Safety Evaluation Report

Flaw indications in the RPVs of Doel 3 and Tihange 2

Addendum to R-SER-13-001-0-e-0

Executive Summary

The present report is an addendum to the Safety Evaluation Report R SER-13-001-0-e-0 issued in January 2013.

The evaluation provided in this report is focused on the actions that address the concerns raised by Bel V in his Safety Evaluation Report of January 2013. These actions are related to the additional mechanical tests performed on the AREVA shell VB 395, also affected by hydrogen flaking and considered by Electrabel as representative of the degradation affecting the Doel 3 and Tihange 2 reactor pressure vessels. A few other actions, although having not been initiated by Bel V, are related to concerns also shared by Bel V. The results of these actions were therefore also evaluated by Bel V and this report documents their evaluation.

The evaluation by Bel V raised no concern preventing the Safety Case of Electrabel to be considered as conclusive.

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1. Introduction

Following the detection of hydrogen-induced degradation in the core shells of the Doel 3 and Tihange 2 reactor pressure vessels, Electrabel provided a technical file documenting his assessment of the serviceability of these reactor pressure vessels. In January 2013, Bel V issued the Safety Evaluation Report R-SER-13-001-0-e-0 documenting his evaluation of the Electrabel technical file. In this report, Bel V had identified a few lacks or uncertainties that could jeopardize the required high confidence of the demonstration of the serviceability of the reactor pressure vessels of Doel 3 and Tihange 2.

The Electrabel technical file was also evaluated by AIB-Vinçotte and different national and international experts groups that provided their own conclusions.

The Belgian Federal Agency for Nuclear Control (FANC) issued in January 2013 a Provisional Evaluation Report that identified the remaining open issues, expressed as requirements to be satisfied. The concerns raised by Bel V in his Safety Evaluation Report made part of the requirements. Most of the requirements have to be considered as short-term requirements, i.e., they are a prerequisite to authorizing the restart of the units. The remaining requirements can be addressed later.

In order to address satisfactorily the requirements set forth by the FANC Provisional Evaluation Report, Electrabel proposed an action plan that was approved by the FANC in February 2013.

This report focuses on the evaluation by Bel V of the results of the actions pertaining to his concerns. Several of the other actions relate to the UT inspection technique and are related to concerns raised by AIB-Vinçotte. As already mentioned in his Safety Evaluation Report of January 2013, for matters related to Non-Destructive Examination, Bel V relies heavily on the expertise of AIB-Vinçotte, the Authorized Inspection Agency (AIA). As a result, Bel V did not evaluate deeply the results of those actions but acknowledged their evaluation by AIB-Vinçotte. A few other actions, although having not been initiated by Bel V, are related to concerns also shared by Bel V. The results of these actions were therefore also evaluated by Bel V and this report documents their evaluation.

The technical basis of the safety evaluation by Bel V is described in the Safety Evaluation Report of January 2013 and is not reproduced here. This report should therefore be considered as an addendum to the Safety Evaluation Report of January 2013.

2. Content

Bel V summarized in the conclusions of his Safety Evaluation Report of January 2013 the three concerns remaining after his evaluation of the technical file provided by Electrabel. These concerns can be expressed as requirements for additional mechanical tests on specimens taken from the AREVA SG lower shell VB 395, also affected by hydrogen-induced degradation and considered by Electabel as representative of the degradation affecting the Doel 3 and Tihange 2 reactor pressure vessels (RPVs).

These three concerns are duplicated below:

(1) *The lack of experimental values of the tensile and fracture material properties that are representative of the local condition of the steel in the vicinity of the hydrogen-induced defects. That lack of data precludes a conservative definition of the local material properties with a high confidence. Electrabel committed to finalise the ongoing test program at SCK.CEN on material tensile and fracture toughness properties on test specimens taken from material with hydrogen flakes. An objective of that test program is to demonstrate that the 50°C shift of RT_{NDT} is appropriate to cover the potential deterioration of the local fracture toughness properties in the vicinity of the hydrogen–induced flaws.*

(2) *Experimental verification of the conservatism of the calculation procedure for flaw evaluation is a necessary condition for having the required high confidence in the analytical demonstration of the serviceability of the RPV. To this end, appropriate large-scale mechanical testing of representative samples with hydrogen-induced flaws is required. Electrabel committed to perform a monitored large-scale test (four-point bending test) on a specimen of about 60x60mm with flakes having a significant tilt angle relative to the specimen axis. A concurrent 3-D finite element analysis of the specimen under the applied testing conditions and applying the analytical procedure used for detailed 3-D calculations of the Safety Case will allow demonstrating the conservatism of the applied analytical evaluation.*

(3) *High confidence in the safety demonstration requires that the presence of hydrogen-induced flaws does not decrease the ductility to an unacceptable level. Electrabel committed to perform tensile testing on large specimen with flakes having a tilt angle of 20 degree relative to the specimen axis. The objective of those tests is to demonstrate that the material has sufficient ductility and load bearing capacity, and that there is no premature brittle fracture.*

Concern (1) is covered by action #9. The evaluation by Bel V of the results of the mechanical tests required under this action is documented in paragraph 3 below. The evaluation of the conservatism of the 50°C shift of RT_{NDT} is given separately in paragraph 4.

Concern (2) is covered by action #15. This report contains in paragraph 7 the evaluation by Bel V of the results of the experimental verification of the conservatism of the calculation procedure for flaw evaluation.

Concern (3) is also covered by action #15. The evaluation by Bel V of whether the results of the tensile tests performed on large specimens with flakes meet the specified objectives is documented in paragraph 5.

At the end of his Safety Evaluation Report of January 2013, Bel V added the following: *In order to account for the actual condition of the Doel 3 and Tihange 2 RPVs and so, to complete the demonstration of the serviceability of the RPVs, a non-destructive test on the RPVs needs to be performed. The objective of the test is to demonstrate that no unexpected condition is present in the RPVs. Practically, the only test that can be performed is a pressure test. With regard to the pursued objective, the pressure test needs to be complemented by acoustic emission testing*.

A load test at a pressure higher than the design pressure has been performed on the Doel 3 and Tihange 2 RPV under action #16. The results are documented in paragraph 8.

Following an issue raised by AIB-Vinçotte relative to the potential non-detection by the UT inspection of flaws having a tilt angle relative to the inside surface exceeding 20°, studies were performed by Electrabel to determine the maximum size of the highly-tilted flaws that could potentially not have been detected in the Doel 3 and Tihange 2 RPV shells. These studies were performed under action #3. These potentially non-detected flaws have an impact on the safety demonstration of the Doel 3 and Tihange 2 RPVs and Electrabel performed the assessment of this impact under action #14. The evaluation by Bel V of the results of the assessment made by Electrabel is documented in paragraph 6 below.

A significant issue would be raised if the residual hydrogen content in the material of a RPV affected by hydrogen-induced degradation was high. Additional tests were performed by Electrabel under action #10 to estimate the content of residual hydrogen. The results of these tests are commented by Bel V in paragraph 9.

3. Additional characterization of the material mechanical properties (Action #9)

3.1. Preliminary remark

In his Safety Evaluation Report issued in January 2013, Bel V expressed his concern about *the lack of experimental values of the tensile and fracture material properties that are representative of the local condition of the steel in the vicinity of the hydrogen-induced defects.* Bel V added that *the lack of data precludes a conservative definition of the local material properties with a high confidence.* Also as mentioned in the conclusions of the Safety Evaluation Report, *Electrabel committed* [in January 2013] *to finalise the ongoing test program at SCK.CEN on material tensile and fracture toughness properties on test specimens taken from material with hydrogen flakes. An objective of that test program is to demonstrate that the 50°C shift of RT_{NDT} is appropriate to cover the potential deterioration of the local fracture toughness properties in the vicinity of the hydrogen–induced flaws*.

The material testing program performed under Action #9 is the program referred to in this conclusion. It consists in mechanical tests performed on specimens taken from the Doel 3 H1 nozzle cut-out and from the AREVA shell VB 395 also affected by hydrogen-induced degradation. 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.

3.2. Additional mechanical test on the Doel 3 H1 nozzle cut-out

Additional characterization of the Doel 3 nozzle cut-out was performed on test specimens taken from the ghost lines. The test specimens include fracture toughness test specimens (bend specimens SE(B) and compact specimens C(T), all having the pre-crack front in the ghost line) and tensile test specimens. These tests complement those performed in 2012 on the specimens taken from the macro-segregated zones and out of the macro-segregated zones of the nozzle cut-out (see paragraph 9.2.1 of the Bel V Safety Evaluation Report of January 2013). The results of the additional characterization tests as reported by Electrabel show that the ghost lines do not affect significantly the mechanical (tensile and fracture toughness) properties of the material. In particular, the Master Curve transition temperature T_o determined in the ghost lines is very near to the temperature T_o of the material out of the ghost lines. However it appears, as reported by Electrabel, that the fracture mode in the brittle-to-ductile transition regime is not identical: the fracture mode is typically cleavage for the specimens out of the ghost lines but, for the specimens in the ghost lines, the specimens show typically intergranular fracture along (or partially along) the crack front but limited to the depth of the ghost line, after which the fracture mode is cleavage.

3.3. Characterization of the material of the AREVA shell VB 395

The characterization of the material of the AREVA shell VB 395 was performed on test specimens taken from locations out the zones affected by hydrogen flaking and from zones containing hydrogen flakes. It is reminded that, in accordance with the approach used by Electrabel, the effects of hydrogen flaking on the mechanical properties of the Doel 3 and Tihange 2 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. In particular the effect of the hydrogen flaking on the nil-ductility reference temperature RT_{NDT} of the Doel 3 and Tihange 2 RPV shells is estimated by comparing the Master Curve transition temperature T_o obtained from specimens taken from the AREVA shell VB 395 in zones affected by hydrogen flaking to the temperature T_o obtained from specimens taken in zones unaffected by hydrogen flaking. It is indeed assumed by Electrabel that $\Delta RT_{NDT}=\Delta T_o$. It should also be emphasized that all the blocks taken from the AREVA shell VB 395 for mechanical testing were submitted to the quenching and tempering heat treatment foreseen by AREVA fabrication procedure (but not performed in the AREVA workshops at the time the shell was rejected) and to the heat treatment simulating the post weld heat treatment performed during the fabrication of the Doel 3 and Tihange 2 RPVs.

3.3.1. Tensile testing

Tensile tests were performed on test specimens taken from the top part of the AREVA shell VB 395 (sound material) and in the ligament between flakes (bottom part of the AREVA shell VB 395) in order to determine the tensile curves representative of the material in both zones. No tensile tests have been performed to characterize the material of the bottom part of the AREVA shell VB 395 in the zone containing no hydrogen flakes. The results, as reported by Electrabel, show that the tensile properties (yield stress and tensile strength) are slightly higher but the ductility (as measured by the reduction of area) slightly lower for the material between the flakes. Bel V mentions that the increase of the yield stress and tensile strength can also be expressed as a temperature shift of about 40°C, i.e., the curves of the mechanical tensile properties (yield stress and tensile strength) as a function of the temperature for the material between the flakes may be obtained by applying a drift of 40°C to the curve of the sound material.

The results of the tensile tests performed in the ligaments between the flakes lead Bel V to conclude that the material in the ligament between the hydrogen flakes has a satisfactory tensile behavior when compared to the sound material. As mentioned by Electrabel, the total elongation

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at 20°C of the sound VB 395 material (as measured in the top part of the VB 395 shell) is lower than the RCC-M requirements. However, 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.

3.3.2. Fracture toughness testing

The fracture toughness testing program on the AREVA shell VB 395 includes:

(1) C(T) fracture toughness test specimens taken from the top part of the shell that is not affected by hydrogen flaking
(2) C(T) fracture toughness test specimens taken from the bottom part of the shell that is affected by hydrogen flaking but out of the zone containing flakes
(3) C(T) fracture toughness test specimens taken from the bottom part of the shell in the zone containing flakes (i.e., specimens taken in ligaments between flakes)
(4) C(T) fracture toughness test specimens where a hydrogen flake is used as a surrogate for the fatigue pre-crack.

The main results of the fracture toughness test program as reported by Electrabel may be summarized as follows.

(1) The results of the fracture toughness tests performed in the bottom part of the AREVA shell VB 395, i.e., in the zone containing no flakes and in the ligament between flakes, do not differ significantly. The Master Curve transition temperature T_o in the material out of the zone containing flakes is -115.1°C and the value of T_o in the material between the flakes is about 10°C higher.
(2) The results of the fracture toughness tests performed on the top part of the AREVA shell VB 395 allow to calculate a Master Curve transition temperature T_o that is about 20°C colder than the temperature T_o of the material in the bottom part of the shell out of the zone containing flakes.
(3) The fracture toughness tests using C(T) specimens with a hydrogen flake provide a Master Curve transition temperature T_o that is higher than the temperature T_o in the ligament between the flakes by about 15°C.

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. Bel V remarks however that a larger scatter of the K_{Jc} values is observed for the material between flakes, which could be attributed to the heterogeneity of this material. Bel V also notices that there are a few K_{Jc} values for the material between flakes that are lower than the K_{Jc} for the material unaffected by flaking.

As mentioned by Electrabel, the use of fracture toughness specimens with a hydrogen flake acting as the fatigue pre-crack puts into question the validity of the procedure used for determining the transition temperature T_o. However Bel V concurs with Electrabel that the K_{Jc} values obtained on these specimens provide valuable information. Besides the results mentioned above, it has also been noticed by Bel V that

(1) most of the K_{Jc} values obtained on fracture toughness test specimens with a flake are below the Master Curve of the material in the ligament between flakes. They are also seen to be comparable to the low values of K_{Jc} obtained on specimens taken between the flakes, i.e., there are no K_{JC} values obtained on fracture toughness test specimens with a flake that are significantly lower than the K_{JC} values obtained on specimens taken between the flakes;
(2) the scatter of the K_{Jc} values obtained on specimens with a flake is smaller than the scatter of the K_{Jc} values obtained on specimens taken between the flakes, even if the K_{Jc} values obtained on specimens with a flake were suspected by Electrabel to have a higher uncertainty than for the standard C(T) specimens due to the irregular crack front of the hydrogen flakes. To Bel V opinion, this lower dispersion could possibly be associated with a lower ductility;
(3) based on the pictures of the fractured C(T) specimens made available by Electrabel, the fracture mode of the specimens (tested in the brittle-to-ductile transition) appears to be cleavage.

From the fracture toughness tests performed on C(T) specimens with a hydrogen flake acting as the fatigue pre-crack, Bel V concludes that the associated K_{Jc} values are not inconsistent with the K_{Jc} values of the material between flakes, even if they are found to be located between the Master Curve and the 5% confidence limit of the material between flakes.

3.3.3. Charpy impact energy curve

Elerctrabel has performed Charpy impact tests on specimens taken from the upper part of the AREVA shell VB 395 in order to determine the Charpy impact energy curve. Bel V remarks that no such tests have been performed in the lower part of the AREVA shell VB 395 neither in the zone out of flakes nor in the ligaments between flakes. Those tests would have allowed to complement the characterization of the AREVA shell VB 395.

3.3.4. Concluding remark

As a conclusion, according to the tests results as reported by Electabel, 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.

4. Conservatism of the additional ΔRT_{NDT} of 50°C

Electrabel assumes that the fracture toughness values to be used in the structural integrity assessment of the affected RPVs are those obtained from the ASME Section XI fracture toughness curve indexed on the nil-ductility reference temperature RT_{NDT}. The applicable RT_{NDT} temperature is obtained by adding to the predicted RT_{NDT} of the shell material at its end-of-life an additional

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temperature shift ΔRT_{NDT} of 50°C (see paragraph 9.2.1 of the Bel V Safety Evaluation Report of January 2013). The additional temperature shift ΔRT_{NDT} of 50°C is said by Electrabel to cover all the other effects not explicitly considered, such as the real properties of the material in the area affected by the flakes. As mentioned in paragraph 3.3 above, the ΔRT_{NDT} measuring a specific potential effect on the fracture toughness is determined by the difference in the Master Curve transition temperature ΔT_o.

As reported by Electrabel, the mechanical test program performed in 2012 on specimens taken from the Doel 3 H1 nozzle cut-out has shown that the effects of macro-segregation and specimen orientation on the fracture toughness could be considered as non-significant ($\Delta RT_{NDT} \approx 0$). The additional mechanical test program performed later on the Doel 3 H1 nozzle cut-out (see paragraph 3.2 above) has shown that the ghost lines had no effect on the fracture toughness. It had also been calculated by Electrabel that the additional ΔRT_{NDT} for accounting for the higher content in Cu, Ni, and P in the macro-segregated zones never exceeded 17°C (see paragraph 9.2.1 of the Bel V Safety Evaluation Report of January 2013).

The potential detrimental effect of the hydrogen flaking on the fracture toughness of the RPV material is determined by Electrabel from the fracture toughness tests performed on the material of the AREVA shell VB 395 (see paragraph 3.3.2 above).

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

(1) the ΔRT_{NDT} (about 10°C) representing the increased brittleness of the material in the ligaments between the flakes
(2) to the ΔRT_{NDT} (about 15°C) representing the increased brittleness of the material in the crack front of the flakes.

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

Electrabel also mentions that, if the predicted fluence at the locations of the most critical flaws is used instead of the maximum predicted fluence in the RPV shells, the maximum additional ΔRT_{NDT} to account for the potential higher embrittlement in the macro-segregated zones due to irradiation effect is 14°C. As a result, the estimated maximum value of the additional ΔRT_{NDT} at the locations of the most critical flaws is 37°C.

The estimation of the effects of the hydrogen flaking degradation on fracture toughness of the RPV material relies heavily on the results of series of fracture toughness tests performed on blocks taken from the AREVA SG shell VB 395. To Bel V opinion, a critical issue in the analysis of the fracture toughness test results is the determination of the T_o temperature in accordance with the Master Curve procedure as provided in the ASTM standard E1921.

In most of the fracture toughness test series, the results exhibit a relatively high scatter: it is not rare that K_{Jc} values are located outside of the 5%-95% confidence limits. A relatively high scatter is observed in particular for the fracture toughness tests performed in the ligaments between flakes. In that case, a potential cause of the scatter has been proposed by Electrabel. However, there is no in-depth evaluation of the effect of the scatter on the determination of T_o.

To Bel V understanding, the issue discussed here is related to the inhomogeneity present in the tested materials. It is here reminded that the estimation method provided in ASTM E1921 is based on a theoretical scatter and makes use of a maximum likelihood estimation method to determine the T_o temperature. This method may only be applied to macroscopically homogeneous steels. If the steel is inhomogeneous, the maximum likelihood estimation method applied in E1921 becomes unreliable. For instance, a statistical anomaly such as a too high K_{Jc} value can provide a too low value of the estimated T_o temperature. This is due to the fact that the maximum likelihood estimation method has the tendency of emphasizing too strongly the effect of a too high K_{Jc} value.

Some analysis methods addressing inhomogeneous materials are available. At Bel V request, Electrabel performed a re-analysis of the series of fracture toughness tests using the non-standard inhomogeneous bimodal Master Curve analysis. In this bimodal analysis, the fracture toughness population is divided into two different fracture toughness populations (referred to as population 1 and population 2), each having its own Master Curve distribution. In addition to the two parameters T_{o1} and T_{o2} that are the respective Master Curve transition temperature T_o of the two populations, a third parameter is needed in the analysis, i.e,. p_1 which is the probability of the toughness belonging to distribution 1.

As expected, the material in the ligament between flakes has the highest inhomogeneity: population 1 having a T_{o1} of -85°C with an occurrence probability of 50 % and population 2 having a T_{o2} of -119°. This is to be compared with temperature T_o of -104°C calculated by the standard Master Curve analysis.

The material out of the flaked zone in the bottom part of the AREVA shell VB 395 is less inhomogeneous: population 2 has a T_{o2} of -118°C with an occurrence probability of 86% (to be compared with temperature T_o of -115°C calculated by the standard Master Curve analysis). The population of the K_{Jc} values obtained on C(T) specimens with a flake is also slightly inhomogeneous: population 2 has a T_{o2} of -93°C with an occurrence probability of 70% (to be compared with temperature T_o of -90°C calculated by the standard Master Curve analysis).

It has been argued by Electrabel that the number of available test specimens is too small for a rigorous application of the inhomogeneous bimodal Master Curve analysis. Bel V recognizes that a larger number of specimens needs to be tested to perform the bimodal analysis compared to the conventional Master Curve analysis. However the number of specimens tested in the program may not be considered as too small. For instance, for the material in the ligament between flakes the number of specimens is 17 while the minimum number is 12 to 15.

The critical issue is therefore the selection of the Master Curve transition temperature T_o that is representative of the material in the ligament between flakes. The bimodal analysis of fracture toughness could justify the selection of a T_o temperature of -85°C as there is an equal potential for any flake to have crack tip near metal with T_o temperature of -85°C rather than metal with T_o temperature of -119°C. However the selection of the highest T_o temperature (-85°C) as a conservative estimate of the representative T_o temperature of the material in the ligament between flakes would affect only sligthly (by +5°C) the estimated maximum value of the additional ΔRT_{NDT} because the contribution of the T_o temperature of the material at the crack front of the flakes should then not be considered.

Should the highest T_o temperature (-85°C) be considered as a conservative estimate of the representative T_o temperature of the material in the ligament, the estimated maximum value of

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the additional ΔRT_{NDT} would be equal to 47°C if the maximum predicted fluence in the RPV shells was used and 42°C if the predicted fluence at the locations of the most critical flaws was used.

Another issue related to the inhomogeneity of the tested materials is the determination of the T_o temperature that is descriptive of unflawed VB 395 material. The value of the T_o temperature of the (unflawed) material at the top of the AREVA shell VB 5395 has been found to be lower by about 20°C than the T_o temperature of the material out of the flakes at the bottom of the shell. Electrabel considers the T_o temperature (-115 °C) determined in the material out of the flaked zone at the bottom of the shell as the descriptive T_o temperature of the unflawed VB-395 material to assess the effect of the hydrogen flaking degradation on the RT_{NDT} temperature. To Bel V opinion, the use of the T_o temperature of -115°C would not be appropriate if the higher brittleness of the unflawed material in the bottom part of the VB 395 shell (compared to the material in the top part of the shell) was due to the hydrogen flaking degradation affecting the bottom part of the shell. Electrabel provided additional information giving, at Bel V satisfaction, some reasons (other than hydrogen flaking degradation) that explain the higher brittleness of the unflawed material in the bottom part of the AREVA VB 395 shell. Bel V finds therefore acceptable to use the T_o temperature of the unflawed material in the bottom part of the AREVA VB 395 shell as the T_o temperature that is descriptive of unflawed VB 395 material when assessing the effects of hydrogen flaking degradation on the RT_{NDT} temperature of the material.

Electrabel considers that the additional temperature shift ΔRT_{NDT} as determined above has not to include any supplementary margin to account for the transposition of the results obtained from fracture toughness tests on the AREVA shell VB 395 to the Doel 3 and Tihange 2 RPV shells. To Bel V opinion, the postulated value (50°C) of the additional ΔRT_{NDT} used in the safety demonstration should include some supplementary margin to account for the effect of transposition. The upper bound of the additional ΔRT_{NDT} (42°C) as determined by Bel V by taking into account a To temperature of-85°C for the material between the flakes and the maximum predicted fluence in the RPV shells provides a supplementary margin of minimum 8°C that is estimated by Bel V to be likely sufficient to cover the potential effect of the transposition.

Bel V also emphasizes that, independently of the required conservatism of the additional temperature shift ΔRT_{NDT}, the predicted value of the RT_{NDT} of the shell material at its end-of-life also includes an implicit conservatism since the FIS formula used to calculate the shift of the RT_{NDT} temperature of the shell material due to irradiation effect envelopes conservatively the results of the embrittlement surveillance program.

Bel V concludes that the additional temperature shift ΔRT_{NDT} of 50°C on RT_{NDT} considered in the Safety Case is appropriate.

5. Large-scale tensile testing (Action #15 Part 1)

To Bel V opinion, the assessment of the serviceability of the RPVs affected by hydrogen flaking is not limited to a “local assessment”, i.e., the demonstration that there is a margin against the initiation of the propagation of the hydrogen flakes under the postulated loading conditions, but it also includes a “global assessment” of the safe structural behaviour of the RPVs.

The mechanical test program performed on (small-scale) tensile test specimens and (small-scale) fracture toughness test specimens participates to the "local assessment" by providing inputs for the characterization of the material of the Doel 3 and Tihange 2 RPVs affected by hydrogen flakes.

The large-scale tensile test program, which is a part of action #15, participates to the "global assessment". This program includes tensile test specimens with a diameter of 25 mm taken from the AREVA shell VB 395. Three types of tensile test specimens were included in the test program:

(1) test specimens with no flakes taken from the upper part of the AREVA shell VB 395;
(2) test specimens with flakes taken from the bottom part of the AREVA shell VB 395 in such a way that the hydrogen flakes are parallel to the specimen axis;
(3) test specimens with flakes taken from the bottom part of the AREVA shell VB 395 in such a way that the hydrogen flakes have a tilt angle of about 20° relative to the specimen axis.

The test specimens with flakes were tested at -80°C and at room temperature. The test specimens containing no flakes were tested at the same temperatures and also at 290°C.

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 failure when ductile fracture is expected).

To Bel V understanding, performing tensile testing of large-scale specimens representative of the RPV zones affected by flaking is an approriate means for meeting these objectives. Because they contain several flakes, the large-scale tensile specimens are considered by Bel V as a practically achievable representation of the RPV shell under pressure loading. However, according to Electrabel, practical considerations, i.e., the maximum size of the material blocks available in the VB 395 shell, limit the diameter of the tensile specimens to 25 mm.

Bel V emphasizes that the large-scale tensile tests are the only tests that simulate the behaviour of the RPVs affected by hydrogen flaking. Even if the simulation can be considered as non-fully satisfactory, the results of these tests are required to be investigated deeply and explained. In particular, the results should be evaluated in order to determine whether some of them are not in conflict with the demonstration of the structural integrity.

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 Doel 3 and Tihange 2 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 core shells (also accounting for a 50°C margin), a test temperature of 25°C is representative of the minimum temperature of the Doel 3 and Tihange 2 RPVs under operating pressure. A total of six specimens were tested at room temperature, i.e., two specimens with flakes oriented at 0°, two specimens with flakes oriented at 20°, and two specimens with no flakes.

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

(1) the stress-strain curves for the specimens without flakes and the curves for the specimens with flakes oriented at 0° overlap on each other;
(2) the yield stress has about the same value for all the tested specimens : specimens without flakes, specimens with flakes oriented at 0°, specimens with flakes oriented at 20°;
(3) the stress-strain curves for the specimens with flakes oriented at 20° overlap on the ones for the specimens without flake up to the strain value 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 curves for the specimens without flakes with the curves for the specimens with flakes oriented at 0° is likely due to the fact that no flake is found to be located in the necking zone. Indeed the presence of a flake in the necking zone would likely have led to a reduction of the total elongation at rupture. This result also suggests that the zones with flakes are not the preferential zones where the fracture occurs.
(2) The overlapping of the stress-strain curves for the specimens with flakes oriented at 20° with the curves for the specimens 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. Otherwise stated, the presence of the tilted flaws should not affect the macroscopic response of the material as long as the response is governed by the constitutive laws of elasto-plasticity.
(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 percent).
(4) The stress-strain curves of the two specimens with tilted flakes differ from each other by the shape of the curve beyond the strain value at which the maximum stress is recorded. This difference could possibly 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 verification whether the requirement for no premature brittle fracture has been met 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 the fracture mode is expected to be ductile, as justified below.

The results of the fracture toughness tests performed on the bottom part of the AREVA shell VB 395 show that the Master Curve transition temperature T_o is -105°C for the material in the ligaments between the flakes. Accounting for the effect of the flakes, the Master Curve transition temperature T_o is about 15°C higher, i.e., -90°C. Knowing that the temperature T_o is slightly above the brittle plateau, specimens tested at a temperature that exceeds T_o by more than 100°C should not fracture in cleavage mode. It should also be noted that application of Code Case N-629 leads to locate the temperature of +25°C in the upper shelf region.

A first analysis of the stress-strain curve (or load-displacement curve) of the two specimens with 20° tilted flaws led Bel V to conclude that the rupture of the test specimens resulted from an unstable fracture process and that a cleavage fracture mode could be suspected.

To Bel V opinion, the fact that the specimens fractured in what could suspected to be a cleavage mode at a temperature for which ductile fracture mode was expected raises an important issue. It could indeed potentially put into question the use of the delta T_o determined from the fracture toughness tests performed on C(T) specimens to account for the increased brittleness of a material affected by hydrogen flaking.

In order to gain more insights into the fracture behaviour of the two tensile test specimens with 20° tilted flaws, Bel V asked Electabel to perform additional metallurgical investigations on these two specimens, including fractographic examinations of the fracture surfaces.

The main results of the metallurgical investigations as reported by Electrabel 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.

To Bel V opinion, the fractographic examinations made available to him do not provide the convincing evidence that the ductile zones observed on the fracture surface correspond undoubtedly to stable ductile crack extension preceding cleavage fracture.

During further discussions, Electrabel maintained that there was no other explanation to the presence of the ductile zones in the fracture surfaces than a stable crack extension by ductile tearing before the unstable cleavage fracture. According to Electrabel who refers to information available in public literature, 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 the upper transition region, some ductile crack extension occurs prior to brittle (cleavage) fracture. In the ductile regime, large stable crack growth can occur under the applied loadings that are usually very high after which cleavage fracture may occur if the local stress conditions exceed the stress threshold for cleavage fracture. The prior ductile crack extension and the loading level at which cleavage fracture occurs depend both on the specimen geometry and size as well as on the test temperature.

To Bel V understanding, the interpretation by Electrabel of the results of the metallurgical examinations relies on the (implicit) assumption that the fracture features of the tensile test specimens may be explained from the results of theoretical and experimental works performed on standard fracture toughness specimens without taking into account the potential specific effects of the hydrogen flakes on the fracture behaviour.

With regard to that, 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 VB 395 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 have allowed to discriminate between the effects of a flake configuration and the effects a notch configuration on the fracture behaviour.

Taking notice of the fracture process as decribed by Electrabel, Bel V considers that a satisfactory answer to the issue discussed here will be obtained if it can be demonstrated that the test temperature (room temperature) is in the upper shelf of the material. To Bel V opinion, as expressed during a meeting held with Electrabel on May 7, 2013, two possible methods are believed, in a first analysis, to provide such a demonstration. Both methods are based on the evaluation of the J-integral (or the corresponding K(J)) at the initiation of ductile crack extension. In both methods, the value of the J-integral (or K(J)) is required to be large enough to conclude that the material is in the upper shelf region. In the first method, the J-integral at the tip of the leading flake in a test specimen is calculated (elasto-plastic calculation) up to a load equal to the measured load corresponding to the initiation of ductile crack extension. The second method requires to perform ductile tearing resistance tests at room temperature on C(T) specimens taken from AREVA shell VB 395 in the material between the flakes in order to determine the critical J_q value at initiation of ductile tearing. In both methods, a value of K(J) exceeding 240 $MPa.m^{1/2}$ (value taken from the fracture toughness curve in the Appendix G to Section XI of the ASME B&PV Code) will provide adequate confidence that the material at room temperature is in the upper shelf region. To Bel V opinion, these two possible methods should be considered as complementary.

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, Electrabel decided to perform 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 in the L-S orientation (crack propagation in the thru-thickness direction). 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 of 240 $MPa.m^{1/2}$.

By mistake, the two first tested specimens were specimens taken in the S-L orientation (crack propagation parallel to the flake planes). As a consequence, two additional specimens machined in the L-S direction as required were tested shortly afterwards.

A mean value of $K(J_q)$ exceeding 270 MPa.m$^{1/2}$ was obtained on the two specimens machined in the S-L orientation. Value of $K(J_q)$ exceeding 300 MPa.m$^{1/2}$ was obtained on the two specimens machined in the L-S orientation.

As it may happen that a value of the fracture toughness K_{Jc} well above the Master Curve curve is obtained when testing a material in the transition region, Bel V considers conclusive that the four tested specimens provide results of $K(J_q)$ exceeding 240 MPa.m$^{1/2}$. The results of the ductile tearing resistance tests at room temperature were therefore found by Bel V to be satisfactory.

Based on the results of the ductile tearing resistance tests at room temperature, Bel V concludes that convincing elements have been provided to demonstrate that the material of the large-scale tensile tests was in the upper shelf region when tested at room temperature.

Without putting into question this conclusion, Bel V reminds his 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 a specimen with 20° tilted flakes showed mostly ductile fracture mode.

6. Assessment of the impact of non-reported highly-tilted flaws (Action #14)

According to a UT sensitivity study performed by Laborelec, it might have happened that, by using the reporting level required by the UT procedure, highly-tilted flaws (with a tilt angle of 20°) were not reported. The impact of the potentially non-reported flaws on the structural integrity of the Tihange 2 and Doel 3 RPVs has been assessed by Electrabel.

Based on the envelope curve providing the largest size of the potentially non-reported highly-tilted flaws as a function of the distance from the cladding, Electrabel divides the wall thickness into several layers, each of them being characterized by the size of the largest non-reported flaw in this layer. The assessment performed by Electrabel relies on the assumption that (1) the number of non-reported flaws in a given layer may be estimated from the distribution of the size of the reported flaws in this layer and (2) the local density of the non-reported flaws is linked to the local density of the reported flaws. In order to account for the unknown location of the non-reported flaws, these flaws are assumed to be distributed randomly but consistently with assumption (2) above. A number of trials is then considered, each of them being defined by a spatial distribution of the non-reported flaws in the different layers. For each trial, the reported flaws are added to the postulated non-reported flaws and the parameters characterizing the degradation for the whole population of the (reported and non-reported) flaws are determined in accordance with the procedure used in the structural integrity assessment. A statistical analysis of the results is performed and flaw acceptance analysis is carried-out. In his conclusions, Electrabel states that the structural integrity of the Doel 3 and Tihange 2 RPV shells taking into account the potentially non-reported highly-tilted flaws is demonstrated.

Bel V also perfoms its own evaluation for the Doel 3 and Tihange 2 RPVs.

<u>Doel 3 RPV</u>

Bel V remarks first that, in the same way as Electrabel did in his assessment, the evaluation of the impact of the potentially non-reported highly-tilted flaws on the safety demonstration of the Doel 3 RPV may be limited to the lower shell as it contains most of the hydrogen flakes. Bel V also assumes that the number of non-reported highly-tilted flaws is only a fraction of the number of reported flaws and that the spatial distribution of the non-reported flaws coincides with the distribution of the reported flaws. These assumptions rely on an analysis of the reported highly-tilted flaws in the lower shell of the Doel 3 RPV.

According to the UT sensivity study, all the highly-tilted flaws in the 25 mm thick layer beneath the inside surface of the RPV are said to be reported. This result, i.e., the absence of non-reported highly-tilted flaws in the first 25 mm within the thickness, is very important because the detrimental effect of the flaws in this layer, even with small dimensions, is high as evidenced by the small value of the acceptable size of the flaws for a ligament S < 25mm. Furthermore, it should also be mentioned that, amongst the 10 flaws (or grouped flaws) exceeding the screening criterion in the lower shell, eight are located in the first 25 mm thick layer. As no highly-tilted flaws have to be postulated in this layer, no potential interaction of a flaw (or grouped flaw) with high $2a/2a_{acc}$ with non reported flaw(s) has to be considered.

The UT sensitivity study also shows that the maximum size (6 mm) of the non-reported highly-tilted flaws in the layer between 25 and 75 mm beneath the inside surface may be qualified as small, when compared to the maximum acceptable size $2a_{acc}$ of the flaws in this layer. All individual non-reported highly-tilted flaws in the 25-to-75 mm layer may therefore be concluded as having a non-significant impact of the safe performance of the RPV as they satisfy the screening criterion. The only potentially detrimental effect would be due to their combination with reported larger flaws by application of the proximity rules. However, the combination of the (small) non-reported flaws with reported larger flaws (or grouped flaws) is only required if the non-reported flaws are in close vicinity to these reported flaws (or grouped flaws) since the proximity rules are based on a min (a_1; a2) rule. The shortest distance between a non-reported highly-tilted flaw and a reported larger flaw should therefore be less than 6 mm for requiring combination. As most of the flaws in the Doel 3 RPV lower shell are located in the layer between 25 and 75 mm beneath the inside surface, it is therefore believed that a shortest distance of less than 6 mm between a non-reported highly-tilted flaw and a reported flaw in the in the 25-to-75 mm layer should not be considered as a rare event. In the 25-to-75 mm layer, there are no individual flaws exceeding the screening criterion. Combining a (small) non-reported highly-tilted with a larger reported flaw (but not exceeding the screening criterion) should not increase significantly the detrimental effect of the reported flaw as the results of a 3-D analysis have shown that the effect of small neighbouring flaws on the K_I of a larger flaw is negligible. Similarly, combining together several non-reported (small) flaws should not lead to an unacceptable size. The only detrimental effect could potentially result from the combination of a non-reported highly-tilted (small) flaw (or non reported highly-tilted flaws) with one of the two grouped flaws that exceed the screening criterion. However, there is no doubt that by performing a detailed 3-D analysis of the newly defined groups including reported and non-reported flaws, all individual flaws would be found acceptable and below the screening criterion.

The UT sensitivity study has finally shown that highly-tilted flaws with increasing size upto 18 mm are potentially not reported in the layers between 75 and 120 mm beneath the inside surface. Such a flaw length may not be qualified as small. However, it is several times smaller than the maximum acceptable size in these layers, i.e., the individual non-reported flaws do not exceed the screening criterion. Here also, the only potentially detrimental effect would be due to their combination with reported larger flaws by application of the proximity rules. However, it should be pointed out that (1) the number of reported flaws in these layers is about 10 times smaller than in the 25-to-75 mm layer and (2) there are also in these layers neither individual flaws nor grouped flaws exceeding the screening criterion. As a result, the required combination between a non-reported flaw and a reported flaw (or grouped flaw) should be rather considered as a rare event. Moreover, should such a combination be required and a ratio $2a/2a_{acc}$ close to 1.0 be obtained for the combined flaws, a 3-D analysis of the flaws would undoubtedly show that all the individual flaws making part of a group are acceptable and below the screening criterion.

The above discussion leads to conclude that the impact of the non-reported highly-tilted flaws on the safety of the lower shell of the Doel 3 RPV should not be significant.

Tihange 2 RPV
When compared to the Doel 3 RPV, the degradation of the Tihange 2 RPV is less severe. The upper shell is the most affected. Bel V has performed for the upper shell Tihange 2 RPV a similar analysis as the one described above and an identical conclusion has been drawn.

Bel V concludes that the potential presence of non-reported highly-tilted hydrogen flakes in the lower shell of the Doel 3 RPV and in the upper core shell of the Tihange 2 RPV should not affect significantly their structural integrity.

7. Large-scale 4-point bending test (Action #15 Part 2)

In paragraph 9.2.4 of his Safety Evaluation Report of January 2013, Bel V mentioned that high confidence in the analytical procedure used for demonstrating the serviceability of the RPV affected by hydrogen flaking required experimental verification. To this end, Bel V required Electrabel (1) to perform tensile testing of large specimen(s) with hydrogen-induced flaws taken from the AREVA shell VB 395 and representative of the degradation affecting the Doel 3 RPV lower shell (that is the most affected shell of the Tihange 2 and Doel 3 RPVs) and (2) to perform concurrently a 3-D finite element simulation of the tests. More precisely, Bel V defined the objective of the test as follows: *the objective of the large-scale tensile testing to be carried out at an adequate temperature is to compare the experimental and calculated values of the crack initiation threshold and to verify the conservatism of the 3-D finite element analysis* [that is used for the detailed analysis of the flaws].
The objective of the large-scale testing has been translated in Action #14 as follows: *the licensee shall complete the ongoing test program by testing larger specimens containing hydrogen flakes, with the following objectives; […] Objective 2: an experimental verification of the suitability and conservatism of the 3-D finite element analysis*.
Following discussions with Electrabel, Bel V accepted to replace the planned large-scale tensile tests by large-scale 4-point bending tests as proposed by Electrabel. The use of bars with a rectangular section is indeed found more convenient by Electrabel. To Bel V opinion performing 4-point bending testing also allows to meet the objective of the test and is therefore acceptable.
The test conditions (size of the bar, test temperature and flake tilt angle) were defined by Electrabel with the objectives of (1) having in the specimens a flake tilt angle relative to the stress direction as representative as possible of the actual maximum orientation of the flakes in the RPV shell and (2) having test conditions that allow brittle crack initiation in linear elastic conditions.

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The objective (2) is required since the detailed 3-D finite element analysis uses Linear Elastic Fracture Mechanics.
In order to meet these objectives, also taking into account that the fracture toughness of the material could be in upper bound, i.e., K_{Jc}(95%), the flakes should have a tilt angle of about 40° relative to the axis of the specimen and the test temperature should be about -130°C.
Large-scale bend testing was performed on two specimens. 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. The fracture toughness curve used is the fracture toughness Master Curve K_{Jc} at 1% confidence limit determined from the fracture toughness tests performed on specimens taken from the material of the AREVA shell VB 395 in the ligaments between flakes. The evaluation of the equivalent stress intensity factor K_{eq} along the flake fronts was performed with the 3D eXtended Finite Element Method as in the detailed evaluation of the most severe flaws or flaw groups.
The results show that the effective failure load of the test specimens exceeds the predicted failure load.
Although the tensile testing (at -80°C) of large-scale specimens with flakes having a tilt angle of 20°C had not been performed to demonstrate the conservatism of the 3-D finite element analysis, Electrabel evaluated the equivalent stress intensity factor Keq along the flake fronts with the 3D eXtended Finite Element Method in the same manner as he did for the large-scale bend test specimens. The results of the calculations were found to be consistent with the experimental failure loads.
After evaluation, Bel V concluded that the results of the large-scale test program were as expected and had no further remark.

8. Load test (Action #16)

In paragraph 9.3 of the Safety Evaluation Report of January 2013 Bel V stated: *In order to account for the actual condition of the Doel 3 and Tihange 2 RPVs and so, to complete the demonstration of the serviceability of the RPVs, a non-destructive test on the RPVs needs to be performed. Theoretically, the non-destructive test should be representative of the most severe loadings applied to the RPV. Practically, the only test that can be performed is a pressure test. The objective of the pressure test is not to validate the analytical demonstration on the RPV itself but to demonstrate that no unexpected condition is present in the RPVs. With regard to that objective, the pressure test needs to be complemented by acoustic emission testing. The acceptance criterion will be that no initiation of crack propagation is recorded. It may indeed be expected that, in the condition of the RPVs as considered in the fitness-for-service evaluation, no initiation of crack propagation is expected under the hydrotest pressure loading.*
The requirement for a non destructive test on the Tihange 2 and Doel 3 RPVs is included in action #16. The test, referred to as a load test, was required to be complemented by acoustic emission measurement and additional UT inspection. For the Tihange 2 RPV, it was also accepted to limit the UT inspection to the upper core shell.
As reported by Electrabel, the acoustic emission 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 was also found to be consistent with the findings of the 2012 inspection.

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Bel V acknowledges the satisfactory results of the tests.

9. Residual content of hydrogen (Action #10)

High content of residual hydrogen in the flakes would be detrimental since in case of concentration at the crack tips it could cause embrittlement and so affect the material properties. A test program has been performed under action #10 to estimate the amount of Hydrogen still present in the flakes. To this end, hot extraction tests were performed at 900°C and 1100°C on flaked and non-flaked specimens taken from the AREVA shell VB 395. The results, as reported by Electrabel, show that the total hydrogen is at the same level in both types of specimens, which leads Electrabel to conclude that there is no significant amount of Hydrogen present inside the flakes. Bel V acknowledges this conclusion.

10. Conclusions

Bel V has evaluated the results of the analyses and tests performed by Electrabel in the frame of the action plan initiated to address the requirements set forth by the FANC in his provisional evaluation report of January 2013.
Bel V has focused his evaluation on the actions that addressed the concerns he stated in his Safety Evaluation Report of January 2013.
The evaluation by Bel V raised no concern preventing the Safety Case of Electrabel to be considered as conclusive.