Report of the National Scientific Expert Group on the RPV Tihange 2
29 April 2013

The National Scientific Expert Group (further termed NSEG) has been installed by the scientific council of the Nuclear Safety authorities (FANC) with the aim of providing an independent technical and scientific assistance for the critical assessment of the technical reports prepared by the license holder regarding the structural integrity of the Doel 3 and Tihange 2 reactor pressure vessels (RPV) containing a very large number of multiple nearly-laminar embedded flaws, occurring in different planes. These flaws were discovered in July 2012.

The current report discusses the results of the additional tests and analyses undertaken by the licensee after the submission of the NSEG report issued on 11 January 2013. The complementary investigations confirm the general conclusions of the first version of the report and answer the concern raised by the NSEG regarding the embrittlement effect of phosphorous in ghost lines and in segregation regions.

After the December 2012 – January 2013 evaluations, the licensee was requested to conduct a number of additional analyses and tests. The additional work consisted of 16 actions, labelled #1 - #16. As requested by the FANC, The NSEG has studied the results of the material property tests (actions #9 and #15). Consequently the observations that are reported here are limited to the results of actions #9 and #15.

1. ***Review of results of actions #9 and #15***

Action #9: *"Additional characterisation of the material mechanical properties"*

Particular attention is paid to the properties (1) in the local ghost lines of the segregated zones and (2) in the zone that is affected by hydrogen flakes. The objective of this analysis is to confirm that a shift of 50°C in the RT_{NDT} is conservative.

Specimens were cut from the VB395 cylinder that was made available by AREVA. This cylinder has flakes, and its material structure and the presence of flakes are considered to be similar to the Doel 3 and Tihange 2 RPVs. Material toughness is measured in the ligament between the flakes and also in a region that is free of flakes. These results show – on average – an 11° shift in the RT_{NDT} due to the presence of flakes. The measurements exhibit significant scatter, though on the order of the ASME code prescription.

The effect of segregation in ghost lines on the shift in the RT_{NDT} was studied by toughness measurements on samples from the Doel 3 H1 cut-out, for which the initial notch is located in the ghost line (ghost line perpendicular to the notch). No detrimental effect could be measured.

Finally, the irradiation embrittlement was evaluated, in the first safety case presented by the license, as a shift in the RT_{NDT} lower than 17-degree shift. This value was found by considering the material composition in the macro-segregated zone in the FIS formula.

In that respect, the 50° 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°). However it is worth noticing that in the ghost lines the concentration of elements such as P was measured as part of action #9 and was found to be higher than the values in the macro-segregated zone. The question of embrittlement of the ghost lines with higher P content was raised by the NSEG to the licensee, who has provided the following argument

- Literature has shown that under irradiation the ghost lines see a lower shift in RT_{NDT} than the macro-segregated zones
- The orientation of the ghost lines is not threatening the vessel integrity in case of embrittlement. Indeed as the crack should propagate in a direction perpendicular to the ghost lines, the embrittlement measured for the macro-segregated zone is the one that matters.

The NSEG agrees with this last remark and consider that the 50-degree shift remains fully appropriate. Nevertheless, it is advised to pursue the study of the ghost-line embrittlement in the future action.

Action #15: "large scale test programme on VB395 material with hydrogen flakes"

The objective of the large scale tests is twofold. On the one hand, tensile and four-point bending samples with multiple inclined hydrogen flakes were loaded to failure to determine (1) sufficient material ductility, (2) load bearing capacity and (3) to demonstrate that brittle failure or fracture below the design load is not expected to occur. On the other hand, these test results are used to validate the results of the calculations with 3D finite element models.

The tensile tests on round bar specimens contained flakes that are tilted by an angle of 20° with respect to the longitudinal axis. The four-point bending test specimens contained flakes at the free surface in the tensile zone. It is appreciated that the licensee used an elaborated procedure to machine the test samples from the available blocks with the correct dimensions and the highest expected flake angle.

Although the objectives of the action are carefully considered and technically justified, there is some contradiction in the objectives (this contradiction is recognized by the licensee too). There is a clear difference between the concept of a material property, which characterises a material, regardless of the shape and size of the sample, and the idea of conducting such a test on a sample containing multiple defects. Even if the test is done according to standards, the results of a test on a sample with defects inevitably include the effects of the shape and size of the sample, including the size, position and orientation of the defects. In addition, the tensile and four-point bending tests cannot be qualified as large scale (structural) tests, but rather as sub-sized tests. Consequently, the term "large scale testing" is inappropriate as only specimens are tested with dimensions that are much smaller than the pressure vessel wall thickness.

Finite element models have been built to simulate both the tensile test and the four-point bending test, with all minute details of the crack accurately represented in the models. Finite element analysis is done by CENAERO. The failure loads that result from both bending tests are well above the predicted values of the FE calculations. Simulation of the same conditions predicts failure at loads of 111kN for the first sample and 79kN for the second one. In the hardware experiment, the specimens failed at 212kN and at 489kN, respectively. The result of the finite simulation does not lead to much additional insight apart of the obvious observation that it is very conservative.

With respect to the comment made above, the NSEG does not endorse the conclusion as it is stated in the reports, claiming that "the material affected by flakes has strain capacity to deform without inducing crack propagation for stress levels well above any level of primary stress that could be experienced by the RPV". This conclusion is not valid for the material, but it is valid for the test sample, as it is cut from the AREVA cylinders. But this remark does not affect the overall justification provided to support the restart of operation of Tihange 2.

2. ***General conclusions***

After thorough and careful analysis of the documents that have been provided by the licensee, the NSEG concludes for the safety case on Tihange 2:

1) that the origin of the recently detected flaw indications in the Tihange 2 RPV is manufacturing related and that the indications were not detected/reported by the inspection equipment/procedure using during manufacturing; and that these indications did not grow significantly during the operations;

2) that the methodology and fracture mechanics calculations that are performed and/or ordered by the licensee are sound and reflect the current state-of-the art;

3) that all assumptions and the numerical values of input parameters - other than the size, orientation and position of flaws - which are used in the fracture mechanics calculations are conservative;

4) that, as a result of 2) and 3), the predictions on the structural resistance of the RPV of Tihange 2 should be considered to represent a worst case scenario;

5) that, as a result of 4), the restart of operations on the nuclear reactor Tihange 2 would have to be taken into consideration;

6) that, after the licensee has successfully subjected the RPV of Tihange 2 to a pressure test, all reasonable verifications and validations have been concluded successfully; note hereby that this observation is based on the fact that none of the members of the NSEG is familiar with the operational aspects of NDT inspection and hydro-tests;

7) that, as a result of 5) and 6), the restart of operations on the nuclear reactor Tihange 2 can be justified provided the authorities have received sufficient guarantees about the procedures that have been followed to determine the real number, size, position and orientation of the flaws.