inspections mentioned in the AIB-Vinçotte assessment shall be fulfilled by the licensee:*

- *REQUIREMENT 1 - CLAD INTERFACE IMPERFECTIONS: The licensee shall re-analyze the EAR acquisition data for Tihange 2 in the depth range from 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.*
- *REQUIREMENT 2 - NON-INSPECTABLE AREAS: The licensee shall demonstrate that no critical hydrogen flake type defects are expected in the non-inspectable areas.*
- *REQUIREMENT 3 - IDENTIFICATION OF POTENTIALLY UNREPORTED HIGHER TILTED FLAWS: The licensee shall demonstrate that the applied ultrasonic testing procedure allows the detection of the higher tilt defects in the Doel 3/Tihange 2 data (2012 inspections) with a high level of confidence.*
- *REQUIREMENT 4 - INDICATIONS WITH 45°T SHEAR WAVE RESPONSE: The licensee shall present the detailed report of all macrographical examinations including the sample with the 45°T reflections and shall also analyze and report additional samples with 45°T reflectivity.*
- *REQUIREMENT 5 - PARTIALLY HIDDEN INDICATIONS: 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.*
- *REQUIREMENT 6 - INCLINATION OF FLAWS DETECTED BY ULTRASONIC TESTING: The licensee shall re-analyze the tilts of the defects in the VB-395/1 block with the same method as applied on-site.*

REQUIREMENT 7 – FULL QUALIFICATION: As soon as possible after the restart of both reactor units: The licensee shall achieve a full qualification program to demonstrate the suitability of the in-service inspection technique for the present case. The qualification shall give sufficient confidence in the accuracy of the results with respect to the number and features (location, size, orientation…) of the flaw indications. Where appropriate, the process shall be substantiated by appropriate experimental data using representative specimens. The full qualification program shall be achieved before the next planned outage for refuelling.

2.2 Review of Licensee actions[1]

2.2.1 Additional information: Flaw Distribution Statistics

Licensee conclusion (§2.1.1 of [3])

During the 2012 UT inspection, precise and complete data about each individual flaw's position and dimensions were collected. In order to provide a good understanding of the flaw distribution, the data have been processed in different ways.

Review by Regulatory Body

The licensee provided additional information on the flaws found in the Doel 3 and Tihange 2 RPV, for example the flaw density and the distance between a flaw and its closest neighbour. The licensee demonstrated that there was no correlation between the positions of the indications and the fluence distribution.

The additional information on flaw distribution statistics was reviewed by the Belgian nuclear safety authority (FANC, Bel V and AIB-Vinçotte), which has no further comments on this topic.

2.2.2 Additional information: Cladding and internal surfaces of forgings

Licensee conclusion (§2.1.2 of [3])

The cladding was not taken into consideration in the Structural Integrity Assessment (SIA), in conformance with the ASME code. Periodic in-service inspections confirm that the cladding is sound.

Review by Regulatory Body

During the in-service inspection in 2012, the cladding of Doel 3 has been subjected to a qualified visual examination VT3. No defects were reported during this in-service inspection which confirms the assumption that the cladding is sound. It should be reminded that the cladding is not considered in the structural integrity assessment in conformance with the ASME Code.

The licensee confirmed that the surface inspections (magnetic testing) performed during the manufacturing of the RPV components, prior to cladding deposit, did not report any flaw indications. This result is not surprising as this surface inspection technique can only detect flaws oriented perpendicularly to the examination surface. Considering the (quasi-)laminar character of the hydrogen flakes, it is not unlikely that surface examinations like penetrant testing or magnetic testing, performed prior to the deposition of the cladding, have not detected the defects. The non-reporting of hydrogen flake-type indications during these surface examinations can be considered as normal.

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[1] *The FANC would like to stress that the requirements related to the verification of the non-destructive examination procedure and the review and follow-up of their qualification program is the responsibility of AIB-Vinçotte, which is the authorized inspection agency in Belgium.*

The additional information on cladding and internal surfaces of forgings was reviewed by the Belgian nuclear safety authority (FANC, Bel V and AIB-Vinçotte), which has no further comments on this topic.

2.2.3 Action 1: Clad interface imperfections at Tihange 2 RPV

Licensee conclusion (§2.1.3 of [3] Tihange 2)

A number of small cladding imperfections were identified at the interface between the cladding and the base metal. A re-analysis of the UT inspection data confirms that these defects should not be considered as hydrogen flakes. Small cladding imperfections are common during the manufacturing process, and harmless.

Review by Regulatory Body (AIB-Vinçotte [5])

The licensee presented the results of the reanalysis of the UT data collected during the 2012 inspection at Tihange 2. The EAR data for a depth range between 0 and 15 mm were evaluated and it was confirmed that no technological cladding defects should have been identified as hydrogen flakes.

AIB-Vinçotte considers the licensee reply to the Action 1 requirement satisfactory and has no more comments related to Action 1.

2.2.4 Action 2: Non-inspectable areas

Licensee conclusion (§2.1.4 of [3] Tihange 2, §2.1.3 of [3] Doel 3)

The capability of the UT inspection technique is to some extent affected by the geometrical features of specific areas of the RPV inner surface.

The Tihange 2 RPV has four of these areas on its inner surface. Since no clusters of flaws are detected near these areas, no critical hydrogen flakes are expected there.

The Doel 3 RPV has four of these areas on its inner surface. Near three of these areas, no clusters of flaws are detected. Therefore no hydrogen flakes are expected there. In the fourth area – behind the brackets – the presence of flakes cannot be excluded. However, the brackets would protect potentially hidden flakes in terms of stress and toughness. Hence, such potentially hidden flakes are not considered to be critical.

Review by Regulatory Body (AIB-Vinçotte [5])

For Tihange 2 the licensee analysis has shown that four types of geometrical discontinuities appear at the inner surface of the vessels. These might deflect sound propagation or make the zone non-inspectable by UT. Taking into account the distribution of the observed flaw indications in the Tihange 2 RPV, the licensee analysis showed that the overall impact of these surface discontinuities on the inspection outcomes is insignificant and that therefore no critical hydrogen flake type defects are expected in the areas non-inspectable by UT.

For Doel 3, the same applies except that the presence of flakes in one area behind two brackets cannot be excluded. The licensee considers these flaws not critical as the brackets would protect potentially hidden flaws in terms of stress and toughness.

AIB-Vinçotte considers the licensee reply to the Action 2 requirement satisfactory for restart.

2.2.5 Action 3: Identification of potentially unreported higher tilted flaws

Licensee conclusion (§2.1.5 of [3] Tihange 2, §2.1.4 of [3] Doel 3)

Additional examinations of higher tilted flaws confirm that the 2012 straight beam UT inspections correctly detected and sized all hydrogen flakes in the block VB-395/1. Flaws with an inclination up to 20°, that would potentially not have been reported, have been determined as a function of the position in the RPV wall. These potential flaws are considered in the Sensitivity Analyses.

Review by Regulatory Body (AIB-Vinçotte [5])

A complementary set of highly tilted (exceeding 10°) indications was cut in the AREVA block VB-395/1. Destructive examination confirmed the correct detection and sizing by the straight beam UT inspection technique of these indications.

To justify the threshold currently used in the analysis of the UT data (-12dB for depths > 30 mm), the licensee did simulations with the CIVA UT software to determine flaws that may exist in the material, but whose UT amplitude would be below the reporting level applied during the 2012 UT inspections at Doel 3 and Tihange 2, and therefore would not have been taken into account in the structural integrity assessment.

Varying dimensions, inclinations and depths were considered for the modeling. Conservatisms were added to the results of modeling to build the enveloping curve that is the input for the structural integrity assessment of the Short Term Action 14:

- Ideal planar circular reflector model
- Flaw inclination of 20°.

It shall be noted that the results of the Action 3 are expressed as characteristics of single flaws (dimension, inclination, depth).

AIB-Vinçotte considers the licensee reply to the Action 3 requirement satisfactory for restart.

2.2.6 Action 4: Indications with a 45°T Shear Wave response

Licensee conclusion (§2.2.1 of [3])

During the 2012 in-service inspection of the reactor pressure vessels (RPVs), a number of very weak 45° T shear wave UT responses were observed. The macrographical examination of three samples of block VB-395/1 showed that there is no correlation between the 45° T UT responses and any radial or volumetric component of the flake.

Review by Regulatory Body (AIB-Vinçotte [5])

The licensee presented the detailed report of all macrographical examinations including the examination results of a set of three indications showing a 45°T UT response.

AIB-Vinçotte considers the licensee reply to the Action 4 requirement satisfactory and has no more comments related to Action 4.

2.2.7 Action 5: Partially hidden indications

Licensee conclusion (§2.2.2 of [3])

Two samples with multiple hydrogen flakes were taken from block VB-395/1 and examined. The dimensions resulting from their ultrasonic examination were compared to the results of their destructive examination. The comparison confirms the capability of straight beam ultrasonic testing (UT) to correctly detect and size hydrogen flakes that are partially hidden by others.

Review by Regulatory Body (AIB-Vinçotte [5])

Based on the results of the ultrasonic examination of the block VB-395/1, the licensee extracted two samples containing several hydrogen flaking flaws to evaluate, by a correlation with the results of their destructive examination, the capability of the ultrasonic testing to correctly detect and size the hydrogen flaking flaws partially hidden by others. The destructive examination performed on the two samples confirmed that the 0°L ultrasonic examination enables the detection and sizing of the indications in the configurations examined.

AIB-Vinçotte considers the licensee reply to the Action 5 requirement satisfactory and has no more comments related to Action 5.

2.2.8 Action 6: Inclination of flaws detected by Ultrasonic Testing

Licensee conclusion (§2.2.3 of [3])

During the 2012 in-service inspection, ultrasonic testing (UT) was performed using a straight ultrasonic beam. The results contained a number of indications with tilts that were evaluated from the straight beam information. At the UT validation, the tilts of the indications in block VB-395/1 were determined using a phased array inspection.

The tilts of the flaws in the block VB-395/1 were re-evaluated using the same straight beam UT method as applied on site. The results confirm a very good correlation between both methods.

Review by Regulatory Body (AIB-Vinçotte [5])

The licensee re-analyzed the tilts of the defects in the block VB-395/1 with the same method as applied on-site. It was done for the indications from the VB-395/1 block for which an inclination was observed along X- or Y-axis with the UT Phased Array transducer. The exercise confirmed the results of the UT Phased Array examinations and showed a good correlation between both methods used to determine the flaw inclinations.

AIB-Vinçotte considers the licensee reply to the Action 6 requirement satisfactory and has no more comments related to Action 6.

2.3 Conclusions on In-Service Inspections

Based on the data provided by the licensee and the review and assessment of AIB-Vinçotte on the in-service inspections, the FANC concludes that all the identified short term open issues on this topic have 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.

As already mentioned in the FANC Provisional Evaluation Report [2], 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 (REQUIREMENT 7 – Full qualification program).

3. Origin and evolution of the indications

3.1 Conclusions and requirements of Provisional Evaluation Report

Based on the data provided by the licensee and the conclusions released by Bel V, AIB-Vinçotte and the expert groups about the metallurgical origin and evolution of the indications, the FANC drew the following conclusions in its Provisional Evaluation Report [2].

> *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 the following requirement about the metallurgical origin and evolution of the indications in its Provisional Evaluation Report [2].

> *REQUIREMENT 8 - FOLLOW-UP IN-SERVICE INSPECTIONS: 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.*

3.2 Review of Licensee actions

3.2.1 Additional information: Root Cause - Link between Manufacturing and Flake Occurrence

Licensee conclusion (§3.1 of [3])

Not all forged components of the Doel 3 and Tihange 2 reactor pressure vessels (RPVs) contain the same amount of hydrogen flakes. Based on an analysis of the ingot size and the combined sulphur and hydrogen content, the forgings were ranked according to their susceptibility to hydrogen flaking. This revealed a good correlation with the amount of flakes found in each forged component.

Review by Regulatory Body

The licensee provided additional information 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). The vessel rings of Doel 3 and Tihange 2 which contain the highest number of flaw indications are those which have the highest susceptibility of hydrogen flaking, based on an analysis of the different ingot sizes and contents of hydrogen and sulphur.

The additional information on the link between manufacturing and flake occurrence was reviewed by the Belgian nuclear safety authority (FANC, Bel V and AIB-Vinçotte), which has no further comments on this topic.

3.2.2 Additional information: Phenomenology of Hydrogen Flaking

Licensee conclusion (§3.2 of [3]):

As mentioned in the Safety Case Report, literature shows that the indications in the RPV shell could be associated with a zone of macro-segregations that originate from the fabrication process. This was confirmed by new tests on reference block VB-395/1.

Moreover, the flaws are situated in very specific locations: the so-called 'ghost lines', which correspond to the residual features of the ingot after forging. In addition, the representativeness of the reference block VB-395/1 and the flaking mechanism have been confirmed. Bridging was found to occur only between flakes that are very close to each other, under circumstances that exclusively exist during manufacturing.

Review by Regulatory Body

The licensee performed new tests on samples from the reference block VB-395 which confirmed that the hydrogen flakes are located in macro-segregated areas, more specifically in ghost lines within these macro-segregated areas.

The additional information on the phenomenology of hydrogen flaking was reviewed by the Belgian nuclear safety authority (FANC, Bel V and AIB-Vinçotte), which has no further comments on this topic.

3.2.3 Additional information: Representativeness of the AREVA Shell with regard to RPV Flaking

Licensee conclusion (§3.4 of [3]):

The representativeness of the AREVA shell VB-395 regarding hydrogen flaking has been confirmed. Therefore, the findings and conclusions of the tests on the AREVA shell can be transferred to the RPVs.

Review by Regulatory Body

The licensee demonstrated that the UT inspections in the AREVA shell VB-395 and the Doel 3 and Tihange 2 RPVs showed similar flaw characteristics and a similar position of flaws versus the macro-segregation. In addition, a comparison of the AREVA shell VB-395 and the Doel 3 RPV H1 nozzle shell cut-out demonstrated a good correlation of the chemical and micro-structural characteristics of both materials.

The additional information on the representativeness of the AREVA shell with regard to RPV flaking was reviewed by the Belgian nuclear safety authority (FANC, Bel V and AIB-Vinçotte), which has no further comments on this topic.

3.3 Conclusions on Origin and Evolution of Indications

Based on the additional information provided by the licensee, the FANC concludes that no open issues on this topic remain.

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 VB-395 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. Therefore, as already mentioned in the FANC Provisional Evaluation Report [2], the licensee will perform an in-service inspection of the RPV on the same zones as inspected in 2012 during the next planned outage, using the identical methodology and equipment. The licensee will only report on a comparison between the 2012 and successive inspection, with special attention to potential detected evolution of selected flaws identified in 2012 (REQUIREMENT 8 - Follow-up in-service inspections).

4. Material properties

4.1 Conclusions and requirements of Provisional Evaluation Report

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 [2].

> *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 RT_{NDT} proposed by the licensee is conservative.*

The FANC issued the following requirements about the material properties in its Provisional Evaluation Report [2].

As a prerequisite to the restart of both reactor units:

- *REQUIREMENT 9 – ADDITIONAL CHARACTERIZATION OF THE MATERIAL MECHANICAL PROPERTIES: 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;*
    - *large-scale (tensile) specimen tests*
- *REQUIREMENT 10 - RESIDUAL HYDROGEN: 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 shall demonstrate that the chosen material properties are still valid, even if the upper bound quantity of hydrogen would still be present in critical flaws.*

As soon as possible after the restart of both reactor units,

- *REQUIREMENT 11 - IRRADIATION PROPERTIES: A further experimental program to study the material properties of irradiated specimens containing hydrogen flakes shall be elaborated by the licensee.*
- *REQUIREMENT 12 - LOCAL MICROSCALE PROPERTIES: 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 the composition on the local mechanical properties (i.e. fracture toughness) shall be quantified.*

- *REQUIREMENT 13 –THERMAL AGEING: The licensee shall further evaluate the effect of thermal ageing of the zone with macro-segregation.*

4.2 Review of Licensee actions

4.2.1 Action 9: Additional characterization of the material mechanical properties

Licensee conclusion (§4.1 and §4.2 of [3])

Tests performed on specimens from the Doel 3 H1 nozzle cut-out show that the ghost lines have no significant impact on the Charpy impact or fracture toughness properties.

Tensile tests on specimens taken from the VB-395 shell show that the ductility of the material in the ligaments between flakes is similar to the ductility of the material free of flakes. Large-scale tests on material containing flakes confirm the good ductility and load bearing capacity.

The fracture toughness tests confirm that the 50 °C shift of RT_{NDT} considered in the Safety Case is appropriate to cover the potential deterioration of the local fracture toughness properties in the vicinity of the hydrogen-induced flaws.

Review by Regulatory Body (AIB-Vinçotte [5], Bel V [6], National Scientific Expert Group [7])

The material testing program performed under Action 9 consists of mechanical tests performed on specimens taken from the Doel 3 H1 nozzle cut-out and from the AREVA shell VB-395 affected by hydrogen flaking. These tests are performed to complement the characterization of the RPV shell material as affected by hydrogen flaking in order to show that the behaviour of the material is as expected, so ensuring the serviceability of the affected RPV.

1) **Additional characterization of Doel 3 H1 nozzle cut out - Properties of local segregated zones (“ghost lines”)**

   The licensee performed mechanical tests (Charpy, fracture toughness and tensile) on specimens with ghost lines from the H1 nozzle cut-out of Doel 3.

   - Impact tests were taken in the T-S orientation with the notch at the level of a ghost line (crack propagation perpendicular to the plane of the ghost line). No difference was observed as compared to the Charpy curves established for the material out of the ghost line.
   - Fracture toughness tests were performed on pre-cracked Charpy specimens tested in 3-point bending in T-S orientation. The crack tip was positioned in the ghost line. No significant difference has been seen as compared to specimens without ghost lines.
   - Tensile tests were performed on specimens with a ghost line parallel to the specimen axis and on specimens with a ghost line perpendicular to the axis. For the tests with the ghost line perpendicular to the axis, the specimen broke outside of the ghost line (which is normal considering the higher yield stress of the ghost line). For the specimens with the ghost line parallel to the specimen axis, the presence of the ghost line leads to an increase of the yield stress and a reduction of the total elongation.

   AIB-Vinçotte concludes that the presented test results showed a limited effect of the ghost lines on the mechanical properties.

   Similarly, Bel V concludes that the results of the additional characterization tests show that the ghost lines do not affect significantly the mechanical (tensile and fracture toughness) properties of the material.

The National Scientific Expert Group also concludes that no detrimental effect could be measured during the tests on the Doel 3 H1 nozzle cut-out.

2) Additional characterization of AREVA shell VB-395 affected by hydrogen flakes – Effect of hydrogen flakes on material properties

The characterization of the AREVA shell VB 395 was performed on test specimens taken from locations out of the zones affected by hydrogen flaking and from zones containing hydrogen flakes. It is reminded that the effects of hydrogen flaking on the mechanical properties of the Tihange 2 and Doel 3 RPV shells are intended to be estimated from the differences between the mechanical properties of the AREVA shell VB 395 determined in the zones affected by flaking and those determined in the zones not affected by flaking.

2 a) Tensile test on the AREVA VB-395 shell affected by hydrogen flakes.

- Tensile properties were measured in the three orientations in the ligament between flakes in the blocks affected by flakes. The yield and tensile stresses are about 22 MPa higher than in the block without flakes, which is consistent with the higher carbon content in the blocks affected by flakes. The ‘reduction of area’ and elongation are slightly reduced compared to the zone out of the segregation.
- Large tensile specimens containing flakes parallel to the specimen axis were tested at room temperature and at 290°C in the L and T orientations. The data points for yield and ultimate stress are practically superposed on the points corresponding to the small specimens taken in the ligament. There is a loss of elongation but the total elongation remains important (> 17% at room temperature and > 14% at 290°C). The reduction of area remains higher than sixty percent.
- Tests of 25 mm specimens with flakes oriented at 20 degrees to the specimen axis were performed in the framework of the “large scale test program”, see Action 15.

According to Bel V, the results show that the tensile properties (yield stress and tensile strength) are slightly higher but the ductility (as measured by the reduction of area) is slightly lower for the material between the flakes.

The results of the tensile tests performed in the ligaments between the flakes lead Bel V to conclude that the material affected by the hydrogen flakes has a satisfactory tensile behavior when compared to the sound material. To Bel V opinion, the material between the flakes has a satisfactory ductility as evidenced by the reduction of area, even if it is lower by about 10% than the value in the sound material.

2 b) Fracture Toughness Tests on the AREVA VB-395 shell affected by hydrogen flakes

From additional experimental fracture toughness tests on VB-395 specimens, the licensee could show the following:

- The fracture toughness measured locally in the ligament between flakes shows only a limited difference with the values obtained out of the zone affected by flakes. An 11°C shift was found on the T_0 temperature of the Master Curve. This difference is compatible with the experimental error on T_0 but has been considered conservatively as a real effect.
- The fracture toughness values measured on specimens with hydrogen flakes as crack initiator (in place of the usual fatigue crack) are not strictly valid according to the standard, in which specific requirements are imposed on the crack front straightness. Nevertheless the licensee performed a Master Curve evaluation of the results that

confirmed that there is no important difference with the specimens taken in the ligament. There is an additional shift of T_0 of the order of 14°C as compared to the specimens in the ligament.

From the results of the fracture toughness tests performed on the bottom part of the AREVA Shell VB 395 Bel V concludes that the brittleness of the material affected by hydrogen flaking is not significantly higher than that of the material unaffected by flaking as evidenced by the higher value by about 10°C of the Master Curve reference temperature T_o of the material between flakes when compared to the temperature T_o of the material in the unaffected zone.

3) **<u>Final conclusions on action 9: Additional characterization of the material mechanical properties</u>**

AIB-Vinçotte considers the Licensee reply to the Action 9 requirement satisfactory for restart.

Bel V concludes that, according to the tests results as reported by the licensee, the characterization of the AREVA shell VB 395 has 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 is considered by Bel V to be limited.

<u>Additional margin of 50°C on the RT_{NDT}-value</u>

A major objective of the test program was to demonstrate that the additional margin of 50°C on the RT_{NDT}-value considered in the structural integrity assessment in the Safety Case is appropriate to cover the potential deterioration of the local fracture toughness properties in the vicinity of the hydrogen induced flaws.

The additional ΔRT_{NDT} due to the effect of hydrogen flaking is estimated by the licensee to 25°C, value obtained by adding

(1) the ΔRT_{NDT} (about 11°C) representing the increased brittleness of the material between the ligaments between the flakes

(2) to the ΔRT_{NDT} (about 14°C) representing the increased brittleness of the material in the crack front of the flakes.

In prior material tests, the licensee already demonstrated that there are no significant effects of orientation or segregation on facture toughness (except a potentially greater sensitivity to irradiation embrittlement of the segregated zone) and that the material between the flaws is sound.

It was shown previously in the Safety Case [1] that the effect of the potentially higher sensitivity of the zone of macro-segregation to irradiation embrittlement is maximum 17°C, at the peak of the segregation and for the peak fluence. Depending on their location, the effect ranges from 4°C to 12°C for the most limiting flaws, due to the spatial variation of the fluence.

Combining all these effects, the estimated maximum value of the additional ΔRT_{NDT} is equal to 42°C.

Bel V and AIB Vinçotte conclude from these results that the 50°C margin on RT_{NDT} considered in the Safety Case is appropriate.

The National Scientific Expert Group also concludes that the 50° C shift considered in the safety case is conservative with regards to the shift measured when considering the presence of flakes (~ 11°) and with regards to the irradiation embrittlement in the segregated zone evaluated using the FIS formula (up to 17°).

4.2.2 Action 10: Residual Hydrogen

Licensee conclusion (§3.3 of [3])

Additional tests confirm that there is no significant amount of residual hydrogen present inside the metal, nor in the flakes. Therefore, the material properties are unaffected.

Review by Regulatory Body (AIB-Vinçotte [5], Bel V [6])

The licensee launched a complementary test program on flaked specimens of the Areva shell VB-395/1. Hot extraction tests at 1100°C showed that no significant amount of H_2 is present inside flakes, which have been kept at room temperature, and so there is no problem expected of remaining H_2 inside the flakes of the Doel 3 and Tihange 2 RPV's. Moreover, all the measured values for flaked and unflaked specimens are well below 0.8 ppm which is generally considered to be a conservative threshold for deterioration of material properties.

In order to confirm the conclusions, melt extraction tests on specimens that underwent hot extraction at 1100°C are ongoing. Moreover, the licensee also launched a test campaign on the direct measurement of hydrogen escaping from flakes opened in vacuum. On the other hand, the worst case scenario considering the maximum amount of H_2 that could be present inside a typical flake has been studied by the licensee. It was concluded that even in that case no adverse effect of hydrogen on the material properties is to be expected.

AIB-Vinçotte considers the licensee reply to the Action 10 requirement satisfactory for restart.

According to Bel V, the results show that the total hydrogen is at the same level in flaked and non-flaked specimens taken from the AREVA shell VB-395. Therefore, Bel V acknowledges the licensee conclusion that there is no significant amount of hydrogen present inside the flakes.

4.3 Conclusions on Material Properties

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 concludes that all the identified short term open issues on this topic have 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 VB-395.

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 VB 395 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 VB-395 specimens, the 50°C margin on RT_{NDT} 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. As already mentioned in the FANC Provisional Evaluation Report [2], the licensee shall fulfill the following requirements before restart after next scheduled outage for refuelling of the reactor units:

REQUIREMENT 11 - IRRADIATION PROPERTIES: A further experimental program to study the material properties of irradiated specimens containing hydrogen flakes shall be elaborated by the licensee.

REQUIREMENT 12 - LOCAL MICROSCALE PROPERTIES: 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 the composition on the local mechanical properties (i.e. fracture toughness) shall be quantified.

REQUIREMENT 13 –THERMAL AGEING: The licensee shall further evaluate the effect of thermal ageing of the zone with macro-segregation.

5. Structural integrity of the reactor pressure vessels

5.1 Conclusions and requirements of Provisional Evaluation Report

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 [2].

> *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 to 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 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 the following requirements about the structural integrity of the reactor pressure vessels in its Provisional Evaluation Report [2].

> *As a prerequisite to the restart of both reactor units, the licensee shall resolve a remaining issue identified in the fracture mechanics evaluation and shall perform an additional experimental validation. In this respect:*
>
> - *REQUIREMENT 14 - SENSITIVITY STUDY OF HIGHER TILTED FLAWS: The licensee shall evaluate the impact of the possible non-reporting of flaws with higher tilts on the results of the structural integrity assessment (taking into account the results of the actions related to the previous requirement on the detection of the higher tilt defects during in-service-inspections).*
> - *REQUIREMENT 15 – LARGE SCALE VALIDATION TESTS : The licensee shall complete the on-going material testing program by testing larger specimens containing hydrogen flakes, with the following 2 objectives:*
>   - *Objective 1: Tensile tests on samples with (inclined) multiple hydrogen flake defects, which shall in particular demonstrate that the material has sufficient*

ductility and load bearing capacity, and that there is no premature brittle fracture.

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

5.2 Review of Licensee actions

5.2.1 Additional information: ASME III Elasto-Plastic Analysis

Licensee conclusion (§5.1 of [3])

After the ASME III NB-3228.3 elasto-plastic analysis, it is shown that the collapse load evaluated for the most penalizing flaw configuration meets the acceptance criterion.

Review by Regulatory Body:

The additional information on ASME III Elasto-Plastic Analysis was reviewed by the Belgian nuclear safety authority (FANC, Bel V and AIB-Vinçotte), which has no further comments on this topic.

5.2.2 Additional information: Flaw Acceptability Analysis Core Shells

Licensee conclusion (§5.2 of [3])

The Flaw Acceptability Analysis was expanded with a flaw-screening criterion approach. Application of the flaw-screening criterion confirms that all the flaws detected in the Tihange 2 RPV are harmless. Only eleven flaws or groups of flaws in the Doel 3 RPV exceed this screening criterion. However, they meet the acceptability criterion. Additional refined analyses show substantial margins.

Review by Regulatory Body (Bel V Provisional Report January 2012)

The application of a screening criterion approach to demonstrate the acceptability of a RPV affected by flaking had been discussed with the Licensee in January 2013. The rationale of this approach is documented in the Bel V Provisional Report of January 2013. As stated in this report, the application of the screening criterion allowed BelV to conclude that the presence of the hydrogen-induced flaws detected in the Doel 3 and Tihange 2 RPV shells has not a significant impact on the level of safety that the Doel 3 and Tihange 2 RPVs were expected to have after the fabrication.

5.2.3 Additional information: Sensitivity Analysis of the Structural Integrity Assessment with Respect to Ligament

Licensee conclusion (§5.3.1 of [3]):

A number of sensitivity analyses were performed on the most penalizing flaw of the two RPVs (Doel 3 flaw Ev2220), considering effects such as the ligament tending to zero, a 5° larger inclination, the actual fluence, the flaw shape, and the Safety Injection water temperature. Results confirm that a significant margin remains in all cases.

Review by Regulatory Body

As requested by the International Review Board, additional sensitivity analyses were performed by the licensee, for example considering the most critical flaw in the structural integrity assessment and investigating how the results of the SIA change when the ligament of the flaw is tending to zero.

The additional information on Sensitivity Analysis of the Structural Integrity Assessment with Respect to Ligament was reviewed by the Belgian nuclear safety authority (FANC, Bel V and AIB-Vinçotte), which has no further comments on this topic.

5.2.4 Action 14: Sensitivity Study of Higher Tilted Flaws

Licensee conclusion (see §5.3.2 of [3]):

The integration of potentially unreported flaws up to 20° inclination in the Structural Integrity Assessment of the upper core shell of Tihange 2 or the lower core shell of Doel 3 does not affect its structural integrity.

Review by Regulatory Body (AIB-Vinçotte [5], Bel V [6])

The licensee assessed whether adding UT-potentially not reported high tilt flaws to the current family of UT-reported flaws has an impact on the demonstration of the structural integrity presented in the Safety Case.

- From the UT sensitivity study in Action 3 and taking into account the actual UT-reported flaw size density into the shell thickness, additional flaws are postulated and spread over the entire shell at the locations with highest UT-reported flaw densities. Their exact position is randomly generated with a sufficient number of trials to reach high confidence level.
- Next, the additional postulated flaws are added to the UT-reported ones and their structural integrity assessment is performed.

The licensee showed that the approach combining UT-sensitivity evaluation and Structural Integrity Analysis demonstrates the structural integrity of the upper shell of the Tihange 2 RPV and the lower core shell of the Doel 3 RPV taking into account the UT-potentially not reported flaws with the highest tilt in addition to the flaws already reported during the 2012 inspections.

AIB-Vinçotte considers the licensee reply to the Action 14 requirement satisfactory and has no more comments related to Action 14.

Bel V concludes that 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 should not affect significantly their structural integrity.

5.2.5 Action 15: Large-Scale Validation Tests

Licensee conclusion (§5.4 of [3])

The material's good ductility and load bearing capacity were demonstrated by the tensile tests described in the previous chapter. These tests confirmed that the ductility of the material in the ligaments between flakes is similar to the ductility of material free of flakes.

The two large-scale tensile specimens with inclined flakes tested at room temperature exhibited significant uniform elongation and local plasticity at crack tips. The results clearly indicate the good ductility and load bearing capacity.

The 3D Finite Element analysis on two large-scale tensile specimens with inclined flakes tested at -80 °C, demonstrated that the specimen failure was as predicted by fracture mechanics, and that there is no premature brittle fracture.

The 3D Finite Element simulation of two large-scale bend bars with flakes tested in four-point bending demonstrated that the failure load calculated according to the same methodology as applied in the Structural Integrity Assessment of the RPVs was significantly lower than the actual failure load.

Review by Regulatory Body (AIB-Vinçotte [5], Bel V [6], National Scientific Expert Group [7])

To meet the Action 15 requirement, the licensee performed tensile and bend tests on material containing hydrogen flakes taken from the Areva shell VB-395. The notion of "large scale" test is to be understood by comparison with the size of the usual mechanical test specimens (6.25 mm diameter tensile specimens and 12.5 mm Compact Tension specimens). In the "large scale" tests, 25 mm diameter tensile specimens and 260 x 60 x 30 mm bend bars were considered.

1. **Large scale tensile tests.**

The objective of this large-scale tensile test program is to provide an experimental contribution to the assessment of the global structural behaviour of the RPVs affected by thousands of flakes. Basically, the satisfactory structural behaviour of the RPVs requires that the material is flaw tolerant with adequate plastic reserve strength. Plasticity is indeed needed to allow the structure to accommodate the flaws.

The objectives of the large-scale tensile test program are therefore to investigate the large-scale flaw-tolerant material properties of the RPVs. More specifically, the objectives of the large-scale tensile test program as defined in action #15 are *to demonstrate that the material has sufficient ductility and load bearing capacity and that there is no premature brittle fracture*.

These objectives can be clarified as follows:

(1) *sufficient ductility*: the zones containing flaws have the necessary strain capacity to deform without inducing crack propagation.
(2) *load bearing capacity*: the stress concentration effects due to the presence of flaws do not decrease the load carrying capacity to a value lower than the one predicted by the net section.
(3) *premature brittle fracture*: the fracture behaviour is in conformity with the expected behaviour as determined by the fracture toughness curve (roughly, there is no brittle fracture when ductile fracture is expected).

The tensile test specimens 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.

AIB–Vinçotte concludes that the stresses on the net section at maximum load were found to be all above the yield. Detailed finite element analyses of two tensile test configurations, presented by the licensee, confirmed the conservatism of the 3D finite element analyses.

Bel V is mainly interested in the tests performed at room temperature for the following reason. According to the pressure-temperature limit curves applicable to the Tihange 2 and Doel 3 RPVs, the operating pressure may be applied only when the temperature is in the range of 140°C to 150°C. Taking into account the difference in nil-ductility transition temperature RT_{NDT} between the AREVA shell VB 395 and the Tihange 2 and Doel 3 irradiated shells (also accounting for a 50°C margin), a test temperature of 25°C is representative of the minimum temperature of the Tihange 2 and Doel 3 RPV under operating pressure.

The main features of the large-scale test results are summarized as follows for the tests performed at room temperature:

(1) The stress-strain curve for the specimen without flakes and the curve for the specimen with flakes oriented at 0° overlap on each other.
(2) The yield stress has about the same value for all the tested specimens: specimen without flakes, specimen with flakes oriented at 0°, specimens with flakes oriented at 20°.
(3) The stress-strain curve for the specimens with flakes oriented at 20° overlaps on the one for the specimen without flake up to the strain where failure initiates.

The evaluation by Bel V of the results of the large-scale tensile tests performed at room temperature is summarized as follows:

(1) The overlapping of the stress-strain curve room temperature for the specimen without flakes and the curve for the specimen with flakes oriented at 0° is likely due to the fact that no flake is found to be located in the necking zone.
(2) The overlapping of the stress-strain curve at room temperature for the specimens with flakes oriented at 20° and the curve for the specimen without flake up to the strain value where failure initiates could be considered as an experimental result suggesting that the tensile behaviour of test specimens with tilted flakes obeys to the behaviour law of the sound material up to the point where the facture initiates.
(3) The "apparent" ductility of the specimens with tilted flaws, as measured by the total elongation at rupture, is decreased when compared to the value recorded for the specimens without flakes or with 0° tilted flakes. However, the apparent ductility remains significant (higher than 5 per cent).
(4) The stress-strain curves of the two specimens tested at room temperature differ by the shape of the curve beyond the strain value at which the maximum stress is recorded. This difference could be explained by the embedding characteristics of the flake from which the fracture has been initiated.
(5) The recorded maximum stress for the specimens with tilted flaws is higher than the tensile strength of the sound material multiplied by the ratio of the net section (obtained from the projected area of the flakes in the fracture zone) to the original cross-sectional area.

From (2) and (3), Bel V concludes that the requirement for sufficient ductility is satisfied. From (5), Bel V concludes that the requirement for sufficient load carrying capacity is satisfied.

The requirement for no premature brittle fracture is discussed below. To Bel V opinion, tensile testing large-scale specimens (with 20° tilted flakes) at room temperature is appropriate for verifying that the requirement for no premature brittle fracture as defined above is satisfied. Indeed at this test temperature, which is about 100°C higher than the Master Curve transition temperature T_o of the material affected by flaking, the material should be in the upper shelf region.

The main results of the large-scale tensile tests performed at room temperatures as reported by the licensee are: (1) the fracture surface is nearly perpendicular to the specimen axis and (2) although the specimens fractured essentially in cleavage mode, the presence of small ductile zones in the fracture surfaces, more particularly at the tips of the flakes, gives evidence that the fracture was initiated by ductile tearing (stable crack growth) that converted to cleavage fracture.

According to the licensee, these fracture features are typical of the fracture behaviour of the low alloy steel (Mn-Ni-Mo) of the RPV shells in the ductile-to-brittle transition zone, extending to the upper shelf region.

In order to confirm that the material at the test temperature of 20°C is well in the upper shelf region of the material and not in the transition region, the licensee performed two additional ductile tearing resistance tests at 20°C on C(T) specimens taken from AREVA shell VB 395 in the material between the flakes. The objective of the test was to demonstrate that the critical J_q value at initiation of ductile tearing is higher than the expected minimum value in the upper shelf region.

The test results were found to be satisfactory.

2. **Large scale bending tests**

Two large scale bend tests were performed also to confirm the conservatism of the 3D finite element calculations. From preliminary analyses and taking into account the practical limitations, the licensee identified a bend bar of 30x60 mm cross section and 260 mm in length, tested in 4-point bending as the optimal geometry. The tests were performed at –130°C and with a surface breaking flaw in the high stress region.

For each specimen, the sizing of the hydrogen flakes, the flaw modelling and the flaw evaluation were performed in strict conformity with the procedure used for the detailed 3-D evaluation of the hydrogen flakes.

After evaluation, Bel V concludes that the results of the large-scale bending test program were as expected and has no further remark.

According to AIB-Vinçotte and the NSEG, the test results confirm the conservatism of the predictions with a failure load well above the predicted load.

In general, AIB-Vinçotte considers the licensee reply to the Action 15 requirement (large scale tensile and bending tests) satisfactory and has no more comments related to Action 15.

5.2.6 Additional information: Conservativeness Embedded in Fatigue Crack Growth Analyses

Licensee conclusion (§5.5.1 of [3])

The conservativeness of the Fatigue Crack Growth (FCG) methodology is demonstrated through an additional analysis based on the actual orientations of the flaws and groups of flaws, also taking into account a more recent edition of the ASME XI.

Review by Regulatory Body (Bel V Provisional Report January 2012)

In January 2013 the licensee transmitted a revised analysis of the fatigue crack growth, considering the actual orientation of the flaws instead of their axial projection and the threshold in the fatigue growth curve of the latest editions of Section XI of the ASME B&PV Code.

Based on those results, Bel V concludes that the fatigue crack growth under service loadings may not be qualified as significant.

5.2.7 Additional information: Conservativeness of Axisymmetric Thermal Loading in case of Cold Water Injection following LOCA

Licensee conclusion (§5.5.2 of [3])

Computational Fluid Dynamics simulations and mock-up tests demonstrate the conservativeness of the Axisymmetric Thermal Loading method, as applied in the Safety Case.

Review by Regulatory Body (Bel V Provisional Report January 2012)

A conservative fracture mechanics flaw assessment requires that the most penalizing transients under all the specified plant operating conditions (Levels A/B and Levels C/D) be considered and that, for each of those transients, the most penalizing applied loadings for the considered application be defined.

Applying that statement to transients involving injection of cold water needs special attention. The thermal loadings applied to the reactor pressure vessel shells under conditions involving injection of cold water are complex. In a first analysis, it may be thought that an axisymmetric distribution of the thermal loads (without plume effect) could not be the most detrimental distribution for the detected flaws.

That issue leads to numerous exchanges with the licensee. Finally, in January 2013, the licensee provided Bel V with information allowing concluding that the "plume effect" may be neglected.

5.3 Conclusions on Structural Integrity of Reactor Pressure Vessels

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 concludes that all the identified short term open issues on this topic have been resolved.

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 VB-395 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 VB-395 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.

6. Load Tests

6.1 Conclusions and requirements of Provisional Evaluation Report

Based on the data provided by the licensee and the conclusions released by Bel V, AIB-Vinçotte and the expert groups about the action plan, the FANC drew the following conclusions in its Provisional Evaluation Report [2].

> *The additional operational measures proposed by the licensee are relevant and will contribute to increase the confidence in the safe operation of the Doel 3 and Tihange 2 reactor pressure vessels.*
>
> *The in-service inspection program proposed by the licensee to follow up the potential evolution of the flaws during operation should focus particular attention on the most adverse flaws, e.g. the largest flaws that are closest to the inner side of the vessel wall or located inside the areas with the highest flaw distributions.*
>
> *The experimental testing program proposed by the licensee is essential to confirm the properties of the affected material and validate the calculations. However, some uncertainties still remain at all levels in the structural integrity assessment and need to be dealt with through additional experimental verification.*

The FANC issued the following requirement about the action plan proposed by the licensee in its Provisional Evaluation Report [2].

> *REQUIREMENT 16 – LOAD TESTS: 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 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.*

6.2 Review of Licensee actions

6.2.1 Action 16: Load test

Licensee conclusion (§6 of [3]):

The Doel 3 and Tihange 2 RPV were subjected to a load test with acoustic emission (AE) measurements, followed by a post-load test UT inspection.

The AE measurements performed did not reveal any source or area for which complementary investigations are required.

The number of flaw indications reported by the post-load test inspection is fully consistent with the findings of the 2012 RPV inspection. The peak amplitude and dimensions of every indication reported by the post-load test inspection match those of the 2012 RPV inspection.

All examination results confirm that the load test did not modify the condition of the material.

Review by Regulatory Body (AIB-Vinçotte [5], Bel V [6], MISTRAS GROUP [8])

The licensee performed a pressure load test of the Doel 3 and Tihange 2 Reactor Pressure Vessels. The maximum pressure that has been reached during the load test is 178.3 bar abs for Tihange 3 and

177.4 bar abs for Doel 3. These pressures are above 110% of the maximum pressure applied on the RPVs during the last cycles.

The load test conditions were justified by the licensee from a structural integrity point of view for all components of the primary loop.

Acoustic Emission measurements were performed on the Doel 3 and Tihange 2 RPV during the Load Test with the main objective of detecting potential evolving defects in the core shells. The configuration that has been chosen for the Acoustic Emission measurements is of zonal type: the localization accuracy is limited to areas corresponding to 60° angular sectors on a height comprised between the nozzles and the RPV bottom head. No Acoustic Emission source corresponding to the Category III according to the reference standard (Guide de Bonnes Pratiques, AFIAP, éd.2009) has been detected.

Ultrasonic Testing inspections were performed on the whole upper core shell of Tihange 2 and the whole lower and upper core shells of Doel 3 after the Load Test and confirmed that there is no evolution of the indications in these RPVs as the number of indications, their amplitude and the dimensions of each indication are consistent with the results of the ultrasonic testing in 2012 and meet the flaw evolution assessment criteria.

AIB-Vinçotte considers the licensee reply to the Action 16 requirement satisfactory for restart.

A specialised company on acoustic emission testing, **Mistras Group**, also evaluated the acoustic emission testing results on both RPVs. After evaluation, they agree with the licensee conclusion that no Acoustic Emission source corresponding to the Category III according to the reference standard (Guide de Bonnes Pratiques, AFIAP, éd. 2009) has been detected.

6.3 Conclusions on Load Tests

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.

7. FANC final conclusions

On 15 April and 26 April 2013 the licensee submitted to the FANC two Addenda to the Safety Case Report that give a structured answer to each of the FANC's (short-term) requirements for the Tihange 2 and Doel 3 reactor unit [3]. They also provide the results and conclusions of additional analyses, tests, and inspections that were performed to complement the original Safety Case Reports for Tihange 2 and Doel 3 of December 2012. These Addenda were reviewed by the internal "Service de Contrôle Physique – Dienst voor Fysische Controle " of Electrabel which gave an overall positive advice regarding the immediate and safe restart of both reactor units [4].

Based on the data provided by the licensee and the review and assessment by Bel V, AIB-Vinçotte, the National Scientific Expert Group and Mistras Group of the Safety case of the Doel 3 and Tihange 2 reactor pressure vessels, the Federal Agency for Nuclear Control draws the following final **conclusions** for each topic assessed in the previous sections:

Regarding the in-service inspections:

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.

Regarding the metallurgical origin and evolution of the indications:

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 VB-395 confirmed that the hydrogen flakes are located in macro-segregated areas, more specifically in ghost lines within these macro-segregated areas.

Regarding the material properties:

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 VB-395.

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 VB 395 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 VB-395 specimens, the 50°C margin on RT_{NDT} 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.

Regarding the structural integrity of the reactor pressure vessels:

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 should not affect significantly its structural integrity.

Large Scale tensile test specimens from the VB-395 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 VB-395 shell were performed also 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.

Regarding the load test:

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.

In conclusion, the FANC together with Bel V and AIB-Vinçotte, have confirmed that all the safety concerns at the origin of the short-term requirements have been solved in a satisfactory manner. As a consequence, the Federal Agency for Nuclear Control considers that the Doel 3 and Tihange 2 reactor units can be restarted safely.

As an additional precautionary measure, whenever a severe transient occurs during the future operation of the Tihange 2 and Doel 3 reactor units (such as an effective safety injection in the reactor coolant system during power operation), an additional in-service inspection of the reactor pressure vessel is required to detect a potential evolution of the flaw indications before the reactor unit will be allowed to resume its operation after this transient.

As already discussed in the licensee Safety Case [1] some additional actions have been taken before the restart of the Tihange 2 and Doel 3 reactor unit, on top of the existing operational measures:

- For Doel 3 and Tihange 2, the licensee has reduced the authorized heat-up and cool-down gradients during start-up and shut-down operations. According to the licensee, this will further reduce the thermal and pressure loadings on the reactor pressure vessels during normal operation.

- For Doel 3, the licensee implemented a permanent preheating of the safety injection water reservoirs to 30°C.
- All operators of the Doel 3 and Tihange 2 reactor units had a refresher training session on the full scope simulator. An extended briefing will be given to all shift personnel about the start-up and changes in the operational parameters and specifications.

A specific restart plan of the Doel 3 and Tihange 2 reactor units after several months of extended shutdown is to be submitted by the licensee for analysis to Bel V. Specific attention will be given to the following topics:

- The possible impact of extended shutdown on maintenance and surveillance activities;
- The assessment of safety related systems which were not used or let in a dormant state during shutdown and the associated pre-operational start-up tests;
- The possible staffing issues (qualification, turnover,...);
- The possibly observed unexpected degradation mechanisms or underestimated rate of degradation;
- The possible specific organization that will be put in place to manage the restart operations.

A specific inspection will be organised during the restart of these units to monitor the different restart operations.

As an important remaining action, already discussed in the licensee Safety Case [1], the Licensee will perform the same UT-inspection of the entire reactor pressure vessels wall thickness at the end of the first cycle of both units.

The implementation of the other actions of the licensee action plan (which do not need to be finished before the restart of the reactor units) will also be followed up by the Belgian safety authorities in the future.

8. Acronyms

AE	Acoustic Emission
AFIAP	Association Française des Ingénieurs en Appareils à Pression
ASME	American Society of Mechanical Engineers
B&PV	Boiler and Pressure Vessel
EAR	Examen d'Accrochage du revêtement (specific straight beam transducer)
FANC	Federal Agency for Nuclear Control
FCG	Fatigue Crack Growth
FIS	Formule d'irradiation supérieure
LOCA	Loss of Coolant Accident
MIS-B	Machine d'inspection en service Belge
NSEG	National Scientific Expert Group
ppm	Parts per million
RDM	Rotterdamsche Droogdok Maatschappij
RPV	Reactor pressure vessel
RT_{NDT}	Reference temperature for nil ductility transition
SIA	Structural integrity assessment
UT	Ultrasonic testing

9. List of references

Reference [1] Safety case reports – Doel 3 & Tihange 2 Reactor Pressure Vessel Assessment - Electrabel – December 2012

Reference [2] Doel 3 and Tihange 2 reactor pressure vessels - Provisional Evaluation Report - FANC – January 2013

Reference [3] Addenda Safety case report – Doel 3 & Tihange 2 Reactor Pressure Vessel Assessment - Electrabel – 15 and 26 April 2013

Reference [4] Reports on independent analysis and advice regarding the safety case – Doel 3 & Tihange 2 Reactor Pressure Vessel Assessment – Electrabel – April 2013

Reference [5a] Report AIB-Vinçotte "Tihange 2 – ISI 2012 – Justification of the Reactor Pressure Vessel (RPV) Shell" – Tiha 169 – May 2013

Reference [5b] Report AIB-Vinçotte "Doel 3 – ISI 2012 – Justification of the Reactor Pressure Vessel (RPV) Shell" – Doel 176 – May 2013

Reference [6] Safety Evaluation Report Bel V – Flaw Indications in the RPVs of Doel 3 and Tihange 2 – May 2013

Reference [7a] Report of the National Scientific Expert Group on the RPV Tihange 2 – April 2013

Reference [7b] Report of the National Scientific Expert Group on the RPV Doel 3– May 2013

Reference [8] Report MISTRAS Group – April 2013