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TO: [redacted] **COMPANY: ELECTRABEL**
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O/ref: DOEL176
related reports: DOEL165
subject : DOEL 3 – ISI 2012 – Justification of the Reactor Pressure Vessel (RPV) shell.

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1. INTRODUCTION

In June 2012, ultrasonic in-service inspections were performed at Doel 3 to check for underclad cracking in the reactor pressure vessel (RPV). No such defects were detected. However unexpected indications in the RPV shells were found. Electrabel ordered a full thickness RPV shell inspection (July 2012) which confirmed high numbers of similar indications. The same type of indications, but to a lesser extent, was also found in the Tihange 2 RPV shells during the September 2012 inspection.

To justify the restart of the Doel 3 and Tihange 2 Nuclear Power Plants, Electrabel developed a Safety Case for each unit. In this context, documents were submitted to the MO/AIA related to the following topics:

- Inspection
- Documentation
- Metallurgy
- Calculations

The scope of the MO/AIA review concerns the verification of the submitted Safety Cases for their compliance with the requirements of the ASME XI ed.1992. It shall be noted that the Licensee makes use of the article IWB-3132.4 : Acceptance by Analytical Evaluation.

The MO/AIA report DOEL165 presented the major comments and conclusions of the MO/AIA at the date of 04/01/2013. These comments were taken into account in the Action Plan requirements agreed between the Licensee and the Belgian Safety Authorities (FANC, BelV, MO/AIA).

The Action Plan includes Short and Medium Term Action requirements. The Licensee shall meet the Short Term Action requirements before the restart of the D3/T2 Nuclear Power Plants can be envisaged. The Medium Term Action requirements shall be met before restart after the next outage.

The current report DOEL176 presents the MO/AIA conclusions and comments after evaluation of the Licensee replies to the Short Term Action requirements limited to the case of Doel 3. Our evaluation consisted in the review of documents, witnessing of material tests, inspection during the load test and participation to discussion meetings with the Licensee.

The point 4 below presents for each Short Term Action requirement a brief summary of the Licensee reply and the MO/AIA conclusions and comments after review of the Action result.

2. MAIN DOCUMENTS IN OUR POSSESSION.

- Safety Case Report Doel 3, Reactor Pressure Vessel Assessment, 5 December 2012
- Safety Case Report Addendum , Doel 3, Reactor Pressure Vessel Assessement, 26 April 2013

3. BASIS OF OUR VERIFICATION

- Royal Decree/Ministerial Decree Steam 1991
- Code : ASME III ed. 1971 add. Winter 73 and ed. 1974 add. Summer 74
- ASME XI ed.1992

4. EVALUATION OF LICENSEE REPLIES TO THE SHORT TERM ACTION REQUIREMENTS.

Short Term Action 1 requirement :

The Licensee shall reanalyze 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.

This short requirement is not applicable for Doel 3.

Short Term Action 2 requirement :

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

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 Doel 3 RPV, the Licensee analysis showed that the presence of flakes behind some brackets cannot be excluded but considers these potential flaws not critical as the brackets would protect them in terms of stress and toughness.

The MO/AIA considers the Licensee reply to the Action 2 requirement satisfactory but asks the Licensee to apply an appropriate visual examination of the concerned bracket zones at the next outage.

Short Term Action 3 requirement :

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.

- A complementary set of 2 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).

The MO/AIA considers the Licensee reply to the Action 3 requirement satisfactory. However, as Medium Term Action, the Licensee shall provide additional validation of the UT simulations.

Short Term Action 4 requirement :

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.

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.

The MO/AIA considers the Licensee reply to the Action 4 requirement satisfactory and has no more comments related to Action 4.

Short Term Action 5 requirement :

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.

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 a good detection and sizing of the indications in the configurations examined.

The MO/AIA considers the Licensee reply to the Action 5 requirement satisfactory and has no more comments related to Action 5.

Short Term Action 6 requirement :

The Licensee shall re-analyze the tilts of defects in the block VB-395/1 with the same method as applied on-site.

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.

The MO/AIA considers the Licensee reply to the Action 6 requirement satisfactory and has no more comments related to Action 6.

Medium Term Actions 7 and 8 : *outside the scope of this report.*

Short Term Action 9 requirement :

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*

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. The tests encompassed :

- fracture toughness tests in an area free of flakes as reference
- fracture toughness tests on specimens taken in the ligament between flakes
- fracture toughness tests at the hydrogen flakes crack tip
- tensile tests on specimens taken in different orientations in the ligament between flakes
- large scale tensile tests on specimens with flakes parallel to the specimen axis
- large scale tensile tests on specimens with flakes oriented at 20° with respect to the specimen axis
- mechanical characterization of the "ghost lines" present in the H1 nozzle cut out of Doel 3

Additional margin of 50°C on the RT_{NDT}-value.

- 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.
- 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.
- From additional experimental fracture toughness tests on VB-395 specimens, the Licensee could show :
  - 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 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.
- It was shown previously in the Safety Case 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.
- From these results follows that the 50°C margin on RT_{NDT} considered in the Safety Case is appropriate.

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. The presented test results showed a very limited effect of the ghost lines on the mechanical properties.

- 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.

Tensile properties of the zone in the AREVA VB-395 shell affected by hydrogen flakes.

● Tensile properties were measured in the three orientations (L,T,S) 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 small 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.

The MO/AIA considers the Licensee reply to the Action 9 requirement satisfactory. However, as Medium Term Action, the Licensee shall provide data about the tensile properties at ambient temperature of specimens with T orientation and taken in ghost lines (ghost line along the specimen axis).

Short Term Action 10 requirement :

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.

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.

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

Medium Term Actions 11, 12 and 13 : *outside the scope of this report.*

Short Term Action 14 requirement :

Taking into account the results of the actions related to the Action 3 requirement on the detection of higher tilt defects during in-service inspections, the Licensee shall evaluate the impact of the possible non reporting of flaws with higher tilts on the results of the structural integrity assessment.

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 Doel 3 taking into account the UT-potentially not reported flaws with the highest tilt in addition to the flaws already reported during the 2012 inspections.

The MO/AIA considers the Licensee reply to the Action 14 requirement satisfactory and has no more comments related to Action 14 in the context of the Doel 3 RPV.

Short Term Action 15 requirement :

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

Objective 1 : Tensile tests on samples with (inclined) multiple hydrogen flake defects, which shall in particular demonstrate that the material has sufficient ductility and load bearing capacity, an that there is no premature fracture.

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

- 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.
- 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. The stresses on the net section at maximum load were found to be all well above the yield.
- The Licensee performed additional toughness tests on CT specimens to confirm that the toughness at room temperature of the VB395 material with hydrogen flakes, measured in the ligaments between flakes, is characteristic of the upper shelf behavior.
- Detailed finite element analyses of two tensile test configurations were presented by the Licensee. The results confirmed the conservatism of the 3D finite element analyses.
- 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. The test results confirm the conservatism of the predictions with a failure load well above the predicted load.

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

Short Term Action 16 requirement :

In addition to the actions proposed by the Licensee and the additional requirements specified by the FANC in the previous sections, the Licensee shall 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.

- The Licensee performed a pressure load test of the Doel 3 Reactor Pressure Vessel. The maximum pressure that has been reached during the Load Test is 177.4 bar abs . The pressure 177.4 bar abs is above 110% of the maximum pressure applied on the RPV during the last cycle.
- 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 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 after the Load Test and confirmed that there is no evolution of the indications as the number of indications, the 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.
The MO/AIA considers the Licensee reply to the Action 16 requirement satisfactory. However, as Medium Term Action, further evidence of the efficiency of the applied Acoustic Emission Technique shall be provided.

5. CONCLUSIONS.

- The calculated safety factors meet the requirements for 'Acceptance by Analytical Evaluation' defined in the ASME XI Code.

- The MO/AIA considers the Licensee replies to the Short Term Action requirements satisfactory with respect to the case of Doel 3.

- Some Additional Medium Term Actions are requested :

- Action 2 : The Licensee shall apply an appropriate visual examination of bracket zones that potentially might hide flakes.
- Action 3 : The Licensee shall provide additional validation of the UT simulations.
- Action 9 : The Licensee shall provide data about the tensile properties at ambient temperature of specimens with T orientation and taken in ghost lines (ghost line along the specimen axis).
- Action 10 : The Licensee shall inform the MO/AIA about the results of the melt extraction tests that are ongoing in order to confirm the results found with the hot extraction tests at 1100°C.
- Action 16 : Further evidence of the efficiency of the applied Acoustic Emission Technique shall be provided.

- The Licensee shall also consider the conclusions and comments of the FANC and BelV.

Yours sincerely,

[redacted]