Flawed Reactor Pressure Vessels in Belgian Nuclear Plants Doel-3 and Tihange-2

Some Comments on the FANC Provisional evaluation report (January 30, 2013)

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Contents

Executive Summary

The Nuclear power plant Doel 3 started operation in 1982, Tihange 2 started operation in 1983. Both PWR (pressurized water reactor)-type NPPs are operated by Electrabel, part of the French GDF-Suez Group.

In the frame of inspections performed complementary to regular inspections in June 2012 at Doel 3 to detect and characterize underclad defects in the whole cylindrical part of the RPV, unexpected flaws were detected in the forged rings of the reactor core (SA-508-cl.3). The flaws were found in the base metal in areas away from the welds. In the core lower shell a total of 7,776 indications were found, in the core upper shell 931 indications. Similar flaws were revealed in September 2012 in the reactor pressure vessel of the nuclear power plant Tihange 2: in the upper core shell 1,931 indications, in the lower core shell 80 indications. In the transition ring no indications have been reported, in the flange 19 indications have been identified.

On December 5, 2012 Electrabel submitted the "Safety Case Report Doel 3 – Reactor Pressure Vessel Assessment" and "Safety Case Report Tihange 2 – Reactor Pressure Vessel Assessment" to the Belgian Nuclear Regulatory Authority FANC.

On February 1, 2013, FANC published its "Doel 3 and Tihange 2 pressure vessels - provisional evaluation Report" together with the evaluation reports from national and international expert groups. The reports of Bel-V, FANC's technical subisidary, and AIB-Vinçotte, the authorized inspection agency, have not been published to date.

Further to her request of December 2012 to evaluate the available facts on the issue, in February 2013, Rebecca Harms, Co-President of the Greens/EFA Group in the European Parliament, asked the author to evaluate the available documents and to evaluate *inter alia* whether the complementary tests that are now scheduled are enough to qualify the re-start of the two nuclear power plants in case the results of these tests are positive or, on the contrary, are not enough to qualify for such a re-start even if the new tests looked positive.

Electrabel's dossier on the observed flaws in the reactor pressure vessels of Doel 3 and Tihange 2 is based on experimental investigations on small-scale specimens made of archive materials from the reactor pressure vessel Doel 3 (without hydrogen-related defects) and a cut-out from a rejected French steam generator shell (AREVA VB 395) containg hydrogen flake type defects, but not having undergone the thermal, neutronic and pressure stresses experienced by the actual RPVs during their 30 years of operation.

These specimens can therefore not be considered to be representative for the reactor pressure vessel materials of concern.

The origin of the observed flaws is supposed to be hydrogen flaking during the manufacturing process. For Electrabel this is the only possible explanation. Electrabel claims that no evolvement of defects or defect growth occurred during operation. These assumptions, however, cannot be proved by the operator.

The nature of the observed flaws cannot be determined without destructive testing - nevertheless Electrabel argues that these flaws are hydrogen flake type defects.

Electrabel cannot explain why not all the shells of the reactor pressure vessels are affected.

It was nowhere discussed whether anything might have happened at the raw ferritic pressure vessel inner surface and/or during the process of cladding that has induced defect growth into the vessel wall during operation. Such processes could explain that only some shells are affected and that the observed flaws are rather close to the interface. Such processes should at least have been taken into account as a possible/likely explanation for the presence of the flaws. Because these processes induce that defects grow during operation, taking them into account should be a prerequisite for any consideration of a restart.

The Regulatory Authority FANC did not explain why the completeness of the manufacturing process was never controlled.

The flaws discovered in 2012 were not detected during the final inspection after manufacture although they should habe been detectable with the ultrasonic testing equipment available at that time. This fact per se implies that the flaws have appeared, evolved or at least grown during the 30 years of operation, but FANC does not consider this as self-evident argument.

The manufacturer and the Owner knew about de detrimental effects of hydrogen flaking, since other components were rejected due to hydrogen flaking, as for instance the transition ring of Tihange 2. The rejection of the transition ring implies that the hydrogen flaking based indications have not been present after manufacture in the rings affected today, since otherwise the components would have been rejected.

According to FANC it cannot be assumed that all potentially critical defects have been found during the 2012 inspections.

FANC does rely on further experimental testing of the available sample material that, as pointed out above, cannot be considered to be representative. This means that FANC accepts Electrabel's logic that results from non-representative specimens can prove the quality of the actual state of the pressure vessel material.

FANC accepts Electrabel's proposal to use an additional shift of the nil-dictility reference temperature RT_{NDT} of 50°C to cover all possible radiation effects on the fracture toughness of the material containing hydrogen flake type defects. There is an inconsistency concerning the the use of this additional shift in Electrabel's dossier, but this is not discussed by FANC. FANC does not request to justify this proposal.

No experimental data exist on radiation embrittlement of reactor materials with hydrogen flaking.

Radiation-enhanced diffusion and radiation-induced segregation effects that could influence the hydrogen flake type defects are neither mentioned in the Electrabel documents nor in the FANC evaluation.

FANC recognizes that the fracture toughness/ductility of the material might by significantly reduced by the hydrogen flake type defects (even without radiation effects) but will accept experimental tensile testing results on specimens that are not representative for the reactor pressure vessel material.

There are no experimental data on low-cycle fatigue effects on materials containing hydrogen flaking. Even more: no information exists on the simultaneous interaction of irradiation, temperature and fatigue on hydrogen flakes.

The interaction of the hydrogen-related defects with each other, including bridging effects has not been considered by Electrabel.

The validity of the pressurized thermal shock analysis should be based on the correct input for the thermohydraulic analysis, i.e. the consideration of the most penalizing transients. This has obviously not been the case.

The flaw grouping method used by Electrabel in the structural integrity assessment is no approved methodology, conservativeness has not been demonstrated. Possible interactions of the individual flaws under operational conditions are not known and are therefore not considered.

FANC requests a pressure test of the reactor pressure vessel as the only possible non-destructive test of the pressure vessel although this test can only reveal flaw growth due to this specific loading, but in case no changes will be observed this fact can certainly not prove that defects will not evolve/grow during further operation of the plant. **It is crucial to keep in mind that the complementary tests that are now scheduled are enough to disqualify the re-start of the two nuclear power plants in case their results are negative, but are not enough to qualify for such a re-start even if the new tests looked positive.**

In summary FANC will mainly rely for the decision on restart of the NPPs Doel 3 and Tihange 2 on the test results from materials that cannot be considered to be representative for the actual state of the reactor pressure vessel material[1]. The materials characteristics of the reactor pressure vessels could be worse, but this fact cannot be investigated without destruction of the pressure vessels.

Keeping in mind that the reactor pressuse vessel of a NPP is a component that is supposed to be infailable, that its failure has therefore not been taken into account in safety studies and that therefore the Owner has to demonstrate that the structural integrity of the reactor pressure vessel is ensured at all times during any mode of normal or accidental operation, FANC should obtain - before authorizing the restart of the affected reactors - absolute certainty that the flaws will not lead to the failure of the RPV. This is obviously not the case at present and will not be the case even of the complementary tests should prove positive.

[1] In this context it is a strange situation that material that was rejected for use as steam generator shell - a component that can be replaced and is not exposed to high neutron irradiation - will be used to qualify the further operation of reactor pressure vessels - components containing radioactive materials that are not allowed to fail.

1. Introduction

1.1 Background

The nuclear power plant Doel 3 started operation in 1982, Tihange 2 started operation in 1983. Both PWR (pressurized water reactor)-type NPPs are operated by Electrabel, part of the French GDF-Suez Group.

In the frame of inspections performed complementary to regular inspections in June 2012 at Doel 3 to detect and characterize underclad defects in the whole cylindrical part of the RPV, unexpected flaws were detected in the forged rings (SA-508-cl.3) of the reactor core region. The flaws were found in the base metal in areas away from the welds. In the core lower shell a total of 7,776 indications were found, in the core upper shell 931 indications. The other parts of the reactor vessel contain some indications, but to a lower extent and these are of a different nature in the transition ring.

Similar flaws were revealed in September 2012 in the reactor pressure vessel of the nuclear power plant Tihange 2: in the upper core shell 1,931 indications, in the lower core shell 80 indications. In the transition ring no indications have been reported, in the flange 19 indications have been identified.[2]

The reactor pressure vessel is the main component of the primary coolant circuit in a pressurized water reactor, enclosing the reactor core where the energy producing nuclear chain reactions take place. The reactor pressure vessel is not replaceable, the pressure vessel failure is not considered a design basis accident and its failure is therefore not taken into account in safety studies, therefore the Owner has to demonstrate that the structural integrity of the reactor pressure vessel is ensured at all times during any mode of normal or accidental operation.

The reactor pressure vessels of the NPPs Doel 3 and Tihange 2 were manufactured by Rotterdamsche Droogdok Maatschappij (RDM), a Dutch company having the ASME N-stamp, from raw material supplied by Krupp. In the meantime RDM has gone bankrupt. Cladding and assembling have then been performed by Cockerill for the lower part (two core shells, transition ring and bottom plate) and by Framatome—now AREVA NP—for the upper part (RPV head, nozzle shell), and the final assembly.[3] The Belgian Nuclear Authority FANC (Federal Agency for Nuclear Control) informed the public in September 2012 that the documentation on the manufacture of the reactor pressure vessels of the

[2] FANC, Flaw indications in the reactor pressure vessel of Doel 3 and Tihange 2, September 3,2012, http://www.fanc.fgov.be/GED/00000000/3200/3288.pdf

[3] FANC, Flaw indications in the reactor pressure vessel of Doel 3 and Tihange 2, September 3,2012, http://www.fanc.fgov.be/GED/00000000/3200/3288.pdf

two NPPs of concern is not complete. It has to be assumed that no dehydrogenation procedures were performed during manufacture at RDM.[4]

Note: FANC was established by a Belgian law April 15, 1994. Bel V is a technical subsidiary of the FANC and has since April 14, 2008, taken over the regulatory controls in nuclear installations formerly carried out by the Authorized Inspection Organization AVN. The FANC is the competent authority in the field of nuclear applications. It relies on the technical expertise of its subsidiary Bel V for carrying out inspections in nuclear power plants and other nuclear installations in Belgium (hospitals, universities, radiological installations,…)[5].

1.2 Electrabel's Safety Case Reports

On December 5, 2012 Electrabel submitted the "Safety Case Report Doel 3 – Reactor Pressure Vessel Assessment" and "Safety Case Report Tihange 2 – Reactor Pressure Vessel Assessment" to the Nuclear Regulatory Authority FANC.

On December 19, 2012 additional reports were submitted by Electrabel: „Report on Independent Analysis and Advice Regarding the Safety Case Doel 3 – Reactor pressure Vessel assessment"[6] and „Report on Independent Analysis and Advice Regarding the Safety Case Tihange 2 – Reactor Pressure Vessel Assessment"[7]

These documents were published on the FANC's web side end January 2013.[8,9]

1.3 Safety Case Report Evaluation by FANC

On February 1, 2013, FANC published its "Doel 3 and Tihange 2 pressure vessels - provisional evaluation Report"[10] together with the evaluation reports form national and international expert groups:

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[4] FANC, Flaw indications in the reactor pressure vessel of Doel 3 and Tihange 2, September 3,2012, http://www.fanc.fgov.be/GED/00000000/3200/3288.pdf

[5] http://www.fanc.fgov.be/fr/page/le-statut-de-l-agence/15.aspx

[6] Electrabel, Report on independent analysis and advice regarding the safety case - Doel 3 Reactor Pressure Vessel Assessment, 19/12/2012
http://www.fanc.fgov.be/GED/00000000/3300/3397.pdf

[7] Electrabel, Report on independent analysis and advice regarding the safety case - Tihange 2 Reactor Pressure Vessel Assessment, 19/12/2012
http://www.fanc.fgov.be/GED/00000000/3300/3398.pdf

[8] Electrabel, Safety case report: Doel 3 - Reactor Pressure Vessel Assessment, 05/12/2012
http://www.fanc.fgov.be/GED/00000000/3300/3390.pdf

[9] Electrabel, Safety case report: Tihange 2 - Reactor Pressure Vessel Assessment, 05/12/2012
http://www.fanc.fgov.be/GED/00000000/3300/3389.pdf

Report of the National Scientific Expert Group on the RPVD3T2, Rudi Denys, Ludovic Noels, Thomas Pardoen, Dirk Vandepitte, NSEG Report – 11 January 2013[11]

Report of the International Expert Review Board on the Doel 3 – Tihange 2 Issue[12]

FANC also relied on the expertise of Bel V, and AIB-Vinçotte, the authorized inspection agency. The full reports of Bel-V and AIB-Vinçotte have not been published to date.

1.4 Letters by the French Nuclear Authorities ASN and IRSN to Bel V and FANC

A letter from the French nuclear authorities ASN (Autorité de sûreté nucléaire) and IRSN (Institut de radioprotection et de sûreté nucléaire) to FANC's technical subsidiary Bel V dating December 21, 2012 is published on the ASN web side. The letter concerned the dossier on the justification of the operational aptitude of the reactor pressure vessels Doel 3 and Tihange 2 presented by Bel V ("*Présentation à l'ASN et à l'IRSN de vos conclusions concernant le dossier de justification de l'aptitude au service des cuves des réacteurs de Doel 3 et Tihange 2"*)[13].

A second letter from ASN concerning the justification of the operational aptitude of the reactor pressure vessels of Doel 3 and Tihange 2 ("*Examen du dossier de justification de l'aptitude au service des cuves des réacteurs de Doel 3 et Tihange 2*") was addressed to the Belgian Nuclear Authority FANC (December 26, 2012)[14]

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[10] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

[11] Report of the National Scientific Expert Group on the RPVD3T2, 11/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3392.pdf

[12] FANC, Doel 3 - Tihange 2 RPV issue: International Expert Review Board Final Report, 15/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3393.pdf

[13] ASN-IRSN, Présentation à l'ASN et à l'IRSN de vos conclusions concernant le dossier de justification de l'aptitude au service des cuves des réacteurs de Doel 3 et Tihange 2, 21-12-2012 http://www.asn.fr/index.php/content/download/36843/272621/file/CODEP-DEP-2012-069143.pdf

[14] ASN-IRSN Examen du dossier de justification de l'aptitude au service des cuves des réacteurs de Doel 3 et Tihange 2, 26-12-2012 http://www.asn.fr/index.php/content/download/36842/272618/file/CODEP-DEP-2012-069419.pdf

2. Assessment of the published documents

Futher to her request of December 2012 to evaluate the available facts on the issue[15], in February 2013, Rebecca Harms, Co-President of the Greens/EFA Group in the European Parliament, asked the author to evaluate the available documents and to evaluate inter alia whether the complementary tests that are now scheduled are enough to qualify the re-start of the two nuclear power plants in case the results of these tests are positive or, on the contrary, are not enough to qualify for such a re-start even if the new tests looked positive.

2.1 Manufacture of the reactor pressure vessels

The reactor pressure vessels (RPVs) of the NPPs Doel 3 and Tihange 2 were manufactured by Rotterdamsche Droogdok Maatschappij (RDM). As mentioned above it is already known since September 2012 that the documentation is not complete.

In contrary Electrabel states:

> *„A close review of all of the original manufacturing data and documentation revealed that the Doel 3 / Tihange 2 reactor pressure vessel was manufactured in accordance with the prevailing international codes and standards, in particular the ASME Boiler & Pressure Vessel Code. All manufacturing inspections required by the construction code were performed and witnessed by the customer and regulatory body and concluded in the acceptance of all parts of the reactor pressure vessels. The manufacturing data and documentation proved to be complete, traceable, and in accordance with international codes and standards."*[16,17]

With respect to the manufacture and inspection of the pressure vessel rings of concern, the Regulatory Authority FANC reports:

> *„It should be noted that a first non-mandatory inspection report of the upper core shell of Doel 3 mentioned a large area of indications. There are elements in favour of the hypothesis that this report, currently filed with the upper core shell, would be in fact related to the lower core shell, where a large number of indications were found in 2012."*

FANC does however not explain whether the „large area of indications"can be correlated with the area of indications found in 2012 (based on the suspicion that the nomenclature for the shells have been interchanged).

The AIB-Vinçotte experts' statement is reported by FANC:

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[15] At that time, the author had no access to operator Electrabel's justification reports nor to their assessment by the Belgian Federal Agency for Nuclear Control (FANC) and/or its self-appointed scientific review teams.

[16] Electrabel, Safety case report: Doel 3 - Reactor Pressure Vessel Assessment, 05/12/2012 http://www.fanc.fgov.be/GED/00000000/3300/3390.pdf

[17] Electrabel, Safety case report: Tihange 2 - Reactor Pressure Vessel Assessment,05/12/2012 http://www.fanc.fgov.be/GED/00000000/3300/3389.pdf

„The non-reporting of hydrogen flake-type indications during these surface examinations can be considered as normal."

According to FANC the members of the Belgian National Scientific Council and the International Review Board are convinced that at the time of the RPV manufacturing, in the late 1970s, the flaws detected in 2012 were detectable already.

„The discrepancy between the indications reported in the acceptance reports of the rings from the 1970s and in the 2012 inspection in the core shells of the two plants remains unresolved, since the UT technology available at that time should have had the capacity to detect the indications found. Furthermore, it is documented that some other parts, like the transition rings, were rejected exactly because of these hydrogen flakes."[18]

"Inspection of the transition ring og Tihange 2 revealed unacceptable indications that were due to hzdrogen flaking, according to RDM/RN. The component was rejected and a new transition ring was manufactured for Tihange 2."[19]

FANC concludes that

„Hence, based on the sole manufacturing files, the presence of flaw indications since the manufacturing stage cannot be confirmed as, for a number of forged components, the indications which were detectable at this stage were not reported in the inspection reports."[20]

Since it has to be assumed that all the available documentation has been assessed, FANC does not formulate any additional requirements in this respect.

The German reactor safety commission RKS has confirmed in a comment that in the ultrasonic testing equipment available at the time of manufacture was appropriate to detect flaws of the type and size as observed in 2012.[21]

REMARKS:

- The documentation on the manufacture is not complete; FANC did not explain why the Licensing Authority did never control the completeness of the documentation.
  In this context it is interesting to note that the former member of the German Nuclear Regulatory Authority Dieter Majer reported that a component for the NPP Biblis has been rejected due to incoherent documentation.[22]

[18] FANC, Doel 3 - Tihange 2 RPV issue: International Expert Review Board Final Report, 15/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3393.pdf

[19] FANC, Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

[20] FANC, Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

[21] RSK-Stellungnahme, (454. Sitzung am 17.01.2013), Ultraschallanzeigen am Reaktordruckbehälter des belgischen Kernkraftwerks Doel, Block 3 (Doel-3)
http://www.rskonline.de/downloads/epanlagersk454hp.pdf

[22] Aachener Aktionsbündnis gegen Atomenergie (http://www.anti-akw-ac.de)

- The document on the final inspection after manufacture exists but does not contain any evidence of observed flaws.
- Flaws as observed in 2012 were detectable with the available equipment at the time of manufacture.
- The manufacturer and the Owner knew about de detrimental effects of hydrogen flaking, since other components were rejected due to hydrogen flaking, as the transition ring of Tihange 2. The rejection of the transition ring implies that the hydrogen flaking based indications have not been present after manufacture in the rings affected today, since otherwise the components would also have been rejected.
- Based on the common knowledge on the hazardousness of hydrogen related defects in steels, AIB-Vinçotte experts' statement that the non-reporting of hydrogen flaking indications is considered to be normal is amazing, esp. in the context of a component such as a nuclear pressure vessel.

2.2 In-service inspection methodology

According to the Regulatory Authority FANC (incl. Bel V and AIB-Vinçotte) the UT methodology used in 2012 is qualified for the detection of cracks in the circumferential welds of the reactor pressure vessel. The methodology is not qualified for detection and sizing of the type of flaws that were discovered in 2012.

The National Scientific Expert Group states:

> *"The available information on the validation of the inspection procedure does not give conclusive evidence that the inspection tool and inspection procedure used ensure that all potentially critical flaws have been detected with certainty"*[23]

According to FANC not all areas of the pressure vessel shells are accessible to ultrasonic testing. It is obviously also not confirmed that all existing defects were detected:

> *„Yet, the national scientific expert group considers that there is still a possibility that potentially critical flaws were not captured during on-site inspection. Indeed, the flaws occur in different planes in very large numbers, the inclination of the individual flaws varies, and it cannot be excluded that potentially critical flaws, damaged or embrittled ligaments, were not captured by the onsite non-destructive procedure used."*[24]

[23] Report of the National Scientific Expert Group on the RPVD3T2, 11/01/2013
http://www.fanc.fgov.be/GED/00000000/3300/3392.pdf

[24] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013
http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

Based on AIB-Vinçotte requests, the Owner is performing a short-term qualification of the methodology with respect to detection efficiency and sizing using hydrogen flakes containing test blocks.

> *„This material is a block (VB-395/1 block) taken from an AREVA steam generator lower shell (VB-395) that was rejected in 2012."*[25]

The description of this block does not include information whether the density of defects is comparable with the flaw density observed in the RPV shells.

This material cannot be considered to be representative for the reactor pressure vessel material (the block is from another nuclear power plant, component, has not the same manufacturing history, is not cladded and has not undergone the same operational history), but is assumed to have similar defects.

The French Nuclear Authorities ASN and IRSN emphasize also the questionable representativeness of the envisaged test block material:

> *„Les essais dans des zones affectées de défauts dus à l'hydrogène ne peuvent être réalisés que sur la virole VB 395 dont la représentativité vis-à-vis de la situation de Doel 3 et Tihange 2 n'est pas avérée."*[26] *[The experiments in the areas with hydrogen-related defects can only be realized using the shell section VB395 whose representativeness for the situation of Doel 3 and Tihange cannot be proven. Translation I.T.]*

According to FANC for a "*fully representative qualification campaign*" a second block (VB-395/2) will be fabricated with a cladding and an additional heat treatment. The tests shall be performed using ultrasonic testing equipment immersed in a testing pool to simulate the realistic conditions. This qualification procedure is not supposed to be finished before a possible restart of the two reactor blocks.

Special attention shall be given to flaws possibly hidden by other defects and tilted flaws that are the more hazardous defects. An adequate detection of bridges between flakes shall be possible.

The National Authority FANC requests also a re-analysis of the near-surface detected flaws in Tihange 2 in order to differentiate between the assumed hydrogen-related defects and technological cladding defects.

REMARKS:

- The large number of detected flaws is confirmed but it is still not sure that all existing defects were detected.

[25] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

[26] ASN-IRSN, Présentation à l'ASN et à l'IRSN de vos conclusions concernant le dossier de justification de l'aptitude au service des cuves des réacteurs de Doel 3 et Tihange 2, 21-12-2012 http://www.asn.fr/index.php/content/download/36843/272621/file/CODEP-DEP-2012-069143.pdf

- The actually used ultrasonic testing equipment is not qualified for detection and sizing of the type of flaws of concern. The envisaged qualification program cannot realistically be completed in short time.
- The available sample material for the qualification program cannot be considered to be representative for the reactor pressure vessels of Doel 3 and Tihange 2 neither with respect to the manufacturing processes, nor with respect to the operational history.
- It is not even known whether the density of defects in the AREVA block is comparable with the density of indications found in the RPVs.

2.3 Origin and nature of the observed flaws

According to Electrabel (Owner) the origin of the indications found during the 2012 in-service inspection of the Doel 3 and Tihange 2 reactor pressure vessels (RPVs) can be attributed to hydrogen flaking during fabrication.

> *„The first diagnosis of hydrogen flaking was evaluated based on:*
> *- An extensive literature study*
> *- A root cause analysis of all potential causes*
> *- An evaluation of the possible flaw formation mechanisms*
> *- A detailed evaluation report of the AREVA metallurgy experts based on the construction files and the shape and size of the indications*
> *This report was challenged and completed by external experts. As a result, the first diagnosis was confirmed. It was also concluded that the identified indications were stable.“*[27]

According to FANC, Bel V accepts this evaluation but

> *„Bel V notes however that no comprehensive root cause analysis could explain why the hydrogen-induced degradation did not evenly affect all the forged components of the Doel 3 and Tihange 2 reactor pressure vessels, though their hydrogen content is comparable.“*[28]

According to FANC the participating expert groups agree that low cycle fatigue resulting from transients is the only theoretically possible propagation mechanism of existing hydrogen flakes. The International review board recommended “*a dedicated follow-up program to monitor the size of at least the most adverse flaws, namely the largest ones closest to the inner side of the vessel wall and the areas with pronounced concentrations of flaws*.”[29]

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[27] Electrabel, Safety case report: Doel 3 - Reactor Pressure Vessel Assessment, 05/12/2012, page 88 http://www.fanc.fgov.be/GED/00000000/3300/3390.pdf

[28] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

[29] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

The Regulating Authority FANC requests:

> *"After the restart of both reactor units, the licensee shall perform follow-up in-service inspections during the next planned outage for refuelling to ensure that no evolution of the flaw indications has occurred during operation."*[30]

The French Regulatory Authorities ASN and IRSN note in their letter to Bel V:

> *„L'ASN et l'IRSN ont également noté qu'il ne figure pas, dans le dossier fourni par Electrabel, de description précise des défauts, même pour les défauts présentant les marges les plus faibles ou ceux situés dans les zones où les fissures sont les plus denses. Par ailleurs, le caractère enveloppe du modèle retenu pour les calculs mécaniques reste insuffisamment justifié. En effet, Bel V a constaté en étudiant des macrographies réalisées par AREVA sur la virole VB 395 que la forme des défauts expertisés peut s'éloigner significativement d'un défaut parfaitement plan."*[31]
> *[ASN and IRSN have also noted that in the dossier presented by Electrabel a precise description of the defects is not given, neither for the defects that present the lowest margins nor those that are situated in the zones with highest crack density. Furthermore, the enveloping character of the model considered for the mechanical calculations remains insufficiently justified. In fact, Bel V has observed studying AREVA's macrographies of the sample VB 395 that the evaluated defects can deviate significantly from a perfect plane defect." Transl. I.T.]*

The German reactor safety commission RSK comments that forgings for German RPVs would have been rejected during RPV manufacture in case of observed indications such as found in the Doel 3 and Tihange 2 RPVs[32]. The RSK indicates also that for German RPVs the tests during manufacture included surface inspections of the rings with respect to hardness and surface impruities using Baumann tests (sulfur prints) that are not required by the ASME code.

REMARKS:

- The participating expert groups agree that the indications can be attributed to hydrogen flaking originating from the manufacturing process although there is no realistic proof.
- The expert groups cannot explain why not all of the pressure vessel shells are affected by these hydrogen-related defects, although the same hydrogen content is assumed.
- Although no literature exists on irradiation experiments performed on defected samples the Regulatory Authority excludes radiation effects enhancement of defect growth or propagation.

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[30] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

[31] ASN-IRSN, Présentation à l'ASN et à l'IRSN de vos conclusions concernant le dossier de justification de l'aptitude au service des cuves des réacteurs de Doel 3 et Tihange 2, 21-12-2012 http://www.asn.fr/index.php/content/download/36843/272621/file/CODEP-DEP-2012-069143.pdf

[32] RSK-Stellungnahme, (454. Sitzung am 17.01.2013), Ultraschallanzeigen am Reaktordruckbehälter des belgischen Kernkraftwerks Doel, Block 3 (Doel-3) http://www.rskonline.de/downloads/epanlagersk454hp.pdf

It was nowhere discussed whether anything might have happened at the raw ferritic pressure vessel inner surface and/or during the process of cladding that has induced defect growth into the vessel wall during operation. Such processes could explain that only some shells are affected and that the observed flaws are rather close to the interface. Such processes should at least have been taken into account as a possible/likely explanation for the presence of the flaws. Because these processes induce that defects grow during operation, taking them into account should be a prerequisite for any consideration of a restart.

2.4 Tests performed by Electrabel

Electrabel claims to have performed a comprehensive materials testing program on more than 400 specimens that were tested in different laboratories (AREVA, Laborelec, SCK.CEN). The specimens were prepared using the following materials:

> *„Archive material from the Doel 3 core shells (SCK.CEN Doel 3 block): an unirradiated weld coupon with the base material of the upper core shell remaining from the RPV embrittlement surveillance program was available at the Belgian nuclear research centre SCK.CEN, with dimensions of 245 x 200 x 610 mm.*
>
> *An AREVA nozzle cut-out: the nozzle cut-out is the circular part removed from the nozzle shell to insert the inlet and outlet nozzles. One such nozzle cut-out from a French unit was available at AREVA. The cut-out was already partially characterized and it was known to have macro-segregations.*
>
> *Also at AREVA, a nozzle cut-out from Doel 3 was available. In this cut-out the presence of a zone of macro-segregations was identified by chemical etching."*[33]

According to the Regulatory Authority FANC the experts from AIB-Vinçotte note that no test samples or specimens with hydrogen flakes are available from the Doel 3 and Tihange 2 reactor pressure vessels shells. Therefore, "*some*" uncertainty about the representativeness of the test program for the actual reactor pressure vessel shells cannot be excluded.[34]

The other participating expert groups agreed that "specimens *containing hydrogen flakes would be desirable*"[35].

Inspite of this "desire" there is no request to produce materials comparable to the affected pressure vessel shells.

REMARKS:

[33] Electrabel, Safety case report: Doel 3 - Reactor Pressure Vessel Assessment, 05/12/2012. Page 60 http://www.fanc.fgov.be/GED/00000000/3300/3390.pdf

[34] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

[35] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013, page 38 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

- The specimens used for the metallurgical/mechanical experimental test cannot be considered to be representative for the actual state of the reactor pressure vessel steel. The specimens represent at best the condition of the pristine manufactured pressure vessel.
- The specimens used for experiental testing are too small to include defect containing regions representative for the pressure vessel material of concern.
- There is no conceivable way to produce specimens that can be considered to be representative for the actual state of the pressure vessel rings of concern, including the thermal, neutronic and pressure stresses undergone by the RPVs during their 30 years of operation.

2.4.1 Mechanical properties

Most of the mechanical tests were fracture toughness measurements (188 tests on precracked Charpy specimens, 138 tests on compact-tension specimens), 42 Charpy-V tests and 64 tensile tests.

In the published document[36] Electrabel reports the results of orientation and macro-segregation effects on fracture toughness values, no significant effects were found. No data are reported from Charpy-V and tensile tests.

According to the regulatory Authority FANC the international review board point to the problem of transferability:

> *„Moreover, the investigations could not be carried out on material that can be proven to be fully representative for the materials in the region of the indications, and the effect of thermal ageing has not been accounted for.“*[37]

FANC concludes that

> *„ However, no test sample or specimen containing hydrogen flakes is available from the Doel 3 and Tihange 2 reactor pressure vessel shells. Therefore, some uncertainty about the representativeness of the test program exists.“*[38]

FANC formulates requests concerning test programs that have to be performed before restart and test programs that have to be performed thereafter.

REMARKS:

[36] Electrabel, Report on independent analysis and advice regarding the safety case - Doel 3 Reactor Pressure Vessel Assessment, 19/12/2012
http://www.fanc.fgov.be/GED/00000000/3300/3397.pdf

[37] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013
http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

[38] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013
http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

- The results of the fracture mechanical testing can only prove that the archive material used for the experiments meets the specifications even in macro-segregated regions. The results can in no way be considered to reveal the mechanical materials characteristics of the actual state of the pressure vessel base metal (thermal aging and radiation effects besides the hydrogen flake type defects).
- No experimental data exist on the fracture toughness degradation of the RPV steel due to hydrogen flaking. Literature data indicate that large ductility degradation is possible.[39,40]
- Even in case of performed tensile tests with large-scale specimens that include hydrogen flakes (AREVA material), acceptable results cannot exclude that the ductility of the pressure vessel material has been degraded in reality.

2.4.2 Radiation-induced effects

Neutrons (with energies above about 0.5 MeV) cause atomic displacements in the materials lattice structure, creating interstitials and vacancies that can diffuse through the lattice, recombine or agglomerate or interact with impurities forming larger defects. These defects may cause embrittlement of the material. Radiation (neutrons, gamma radiation) reaching the RPV wall without displacing atoms in the materials lattice structure, can enhance diffusion of impurities by the deposited energy, the so-called radiation-enhanced diffusion (RED). Another effect originating from radiation impact on materials is the radiation-induced segregation (RIS), defined as a radiation-induced redistribution of alloy constituents and impurities at point defect sinks.

Radiation embrittlement of reactor pressure vessel (RPV) materials (base metal, weld, heat-affected zone) is monitored in the frame of the surveillance program using irradiation capsules with samples irradiated with a so-called lead factor (ratio of the neutron flux at the capsule position and the the neutron flux at the RPV wall). According to Electrabel the irradiation capsules of Doel 3 and Tihange 2 have all been withdrawn and evaluated.

The samples used in the surveillance program have to be fabricated from RPV specific archive materials. It can be assumed that the surveillance program specimens of Doel 3 and Tihange 2 did not contain hydrogen flakes. Therefore no experimental information exists on the radiation embrittlement of hydrogen-defect containing material.

Radiation embrittlement causes a shift of the ductile-brittle transition temperature of the material to higher values, i.e. the material that is normally ductile at operation relevant temperatures could become brittle in this temperature range. In order to prevent this hazardous state radiation

[39] B.I.Voronenko, Hydrogen and flakes in steel, Metal science and heat treatment, November 1997, Volume 39, Issue 11, pp 462-470

[40] A.R. Elsea, E.E.Fletcher, Hydrogen-induced delayed brittle failures of high-strength steels, Defense Metals Information Center, Batelle Mem.Inst. Columbus, Ohio, DMIC Report 196, 1964 http://www.dtic.mil/cgi-bin/GetTRDoc?AD=AD0601116

embrittlement is monitored by the surveillance program on the one hand and by the predictive FIS[41]-curves temperatures on the other hand. These curves describe the shift of the so-called nil-ductility reference temperature RT_{NDT} as function of the neutron fluence dependent on copper and phosphorus impurity content of the materials.

Due to the fact that no information exists on radiation embrittlement materials containing hydrogen-related defects Electrabel has proposed to add 50°C to RT_{NDT} "*on top of the irradiation effect*". Electrabel considers this procedure as "*very conservative*"[42] (emphasis added by the author).

There is a remarkable inconsistency about this 50°C shift in Electrabel's documents:

On page 58 of the Electrabel document[43] it is stated:

> *„A conservative approach was followed to determine the material properties to be used in these assessments. They were also performed on the basis of the* ***RT_{NDT} evaluated by the FIS formula (for the nominal composition), with an additional shift of 50°C****". (marking by the author)*

For end-of-life RT_{NDT} (FIS) is about 73°C (in case of Doel 3), with the additional 50°C the resulting $RT_{NDT}^{(FIS+50)}$ would be **about 123°C** (see figure 1).

And on page 82 of the same document:

> *"The RTNDT of the core shells at the end of the RPV's service lifetime was calculated* **as the sum of the RTNDT evaluated in the framework of the Doel 3 RPV Surveillance Program and the additional RT_{NDT} shift of 50 °C** *that covers the effect of macro-segregations on the fracture toughness." (*marking by the author*)*

For end-of-life the resulting RT_{NDT} (for Doel 3) including the 50°C shift would be 106.5°C (Electrabel document, page 82) as can be seen in the following figure:

[41] FIS : formule d'irradiation supérieure

[42] Electrabel, Safety case report: Doel 3 - Reactor Pressure Vessel Assessment, 05/12/2012, page 58 http://www.fanc.fgov.be/GED/00000000/3300/3390.pdf

[43] Electrabel, Safety case report: Doel 3 - Reactor Pressure Vessel Assessment, 05/12/2012 http://www.fanc.fgov.be/GED/00000000/3300/3390.p

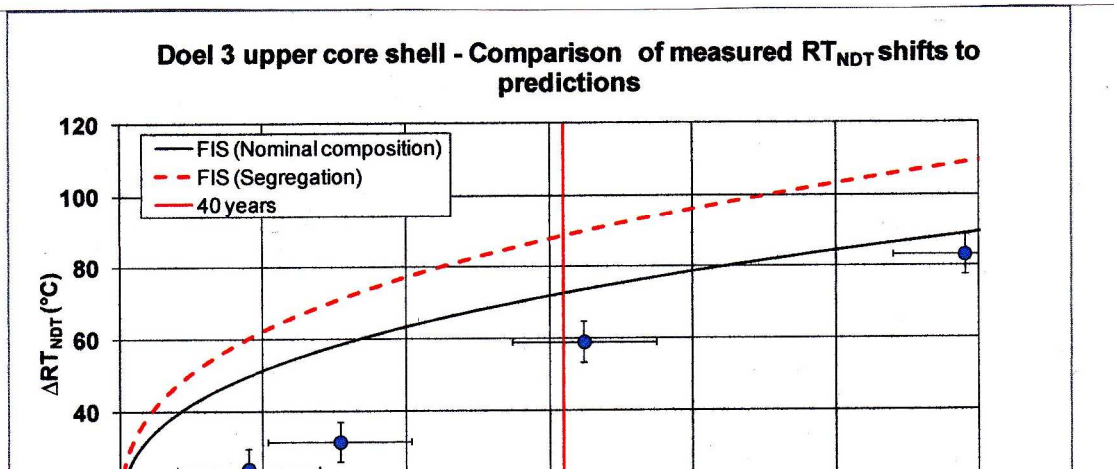

Figure 1: Radiation embrittlement of the base metal of Doel 3 RPV, FIS formula for nominal composition (Cu, P impurities) and for the case of segregation; experimental data from the surveillance program. From Electrabel, Safety case report: Doel 3 - Reactor Pressure Vessel Assessment, 05/12/2012.

According to FANC the Bel V experts note with respect to the value of 50°C:

> *"There is so far no demonstration that the 50°C shift in RT_{NDT} proposed by the licensee to take account of the hydrogen-induced flaws is appropriate to cover the potential deterioration of the local fracture toughness properties in the vicinity of the flaws."*[44]

According to FANC, Bel V and AIB-Vinçotte have therefore requested appropriate test programs:

> *„High confidence in the safety demonstration also requires that the presence of hydrogen-induced flaws does not decrease the ductility to an unacceptable level. Tensile testing on large specimen with flakes parallel to the specimen axis is planned as part of the complementary testing program. The results of those tests will provide useful information on the ductility. AIB-Vinçotte has also required performing additional tensile testing on large-scale specimen with flakes having a tilt angle of about 20° 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."*[45]

[44] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

[45] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

These requests are endorsed by the Nuclear Safety Authorities expert working groups. These experts have also noted that:

> *„The impact of irradiation on the in-service evolution of hydrogen flakes is difficult to evaluate, since it is not possible to compare the flakes with their initial characteristics (this information is not available). No experiment exists on this topic.“* [46]

The Regulatory Authority FANC concludes that

> *„Within a limited time frame, a material testing program was performed by the licensee on the available specimens. However, no test sample or specimen containing hydrogen flakes is available from the Doel 3 and Tihange 2 reactor pressure vessel shells. Therefore, some uncertainty about the representativeness of the test program exists.*
>
> *Furthermore, there is at present little experimental data available about the (local) mechanical properties of materials in zones with macro-segregations containing hydrogen flakes. This applies even more to irradiated materials containing hydrogen flakes. Hence more experimental data on tensile and toughness properties of the materials are needed to validate the approach followed in the structural integrity assessment for both reactor pressure vessels and especially to confirm that the additional 50° shift in RT_{NDT} proposed by the licensee is conservative.“* [47]

In the context of the proposed additional 50°C shift of RT_{NDT} the French Regulatory Authorities point to the fact that the used FIS-curves are no more considered to be conservative for high fluences:

> *“Bien que ce point soit d’une moindre importance que les éléments mentionnés ci-avant, l’ASN et l’IRSN vous informent également que la prise en compte des effets de l’irradiation par Electrabel repose sur l’utilisation de l’ancienne version de la formule FIS dont l’ASN a considéré qu’elle était insuffisamment conservative aux fortes fluences.”*[48] *[“Although it is of less importance than the elements mentioned above ASN and IRSN inform you that the consideration of radiation effects by Electrabel is based on the old version of the FIS formula which ASN considers to be insufficiently conservative for high fluencies.” Transl. I.T.]*

The indication that the predictive curves used for French/Belgian reactor base metals are not considered to be conservative anymore can also be found in a contribution from Tractebel:

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[46] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013, page 38 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

[47] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

[48] ASN-IRSN, Présentation à l’ASN et à l’IRSN de vos conclusions concernant le dossier de justification de l’aptitude au service des cuves des réacteurs de Doel 3 et Tihange 2, 21-12-2012 http://www.asn.fr/index.php/content/download/36843/272621/file/CODEP-DEP-2012-069143.pdf

"However, tendency to overestimate the welds embrittlement while underestimating the base materials embrittlement at high fluence."[49]

With respect to the envisaged irradiation programs ASN and IRSN note in their letter to BelV:

"La réalisation d'essais sur des zones présentant des défauts dus à l'hydrogène et irradiées nécessiterait une irradiation à haut flux qui soulèverait des problèmes de représentativité."[50] *[The realization of experiments on irradiated zones with hydrogen-related defects would need high flux irradiation which would raise problems of representativeness."Transl. I.T.]*

The US regulation 10CFR50.61 "fracture toughness requirements for protection against pressurized thermal shock" (PTS) requires that the RT_{NDT} of the base metal of the Doel 3 RPV forged components will remain below 132 °C at the end of its service lifetime (screening criterion).

Electrabel notes:

„The RT_{NDT} of the core shells at the end of the RPV's service lifetime was calculated as the sum of the RT_{NDT} evaluated in the framework of the Doel 3 RPV Surveillance Program and the additional RT_{NDT} shift of 50 °C that covers the effect of macro-segregations on the fracture toughness. The maximum RT_{NDT} obtained for the upper core shell is 106.5 °C, which is still below the acceptable value of 132 °C."[51]

It has to be repeated here that the other version in Electrabel's dossier results in 123°C (without scatter of the data) which is already quite close to 132°C.

In this context the recommendation of the International Review Board (according to FANC) to use an additional RT_{NDT} shift of 100°C for sensitivity analyses[52] is surprising since additional 100°C would surmount the screening criterion value of 132°C.

REMARKS:

- No experimental data exist on radiation embrittlement of reactor materials with hydrogen flaking.
- Since no information exists on the toughness degradation of the RPV steel without irradiation due to hydrogen flaking, the application of the FIS formula to estimate the actual radiation embrittlement cannot be considered to be conservative.

[49] A-S. Bogaert, R. Gérard, R. Chaouadi; Belgian RPV embrittlement studies for LTO issues; IAEA Technical Meeting on Irradiation Embrittlement and Life Management of Reactor Pressure Vessels in Nuclear Power Plants, Znojmo, 18-22 October 2010
http://www.iaea.org/NuclearPower/Downloads/Engineering/meetings/2010-10-TM-Czech/48.pdf

[50] ASN-IRSN, Présentation à l'ASN et à l'IRSN de vos conclusions concernant le dossier de justification de l'aptitude au service des cuves des réacteurs de Doel 3 et Tihange 2, 21-12-2012
http://www.asn.fr/index.php/content/download/36843/272621/file/CODEP-DEP-2012-069143.pdf

[51] Electrabel, Safety case report: Doel 3 - Reactor Pressure Vessel Assessment, 05/12/2012, p.82
http://www.fanc.fgov.be/GED/00000000/3300/3390.pdf

[52] FANC Doel 3 - Tihange 2 RPV issue: International Expert Review Board Final Report, 15/01/2013
http://www.fanc.fgov.be/GED/00000000/3300/3393.pdf

- There is an inconsistency in the Electrabel document with respect to the additional 50°C shift: additional to the RT_{NDT} value from the FIS formula or additional to a mean experimental value of RT_{NDT}? The difference is at least 15°C, without consideration of the experimental data scatter (this means that the safety margin is smaller than claimed).

- The safety margin of 50°C additional to the measured RT_{NDT} shift (mean value, not the upper bound value) in the frame of the surveillance program to cover all possible impurity and hydrogen flaking effects has to be considered rather arbitrary.

- An additional uncertainty results from the application of the old version of the FIS formula that has to be considered as not conservative as mentioned in the ASN/IRSN letter.

- Irradiation programs in the future would require high-flux irradiation in order to get results in reasonable time periods. Due to a possible dose rate effect[53] high-flux irradiation results might underestimate the real embrittlement.

- It has to be kept in mind that no RPV specific material exists for such an irradiation program. The specimens from the AREVA material cannot be considered to be representative.

- Radiation-enhanced diffusion and radiation-induced segregation effects that could influence hydrogen flaking type defects are neither mentioned in the Electrabel documents nor in the FANC evaluation. Such processes should at the very least have been taken into account.

2.4.3 Thermomechanically caused effects (low-cycle fatigue)

Besides the radiation effects the materials characteristics can also be degraded by thermal aging and low-cycle fatigue due to operational transients (temperature and pressure changes, for instance during shut-down and start-up). Thermal aging effects are considered to be covered by the surveillance program. It has to be underlined that thermal aging effects on materials with hydrogen flaking have not been investigated.

Electrabel has performed a fatigue crack growth analysis in accordance with the rules of ASME XI Appendix A with the result:

> *„The flaws propagate with less than 2.4 % of the flaw size, over a period of 40 years. For instance, for the largest flaw, the growth would be less than 1.1 mm in 40 years."*[54]

The Regulatory Authority FANC summarizes their experts view on fatigue effects:

> *„Regarding the fatigue crack growth, Electrabel provided calculations of the fatigue crack growth of the hydrogen flakes. The calculated fatigue crack growth in depth was found to be less than 2% for a 40 year lifetime. Bel V considers that, even if the calculated fatigue growth could possibly be*

[53] Dose rate effect: embrittlement may be higher at lower irradiation flux compared with the embrittlement at higher flux for the same total radiation dose

[54] Electrabel, Safety case report: Doel 3 - Reactor Pressure Vessel Assessment, 05/12/2012, p.56 http://www.fanc.fgov.be/GED/00000000/3300/3390.pdf

qualified as low in the absolute, it may not be considered as non-significant in the context of the reactor pressure vessels issue. In fact, Bel V considers that the hydrogen-induced flaws are required to experience no fatigue growth."[55]

REMARKS:

- There are no experimental data on low-cycle fatigue effects on materials containing hydrogen flaking. Even more: no information exists on the simultaneous interaction of irradiation, temperature and fatigue on hydrogen flakes.
- The interaction of the hydrogen-related defects with each other, including bridging effects has not been considered at all by Electrabel.
- The fatigue crack growth analysis performed by Electrabel assumes that cracks with the size of the observed flaw indications will grow less than 2 % in 40 years. As Bel V mentioned this is no relevant result since any growth of the hydrogen flake type defects has to be excluded.

2.4.4 Structural integrity of the reactor pressure vessels - pressurized thermal shock analysis

The deterministic structural integrity assessment (SIA) of reactor pressure vessels includes a fracture mechanical analysis of the RPV during normal and accidental operation, the so-called pressurized thermal shock (PTS) analysis, that is required in the frame of the safety analysis according to the Standards (ASME code, KTA, etc.). Under severe transients (thermal shock under pressure) an existing critical-size flaw could propagate rapidly through the vessel wall due to the evolving stresses and cause vessel rupture with catastrophic consequences. Using thermal-hydraulic codes and fracture mechanical methods, the thermal stresses on a hypothetical crack are calculated for assumed transients and the resulting stress intensity curves are then compared with the experimental fracture toughness characteristics. The Standards (PTS Rule in Title 10, Section 50.61, of the Code of Federal Regulations 10 CFR 50.61; KTA 3201.2) define the shape and size of the cracks to be considered. A probabilistic analysis is considered as a complementary effort.

Electrabel summarized their structural integrity assessment (SIA):

„After studies and testing, the multidisciplinary team developed detailed methodologies for assessing the structural behaviour of each flaw detected in the vessels shell, in all possible operational modes and transients. These methodologies have been validated after research and were challenged by external experts specialized in fracture mechanics and structural analysis, who confirmed the conservativeness of the methods.
Based on these methodologies, detailed calculations were made using state-of-the-art modelling and computing techniques, in order to verify the applicable structural integrity requirements. Calculations were performed using conservative data: in particular, very conservative fracture toughness data were used compared to actual material test results. These calculations included

[55] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

the following:
- Deterministic calculations according to ASME Section III, to assess general stresses in the vessel
- Deterministic calculations according to ASME Section XI, to demonstrate that the dimensions of every flaw and group of flaws are well below the allowable dimensions, in all operating conditions
- Probabilistic safety analyses based on the US regulation.
All studies and calculation results have been thoroughly reviewed internally and by external experts and academics. The calculations confirm that the acceptance criteria of the deterministic studies are met with a significant safety margin. The criterion of the probabilistic safety analysis is widely satisfied as well, even under the conservative assumptions."[56]

The existence of a large amount of indications as observed in the RPVs of Doel 3 and Tihange 2 is not covered by the standards (ASME code, German KTA). Therefore Electrabel has introduced its own method of grouping the flaws.

According to FANC the experts of AIB Vinçotte state:

„In addition, the approach described in ASME XI code is in principle applicable for the justification of indications originating from in-service degradation mechanisms and not for the justification of large numbers of fabrication flaws in base materials, the exact origin of these defects being uncertain. Hence the suitability and conservativeness of the approach shall be validated on the large-scale tests (short-term requirement). This test on a sample with multiple hydrogen flake defects, shall in particular demonstrate that there's no risk for brittle fracture and that the material has sufficient ductility."[57]

The Regulatory Authority FANC concludes:

„A deterministic flaw evaluation of each detected indication in accordance with the basic principles of Section XI of the ASME Code was performed by the licensee. However, the approach described in this ASME code is in principle applicable for the justification of indications originating from in-service degradation mechanisms and not for the justification of large numbers of interacting flaws in base materials. Therefore, though the philosophy and background of the ASME code can be used for reference, the suitability of the approach adopted by the licensee to justify the structural integrity of the reactor pressure vessels needed to be validated on some topics. Several issues in the fracture mechanics evaluation were therefore studied more in detail to ensure that sufficient conservatism was included in the analytical flaw calculations: modelling of flaws, grouping criteria used for flaw interactions, use of most penalizing transients,…
The development of a "screening criterion" for the analytical flaw evaluation was in this way also useful to clearly identify the flaws that are most detrimental for the safety of the reactor pressure vessels and focus attention on these flaws. The licensee's calculations show that a very large majority of indications has no safety impact."[58]

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[56] Electrabel, Safety case report: Doel 3 - Reactor Pressure Vessel Assessment, 05/12/2012, page 7 http://www.fanc.fgov.be/GED/00000000/3300/3390.pdf

[57] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

[58] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

It has to be mentioned that the grouping approach is not validated and presumably there is a need for official approval by the Regulatory Authority.

With respect to the transients used in the structural integrity analysis the French Regulatory Authorities ASN and IRSN mention in their letter to Bel V:

> *„L'ASN et l'IRSN ont noté que ces aspects sont pris en compte de façon bien moins détaillée que ce qui est exigé dans les dossiers examinés en France. En particulier, le nombre de transitoires étudié est limité sans justification probante et des transitoires comme les brèches sur les tuyauteries vapeur ou les tuyauteries d'alimentation en eau ne sont pas étudiés. Le transitoire conduisant, dans l'étude probabiliste, à la probabilité conditionnelle d'amorçage des défauts la plus élevée n'est pas étudié."*[59] *[ASN and IRSN noted that these aspects have been considered in a much less detailed way than it would be required in dossiers in France. In particular the number of transients studied is limited without convincing justification and transients like the steam line break or feed water line break have not been studied. The leading transient in the probabilistic assessment with the highest contribution to the conditional probability of defect growth has not been studied." Transl I.T.]*

In a letter to the Regulatory Authority FANC the French Authorities ASN and IRSN state that in a safety case comparable to Doel 3 and Tihange 2 the French authorities would request (among others):

> *„la justification du choix des transitoires étudiés dans les calculs mécaniques, ou l'étude de scénarios d'accidents complémentaires, et la justification du caractère conservatif de leur description (en effet, les études réalisées en France ont montré que certains scénarios accidentels pouvaient conduire à des sollicitations des défauts plus pénalisantes que les brèches primaires).*[60] *[„the justification of the selection of transients studied in the mechanical calculations or the study of complementary accident scenarios and the justification of the conservative character of their description (in fact the studies performed in France have shown that specific accident scenarios can cause higher stresses on the defects than primary breaks.)" Transl. I.T.]*

REMARKS:

- The validity of the pressurized thermal shock analysis should be based on the correct input for the thermohydraulic analysis[61], i.e. the consideration of the most penalizing transients. This has obviously not been the case in Electrabel's analysis.

[59] ASN-IRSN, Présentation à l'ASN et à l'IRSN de vos conclusions concernant le dossier de justification de l'aptitude au service des cuves des réacteurs de Doel 3 et Tihange 2, 21-12-2012
http://www.asn.fr/index.php/content/download/36843/272621/file/CODEP-DEP-2012-069143.pdf

[60] ASN-IRSN Examen du dossier de justification de l'aptitude au service des cuves des réacteurs de Doel 3 et Tihange 2, 26-12-2012
http://www.asn.fr/index.php/content/download/36842/272618/file/CODEP-DEP-2012-069419.pdf

[61] Thermohydraulic calculations are needed to determine the temperature distribution at the RPV wall during hypothetical transients

- It is known that asymmetric cooling conditions at the RPV wall may occur during severe transients causing thermal stress gradients in the RPV wall ("cold tongues" or "plume effect"). This effect has obviously not been included ("*Electrabel provided Bel V with information allowing concluding that the "plume effect" may be neglected*.")[62]

- The demonstration of the reactor pressure vessel's structural integrity by PTS analysis depends also on the correct input data concerning the radiation embrittlement. It is not clear which data for the RT_{NDT} shift have been used.

- In this context it has to be repeated that no reliable data on the radiation embrittlement of specimens with high hydrogen flaking exist. Respective data cannot be produced due to the lack of representative samples.

- It has also to be repeated that the effect of high hydrogen flaking on the fracture toughness (without radiation effects) is not known. Again: respective data cannot be produced due to the lack of representative samples.

- The flaw grouping method used by Electrabel is no approved methodology; conservativeness has not been demonstrated. Possible interactions of the individual flaws under operational conditions are not known and are therefore not considered in the frame of the structural integrity analysis provided by Electrabel.

2.5 Electrabel's action plan

The action plan proposed by Electrabel includes operational measures (reduction of the heat-up and cool-down temperature gradients, permanent warming of the safety-injection water, enhanced training of the personnel), qualification of the testing equipment for the outage after the first cycle and a material testing program involving small-scale samples and testing of large tensile specimens in the long term (one year).

According to FANC, Bel V proposed an additional pressure test:

> *„The objective of the pressure 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. 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."* [63]

[62] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013, page 44 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

[63] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

The German Standards (KTA 3201.4, paragraph 4.5.1) define "*that the pressure tests shall basically be performed at 1.3 times the design pressure*".[64] According to the letter of the French Authorities ASN and IRSN to Bel V the pressure has to be minimum 1.2 times the design pressure.

With respect to the acoustic emission measurement the French Authorities ASN and IRSN note in their letter to Bel V:

„L'ASN et l'IRSN notent les difficultés pratiques liées à la mise en place d'une écoute acoustique:
· instrumentation de la cuve;
· absence de point 0 sur la cuve neuve et prise en compte du bruit de fond;
· forte épaisseur de la cuve."[65]
[„ASN and IRSN note the practical difficulties in connection with the application of acoustic emission measurements:
- instrumentation of the vessel;
- absence of the zero measurement on the new RPV and consideration of the background noise;
- important wall thickness of the vessel". transl. I.T.]

The Regulatory Authority FANC concludes on the issue:

„In addition to the actions proposed by the licensee and the additional requirements specified by the FANC in the previous sections, the licensee shall, as a prerequisite to the restart of both reactor units, perform a load test of both reactor pressure vessels. The objective of the load test is not to validate the analytical demonstration on the reactor pressure vessel itself but to demonstrate that no unexpected condition is present in the reactor pressure vessels. The methodology and associated tests (acoustic emission and ultrasonic testing...) will be defined by the licensee and submitted to the nuclear safety authority for approval. The acceptance criterion will be that no crack initiation and no crack propagation are recorded under the pressure loading."[66]

REMARKS:

- The performance of a pressure test might be a possibility to find out if a rather short exposure to the selected pressure induces the growth of individual flaws, but nothing more than this. This would require that every observed flaw indication (by means of the same UT technique as the one used in 2012) should be compared carefully with the data before the pressure test. In case any size change would be observed this would show that the flaws have at least grown (if not evolved) during operation. But the reverse conclusion might not be true (i.e. "no change" does not mean "no operational effect"). In other words, i**t is crucial to keep in mind that the complementary tests that are now scheduled are enough**

[64] KTA 3201.4 (2010-11), Components of the Reactor Coolant Pressure Boundary of Light Water Reactors; Part 4: In-service Inspections and Operational Monitoring
http://www.kta-gs.de/e/standards/3200/3201_4_engl_2010_11.pdf

[65] ASN-IRSN, Présentation à l'ASN et à l'IRSN de vos conclusions concernant le dossier de justification de l'aptitude au service des cuves des réacteurs de Doel 3 et Tihange 2, 21-12-2012
http://www.asn.fr/index.php/content/download/36843/272621/file/CODEP-DEP-2012-069143.pdf

[66] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013
http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

to disqualify the re-start of the two nuclear power plants in case their results are negative, but are not enough to qualify for such a re-start even if the new tests looked positive.

- Acoustic emission measurements might represent interesting additional information but cannot be compared with any relevant measurement after pressure vessel manufacture (zero plot), therefore the measurements are rather useless with respect to the questions of concern.
- It has to be mentioned that every pressure test is an additional loading on the pressure vessel materials that might have effects on the materials properties (low-cycle fatigue).

3. FANC Requirements

The summarized requirements of the Regulatoty Authority FANC[67]

Manufacture: no additional requirements

In-service inspections:

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

- *The licensee shall re-analyze the EAR acquisition data for Tihange 2 in the depth range from 0 to 15 mm in the zones with hydrogen flakes to confirm whether or not some of these technological cladding defects have to be considered as hydrogen flakes.*
- *The licensee shall demonstrate that no critical hydrogen flake type defects are expected in the non-inspectable areas.*
- *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.*
- *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 shall include a set of defects partially hidden by other defects for macrographic examination, to confirm whether the sizing method continues to function well.*
- *The licensee shall re-analyze the tilts of the defects in the VB-395/1 block with the same method as applied on-site.*

[67] FANC, Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2, Technical information note – 2013.02.01
http://www.fanc.fgov.be/GED/00000000/3300/3387.pdf

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

- *The licensee shall achieve a full qualification program to demonstrate the suitability of the in-service inspection technique for the present case. The qualification shall give sufficient confidence in the accuracy of the results with respect to the number and features (location, size, orientation…) of the flaw indications. Where appropriate, the process shall be substantiated by appropriate experimental data using representative specimens. The full qualification program shall be achieved before the next planned outage for refuelling."*

Metallurgical origin and evolution of the indications:

"After the restart of both reactor units:

- *The licensee shall perform follow-up in-service inspections during the next planned outage for refuelling to ensure that no evolution of the flaw indications has occurred during operation."*

Material properties:

"As a prerequisite to the restart of both reactor units:

- *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 shall perform additional measurements of the current residual hydrogen content in specimens with hydrogen flakes, in order to confirm the results of the limited number of tests achieved so far. For example, the licensee has estimated an upper bound on the amount of residual hydrogen that might still be present in the flaws. The licensee shall demonstrate that the chosen material properties are still valid, even if the upper bound quantity of hydrogen would still be present in critical flaws.*

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

- *A further experimental program to study the material properties of irradiated specimens containing hydrogen flakes shall be elaborated by the licensee.*
- *The licensee shall further investigate experimentally the local (micro-scale) material properties of specimens with macro-segregations, ghost lines and hydrogen flakes (for example local chemical composition). Depending on these results, the effect of the composition on the local mechanical properties (i.e. fracture toughness) shall be quantified.*
- *The licensee shall further evaluate the effect of thermal ageing of the zone with macro-segregation."*

Structural integrity oft the reactor pressure vessels:

"As a prerequisite to the restart of both reactor units:

- *Taking into account the results of the actions related to the previous requirement on the detection of the higher tilt defects during in-service-inspections, 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 shall complete the on-going material testing program by testing larger specimens containing hydrogen flakes, with the following 2 objectives:*
  Objective 1: Tensile tests on samples with (inclined) multiple hydrogen flake defects, which shall in particular demonstrate that the material has sufficient ductility and load bearing capacity, and that there is no premature brittle fracture.
  Objective 2: An experimental confirmation of the suitability and conservatism of the 3D finite elements analysis."

Action plan:

"As a prerequisite to the restart of both reactor units:

- *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 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."*

REMARKS:

- Regarding the origin of the flaws and the not explainable fact that only several rings are affected, FANC does not require further root cause analysis, for instance investigations on possible impurity ingress/corrosion attacks before or during the cladding process. Such processes could explain why not all of the shells are affected and why the flaws are unsymmetrically distributed rather close to the inner surface of the vessel. Because these processes induce that defects grow during operation, taking them into account should be a prerequisite for any consideration of a restart
- FANC did not request research programs on the development of hydrogen flaking in steels without dehydrogenation during manufacture in order to reproduce the development of the observed flaws.
- FANC did not request experiments with components containing hydrogen-flake-type defects to study effects of pressure and temperature on such defects.
- FANC did not request inspections of the pressure vessel parts ouside the cylindrical shells (lower and upper head).

- FANC did not define the follow-up-inspection intervals in the future to control possible flaw development (only the one during the next outage for refueling).
- FANC did not request Electrabel to demonstrate the conservativeness of the proposed additional RT_{NDT} shift of 50°C to cover interactions of radiation and thermal effects on of materials containing hydrogen flake type defects.
- With respect to the requested irradiation program FANC did not adress the problem of representativity of the results due to the dose-rate effect.
- FANC did not request to complete the structural integrity assessment/pressurized thermal shock analysis considering the transients mentioned by ASN/IRSN.
- FANC did not request a precise description of the observed defects, as remarked by ASN/IRSN.

4. Conclusions

Electrabel's dossier on the observed flaws in the reactor pressure vessels of Doel 3 and Tihange 2 is based on experimental investigations on small-scale specimens made of archive materials from the reactor pressure vessel Doel 3 (without hydrogen-related defects) and a cut-out from a rejected French steam generator ring (AREVA VB 395) – i.e. not a RPV - containg hydrogen flake type defects but not having undergone neutron irradiation and the thermomechanical cycling as the RPVs in their 30 years of operation.

These specimens cannot be considered to be representative for the reactor pressure shell materials of concern.

The origin of the observed flaws is supposed to by hydrogen flaking during the manufacturing process. This assumption cannot be proved, for Electrabel it is the only possible explanation. Other possible explanations are not considered/investigated. Electrabel claims that no evolvement of defects or growth occurred during operation.

The nature of the observed flaws cannot be determined without destructive testing - nevertheless Electrabel argues that these flaws are hydrogen flake type defects.

Electrabel cannot explain why not all the shells of the reactor pressure vessels are affected.

The Regulatory Authority FANC did not explain why the completeness of the manufacturing process was never controlled.

FANC notes the remaining uncertainty on the origin of the observed flaws but does not request any research on this issue, for instance regarding possible processes on the ferritic pressure vessel wall before and during the cladding procedure. Such processes could explain the unsymmetric

distribution of the defects rather close to the inner surface and why not all rings are affected. Because such processes induce that defects grow during operation, taking them into account should be a prerequisite for any consideration of a restart.

The flaws discovered in 2012 were not detected during the final inspection after manufacture although they should have been detectable with the ultrasonic testing equipment available at that time. This fact per se implies that the flaws have appeared, evolved or at least grown during the 30 years of operation, but FANC does not consider this as self-evident argument.

The manufacturer and the Owner knew about de detrimental effects of hydrogen flaking, since other components were rejected due to hydrogen flaking, as the transition ring of Tihange 2. The rejection of the transition ring implies that the hydrogen flaking based indications have not been present after manufacture in the rings affected today, since otherwise the components would also have been rejected.

According to FANC it cannot be assumed that all potentially critical defects have been found during the 2012 inspections.

FANC does rely on further experimental testing of available sample material that cannot be considered to be representative. This means that FANC accepts Electrabel's logic that results from non-representative specimens can prove the quality of the actual state of the pressure vessel material.

FANC accepts Electrabel's proposal to use an additional shift of the nil-dictility reference temperature RT_{NDT} of 50°C to cover all possible radiation effects on the fracture toughness of the material containing hydrogen flake type defects. There is an inconsistency concerning the the use of this additional shift in Electrabel's dossier, but this is not discussed by FANC. FANC does not request to justify this proposal.

Since no information exists on the toughness degradation of the RPV steel without irradiation due to hydrogen flaking, the application of the FIS formula to estimate the actual radiation embrittlement cannot be considered to be conservative.

No experimental data exist on radiation embrittlement of reactor materials with hydrogen flaking. Irradiation programs in the future would require high-flux irradiation in order to get results in reasonable time periods. Due to a possible dose rate effect high-flux irradiation results might underestimate the real embrittlement.

It has to be kept in mind that no RPV specific material exists for such an irradiation program. The specimens from the AREVA material – a rejected steam generator ring - cannot be considered to be representative.

Radiation-enhanced diffusion and radiation-induced segregation effects that could influence hydrogen flaking are neither mentioned in the Electrabel documents nor in the FANC evaluation.

FANC recognizes that the fracture toughness/ductility of the material might by significantly reduced by the hydrogen flake type defects (even without radiation effects) but will accept experimental tensile testing results on specimens that are not representative for the reactor pressure vessel material.

There are no experimental data on low-cycle fatigue effects on materials containing hydrogen flaking. Even more: no information exists on the simultaneous interaction of irradiation, temperature and fatigue on hydrogen flakes.

The interaction of the hydrogen-related defects with each other, including bridging effects has not been considered by Electrabel.

The validity of the pressurized thermal shock analysis should be based on the correct input for the thermohydraulic analysis, i.e. the consideration of the most penalizing transients. This has obviously not been the case.

It is known that asymmetric cooling conditions at the RPV wall may occur during severe transients causing thermal stress gradients in the RPV wall ("cold tongues" or "plume effect"). This effect has obviously not been included ("*Electrabel provided Bel V with information allowing concluding that the "plume effect" may be neglected*.")[68]

The flaw grouping method used by Electrabel in the structural integrity assessment is no approved methodology, conservativeness has not been demonstrated. Possible interactions of the individual flaws under operational conditions are not known and are therefore not considered.

FANC requests a pressure test of the reactor pressure vessel as only possible non-destructive test of the pressure vessel although this test can only reveal flaw growth due to this specific loading, but in case no changes will be observed this can certainly not prove that defects will not evolve/grow during further operation of the plant.

In summary FANC will mainly rely for the decision on restart of the NPPs Doel 3 and Tihange 2 on the test results from materials that cannot be considered to be representative for the actual state of the reactor pressure vessel material. The materials characteristics of the reactor pressure vessels could be worse, but this fact cannot be investigated without destruction iof the pressure vessels. [69]

Keeping in mind that the reactor pressuse vessel of a NPP is a component that is supposed to be infailable, that its failure has therefore not been taken into account in safety studies and that therefore the Owner has to demonstrate that the structural integrity of the reactor pressure vessel is ensured at all times during any mode of normal or accidental operation, FANC should obtain - before authorizing the restart of the affected reactors - absolute certainty that the flaws will not lead to the failure of the RPV. This is obviously not the case at present and will not be the case even of the complementary tests should prove positive.

It is crucial to keep in mind that the complementary tests that are now scheduled are enough to disqualify the re-start of the two nuclear power plants in case their results are negative, but are not enough to qualify for such a re-start even if the new tests looked positive.

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[68] FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, 30/01/2013, page 44 http://www.fanc.fgov.be/GED/00000000/3300/3391.pdf

[69] In this context it is a strange situation that material that was rejected for use as steam generator shell - a component that can be replaced and is not exposed to high neutron irradiation - will be used to qualify the further operation of reactor pressure vessels - components containg that are not allowed to fail.