Flaw indications in the reactor pressure vessel of Doel 3

This note provides a summary of the information available on the 3rd of September 2012.

1. Purpose

Summary of the available information and preliminary evaluation pertaining to the indications of defects found in the Doel 3 RPV in June - July 2012.

2. Background

- Belgian nuclear power plants have been built and are operated following the American codes and regulations, transposed in the Belgian context.
- The reactor vessel of Doel 3 has been ordered in 1974, so the ASME Code ed. 1973 (and addenda of 1974) was applicable. Some “Complementary Applicable Conditions” were also required in addition to those of the ASME Code. The reactor vessel has been installed in 1978.
- Belgian reactor pressure vessels (RPV) are inspected according to ASME XI. Since 1982, several in-service inspections have been performed on the vessel. Following the rules of the ASME Code Section XI, volumetric in-service-inspections of the beltline area are normally limited to the circumferential welds (there are no axial welds in the Belgian RPVs) and the surrounding heat affected zone and base material, within the limits set by the code.
- Additionally, as a result of the experience at Tricastin, inspections aiming at detecting possible underclad defects in the pressure vessel beltline region are planned for all Belgian plants. The first inspection of this kind took place at Doel 3 this summer.
- Since the beginning of the operating, all volumetric in-service inspections of the reactor vessel have been carried out by the French company Intercontrôle, also in charge of the same inspections in France. The tool employed for these inspections has been upgraded continuously. Some indications have been noticed during these in-service inspections, but none being of the nature or of the scale of the phenomenon observed during the 2012 inspections.
- Doel 3 started operation in 1982. The Doel NPP is operated by Electrabel, part of the GDF-Suez Group.

3. Inspections performed at Doel 3 in June-July 2012

3.1 Description of the inspections performed

Three successive inspections were performed in June-July 2012:

1. The regulatory inspection according to ASME XI, IWB-2500-1, which is restricted to the welds and surrounding material (HAZ, base material). This inspection was performed from the inside of the vessel, with the usual qualified procedure for in-service inspection. Those inspections encompass the full circumference and 100% of the wall thickness (in this case 205 mm), over a length of ½ t on both sides of the weld (see ASME XI fig. IWB-2500-1). There is no significant evolution to mention with respect to the former inspection.

2. The complementary planned inspection aiming at detecting possible under clad defects – which incidentally detected the defects under discussion, but no under clad defect as such – using a specific qualified procedure was the first inspection of that kind in Belgium. The inspection was performed from the inside of the vessel. It covers the full circumference and the first 25 mm (including 8 mm of cladding) of the thickness, from the inside of the vessel. The height of the inspected zone is 4080 mm (starting from 3320mm under the vessel flange up to 7400 mm, thus covering the full height of the core). This means that cladded base material is inspected where no volumetric in-service inspection has been performed up to now. No under clad defect has been detected. See hereafter for other defects.
3. A supplementary inspection was performed to better detect and characterize the unexpected defects detected during the former inspection, through the whole thickness of the shells. This supplementary inspection makes use of the available UT-technique on site at that time, i.e. the one used for the regulatory inspection according to ASME XI, IWB-2500-1 (see 1.). It covers the full height of the forged vessel rings (which is slightly more than the previous inspection (see § 2)) and 100% of the wall thickness. To characterize the defect indications, additional data have been numerically recorded for a region which is particularly affected by the observed phenomenon. This region is 1,5m height, 120° large, and 135mm deep.

3.2 UT-techniques and qualification

- Both inspection techniques are qualified to detect and size defects in the weld area.
- No formal demonstration according ASME XI appendix VIII has been done. Actually both inspection techniques have been qualified applying the ENIQ principles. For under clad defects, use was made of the qualification file for France, completed with specificities for Belgium reactors.
- For under clad defects, the qualification was performed using relevant test block with relevant defect simulations to demonstrate the measurement accuracy of the sizing capability and reliability. For the base material examination, no additional test blocks made from base material only were used. Everything is based on experience with weld examination procedure. The qualification includes procedure, personnel/operators and equipment.
- The tolerances that can be expected in defect sizing with the qualified procedures are as follows:
    - Sub-clad defects : +/- 1 mm average
    - Base material defects : +/- 3 mm average (same as for welds)

3.3 Results of the inspection performed to detect and characterize underclad defects (June 2012)

- According to the licensee no underclad defects were detected. The cladding itself is intact.
- Nevertheless, 158 defect indications of an apparently different type were selected on the basis of the criteria used for by this UT-inspection, especially in one of the three forged rings (SA-508-cl.3).
- These indications appear to be a quasi-laminar type of flaw. The flaws are more or less parallel to the inner/outer surface of the pressure vessel (slopes up to 10° could be observed), located in and outside the inspected zone.

- Considering the fact that this inspection method is not qualified for detection at such locations nor for this (new) type of indications, precise information about shape or dimension was not available at this stage. A first evaluation shows that these sub-surface flaws are almost circular in shape with a mean diameter of about 15 mm (maximum 30 mm), with a flaw density up to 40 indications per dm^3.
- Obviously, it was not possible at this moment to justify these indications on a one-by-one basis by means of an analytical evaluation according to the App. A of ASME XI code requirements.

3.4 Results of the supplementary inspection performed to detect and characterize base material defects detected in June 2012 (July 2012)

Considering the limitations of the inspection method which revealed the presence of the defects in the base material, an inspection of the whole height of the RPV with the UT-qualified method used to control the beltline welds has subsequently been performed. This inspection covered the whole thickness and the whole height of the RPV.

The *preliminary* results of this supplementary inspection can be so far summarized as follows:

- This inspection confirms the presence of a large amount of quasi-laminar indications in the upper and lower shell rings. All these flaws have been analysed, and distribution of these flaws in function of their depths or of their sizes have been established.
- There is a marked disparity in the flaw densities between the upper and the lower shell rings. The core lower shell is the most affected with a total of 7776 indications. The core upper shell contains 931 indications. The other parts of the reactor vessel contain some indications, but to a lower extend, and these are of a different nature in the transition ring.
- The shape of the flaw distribution is very similar in both cases.
- The bulk of the indications are located in the base material, outside the weld regions, throughout a zone extending from about 30mm from the inner surface to one half of the RPV thickness.
- These flaw indications seem to be laminar in shape and have an average diameter of 10-14 mm, while some indications have diameters of more than 20-25 mm.

4. Current status of the investigations performed by the licensee

4.1 Overview of the investigations performed by the licensee

- The Licensee is currently finalizing the analysis of the inspection results.
- In the absence of any other explanation at this stage, the licensee supposes the presence of fabrication defects, but does not exclude other explanations. Investigations were conducted to retrieve information pertaining to the fabrication and the associated controls.
- Investigations are underway to investigate various metallurgical aspects.
- Studies are being performed to analyse and, if possible, to validate and confirm the structural integrity of the vessel. A justification of the observed defects for further operation is required by the Belgian regulations, based on ASME XI, App. A. According to first evaluations made by the Licensee, alternative requirements will be

necessary. The Licensee is investigating a. o. alternative rules for regrouping individual indications. A PTS study based on 10CFR50.61a is planned.

- An inspection similar to the inspection performed in July 2012 at Doel 3 will be performed at another Belgian reactor vessel (unit 2 Tihange NPP), during the current outage (September 2012).

4.2 History of vessel fabrication: current status

- Different companies have participated in the fabrication stages of the reactor vessel. The raw material of the reactor shells has been supplied by Krupp, and the forging has been performed by Rotterdamsche Droogdok Maatschappij (RDM), a Dutch company having the ASME N-stamp. RDM has since gone bankrupt. The cladding and the assembling have then been performed by Cockerill for the lower part (two core shells, transition ring and bottom plate) and by Framatome for the upper part (RPV head, nozzle shell), and the final assembly.
- The upper and lower vessel rings of the Doel 3 and Tihange 2 RPVs were forged by the Rotterdam Droogdok Maatschappij (also referred to as Rotterdam Dockyards or RDM), at the same time and under the same contract.
- The fabrication of both RPVs took place in the same period, following the same requirements.
- Most of the fabrication steps have been documented, and most of this documentation has been retrieved by has been recovered by Electrabel and Tractebel Engineering (engineering studies). In this way, some data about the fabrication process of Krupp are known, such as chemical composition (and hydrogen in particular) of the blooms. However, some documents are lacking. Notably, detailed documentation about the first thermal treatment performed by RDM (which according to the LOFC has been done), an intermediate UT inspection and some RDM specifications are lacking. On the other hand, the fabrication steps by RDM have been followed by Cockerill and the AIA, and the certificates proving the conformity with the fabrication specifications have been retrieved.
- Similar investigations have been carried out for Tihange 2. According to the licensee, the hydrogen contents in the shells of Tihange 2 are similar to those of Doel 3.

4.3 Inspection at the fabrication stage

- Inspections at the fabrication stages have been carried out following the rules of the ASME Code Section III, edition 1974. These inspections involved UT controls and volumetric examinations. These examinations were performed manually and from the external surface of the vessel. In addition to the ASME Code, the CCA imposed some complementary controls (for the welds in particular), but these didn’t lead to the observation of indications.
- For the core upper shell, the first inspections carried out during the fabrication indicated the presence of a large zone containing acceptable indications. During the intermediate inspection, this affected zone has however not been observed anymore. During the final inspection, 12 flaws were observed, but it has been concluded that these flaws were acceptable according to the applicable criteria.
- For the core lower shell, only the documentation regarding the final inspections has been retrieved. During this final inspection, no flaws have been noticed.
- The inspections of 2012 were carried out from the inner surface of the vessel wall, and are more sensitive than the inspections performed during fabrication. Despite the

extent of the observations, it is reasonable, according to the licensee, to believe that the flaws observed during the 2012 inspections would not necessarily have lead to reject the shells according to the applicable design criteria of the ASME Code. The licensee is currently evaluating to which extent the UT-procedures used during fabrication were able to detect and size flaws the type of which were found this year.

4.4 Metallurgical aspects: current status of the investigations

- The flaws would have appeared during fabrication. During the casting of the ingots, some segregation zones develop inevitably. These correspond to a modification in the content of some constituents, which locally implies a change of the physical properties. In this way, during the thermal treatments applied on the shells, hydrogen present in the material behaves differently according to the region it crosses. More specifically, during the cooling steps, hydrogen diffuses more into the segregation region, and accumulates there. If the initial hydrogen content is sufficient, the hydrogen accumulation may imply the formation of flaws. These flaws then appear in large numbers, with a flake shape. Dimensions are typically between 4 and 14 mm. These flaws are quasi-laminar for reasons related to the fabrication process. Moreover, for the reasons explained above, they are essentially located inside the segregation zones, which have a particular shape, starting near the surface of the wall, and diving into the wall progressively.
- All these elements seem in good agreement with the observations made during the inspections of June and July 2012.
- Experience gained since several decades shows that it is possible to avoid the formation of these flaws if the hydrogen content is kept below a certain level, if long annealing is applied, and if a dehydrogenation step is carried out. During the fabrication of the shells of the Doel 3 reactor vessel, no trace of a dehydrogenation treatment at RDM can be found.
- According to the licensee, it is improbable that these flaws have evolved since their formation.
- In order to obtain more information on these flaws and on their behaviour, non-destructive and destructive examinations are foreseen on monsters which are affected by this phenomenon.

5. Actions taken by the Belgian Authorities

- Communication with foreign countries: preliminary IRS; direct contacts with Safety Authorities of foreign countries having RPVs fabricated by RDM.
- Review of the available information w.r.t. the fabrication of the Doel 3 and Tihange 2 RPVs.
- Preliminary evaluation of the approaches aiming at justifying the observed defects for further operation.
- International meeting aiming at informing selected foreign countries (Brussels, 16th of August)
- Proposal to form three international expert working groups:
  - WG 1: Non-destructive Examination techniques
  - WG 2: Structural mechanics & fracture mechanics – Approach for justification file
  - WG 3: Metallurgical origin / root causes of the flaw indications

- Proposal to establish independent international expert review team
- Further contacts with the Licensee