Flawed Reactor Pressure Vessels in the Belgian NPPS Doel 3 and Tihange 2

Comments on the FANC Final Evaluation Report 2015

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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 ENGIE Group.

In the frame of ultrasonic inspections in 2012 thousands of flaws were detected in the base metal of the reactor pressure vessels (RPV) in both reactors.

The owner Electrabel claimed that the flaws were “most likely” hydrogen flakes introduced during manufacture, no growth had occurred during operation of the reactor. The Belgian Regulatory Authority approved restart of both units in May 2013. The approval included requirements of irradiation experiments using samples from a rejected steam generator block AREVA VB395 that contained hydrogen flakes.

These samples cannot be considered to be representative for the affected reactor pressure vessel shells since the manufacture and heat treatment history is certainly not the same. Electrabel considered the samples as representative due to the similar flaw appearance, FANC accepted this argument.

The results of the first irradiation campaign showed an unexpected high neutron embrittlement. As a consequence both reactors were shutdown in March 2014. Further irradiation campaigns were performed using also samples from German FKS (Forschungsvorhaben Komponentensicherheit) experiments (KS02).

On November 17, 2015 FANC authorized the restart of both plants.

In December 2015, Rebecca Harms, Co-President of the Greens/EFA Group in the European Parliament, asked the author to evaluate the available documents published by FANC in connection with the authorization for restart with special emphasis to the irradiation results and their interpretation by the different expert groups working for Electrabel and FANC.

The evaluation of the published documents was aimed to clarify the scientific arguments that are supposed to justify the authorized restart.

Although the nature of the flaws detected in two shells of the reactor pressure vessels is not proven, FANC has adopted Electrabel’s statement that he flaws are hydrogen flakes. In spite of the fact that the ultrasonic inspection did not show reportable indications after manufacture but 30 years later thousands of flaws were found with sizes up to 179 mm FANC has adopted the licensee’s opinion that no growth of the flaws has occurred during operation.

It is understandable that a more sensitive ultrasonic testing method will show more small flaws, but it is not comprehensible that a less sensitive ultrasonic technique should not detect large flaws. The reverse observation has to be expected: large flaws detected with a less sensitive technique appear to be an assembly of small flaws using a more sensitive technique.

Thus the licensee is not able provide an explicit proof that no growth of flaws has occurred during operation.

The fact that no indications were observed after manufacture but thousands of flaws 30 years thereafter with an increase in size in the latest UT test results can only be explained by defect development/growth during operation.

It still cannot be explained by the licensee why only four shells are affected and why these flaws appeared only in these two reactor pressure vessels.

One member of the International Review Board (IRB) argued that some repair processes of the base metal could have occurred before cladding that introduced defects that could have grown during operation. A similar assumption was expressed by the author in the study in 2013. This possibility was not discussed by FANC.

W.Bogaerts and D.Macdonald assume a possible growth mechanism due to radiolytic/electrolytic hydrogen into the RPV wall. FANC rejected this hypothesis.

The defense-in-depth approach as stated by Bel V (comparable to the Germans basic safety principle) is based on the superior quality of the reactor pressure vessel after manufacture that has to be maintained throughout operational life. This basic requirement is certainly not fulfilled. A reactor pressure vessel with thousands of flaws – and with these large flaw sizes – would not be licensable - neither today nor at the time of manufacture.

The irradiation campaigns were part of the FANC requirements for restart in 2013. These campaigns were performed using samples from a rejected steam generator block (AREVA VB395), Doel nozzle cuts (that contain no flaws) and for the last campaign German FKS samples (KS02). Neither VB395 nor KS02 can be considered to be representative for the RPV base material, the nozzle cuts are only representative for the defect-free RPV material but does not have the operational history of the RPV. Electrabel performed the experiments based on the assumption that the samples are representative.

The unexpected embrittlement of the VB395 samples irradiated in the BR2 test reactor was finally explained to be due to a yet unknown embrittlement mechanism, now the samples are declared to be abnormal outliners. A similar enhanced embrittlement in the D3T2 shells is not expected by Electrabel/FANC.

In the past the experimental findings on embrittlement of similar steels were always included into the embrittlement data base that is used to define predictive embrittlement curves as enveloping upper boundaries. Neutron embrittlement is a complex effect of stochastic processes including several possible mechanisms. Eliminating unexpected findings by the designation of “abnormal outliners” cannot be considered to be sound scientific practice.

Embrittlement trend curves are used in the frame of the pressurized thermal shock (PTS) analysis to calculate the fracture toughness curves dependent on the neutron fluence. In the French standards the so called FIS curves were enveloping upper boundaries based on the experimental embrittlement data of similar steels. Electrabel defined new predictive curves replacing the so far used FIS curves. The terms used in the new equation are supposed to consider uncertainties of the actual state of the fracture toughness of the RPV steel. No justification for the used factors in the different terms is given – but it is clear that the new trend curve is no more an enveloping upper bound curve for the shift of the reference temperature for ductile-brittle transition RT_{NDT}.

For the structural integrity assessment the temperature field at the reactor pressure vessel wall has to be calculated for severe accident transients (for instance loss of coolant accidents) assuming cold safety injection water impinging on the hot vessel wall. The temperature gradients will induce thermal stresses in the vessel wall that could promote uncontrolled growth of cracks depending on the mechanical characteristics of the material. These fracture mechanical calculations are performed using assumptions on the actual fracture toughness of the material and the predictive trend curves to include the neutron embrittlement effect. The calculations have to be performed for each detected crack (size, shape, location); it has to be demonstrated that for no crack uncontrolled growth is occurring in case of the assumed accident transient (ASME criterion).

Concerning the mechanical characteristics there are doubts that the fracture toughness (without radiation effects) in the defect-containing steel is the same as for defect-free steel. In the new predicting trend curve the initial fracture toughness of the defect-free material is used. Electrabel claims that an extra term in the new predictive trend curve is supposed to cover (unexpected) unknown radiation-induced embrittlement in the magnitude of the embrittlement observed in the VB395 samples. The term is not quantified by Electrabel; evidence for the used numerical values can be found in the ORNL report indicating that the value was not enveloping the experimental embrittlement results but was fitted to the limiting requirement for embrittlement in the standards.

In the frame of this structural integrity assessment several flaws did not comply with the ASME acceptance criterion. Therefore the ORNL calculations included the so called warm prestress effect – that is not foreseen to be applied in the PTS analysis according to the French and German standards – to accomplish compliance with the ASME acceptance criteria. For one flaw this procedure was not sufficient to reach compliance. Finally a “more realistic” modeling of the flaw was necessary to reach compliance with the ASME criterion. It is certainly a further reduction of conservatism.

For positive SIA calculations it had also to be assumed that the water for the safety injection system is warmed up to 40°C (according to Electrabel). ORNL has sed the temperature of 40°C for their calculations. In the FANC final Report 2015 the safety injection water temperature is not quantified. The director of FANC Jan Bens has informed the Belgian Chamber of Representatives that this temperature has been increased to 45-50°C. The 50°C is the limit with respect to the core coolability in case of an accident.

This is raising a further problem: the large amount of safety injection water (presumably about 1800 m^3) has to be continuously warmed up to about 45°C. The temperature may not be lower than 40°C because this would violate the requirements for the structural integrity in case of an accident and may not reach 50°C because this would endanger the coolability of the core under accidental conditions.

It is clear that the tolerance window is rather small and there is no safety margin at all.

The evaluation of the published documents has revealed the reduction of conservatism throughout the performed Safety Case analysis. The non-representative samples used in the irradiation campaigns that were supposed to confirm the safety margin in the uncertainty assessment in the

Safety Case 2012 have converted to abnormal outliners. Keeping in mind that growth of the flaws in the RPV shells during operation cannot be excluded the authorized restart of the two nuclear power plants is not understandable.

Inhaltsverzeichnis

1. Introduction

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 ENGIE 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.[1]

On May 17, 2013 FANC experts gave positive opinion on restart Doel 3 & Tihange 2 reactor units.[2] Linked to the authorization for restart FANC imposed requirements concerning further studies and experiments on the licensee. (FANC: Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report[3] and Doel 3 and Tihange 2 reactor pressure vessels, Final evaluation report[4]). Several of these actions had already been completed before the restart, whereas the rest had to be completed after one complete reactor cycle, by June 2014.

On 25 March 2014, Electrabel informed FANC of its decision to advance the planned outage of its nuclear reactors Doel 3 and Tihange 2.[5]

On July 1st, 2014 FANC published a further press release concerning the continuing outage:

> *"The results of these tests indicate that a mechanical property (fracture toughness) of the material is more strongly influenced by irradiation than experts had expected. Additional testing and research are necessary to interpret and assess these unexpected results."*[6]

August 22, 2014 FANC published the next press release concerning the irradiation experiments performed by Electrabel:

> *"In order to explain these unexpected results, Electrabel immediately initiated a second test campaign and announced that this would last until autumn 2014."*[7]

February 13, 2015 FANC published a further update on D3/T2 including the information of new ultrasonic tests performed by Electrabel in 2014:[8]

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[1] 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
[2] FANC press release on restart authorization, http://www.fanc.fgov.be/GED/00000000/3400/3430.pdf
[3]FANC, Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, http://www.afcn.fgov.be/GED/00000000/3300/3391.pdf
[4]FANC, Doel 3 and Tihange 2 reactor pressure vessels. Final evaluation report, http://www.afcn.fgov.be/GED/00000000/3400/3429.pdf
[5] FANC press release on earlier outage of D3/T2, http://www.fanc.fgov.be/nl/news/doel-3-and-tihange-2-reactors-in-outage-earlier-than-planned/669.aspx
[6] FANC press release on continuing outage in D3/T2, http://www.fanc.fgov.be/GED/00000000/3600/3657.pdf
[7]FANC press release on update of the situation , http://www.fanc.fgov.be/nl/news/doel-3-and-tihange-2-update-on-the-situation/701.aspx

"In 2014, a further inspection was carried out based on the improved procedure and the modified settings of the machine, resulting in the detection of a greater number of flaw indications than was measured in 2012 and 2013. This means that Electrabel now has to take into account 13 047 flaw indications for Doel 3 and 3149 flaw indications for Tihange 2 in its calculations. These additional flaw indications are similar to those which were previously considered and are located in the same area of the RPV."

With respect to the irradiation campaigns FANC informed about tests with a German sample:

" Currently a 4th irradiation campaign is being executed in the research reactor BR2 of the SCK, where, next to hydrogen-flaked samples of the French VB395 test material, other hydrogen-flaked samples of another test material of German origin are also being irradiated. The results of this irradiation campaign and of the subsequent material tests are expected by April 2015."

"On 17 November 2015, the Federal Agency for Nuclear Control (FANC) authorized the licensee Electrabel to restart the Doel 3 and Tihange 2 reactor units. Both reactors have been shut down for some time now because of concerns about their safety".[9]

The following documents were published at the same time on the FANC homepage:

- FANC, Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2 Final Evaluation Report 2015[10]
- Bel V Safety Evaluation Report, Quasi-laminar flaw indications in the Doel 3 and Tihange 2 reactor pressure vessels. Evaluation of the impact of the hydrogen flaking damage in the serviceability of the Doel 3 and Tihange 2 reactor pressure vessels.[11]
- AIB-Vinçotte, Synthesis report Doel 201[12]
- AIB-Vinçotte, Synthesis report TIHA 186[13]
- Electrabel, Safety Case 2015, Doel 3 reactor pressure vessel assessment[14]
- Electrabel, Safety Case 2015, Tihange 2 reactor pressure vessel assessment[15]
- Report on independent analysis and advice regarding the safety case2015, Doel 3 reactor pressure vessel assessment[16]
- Report on independent analysis and advice regarding the safety case2015, Tihange 2 reactor pressure vessel assessment[17]
- Doel 3 and Tihange 2 issue: International Review Board Final Report[18]
- ORNL Evaluation of Electrabel Safety Cases for Doel 3 / Tihange 2: Final Report[19]

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[8] FANC press release on further update, http://www.fanc.fgov.be/nl/news/doel-3/tihange-2-new-update/745.aspx
[9] http://www.fanc.fgov.be/GED/00000000/4000/4032.pdf
[10] http://www.fanc.fgov.be/GED/00000000/4000/4027.pdf
[11] http://www.fanc.fgov.be/GED/00000000/4000/4028.pdf
[12] http://www.fanc.fgov.be/GED/00000000/4000/4033.pdf
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[16] http://www.fanc.fgov.be/GED/00000000/4000/4025.pdf
[17] http://www.fanc.fgov.be/GED/00000000/4000/4026.pdf
[18] http://www.fanc.fgov.be/GED/00000000/4000/4029.pdf

In March 2013 the author has performed an analysis of the available documents following the publication of the FANC Provisional evaluation Report February 1, 2013.[20]

In December 2015, Rebecca Harms, Co-President of the Greens/EFA Group in the European Parliament, asked the author to evaluate the available documents published by FANC in connection with the authorization for restart with special emphasis to the irradiation results and their interpretation by the different expert groups working for Electrabel and FANC.

2. Assessment of the available documents

2.1 Basic safety

The reactor pressure vessel (RPV) is the central component of a nuclear power plant; RPV failure has to be excluded since the reactor safety systems are not designed to cope with this accident, RPV failure would cause meltdown and severe fission product release as a consequence. For manufacture and licensing of a reactor pressure vessel it is therefore of main importance that the pressure vessel is free of defects and with appropriate material properties according to the specifications and the state of science and technology ("basic safety").

Bel V states in the introduction of the Safety Case 2015 evaluation (page 4):

> *"The defense-in-depth philosophy has traditionally been applied in reactor design and operation. In a defense-in-depth approach, the greatest emphasis should be placed on the first level of defense that requires a superior quality in design, construction and operation. The second level of defense is also of prime importance by requiring, amongst others, that in-service measures are taken to ensure that no alterations to materials appear compromising the prevention of the failure modes."*[21]

The required basic safety during manufacture of the RPVs in Doel 3 and Tihange 2 cannot be demonstrated because the documentation is not complete[22], esp. with respect to the heat treatment (dehydrogenation treatment) of the steel.

The detection of thousands of indications in the reactor pressure vessel wall in 2012 is per se the demonstration that the pressure vessel cannot be considered to be of "superior quality" in the sense of basic safety or in the defense-in-depth-approach. Neither today nor at the time of manufacture such a component would be licensable. The ultrasonic testing technology at the time of manufacture was appropriate to detect flaws as those found in 2012, flawed components were rejected:

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[19] http://www.fanc.fgov.be/GED/00000000/4000/4030.pdf

[20] Ilse Tweer, Flawed Reactor Pressure Vessels in Belgian Nuclear Plants Doel-3 and Tihange-2 Some Comments on the FANC Provisional evaluation report (January 30, 2013), March 2013, http://www.greens-efa.eu/fileadmin/dam/Documents/Studies/Flawed%20Reactor%20Pressure%20Vessels.pdf

[21] Bel V Safety Evaluation Report, Quasi-laminar flaw indications in the Doel 3 and Tihange 2 reactor pressure vessels, http://www.fanc.fgov.be/GED/00000000/4000/4028.pdf

[22] 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

„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."[23]

Bel V is in accordance with the conclusion that basic safety is not met for the two RPVs:

"The presence of hydrogen flaking is therefore to be considered as a major deviation from the requirement of having RPV material meeting the highest quality standards and being in particular as defect-free as possible within the limitations of the best available manufacturing technology."[24]*(page 5)*

Fazit:

- Basic safety or highest quality in accordance with defense in depth during manufacture of the reactor pressure vessels of Doel 3 and Tihange 2 cannot be demonstrated due to the incomplete documentation.
- The detection of thousands of flaws proofs that highest quality is not given, the pressure vessels were not licensable neither today nor at the time of manufacture. It is therefore highly questionable in the frame of basic safety or defense-in-depth approach that 30 years thereafter the nuclear authority is authorizing the restart of both plants.

2.2 Detected UT indications

2.2.1 Origin and nature of the flaws

Already in 2012 the Owner of the NPPs Electrabel claimed that the defects causing the UT indications were due to manufacture. This statement is only based on plausibility considerations and conclusions by analogy arguments - an experimental proof is not possible without destructive testing.

"The full screening of all potential forming mechanisms confirms the hydrogen flaking as the most likely origin of the indications."[25]*(page 88)*

The assumption of hydrogen flakes due to manufacture was accepted by FANC and this has not changed in 2015:

"Concerning the origin of the indications, the conclusions issued by the FANC in May 2013 remains unchanged. The most likely origin of the flaw indications identified in the Doel 3 and Tihange 2 reactor pressure vessels is hydrogen flaking due to the manufacturing process."[26]

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[23] 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

[24] Bel V Safety Evaluation Report, Quasi-laminar flaw indications in the Doel 3 and Tihange 2 reactor pressure vessels, http://www.fanc.fgov.be/GED/00000000/4000/4028.pdf

[25] Electrabel, Safety Case Report: Doel 3 - Reactor Pressure Vessel Assessment, December 2012.

The assumption of hydrogen flakes cannot explain why such defects were only found in the four shells of the two NPPs and were not detected in the other 19 pressure vessels produced by the same manufacturer.

According to FANC there were obviously similar doubts at Bel V in 2012:

> *„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."*[27]

In the report of the International Review Board (IRB) from 2015 one member is quoted to disagree with this hydrogen flaking hypotheses (the complete minority statement can be found in the attachment, section 4.):

> *„The distribution of near surface indications of the Lower Core Shell in D3 shows a type of truncation which differs considerably from the other shells and need to be explained in conjunction with the basic hypotheses of hydrogen flaking."*[28]*(page 29)*

It is interesting to note that neither FANC nor Electrabel discussed the possibility that before or during the cladding process something might have happened that caused the ingress of impurities into the vessel wall with subsequent defect formation and/or growth during operation. Such processes could explain the open questions.

The author (I.Tweer) considered such a possibility in the report from 2013:

> *"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."*[29] *(page 14)*

A similar assumption was introduced by one member of the IRB:

> *"Based on the type of distribution mentioned above the expert sees no reason why the segregations would not be present up to the surface of the D3 Lower Core Shell affecting the cladding interface material properties. Furthermore it is possible that base metal repairs were*

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[26] FANC, Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2 Final Evaluation Report 2015, page 43, http://www.fanc.fgov.be/GED/00000000/4000/4027.pdf

[27] 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

[28] Doel 3 – Tihange 2: RPV issue - International Expert Review Board - Final Report, http://www.fanc.fgov.be/GED/00000000/4000/4029.pdf

[29] Ilse Tweer, Flawed Reactor Pressure Vessels in Belgian Nuclear Plants Doel-3 and Tihange-2 Some Comments on the FANC Provisional evaluation report (January 30, 2013), March 2013, http://www.greens-efa.eu/fileadmin/dam/Documents/Studies/Flawed%20Reactor%20Pressure%20Vessels.pdf

made before cladding to remove surface defects in this region and, given the manufacturing practice at the time, not documented."[30]*(page 29)*

In 2015 W. Bogaerts and D.D. MacDonald discussed the hypothesis that during operation hydrogen that is produced by electrolytic processes (corrosion) could diffuse into the reactor pressure vessel wall and agglomerate with hydrogen flakes which could than induce dangerous blistering.[31] According to the FANC Final Report 2015 this hypotheses was discussed and finally rejected by the FANC experts:

> *"Taking into account - the initial arguments from the Licensee and the two professors Bogaerts and Macdonald ; the comments from the NSEG group; the additional studies and calculations provided by the Licensee to fulfill the NSEG recommendations; the evaluation by Bel V; the comments stated by three international experts which are worldly recognized as specialists in hydrogen induced corrosion issues the FANC draws the following conclusions in its HIC Synthesis:*
> *The only theoretical propagation mechanism for the flakes detected in the Doel 3 and Tihange 2 reactor pressure vessels is low cycle fatigue, which is considered to have a limited effect. Other phenomena (such as hydrogen blistering or hydrogen induced cracking) have been evaluated and ruled out as possible mechanisms of in-service crack growth."*[32](page 41ff)

Bogaerts' and Macdonald's hypothesis cannot (yet) explain why the thousands of indications appear only in the four shells of Doel 3 and Tihange 2 and not in all other RPVs worldwide although the possibility of diffusing hydrogen attachment to other defects is certainly given in most pressure vessels. Bogaerts' hypothesis can explain the increased flaw sizes published by FANC in 2015 assuming further hydrogen induced growth. (see 2.2.3).

FANC concludes in the Final Evaluation Report 2015:

> *"The most likely origin of the flaw indications identified in the Doel 3 and Tihange 2 reactor pressure vessels is hydrogen flaking due to the manufacturing process." and "All mid-term requirements concerning the origin and evolution of the flaw indications found in the core shells of the reactor pressure vessels of Doel 3 and Tihange 2 have been satisfactorily replied to and closed by the Safety Authority." (page 43)*

Fazit:

- The real nature of the defects that cause the indications found by ultrasonic testing can only be disclosed by destructive testing. The hydrogen flakes assumption by Electrabel and accepted by FANC is only based on plausibility considerations.

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[30] Doel 3 – Tihange 2: RPV issue - International Expert Review Board - Final Report, http://www.fanc.fgov.be/GED/00000000/4000/4029.pdf

[31] W.F.Bogaerts, Z.H.Zheng, A.S.Jovanovic, D.D.Macdonald, Hydrogen-induced damage in PWR reactor pressure vessels, Research in Progress Symposium at CORROSION, 15th-19th March 2015, Dallas, USA, preprint

[32] FANC, Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2 Final Evaluation Report 2015, , http://www.fanc.fgov.be/GED/00000000/4000/4027.pdf

- The hydrogen flaking assumption cannot explain why only the four shells in the NPPs Doel 3 and Tihange 2 are affected and not all of the RPVs produced by the same manufacturer.
- The hydrogen flaking assumption cannot explain why the flaws have not been detected during acceptance testing after manufacture.
- The possibility of processes before or during cladding of the RPV that could have introduced impurities into the vessel wall with following growth during operation has not been discussed by Electrabel and FANC.
- The hypothesis of electrolytic/radiolytic hydrogen that could contribute to the growth of defects during operation (W.Bogaerts, D.D.Macdonald) was rejected by FANC.
- In the further argumentation by FANC and the different expert groups the defects behind the UT indications are assumed as hydrogen flakes without any restriction although still no proof for this assumption exists.

Note (I.T.) on hydrogen flaking

The deleterious effects of hydrogen in steels are known as hydrogen embrittlement, delayed fracturing, hydrogen-induced cracking (HIC), etc. Therefore dehydrogenation treatments are required in the steel making industry for vessel manufacturing. Hydrogen flaking is described in the scientific literature as a very dangerous defect causing severe serious failures (see for example NRC[33], Voronenko[34])

Due to the dangerous effects of hydrogen flakes components containing hydrogen flakes were rejected after manufacture like a shell of Tihange or the steam generator component AREVA VB395.

Even Bel V states that hydrogen flaking is to be considered as a major deviation from the requirement of having RPV material meeting the highest quality standards and being in particular as defect-free as possible.

Nevertheless FANC (assuming that the flaws are hydrogen flakes) closed the issue “all mid-tern requirements concerning origin and evolution of flaw indications” in its authorization for restart.

Is this FANC’s interpretation of the responsibility of a Nuclear Regulating Authority to ensure highest quality and safety in the national nuclear facilities?

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[33] NRC, Metallurgical aspects influencing the potential for hydrogen flaking in forgings for reactor pressure vessels, http://pbadupws.nrc.gov/docs/ML1322/ML13226A174.pdf

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

2.2.2 Number and size of the defects

In the Provisional Report 2013 FANC stated about number and size of the detected flaws:

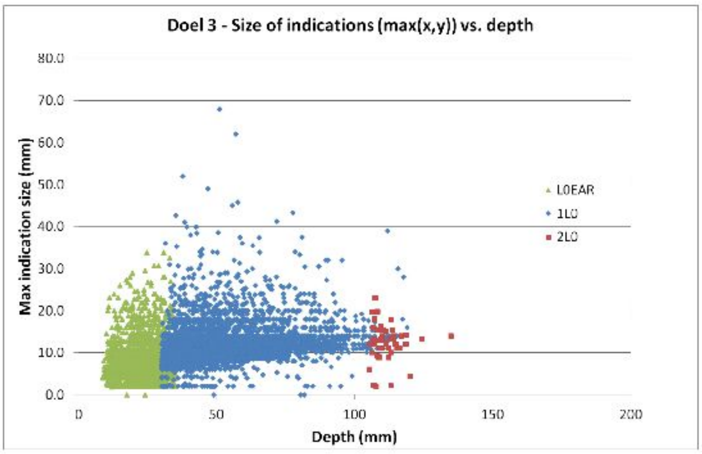
For Doel 3:

> *„In both core shells, the laminar flaws form a cluster in the central strip of the shell, which ranges in depth from the stainless steel clad interface up to 120 mm. The indications measure on average 10-14 mm in diameter (with some even exceeding 20-25 mm)."[35] (page 23)*

And Tihange 2:

> *"Inside the core shells, which are the most affected, flaws have been observed up to a depth of 100 mm from the inner surface. However, most of the flaws are located between 20 mm and 70 mm. Regarding the flaw dimensions, flaws up to 24 mm large have been observed. However, most flaws are smaller than 10 mm.)."(page 24)*

These statements are remarkable because in the Electrabel safety case 2012 the diagram (here for Doel 3) shows that the number of flaws larger than 20-25 mm is significantly higher than "some".



Source: Electrabel[36]

In February 2015 FANC informed on new findings concerning the number of flaws and their sizes[37]: According to FANC the operator of the two power plants has found during the required qualification of the inspection method that this method did "*not allow to detect all flaw indications, and that the method used for the interpretation of the signals tended to underestimate the dimensions of a small part of the detected flaw indications. In May and June 2014 the operator conducted new ultrasonic inspections in Doel 3 and Tihange 2 with the result of even higher flaw indication sizes.*" The corrected data show an increase of the number of flaws of about 60% and a strong increase of mean and maximum flaw indication size.

[35] FANC Provisional evaluation report (January 30, 2013), March 2013, http://www.greens-efa.eu/fileadmin/dam/Documents/Studies/Flawed%20Reactor%20Pressure%20Vessels.pdf

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

[37] http://www.fanc.fgov.be/fr/news/doel-3/tihange-2-clarifications-regarding-the-detection-the-position-and-the-size-of-the-flaw-indications/753.aspx

As an example the data for the lower shell of Doel 3 reported in the mentioned FANC "clarification" information are compared:

DOEL-3	2012 lower shell	2012_"reinterpr". lower shell	2014 lower shell
number of detected indications	7205	6936	11607
mean axial length of flaws (mm)	9.6	13.2	16
mean azimuthal length of flaws (mm)	7.6	11.7	12.7
maximum size of axial flaws (mm)	67.9	90.6	179
maximum size of azimuthal flaws (mm)	38.4	47.2	72.3

The new test runs were performed by Electrabel in the frame of the qualification procedure of nondestructive testing (NDT) as required by FANC. FANC concludes with respect to these results:

> *"- The number of reported indications is significantly higher than in 2012, mainly due to a lowering of the detection thresholds and to the use of a more sensitive transducer.*
>
> *- The update of the flaw sizing procedure resulted in an increase of the flake sizes to be considered in the structural integrity assessment. The tendency of the updated flaw sizing procedure to report clusters of indications as large individual flakes leads also to the reporting of larger average dimensions and much larger maximum dimensions in 2014.*
>
> *- The newly reported indications are located in the same zones as the indications reported in 2012.*
>
> *- No significant radial connections between hydrogen flakes are detected in the RPV core shells."*[38]*(page 77)*

It has to be expected that a more sensitive measuring technique will show an increased number of indications, but is hard to understand that large defect were not detected with the less sensitive techniques. The reverse effect seems to be plausible: large defects detected by a less sensitive method will appear as clusters of small defects using a more sensitive method.

According to Bel V the information given by Electrabel with respect to the site distribution of detected indications was not complete:

> *"No exhaustive information has been made available allowing to compare the statistical parameters characterizing the distribution of the tilt angle of the flaw indications. For the Doel 3 lower core shell, the tilt angle distribution curves for the 2012 and 2014 inspection have been*

[38] FANC, Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2 Final Evaluation Report 2015, , http://www.fanc.fgov.be/GED/00000000/4000/4027.pdf

made available and they do not evidence any significant change of the average value and standard deviation."[39]*(page 8)*

Bel V concludes:

"Bel V also considered that they were not able to provide an overall picture of the increased severity of the damage."(page 8)

On request of Bel V Electrabel had to investigate whether radial connections between the defects exist that could generate critical radial flaw extensions.

FANC concludes that:

"No significant radial connections between hydrogen flakes are detected in the RPV core shells of Doel 3 and Tihange 2." [40]*(page 31)*

Keeping in mind the statements of FANC in 2013 with respect to the flaw sizes the wording "*no significant*" might mean that there are radial connections.

One member of the International Review Board stated in that respect:

"The distribution of indications of the 2014 inspection compared to the 2012 inspection show to some extent a more densely population in the axial direction which could result in a decrease of ligament sizes indicated in and would make it difficult to exclude non-detectable small defects or weak grain boundaries in the ligaments."[41]*(page 29)*

Summarizing the cited statements there is obviously some concern in FANC and the associated expert groups about comparability of the measured flaw sizes in 2012 and 2014 that indicate possible growth of defects. Therefore FANC includes a single requirement in the statement on the restart authorization:

"The FANC requires the Licensee to perform follow-up UT-inspections, using the qualified procedure on the RPV core shells wall thickness at the end of the next cycle of Doel 3 and Tihange 2, and thereafter at least every three years."[42] *(page 80)*

Fazit:

- The fact that no reportable defects have been found during the acceptance testing after manufacture is obviously no issue for FANC and the consulting expert groups.

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[39] Bel V Safety Evaluation Report, Quasi-laminar flaw indications in the Doel 3 and Tihange 2 reactor pressure vessels. Evaluation of the impact of the hydrogen flaking damage in the serviceability of the Doel 3 and Tihange 2 reactor pressure vessels. http://www.fanc.fgov.be/GED/00000000/4000/4028.pdf

[40] FANC, Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2 Final Evaluation Report 2015, http://www.fanc.fgov.be/GED/00000000/4000/4027.pdf

[41] Doel 3 and Tihange 2 issue International Review Board Final Report, 2015 http://www.fanc.fgov.be/GED/00000000/4000/4029.pdf

[42] FANC, Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2 Final Evaluation Report 2015, http://www.fanc.fgov.be/GED/00000000/4000/4027.pdf

- The restricted comparability between the measurements in 2012 and 2014 is also only a minor concern for FANC and the expert groups.

- It is implausible that a more sensitive UT technique reveals large defects that were not detected by a less sensitive technique. The reverse observation has to be expected: large flaws detected with a less sensitive technique appear to be an assembly of small flaws using a more sensitive technique.

- The imprecise exclusion of radial connections between the flaws that implies that there exist radial connections indicates a further reduction of the strength of the reactor pressure vessel wall.

2.2.3 Growth of flaws during operation

The fact that no indications were found during acceptance testing after manufacture of the RPV and the thousands of flaws were detected 30 years of operation indicates that defect development or at least growth has occurred during operation. Another evidence for growth during operation is the detection of very larger flaw sizes during the tests in 2014 compared to the data in 2012.

Bel V reports Electrabel's claim that no in-service growth has occurred and manifests at the same time the own doubts:

> *"According to Electrabel, the comparison led to conclude that no new indication was detected in 2014 and no in-service growth of the indication was identified.*
> To Bel V opinion, considering that the time elapsed between the restart in 2013 and the shutdown in 2014 is less than one year, the results of the comparison do not allow to claim that there is an experimental evidence of no in-service growth. However, they should be considered as positive results."(page 17)[43]

In the beginning of 2015 a paper was presented at the meeting CORROSION 15 in Dallas concerning corrosion in PWR reactor pressure vessels[44] discussing the possibility that electrolytic or radiolytic hydrogen might diffuse into the RPV wall inducing hydrogen blistering phenomena. Such effects would indicate operational development/growth of defects in the RPV wall and could be a problem worldwide[45]. FANC reports in the Final Evaluation Report 2015:

> *"A hypothesis of hydrogen blistering or hydrogen-induced cracking was put forward by Prof. W. Bogaerts (KU Leuven) and Prof. D.D. Macdonald (UC Berkeley) who state that the exposure of the reactor pressure vessels to the primary water during operation could result in a molecular hydrogen accumulation and consequently a pressure increase in the (hydrogen-induced) flakes, and lead to their growth during the operation of the RPV."(page 40)*

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[43] Bel V Safety Evaluation Report, Quasi-laminar flaw indications in the Doel 3 and Tihange 2 reactor pressure vessels, http://www.fanc.fgov.be/GED/00000000/4000/4028.pdf
[44] W.F.Bogaerts, Z.H.Zheng, A.S.Jovanovic, D.D.Macdonald, Hydrogen-induced damage in PWR reactor pressure vessels, Research in Progress Symposium at CORROSION, 15th-19th March 2015, Dallas, USA, preprint
[45] http://www.3sat.de/mediathek/index.php?mode=play&obj=49691

Electrabel mentioned the discussion of the blistering hypothesis only very shortly:

> *"As the hydrogen content and pressure in the flakes is too low, no primary side hydrogen impact is expected on the material properties and no hydrogen-related propagation mechanism is possible. The approach and calculation hypotheses have been validated by measurements of residual H content in flakes (showing no significant H content), through literature review and advice from international experts. The absence of H-induced flake propagation is also confirmed by the absence of evolution of the flakes after one complete cycle and shutdown.[46]"(page 61)*

The external experts working for Electrabel state to the issue:

> *"The SCP Review Team has followed the discussion regarding the H2 blistering issue. Several meetings with international experts were held and aimed at exchanging about the possible mechanisms to investigate more deeply. The conclusions of those meetings, also covered by FANC and Bel V, were that the considered mechanisms were sufficiently investigated and that no doubt regarding H2 blistering issue subsists."[47] (page 20)*

FANC discussed the hypothesis also with NSEG experts and concludes in the Final Evaluation Report 2015 with respect to the growth of flaws during operation:

> *"The only theoretical propagation mechanism for the flakes detected in the Doel 3 and Tihange 2 reactor pressure vessels is low cycle fatigue, which is considered to have a limited effect. Other phenomena (such as hydrogen blistering or hydrogen induced cracking) have been evaluated and ruled out as possible mechanisms of in-service crack growth."(page 42)*

FANC does not discuss radiation effects like Frenkel defects (interstitials and vacancies), interstitial or vacancy agglomeration, radiation- induced segregation, radiation enhanced diffusion, helium generation (as a consequence of nuclear decay and fission product generation) and diffusion, precipitation of impurities at dislocations, grain boundaries and microcracks, evolving nanostructures including stable matrix features (SMF) that persist or grow under irradiation even in steels with low or no copper; all these processes could possibly contribute to defect/crack growth during operation.

Fazit:

- The fact that no indications were observed after manufacture but thousands of flaws 30 years thereafter with an increase in size in the latest UT test results can only be explained by defect development/growth during operation.
- Thus Electrabel is not able provide an explicit proof that no growth of flaws has occurred during operation.
- The exclusion of any defect growth except low cycle fatigue during operation is inconsistent with the state of science and technology.

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

[47] Report on independent analysis and advice regarding the safety case2015, Doel 3 reactor pressure vessel assessment, http://www.fanc.fgov.be/GED/00000000/4000/4025.pdf

- Even in case the observed flaws were hydrogen flakes growth mechanisms as described by Bogaerts and Macdonald cannot be ruled out.

2.3 Mechanical properties

For the structural integrity of a reactor pressure vessel (RPV) the mechanical properties of the steel (strength, hardness, fracture toughness, etc.) are of safety relevant importance. These properties are affected by temperature and neutron irradiation, it is therefore required to demonstrate that the specified mechanical are maintained throughout service life.

2.3.1 Initial fracture toughness of base metal

The appearance of thousands of defects in the base metal of the RPV wall raised doubts that the ductility (fracture toughness) of the steel can be assumed to be identical with that of the faultless material. The documented material characteristics of the base metal in the non-irradiated state were measured using defect-free material. There exists not representative material with a defect density comparable to the observed actual state

FANC states in the Final Evaluation Report 2015 concerning the samples:

> *"No flaked specimens from Doel 3 and Tihange 2 are available as the surveillance specimens were taken far from the macrosegregated areas in which the hydrogen flakes form. Most test materials were thus performed on representative flaked material such as theVB395, KS02 or unflaked materials such as the nozzle cuts of Doel 3 and Tihange 2 and some reference materials."*[48]*(page 44)*

The statement „representative flaked material" is certainly not correct, since neither VB395, nor KS02 have the same manufacture, heat treatment and operational history as the RPV steel.

> *"The D3T2 RPV forgings are made according to the US standard SA508 Cl.3, and VB395 is made of French steel type 18MND5. Both steels belong to the same family of MnMoNi RPV steel. On the other hand, KS 02 is made of German 22NiMoCr37 steel belonging to the family of NiMoCr RPV steel."*[49]*(page 35)*

Even with respect to the hydrogen flakes the representativeness is not given, since it not proven that the observed flaws in the RPV shells are really hydrogen flakes.

Thus, the test results using VB395/KS02 can only describe the mechanical characteristics and radiation sensitivity of the respective test block material but not the actual state of the RPV steel. Irradiation test results can only be used to enhance the data base for neutron embrittlement of RPV steels.

Bel V reports with respect to the fracture toughness reduction as a consequence of hydrogen flakes:

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[48] FANC, Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2 Final Evaluation Report 2015, http://www.fanc.fgov.be/GED/00000000/4000/4027.pdf

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

"In the 2012 Safety Case reports, Electrabel considered that the potential effect of the flakes on the material fracture toughness would be adequately taken into account by an additional shift in RTNDT. A value of 50°C (in addition of the shift calculated by the French predictive equation for the nominal content of the RPV forgings in embrittling elements) was selected by Electrabel. That additional shift comprised of
(i) a term of 11°C that accounts for the possible lower crack initiation fracture toughness (under unirradiated condition) of the material in the macro-segregated areas of the forgings where the hydrogen flakes have been detected when compared to the unsegregated areas,
(ii) a term of 14°C that accounts for the possible lower crack initiation fracture toughness for the flakes under unirradiated condition when compared to the crack initiation fracture toughness of the material in the ligaments between the flakes,..".[50] *(page 9)*

That means that all the experts agreed in 2013 that hydrogen flaking reduces the fracture toughness of the material.
Bel V states in 2015 based on the Electrabel experiments using VB395 samples:

"Bel V concludes that the hydrogen flaking as a damage has no effect on the fracture toughness of the material and the fracture resistance of the flakes is governed by the fracture toughness of the macro-segregated material where the flakes are located. The flakes may therefore be evaluated as any other crack in a sound material, the latter being in the present case the macro-segregated material where the flakes are located. This conclusion assumes that the stability of the flakes under single loading and their growth under repeated loadings may be assessed using the same methods as those currently used for mechanically-induced cracks (e.g., fatigue cracks)."(page 12)

Again: it hast to be kept in mind that the assumption of hydrogen flakes in the RPV is still not proven – therefore the conclusion (based on VB395 experiments) that the high defect density observed does not change the base metal fracture toughness in the unirradiated condition is highly questionable.

With respect to the segregations found in the material Bel V says:

"The estimated difference in RT_{NDT} *between the non-segregated and the segregated zones of the Doel 3 and Tihange 2 core shells was in the range of 0°C to 20°C. That is to say that those values of 0°C and 20°C are to be considered respectively as the estimated lower bound and the upper values of the difference in* RT_{NDT}*. Then, there are some unpublished experimental data which show that the segregation effect increases by about 10°C the* RT_{NDT} *temperature in the zones with positive segregation when compared to the zones with a carbon segregation equal to zero. So, Bel V concluded that a value of 10°C for* $\Delta RT_{NDT\ init\ (segregation)}$ *and a value of 5°C for the associated uncertainty (1σ) were acceptable."*[51]*(page 29)*

This argumentation shows clearly the Belgian Authority experts tend to minimize safety standards based on unpublished results while facing fundamental uncertainties. There is enough indication in the scientific literature that defects reduce the fracture toughness of materials.

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[50] Bel V Safety Evaluation Report, Quasi-laminar flaw indications in the Doel 3 and Tihange 2 reactor pressure vessels, http://www.fanc.fgov.be/GED/00000000/4000/4028.pdf
[51] Bel V Safety Evaluation Report, Quasi-laminar flaw indications in the Doel 3 and Tihange 2 reactor pressure vessels, http://www.fanc.fgov.be/GED/00000000/4000/4028.pdf

The International Review Board (IRB) remarks some doubts that the initial fracture toughness is supposed to be identical to that of the faultless material:

> *"The method proposed by Electrabel to estimate beginning of life toughness is consistent with the approaches used in other countries. However, the IRB has a* **minor concern** *that the uncertainty allowance for the values used might be too low. This could be the case if there were an unusually high systematic difference (bias) in toughness properties between the location from which test data were obtained and the regions of the vessels containing the flakes."[52](page 23)*

One member of the IRB is even not convinced that the toughness of the base metal is not affected by the flaws.

> *"The initial fracture toughness values may be not conservative for the zones with a high density of UT indications because these are probably correlated with a high degree of segregation." (IRB report page 29)*

FANC concludes:

> *"Complementary investigations on the flaked materials available (VB395 and KS02) show that the presence of flakes has no direct effect on the fracture toughness of the RPV material (in unirradiated or irradiated conditions)".[53] (page 53)*

Fazit:

- The fracture toughness of the defect-containing base metal (without the irradiation effect) is not known. Due to the lack of representative sample material there is no possibility for experimental determination.
- Experimental results from non-representative samples cannot be used for a credible prediction of the actual mechanical properties.
- FANC does not mention the slightest restriction concerning the transfer of results from the non-representative samples to the characteristics of the RPV material.
- The possible reduction of fracture toughness due to the defects assumed in 2012/2013 has been reduced to zero – this is a considerable reduction of conservatism.

2.3.2 Radiation effects on the ductility (toughness) of the steel

For safe reactor operation the RPV material has to be in the ductile state during all operational (normal and accidental) conditions. The transition from ductile material characteristics to low temperature brittle behavior is called ductile–brittle transition temperature (or nil ductility

[52] Doel 3 and Tihange 2 issue International Review Board Final Report, 2015 http://www.fanc.fgov.be/GED/00000000/4000/4029.pdf

[53] FANC, Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2 Final Evaluation Report 2015, http://www.fanc.fgov.be/GED/00000000/4000/4027.pdf

temperature) RT_{NDT}, defined as the temperature at 41 J in a standard Charpy test (measurement of the absorbed energy during fracture). During the last years the so called Master Curve method (direct fracture toughness measurements) is also used, but the comparability with the previous results (from Charpy tests) performed for a specific RPV material is still matter of discussion.

Neutron irradiation is known to induce embrittlement in the steel, observed by an increase of the reference transition temperature RT_{NDT}. In order to predict the embrittlement of the RPV steel the increase of RT_{NDT} with neutron fluence is calculated using so called predictive formulae that are supposed to be derived as enveloping upper bound curve based on a comprehensive irradiation study with comparable RPV steels (in the French standards the FIS formula). The formula includes a term considering the chemical composition of the steel.

Besides the predictive calculation of the embrittlement representative samples from the RPV manufacture are irradiated during operation in capsules close to the RPV wall. Due to the higher neutron flux compared to the RPV wall the samples show an accelerated embrittlement behavior and may be used for experimental control of the predictive calculations.

There is no information on the irradiation behavior of RPV material with the high flaw density as observed in the RPV shells of D3/T2.

As a requirement of FANC for the restart in May 2013 Electrabel had to perform irradiation experiments using samples from the rejected steam generator block AREVA VB395. The irradiation was performed in the BR2 test reactor.

As a consequence of the first irradiation campaign results showing higher embrittlement than predicted both reactor blocks were shut down in March 2014.

In order to clarify these results charged an international expert group with an explicit limitation to the radiation damage issue:

> *„The FANC charged the International Review Board to conduct an independent review and to address two specific, limited topics. The implication of the IRB is therefore limited to the first step of the review process, the evaluation of the methodology proposed by the Licensee:*
>
> ***T1.** Assessment of the predicting formula for the transition temperature shift as proposed by Electrabel for use in the structural integrity evaluation of the Doel 3 and Tihange 2 RPV core shells and in prevention of brittle failure (P-T limit curve, PTS). In particular, the transferability of the results of the tests performed on the (French) VB395 material and (German) KS02 material to the Doel 3 and Tihange 2 RPV core shells material shall be assessed.*
> ***T2**. Assessment of the following Electrabel conclusion on the root cause analysis:*
> *Precise mechanism of non-hardening embrittlement and precise root cause of non-hardening embrittlement of VB395 remain unidentified but hydrogen-related and hydrogen-flaking related mechanisms are excluded."[54](pages 47-48)*

[54] FANC, Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2 Final Evaluation Report 2015, http://www.fanc.fgov.be/GED/00000000/4000/4027.pdf

2.3.2.1 Samples for irradiation experiments

Since no archive samples of RPV material with high defect density were available FANC and Electrabel agreed to perform additional irradiation experiments using the rejected AREVA steam generator component VB395. Further irradiation experiments were performed using nozzle cuts (these samples are representative for the defect-free RPV material) and for a later campaign a German defect-containing block KS02 (from experiments in the frame of the Forschungsvorhaben Komponentensicherheit).

Representative material has to be from the same steel charge, has to have identical manufacture, heat treatment and operational history as the respective component. These requirements are not fulfilled for VB305 and KS02. The nozzle cuts are archive materials but do not contain dense flaws as the RPV shells-

IRB also clarifies that the VB395 is not a representative material for Doel 3 and Tihange 2:

> *"In the opinion of the IRB, VB395 is likely, in terms of irradiation shift, an anomalous and unrepresentative material."*[55]*(page 23)*

ORNL considers VB395 only as relevant for radiation effects on hydrogen flakes containing material:

> *"The VB395 and KS02 materials are only relevant to D3/T2 primarily with regard to the fact that they each contain a high density of hydrogen flakes that is valuable in assessing if the hydrogen flakes have significant effects on the mechanical properties and fracture toughness of the D3/T2 forgings as a consequence of exposure to irradiation."*[56]*(page 54)*

Fazit:

- The sample materials VB395 and KS02 are not representative for the RPV material in the sense of identical manufacture, heat treatment and operational history, even the steel is only similar but not identical.
- The sample materials VB395 and KS02 are also not representative for the defect-containing RPV wall because the nature of defects in the D3T2 shells is still not proven.
- The results from irradiation experiments performed using VB395 and KS02 samples characterize these materials with respect to their specific mechanical characteristics and the radiation sensitivity, but will not allow to deduce credible information on the actual state of the RPV vessel wall. The data could only be used to increase the embrittlement data base of comparable steels.

2.3.2.2 Predictive embrittlement formula

The outcome of irradiation experiments as measured using Charpy tests of fracture measurements (Master curve) are compared with the predictive formula. These formulae are derived from extensive

[55] Doel 3 and Tihange 2 issue International Review Board Final Report, 2015 http://www.fanc.fgov.be/GED/00000000/4000/4029.pdf

[56] ORNL Evaluation of Electrabel Safety Cases for Doel 3 / Tihange 2: Final Report, http://www.fanc.fgov.be/GED/00000000/4000/4030.pdf

irradiation experiments and surveillance data of different similar RPV steels and are supposed to cover the scatter of experimental data conservatively.

In the Safety Case 2012 Electrabel[57] has used the FIS formula as developed for French RPV steels based on comprehensive irradiation studies of RPV steels and consider the chemical composition of the steels.

$RT_{NDT} = RT_{NDT\ init} + \Delta RT_{NDT\ FIS,\ segregation}$

In the Safety Case 2015 new trend curves were introduced by Electrabel[58] referring to RSE-M[59] (Ed.2010) (page 69):

"$RT_{NDT} = RT_{NDT,init} + RT_{NDT,init,segr} + RT_{NDT,RSE\text{-}M} + RT_{NDT,VB395} + M$

$RT_{NDT,init}$ corresponds to the initial RT_{NDT} of the core shells as determined by RDM[60]

$RT_{NDT,init,segr}$ covers the potential lower fracture toughness of the material in the macrosegregated areas containing hydrogen flakes, as requested by the FANC. On the basis of material representative of the D3T2 core shells, this effect was estimated as 10°C. It should be pointed out that this additional shift is generally not considered in the international practice which addresses the effect of segregations through enrichment factors in the embrittlement trend curves.

$RT_{NDT,RSE\text{-}M}$ corresponds to the shift in RT_{NDT} as a function of fluence, as given by the French RSE-M (Ed.2010) embrittlement trend curve evaluated for the D3T2 core shell chemical composition (thereby considering enrichment factors to account for the composition of macro-segregations)

$RT_{NDT,VB395}$ is an additional fluence dependent shift as observed on the VB395 material. It is taken as the difference between the observed atypical embrittlement of the material between hydrogen flakes and the embrittlement that can be expected for this material on the basis of the RSE-M trend curve"

M is a margin based on the uncertainties of the different terms: M equals 2 times the quadratic combination of the uncertainty on the effect of the macro-segregation (evaluated as 5°C) and the standard deviation of the RSE-M formula (9.3°C)

It should be pointed out that these trend curves are very conservative because they are based on the assumption that the D3T2 RPV core shells have an additional sensitivity to irradiation embrittlement of the same magnitude as the VB395 material, which is very unlikely taking into account the results of the test programme and the assessment of the atypical embrittlement of VB395."

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

[58] Electrabel, Safety Case 2015, Doel 3 reactor pressure vessel assessment, http://www.fanc.fgov.be/GED/00000000/4000/4023.pdf

[59] Règles de Surveillance en Exploitation des Matérials Mécaniques des Illots Nucléaires French code providing Rules for Inservice Inspection of Nuclear Power Plant Components

[60] Rotterdamsche Droogdok Maatschappij

By definition a predictive trend curve is supposed to be the enveloping bound for all tested similar steels. All surveillance data (except the value for very high fluence) including the measuring scatter ranges are below the FIS curve as can be seen in the left diagram, below (figure 4.29, Electrabel Safety Case 2012, page 67.)

The new predictive curve designed by Electrabel is shown to fit the surveillance data from D3T2 "perfectly" can be seen in the right diagram below (Electrabel Safety Case 2015 figure 5.15, page 50), this figure shows that the experimental data and the scatter are not enveloped by the trend curve, the 2σ standard deviation is necessary for enveloping.

<u>Remark</u>: the experimental data differ in the figures from 2012 (FIS curve) and 2015 (the new trend curve): compare for instance the third D3 point from the left (in 2012 ΔRT_{NDT} is slightly below 60°C, in 2015 slightly above). Keeping in mind the experimental scatter, this difference is in fact negligible, but remarkable.

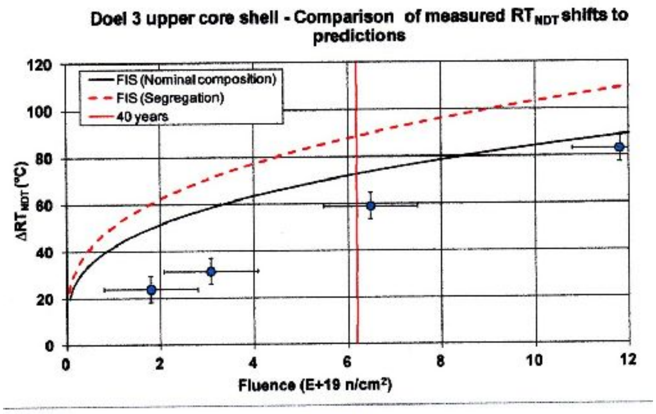


Figure 4.29

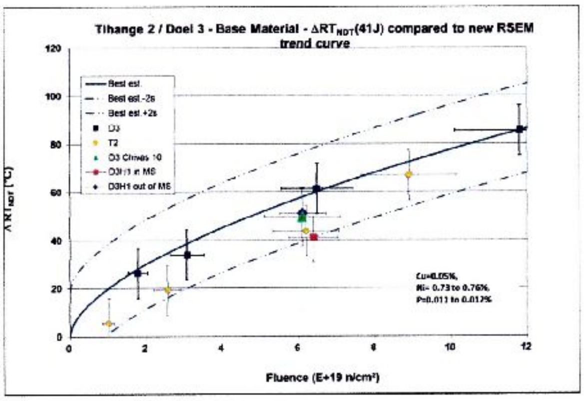


Figure 5.15: CHIVAS-10 results for D3 UCS and D3H1 compared to RPV Surveillance results and to RSE-M prediction.

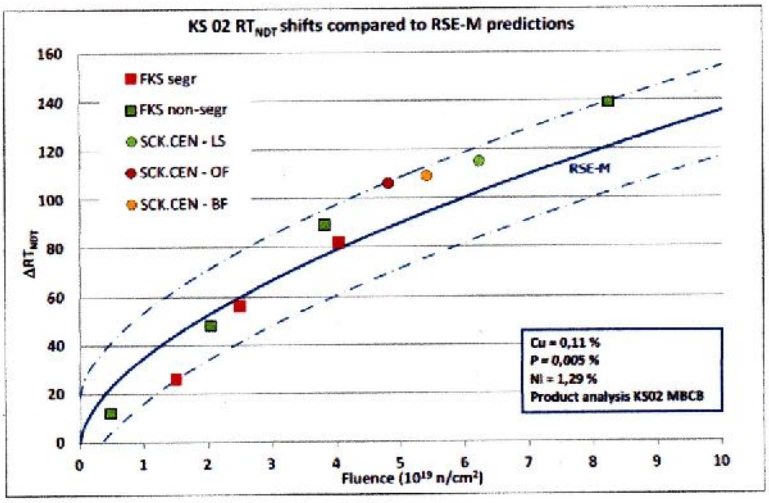
Source: Electrabel Safety case 2012

Source: Electrabel Safety Case 2015

The inherent safety margin by using the FIS formula is completely lost by the use of the new Electrabel trend curves, because the deviation lines do not appear anymore in the curves t be used for SIA.

This demonstrates that new predictive trend curves are certainly not "very conservative", they are fitted to the given D3T2 data. The additional shift of RT_{NDT} ($RT_{NDT,init,segr}$ + $RT_{NDT,VB395}$ + M) that is supposed to be a safety margin in the magnitude of the observed higher embrittlement in the VB395 samples seems to be designed in way that the limiting 132° for RT_{NDT} will not be reached before end of life.

The RT_{NDT} shifts of the German RPV steel sample KS02 (as a comparable steel) should also be enveloped by the new predictive trend curve. The figure 11 in the SCP report on the Safety Case 2015 (page 21) shows that most of the experimental data points are above the curve.



Source: SCP[61]

Figure 11: Shift in RT_{NDT} ($\Delta T=41J$) versus fluence (LS = 'Less Segregated Zone', OF = 'out of flakes', BF = 'Between Flakes')

Thus the Electrabel designed predictive curves cannot be considered to be conservative enveloping trend curves.

The value of $RT_{NDT,init,segr}$ - requested by FANC - estimated by Electrabel to 10°C is certainly not an extra safety margin, it is obviously disappearing in the standard deviation.

The extra shift $RT_{NDT,VB395}$ includes an undefined factor and an unexplained exponent, it can be assumed that this shift is designed so that RT_{NDT} does not reach the limit of 132°C before end-of-life. (see section 2.3.2.4)

Some more detail can be found in the ORNL Final Report[62](page 66):

Doel 3 upper core shell: RT_{NDT} = **-22 °C** + **39.5 $F^{0.59}$** + **31 °C**
Doel 3 lower core shell: RT_{NDT} = **-22.2 °C** + **37 $F^{0.59}$** + **36.2 °C**
Tihange 2 upper core shell: RT_{NDT} = **-25.4 °C** + **40 $F^{0.59}$** + **31 °C**
Tihange 2 lower core shell: RT_{NDT} = **-27.2 °C** + **37.2 $F^{0.59}$** + **36.2 °C**

Yet it is not clear how the three terms fit to the given equation
$RT_{NDT} = RT_{NDT,init} + RT_{NDT,init,segr} + RT_{NDT,RSE\text{-}M} + RT_{NDT,VB395} + M$
with five terms and why the factor of the fluence-term varies for the different shells.

Fazit:

- The predictive FIS formula from the French standards has been replaced by “Electrabel made” predictive trend curves that are supposed to include an extra safety margin based on the VB395 embrittlement. There is no quantitative explanation or justification for the different terms of the equation.

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61 Report on independent analysis and advice regarding the safety case2015, Doel 3 reactor pressure vessel assessment, http://www.fanc.fgov.be/GED/00000000/4000/4025.pdf
62 ORNL Evaluation of Electrabel Safety Cases for Doel 3 / Tihange 2: Final Report, http://www.fanc.fgov.be/GED/00000000/4000/4030.pdf

- The new predictive formula does not fulfill the definition to be an enveloping upper boundary for similar steels.
- The trend curves to be used for the structural integrity assessment show that RT_{NDT} for 40 years of operation is slightly below the limit of 132°C. This indicates that the so called “variable margin” is designed to consider this limit.

2.3.2.3 Results of the irradiation campaigns (RT_{NDT} shift)

The results from different irradiation campaigns using samples from VB395 showed remarkable higher embrittlement than predicted by the new predictive trend curves.

The last irradiation campaign was performed with samples from a German hydrogen flakes containing similar steel (FKS: Forschungsvorhaben Komponentensicherheit) for further comparison. The measured RT_{NDT} shifts of this campaign also exceeded the trend curves by up to 20°C [63](figure 11, page 21).

Electrabel used these results to rule out hydrogen flaking as root cause for the enhanced embrittlement of the VB395 material and in consequence for the D3T2 shells (based on the assumption that the flaws in D3T2 are hydrogen flakes).

In order to explain the irradiation results Electrabel proposed a second embrittlement mechanism occurring in the VB395 material. Bel V agrees:

> *“Those results suggest that a second embrittlement mechanism is acting in addition to the irradiation hardening mechanism in the VB395 material.”[64](page 27)*

But Bel V also writes:

> *“Based on the available information, the VB 395 material and the Doel 3/Tihange 2 RPV core shells material belong to the same family of material. The fact that enhanced irradiation embrittlement has not been identified in the Doel 3 nozzle shell and upper core shell does not allow to conclude that the occurrence of enhanced irradiation embrittlement may be excluded for the Doel 3 lower core shell and Tihange 2 upper core shells (which are the most affected by hydrogen flaking).” (page 30)*

The experts of AIB-Vinçotte even declare that the radiation effects in the RPV shells need not necessarily to be higher than in the defect-free material (nozzle cuts).

> *„From the presented test results followed that the only material exhibiting an atypical embrittlement is the VB395 material and there is no reason to conclude that the material*

[63] SCP report on Safety Case 2015 RPV Doel, http://www.fanc.fgov.be/GED/00000000/4000/4025.pdf
[64] Bel V Safety Evaluation Report, Quasi-laminar flaw indications in the Doel 3 and Tihange 2 reactor pressure vessels, http://www.fanc.fgov.be/GED/00000000/4000/4028.pdf

properties in the flaked RPV shell of Doel 3 are necessarily worse than in a shell without flakes like the Doel 3 H1 cut-out."[65]*(page 9)*

This is certainly true, but it is also true that the radiation effect in the defect-containing RPV shells D3T2 could be by far stronger.

The SCP team states[66]:

> *"There is no technical basis for stating that the steel of the Doel 3 and Tihange 2 RPVs would react in any way worse than that of the VB395 regarding the embrittlement under irradiation in the flaked area." (page 23)*

There is also no technical basis to prove that this assumption is conservative.

However, the SCP team remarks with respect to the uncertainty of the sample relevance:

> *"This extra shift has been used as input for the structural integrity assessment, providing a conservativeness that could not be quantified exactly (since we do not know the exact behaviour of the flaked areas in the Doel 3 and Tihange 2 RPV shells under irradiation)."(page 24)*

ORNL does also declare the embrittlement behavior as abnormal:

> *"The root cause for the abnormal and excessive embrittlement of the VB395 forging is not thoroughly known at this time. Although not necessary for application to D3/T2, ORNL suggests that further research be conducted to discern the exact mechanism(s) of the abnormal embrittlement to provide additional knowledge regarding behavior of forgings with hydrogen flakes."*[67] *(page 55)*

Summarizing the different expert groups consider VB395 before the irradiation campaigns as relevant with respect to the radiation effects in the defect containing D3T2 shells but the unexpected embrittlement is than declared to be an abnormal feature of the sample. It has to be kept in mind that Electrabel and FANC choose VB395 as representative sample to proof that irradiation does not affect hydrogen flakes containing material seriously. As it turned out that the radiation effect is more serious than expected VB395 is declared to be an abnormal outliner.

The question is: Why not conclude that the trend curve is obviously not conservative?

The direct fracture toughness measurements of irradiated VB395 samples (Master Curve) showed fracture toughness shifts (ΔT_0) for VB395 samples (figure 5.19, page 53) remarkably higher than the RT_{NDT} shifts measured by Charpy tests (figure5.18, page 54)[68], the difference estimated from the figures is about 40 °C. (i.e. the Master Curve shift at EOL is about 100°C).

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[65] AIB-Vinçotte, Synthesis report Doel 201, http://www.fanc.fgov.be/GED/00000000/4000/4033.pdf
[66] SCP report on Safety Case 2015 RPV Doel, http://www.fanc.fgov.be/GED/00000000/4000/4025.pdf
[67] ORNL Evaluation of Electrabel Safety Cases for Doel 3 / Tihange 2: Final Report, http://www.fanc.fgov.be/GED/00000000/4000/4030.pdf
[68] Electrabel, Safety Case 2015, Doel 3 reactor pressure vessel assessment, http://www.fanc.fgov.be/GED/00000000/4000/4023.pdf

Electrabel concludes with respect to the irradiation results of VB395 samples:

> *"Since the larger than predicted shift in transition temperature after irradiation of VB395 is not linked with the hydrogen flaking and since none of the above mentioned manufacturing specificities are reported for the D3T2 RPVs, it is expected the D3T2 RPV shells do not suffer from the atypical embrittlement observed on VB395."*[69] *(page 67)*

The application of trend curves can certainly not be restricted with respect to "*manufacturing specificities*", otherwise they might not be applicable to D3T2 shells either, because of manufacturing deficiencies.

The conclusion that the D3/T2 RPV shells do not suffer worse embrittlement than VB395 samples cannot be proven at all.

All irradiation experiments have been performed in the Belgian BR2 test reactor with very high neutron flux, so that the RPV neutron fluence at end of life can be simulated by rather short irradiation times. Due to a possible dose rate effect[70] high-flux irradiation results might underestimate the real embrittlement. The dose rate effect has been observed in Western RPV steels[71] and Russian RPV steels[72,73]. Up to now the consideration of the dose rate effect for the embrittlement prediction has not been included in the national standards.

Electrabel remarks with respect to the influence of neutron flux:

> *"The CHIVAS-12 results are in line with the historical German results. This confirms the absence of significant flux effect for this material, the BR2 flux being an order of magnitude higher than in the German irradiations."*[74] *(page 51)*

This does certainly not exclude a possible flux (dose rate) effect, because the neutron flux of the German research reactor irradiation was still at least a magnitude higher than the flux at the RPV wall.

Fazit:

- The observed remarkable embrittlement in the VB395 samples surmounting the predictive trend curves shows that this material should not be applied for RPV manufacture due to its

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[69] Electrabel, Safety Case 2015, Doel 3 reactor pressure vessel assessment, http://www.fanc.fgov.be/GED/00000000/4000/4023.pdf

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

[71] 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

[72] Ya. Strombach, RRCKI, *Examination of WWER-440 RPV steel re-irradiation behaviour using materials from operating units*, Journal of Pressure Vessels and Piping 77 (2000)

[73] A.A. Chernobaeva, Radiation embrittlement of RPV materials, Joint scientific program: Joint Helmholtz – ROSATOM school and ITEP winter school of physics «extreme state of matter», Feb. 19th – Feb. 26th 2012

[74] Electrabel, Safety Case 2015, Doel 3 reactor pressure vessel assessment, http://www.fanc.fgov.be/GED/00000000/4000/4023.pdf

severe radiation sensitivity but these results cannot be utilized to rule out enhanced embrittlement of the D3T2 shells.

- It is not possible to rule out enhanced embrittlement for the D3T2 shells based on the assumption that the flaws in D3T2 are hydrogen flakes and the additional assumption that the strong embrittlement is not linked to hydrogen flakes.

- The observed embrittlement exceeding the predictive trend curves could as well be an indication that the predictive trend curve is not conservative.

- There is no proof that the embrittlement of the flawed D3T2 shells could not be by far higher than assumed.

- A possible flux effect (higher embrittlement at lower irradiation flux compared with the embrittlement at higher flux for the same total radiation dose) cannot be excluded.

2.3.2.4 Uncertainties – safety margins

In the Safety Case 2012 Electrabel had proposed to add an extra shift of RT_{NDT} of 50°C to the predictive trend curves in order to cover all uncertainties concerning a possible fracture toughness reduction due to the dense flaws and possible radiation effects. It has to be noted that the former International Review board recommended the use of a shift of 100°C instead of the 50°C. This of course would have surmounted the regulatory limit of 132 °C for RT_{NDT} (this fact might be the reason why the IRB recommendation was no more included in the FANC Final Evaluation Report 2013).

In the Safety Case 2015 Electrabel has eliminated this 50° shift and replaced by a "*variable margin*":

> *"Embrittlement law (2014 vs 2012): reassessment of the RT_{NDT} shift of the core shell material from the transposition of the properties obtained on shell VB395 (addition of a variable margin on top of the RSE-M formula), instead of the consideration of a fixed margin 50°C on top of the FIS formula.[75](page 104)*

The variable margin is defined according FANC Final Evaluation Report 2015[76](page 54) as $\Delta RT_{NDT(VB395)}$ = $factor_{(VB395)} * \Phi^{*}0.59$; the text does not say the value of this $factor_{(VB395)}$. There is no scientific justification for the $factor_{(VB395)}$ and the exponent (0.59) in this formula.

More detail can be found in the ORNL Final Report[77] (page 66), but this does not answer the open questions (see preceding section).

FANC concludes in the Final Evaluation Report 2015:

> *„The 50°C margin on RT_{NDT} considered in the 2013 Safety Case is discarded and replaced by predictive equations depending on the material properties. Considering the VB395 to be an*

[75] Electrabel, Safety Case 2015, Doel 3 reactor pressure vessel assessment, http://www.fanc.fgov.be/GED/00000000/4000/4023.pdf

[76] FANC, Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2 Final Evaluation Report 2015, http://www.fanc.fgov.be/GED/00000000/4000/4027.pdf

[77] ORNL Evaluation of Electrabel Safety Cases for Doel 3 / Tihange 2: Final Report, http://www.fanc.fgov.be/GED/00000000/4000/4030.pdf

outlier for material behaviour under irradiation, the core shells of Doel 3 and Tihange 2 are unlikely to be more sensitive to irradiation. Nevertheless, as a safety provision, the Doel 3 and Tihange 2 predictive equations take into account the atypical embrittlement observed in the VB395 flaked material. Therefore the FANC deems the predictive equations for the irradiation embrittlement featured in the 2015 Licensee Safety Cases are acceptable."(page 55-56)

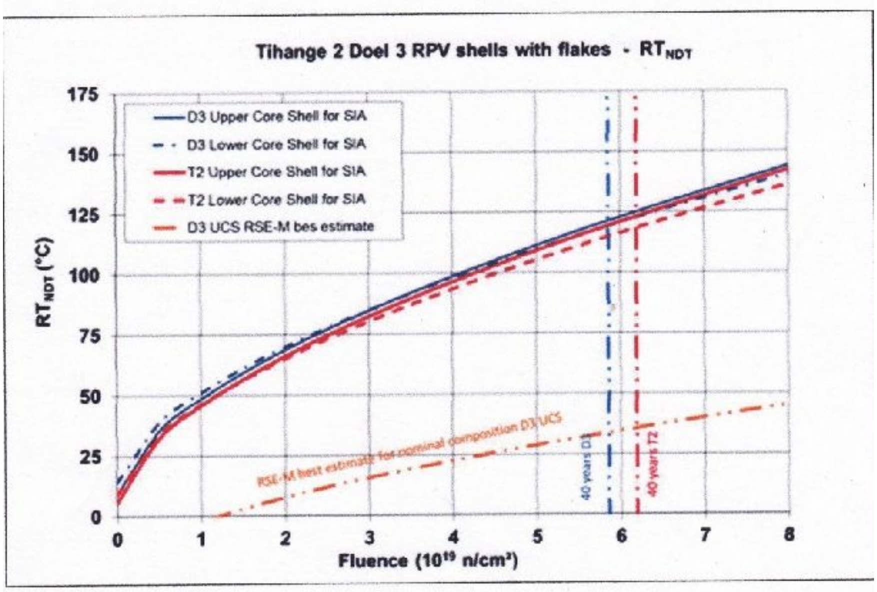

Figure 5.27: RT_{NDT} trend curves for the D3T2 core shells used in the SIA.

Source: Electrabel Safety Case 2015, page 71

The figure 5.27 (page 71) in the Electrabel Safety Case 2015 allows the estimation of the used extra shift of RT_{NDT} supposed to be in the magnitude of the VB395 embrittlement at EOL: Assuming that the shift due to the FANC request is about 10°C, M about 15°C, the remaining difference is about 55-60°C. As derived in the preceding section the shift of the VB395 Master Curve is about 100°C. That means that the extra shift is de facto a random value, very probably fitted to the requirement that RT_{NDT} remains below 132°C until end-of-life. The figure shows that the trend curves to be used for SIA comply with this requirement.

As will be shown in the next section (2.4) the embrittlement has also to be coped with the warming up the emergency cooling water otherwise the structural integrity cannot be demonstrated:

"Safety Injection System water temperature: 40°C (2014) vs. 7°C (2012)". (page 104)

According to the director of FANC the safety injection water will be heated to 45°C.

Fazit:

- The FANC requirements concerning irradiation experiments using samples of the rejected steam generator block AREV VB395 were based on the agreement between Electrabel and FANC that VB395 is representative for the RPV steel. As a consequence of the unexpected results the VB935 was defined as an abnormal outliner.

- The still valid predefinition of hydrogen flakes in the D3T2 shells ignores the fact that this cannot be proven. With respect to the irradiation experiments the unexpected embrittlement of VB395 is defined as not yet clarified but not due to hydrogen flakes. In fact there are no credible experimental results on the radiation effect in the flaw-containing RPV shells.

- The procedure to declare VB935 as abnormal outliner because of the unexpected embrittlement and to exclude based on this definition a higher embrittlement for the D3T2 shells is highly questionable. The embrittlement could be by far higher.
- The experimental data on radiation effects using the samples VB935 and KS02 show that the new trend curve is not conservative. The date scatter of up to 20°C above the trend curve should trigger the requirement of an extra safety margin or an adjustment of the trend curve to an enveloping upper bound.
- The safety margin "in the magnitude of the VB935 embrittlement" to be used for the structural integrity assessment is not quantified. The figures show that this extra margin might only be an adjustment to the requirement that RT_{NDT} has to remain below 132°C until end-of-life and by far smaller than the observed VB395 embrittlement.
- Since it cannot be excluded that the enhanced embrittlement does occur in the D3T2 shells the so called extra shift defined by Electrabel is not a safety margin. It might not even be a conservative estimate of the possible embrittlement.

2.4 Structural integrity assessment (SIA)

The demonstration of the RPV structural integrity throughout service life is performed by a PTS (pressurized thermal shock) analysis. The temperature distribution in the RPV wall as a consequence of normal and accidental transients is calculated using thermohydraulic codes. The thermal stress field due to possible temperature gradients on an assumed crack in the RPV wall is than calculated with fracture mechanical methods for the progressing accident transient. This load path is than compared with the actual expected fracture toughness curve (trend curve for SIA), see preceding sections).

For the assumed crack the size and location of the documented flaws have to be used. The neutron fluence depends on the location of the assumed crack and the expected embrittlement is deduced from the predictive trend curves.

Comparing the calculated load path (stress intensity versus temperature during the accidental transient) with the lower bound fracture toughness curve the tangency of the two curves gives the critical RT_{NDT}. This critical value may not be reached until end of life. This is the so called ASME acceptance criterion:

$RT_{NDT(crit)} – RT_{NDT(final)} > 0$: acceptance criterion is satisfied

$RT_{NDT(crit)} – RT_{NDT(final)} < 0$: acceptance criterion is not satisfied

Alternative parameter for application of ASME flaw acceptance criterion:

$RT_{NDT(final)} / RT_{NDT(crit)} < 1$: acceptance criterion is satisfied

$RT_{NDT(final)} / RT_{NDT(crit)} > 1$; acceptance criterion is not satisfied

According to Bel V the structural integrity assessment (SIA) has only be updated with respect to the adjusted neutron fluence, the new Electrabel trend curves and the flaw sizes;

> *"Basically the Licensee applied the same methodology as in the anterior Safety Case and its addendum presented by the Licensee in 2012-2013."*
> *The Licensee established a new Safety Case to take into account the following updated input data:*
> *• The updated predictive equation for the RT_{NDT} as a function of fluence;*
> *• The updated RPV fluence distribution after 38 years of operation (40 years of lifetime);*
> *• The increased Safety Injection (SI) water temperature implemented in Doel 3 NPP;*
> *• The updated UT indications cartography, obtained by application of the qualified inspection procedure."* [78]*(page 10)*

The warming-up of the safety injection water (for emergency cooling) is defined in the Electrabel Safety Case 2015 to 40°C as new input parameter:

> *"Safety Injection System water temperature: 40°C (2014) vs. 7°C (2012)."*[79] *(page 105)*

It is interesting to note that in the FANC Final report 2015 the value of the increased safety injection temperature is not quantified:

> *"The increased Safety Injection (SI) water temperature implemented in Doel 3 NPP"*[80] *(page 63)*

According to Jan Bens, director of FANC, this temperature has even been increased to 45-50°C.

> *"Les études d'incidence tiennent compte du fait que l'eau de refroidissement que l'on verse sous certaines conditions dans le coeur peut avoir une température située entre 8 et 50 degrés. Pour éviter le choc thermique, on a rehaussé le seuil bas et on a préchauffé cette eau à 45 degrés."* [81]*(page 5)*

Jan Bens is concretizing that the 50°C are a limit because higher temperatures might trigger another safety relevant problem: the coolability of the reactor core in the accidental case:

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[78] AIB-Vinçotte, Synthesis report Doel 201, http://www.fanc.fgov.be/GED/00000000/4000/4033.pdf
[79] Electrabel, Safety Case 2015, Doel 3 reactor pressure vessel assessment, http://www.fanc.fgov.be/GED/00000000/4000/4023.pdf
[80] FANC, Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2 Final Evaluation Report 2015, http://www.fanc.fgov.be/GED/00000000/4000/4027.pdf
[81] CRIV 54 **COM 281,** Chambre des représentants de Belgique, Sous-commision de la sécurité nucléaire, Compte rendue generale, 02-12-2015

“Ces 50 degrés sont la valeur considérée dans les études d'accident. Il s'agit de voir comment se comporte le coeur du réacteur en cas d'incident et on tient compte d'une certaine valeur, maximale dans ce cas-ci, de temperature de l'eau qui est injectée. Avec cette valeur-là, est-il encore possible de refroidir le coeur du réacteur? Ces calculs ont été faits il y a des années avant la construction de la centrale avec une valeur fixée à 50 degrés. C'est pourquoi nous avons fixé la limite à 50 degrés. Pourrait-on faire les calculs avec une autre valeur? C'est possible, mais nous n'avons pas fait l'exercice.” (page 13)

This shows that the required “new parameter” cannot be defined with safety margins, the value is necessary for the demonstration of the structural integrity on the one hand and is on the other hand limited by the requirement of core coolability in case of an accident.

The ORNL calculations have been performed using the safety injection (SI) water temperature of 40°C, as the description of for instance the figure B.3 in the ORNL report shows:

“Fig. B.3 LOCA transient used by ORNL for screening assessment of Doel 3 (SLOCA 3 in; SI=40°C)”[82] *(page 69)*

This is raising a further problem: the large amount of safety injection water (presumably about 1800 m^3) has to be continuously warmed up to about 45°C. The temperature may not be lower than 40°C because this would violate the requirements for the structural integrity and may not reach 50°C because this would endanger the coolability of the core under accidental conditions.

It is clear that the tolerance window is rather small and there is no safety margin at all.

Obviously no updating was performed with respect to the set of accident transients for the thermohydraulic calculations. In 2012 the French authorities had indicated that there was some possible non-conservatism.[83]

In the frame of the Safety Case 2012 the thermal hydraulic calculations used symmetric cooling conditions at the RPV wall although this is not usual in the international PTS studies. 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*.”)[84]

The increase of the safety injection water temperature indicates that otherwise a successful PTS analysis was not possible.

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[82] ORNL Evaluation of Electrabel Safety Cases for Doel 3 / Tihange 2: Final Report, http://www.fanc.fgov.be/GED/00000000/4000/4030.pdf

[83] 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

[84] 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

ORNL was asked by FANC to "*provide a thorough assessment of the existing safety margins against cracking of the RPVs due to the presence of almost laminar flaws found in each RPV*."[85]

The fracture mechanical analysis used as in 2012 a Grouping method that was adopted by ORNL.

Electrabel had developed specific grouping rules for closely spaced flaws using 3-D finite element modeling in the frame of the Safety Case 2012 according to the principles of the proximity rules given by the ASME Code Case N-848. The ASME rules were developed for two or three close flaws. It is doubtful that the Grouping method is valid for the case of D3T2.

ORNL adopted the results of the grouping process performed by Electrabel (ORNL Final Report, page 62). It turned out that several grouped and individual flaws did not comply with the ASME acceptance criteria. Therefore ORNL included the so called WPS (warm prestress) effect

> *"WPS model implemented into FAVOR is invoked to re-assess the four EBL-characterized flaws listed in Table 5.2 (b) that are non-compliant according to ASME Section XI (2004). The three noncompliant EBL-characterized flaws found in Doel 3, i.e., Flaw Groups GP0817 and GP0818, as well as individual flaw 492, are shown to be compliant with application of the WPS model. For the individual flaw 1660, found in Tihange 2 and subjected to LOCA 1, the screening criterion $RT_{NDT(final)}/RT_{NDT(crit)}$ decreases from 1.49 to 1.20; thus, flaw 1660 remains non-compliant according to the ASME acceptance criterion with or without WPS." (page 32)*

Warm prestress is a phenomenon that the fracture toughness of steels in the lower shelf region is enhanced by preloading at high temperatures. The effect was observed at notched samples and has been studied with a variety of experimental conditions. The effect seems to be dependent on these conditions.[86] The experiments were performed with small and component-like samples but not with complete pressure vessels.

The inclusion of the WPS effect in the PTS analysis is allowed in the US Regulatory environment but not within KTA and not in the French standard.

The effect of the WPS effect is demonstrated by ORNL for a specific flaw:

> *"Without WPS, a value of RTNDT-CRIT = 77.9 °C provides a point of tangency between applied KI(t) and the fracture toughness curve. That point of tangency occurs after the maximum value, K_{Imax}, has occurred and, thus, does not satisfy the WPS criteria. Inclusion of WPS increases the critical value to $RT_{NDT(CRIT)}$ = 102 °C. Thus $RT_{NDT(final)}/RT_{NDT(crit)}$ = 1.15 without WPS and $RT_{NDT(final)}/RT_{NDT(crit)}$ = 0.88 with WPS."[87](page 72)*

This means that only by including the WPS effect the flaw in compliance with the ASME acceptance criterion.

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[85] ORNL Evaluation of Electrabel Safety Cases for Doel 3 / Tihange 2: Final Report, http://www.fanc.fgov.be/GED/00000000/4000/4030.pdf

[86] U.Alsmann, Werkstoffmechanische Untersuchungen zu den Mechanismen des Vorbelastungseffekts, Dissertation, MPA Stuttgart, 2002

[87] ORNL Evaluation of Electrabel Safety Cases for Doel 3 / Tihange 2: Final Report, http://www.fanc.fgov.be/GED/00000000/4000/4030.pdf

For the flaw 1660 of the WPS inclusion was not enough the reach compliance, therefore ORNL used a "more realistic" modeling of the flaws until the compliance was reached:

> *"ORNL's independent refined analysis demonstrated the EBL-characterized flaw 1660, which is non-compliant in the ORNL and EBL screening assessment, is rendered compliant when modeled as a more realistic individual quasi-laminar flaw using a 3-D XFEM analysis approach." (page 12).*

FANC concludes concerning SIA:

> *"The presented structural analysis shows that the Doel 3 and Tihange 2 RPVs with hydrogen flakes meet the ASME XI requirements for 'Acceptance by Analytical Evaluation' for the specified loading and material properties.*
> *The foregoing results and conclusions confirm the structural integrity of Doel 3 and Tihange 2 under all design transients with ample margins."[88] (page 73)*

Fazit:

- Compared to the structural integrity assessment in 2012 Electrabel has updated the neutron fluence distribution and the flaw sizes, has replaced the FIS formula by a new predictive trend curve and has introduced the warming of the safety injection water to 40°C. FANC does not quantify this temperature in the Final report 2015; Jan Bens (director of FANC) stated in the Belgian chamber representatives that the temperature of the safety injection water will be 45-50°C.

- The heating requirement of the safety injection water is raising a further problem: the large amount of safety injection water (presumably about 1800 m^3) has to be continuously warmed up to about 45°C. The temperature may not be lower than 40°C because this would violate the requirements for the structural integrity and may not reach 50°C because this would endanger the coolability of the core under accidental conditions. It is clear that the tolerance window is rather small and there is no safety margin at all.

- No experimental validation has been presented for the grouping method introduced by Electrabel in 2012.

- The doubts of the French regulatory Authority that the set of studied accident transients included the most penalizing scenarios have not been discussed.

- According to the ORNL calculations several flaws did not comply with the ASME acceptance criterion.

- It was necessary to include the WPS effect (which is not foreseen by the French standards) to reach compliance for most flaws.

- For one flaw this procedure was not enough, a "more realistic" modeling had to be adopted to reach the required compliance. This is equivalent with a reduction of conservatism.

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[88] FANC, Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2 Final Evaluation Report 2015, http://www.fanc.fgov.be/GED/00000000/4000/4027.pdf

- It has to be kept in mind that the inherent safety margin of the FIS formula has been eliminated by the new predictive formula. The extra shift supposed to consider possible higher embrittlement does not envelop the experimental results.

3. Conclusions

The defense in depth approach (in Germany the basic safety philosophy) requires for the safe operation of nuclear power plants superior quality of design, materials and operation.

- Basic safety or highest quality in accordance with defense in depth during manufacture of the reactor pressure vessels of Doel 3 and Tihange 2 cannot be demonstrated due to the incomplete documentation.
- The detection of thousands of flaws proofs that highest quality is not given, the pressure vessels were not licensable neither today nor at the time of manufacture. It is therefore highly questionable in the frame of basic safety or the defense-in-depth approach that 30 years thereafter the nuclear authority is authorizing the restart of both plants.

The evaluation of the documents showed with respect to the detected flaws:

- The real nature of the defects that cause the indications found by ultrasonic testing can only be disclosed by destructive testing. The argumentation by Electrabel and accepted by FANC is only based on plausibility considerations.
- The hydrogen flaking assumption cannot explain why only the four shells in the NPPs Doel 3 and Tihange 2 are affected and not all of the RPVs produced by the same manufacturer.
- The hydrogen flaking assumption cannot explain why the flaws have not been detected during acceptance testing after manufacture.
- The possibility of irregular processes before or during cladding of the RPV that could have introduced impurities into the vessel wall with following growth during operation has not been discussed by Electrabel and FANC.
- The hypothesis of electrolytic/radiolytic hydrogen that could contribute to the growth of defects during operation (W.Bogaerts, D.D.Macdonald) was rejected by FANC.
- In the further argumentation by FANC and the different expert groups the defects behind the UT indications are assumed as hydrogen flakes without any restriction although still no proof for this assumption exists.

With respect to number and size of the defects and the indication of growth during operation:

- The fact that no defects have been found during the acceptance testing after manufacture is obviously no issue for FANC and the consulting expert groups.
- The restricted comparability between the measurements in 2012 and 2014 is also only a minor concern for FANC and the expert groups.

- It is implausible that a more sensitive UT technique reveals larger defects that were not detected by a less sensitive technique. The reverse observation has to be expected: large flaws detected with a less sensitive technique appear to be an assembly of small flaws using a more sensitive technique.

- The imprecise exclusion of radial connections between the flaws that implies that there exist radial connections indicates a further reduction of the strength of the reactor pressure vessel wall.

- The fact that no indications were observed after manufacture but thousands of flaws 30 years thereafter with an increase in size in the latest UT test results can only be explained by defect development/growth during operation.

- The exclusion of any defect growth except low cycle fatigue during operation is inconsistent with the state of science and technology. Even in case the observed flaws are hydrogen flakes growth mechanisms as described by Bogaerts and Macdonald cannot be ruled out.

For the structural integrity of the reactor pressure vessels during operation the state of the mechanical characteristics throughout service life are of crucial importance.

- The fracture toughness of the defect-containing base metal (without the irradiation effect) is not known. Due to the lack of representative sample material there is no possibility for experimental determination.

- Experimental results from non-representative samples cannot be used for a credible prediction of the actual mechanical properties.

- FANC does not mention the slightest restriction concerning the transfer of results from the non-representative (VB395 and KS02) samples to the characteristics of the RPV material.

- The possible reduction of fracture toughness due to the defects assumed in 2012/2013 has been reduced to zero – this is a considerable reduction of conservatism.

In order to study radiation effects on defect containing material FANC had decided that Electrabel should use samples from the rejected steam generator block VB395 and the German FKS material KS02 since no representative RPV material was available.

- The sample materials VB395 and KS02 are not representative for the RPV material in the sense of identical manufacture, heat treatment and operational history, even the steel is only similar but not identical.

- The sample materials VB395 and KS02 are also not representative for the defect-containing RPB wall because the nature of defects in the D3T2 shells is still not proven.

- The results from irradiation experiments performed using VB395 and KS02 samples characterize these materials with respect to their mechanical characteristics and the radiation sensitivity, but will not allow to deduce credible information on the actual state of the RPV vessel wall. The results could be used to enhance the embrittlement database for similar steels.

- The predictive FIS formula from the French standards has been replaced by "Electrabel made" predictive trend curves that are supposed to include an extra safety margin based on the VB395 embrittlement. There is no quantitative explanation or justification for the different terms of the new equation.
- The new predictive formula does not fulfill the definition to be an enveloping upper boundary for similar steels.
- The trend curves to be used for the structural integrity assessment show that RT_{NDT} for 40 years of operation is slightly below the limit of 132°C. This indicates that the so called "variable margin" is designed to consider this limit.
- The observed remarkable embrittlement in the VB395 samples surmounting the predictive trend curves shows that this material is not applicable for RPV manufacture due to its severe radiation sensitivity but cannot be utilized to rule out enhanced embrittlement of the D3T2 shells.
- It is not possible to deduce that enhanced embrittlement cannot be expected for the D3T2 shells based on the assumption that the flaws in D3T2 are hydrogen flakes and the additional assumption that the strong embrittlement is not linked to hydrogen flakes.
- The observed embrittlement exceeding the predictive trend curves could as well be an indication that the predictive trend curves are not conservative.
- A possible flux effect (higher embrittlement at lower irradiation flux compared with the embrittlement at higher flux for the same total radiation dose) cannot be excluded.
- The FANC requirements concerning irradiation experiments using samples of the rejected steam generator block AREV VB395 were based on the agreement between Electrabel and FANC that VB395 is representative for the RPV steel. As a consequence of the unexpected high embrittlement results the VB935 was defined as an abnormal outliner.
- The procedure to declare VB935 as abnormal outliner because of the unexpected embrittlement and to exclude based on this definition a higher embrittlement for the D3T2 shells is highly questionable.
- The still valid predefinition of hydrogen flakes in the D3T2 shells ignores the fact that this cannot be proven. With respect to the irradiation experiments the unexpected embrittlement of VB395 is defined by Electrabel as not yet clarified but not due to hydrogen flakes. In fact there are no credible experimental results on the radiation effect in the flaw-containing RPV shells.
- The experimental data on radiation effects using the samples VB935 and KS02 show that the new trend curves are not conservative. The date scatter of up to 20°C above the trend curve

should trigger the requirement of an extra safety margin or an adjustment of the trend curve to an enveloping upper bound.

- The safety margin "in the magnitude of the VB935 embrittlement" to be used for the structural integrity assessment is not quantified. The figures show that this extra margin might only be an adjustment to the requirement that RT_{NDT} has to remain below 132°C until end-of-life.
- Since it cannot be excluded that the enhanced embrittlement does not occur in the D3T2 shells the so called extra shift defined by Electrabel is not a safety margin. It might not even be a conservative estimate of the possible embrittlement.

The structural integrity assessment in the Safety Case 2015 has been adjusted to the new data but not with respect to the methodology.

- Compared to the structural integrity assessment in 2012 Electrabel has updated the neutron fluence distribution and the flaw sizes, has replaced the FIS formula by a new predictive trend curve and has introduced the warming of the safety injection water to 40°C. FANC does not quantify this temperature in the Final report 2015; Jan Bens (director of FANC) stated in the Belgian chamber representatives that the temperature of the safety injection water will be 45-50°C.
- The heating requirement of the safety injection water is raising a further problem: the large amount of safety injection water (presumably about 1800 m^3) has to be continuously warmed up to about 45°C. The temperature may not be lower than 40°C because this would violate the requirements for the structural integrity and may not reach 50°C because this would endanger the coolability of the core under accidental conditions. It is clear that the tolerance window is rather small and there is no safety margin at all.
- No experimental validation has been presented for the grouping method introduced by Electrabel in 2012.
- The doubts of the French regulatory Authority that the set of studied accident transients included the most penalizing scenarios have not been discussed.
- According to the ORNL calculations several flaws did not comply with the ASME acceptance criterion.
- It was necessary to include the WPS effect (which is not foreseen by the French standards) to reach compliance with the ASME criterion for most flaws.
- For one flaw this procedure was not enough, a "more realistic" modeling had to be adopted to reach the required compliance. This is certainly a further reduction of conservatism.
- It has to be kept in mind that the inherent safety margin of the FIS formula has been eliminated by the definition of the new predictive formula. The extra shift supposed to consider possible higher embrittlement does not envelop the experimental results.

The evaluation of the published documents has revealed the reduction of conservatism throughout the performed Safety Case analysis. The non-representative samples that were supposed to confirm the safety margin in the uncertainty assessment in the Safety Case 2012 have converted to abnormal outliners. Keeping in mind that growth of the flaws in the RPV shells during operation cannot be excluded the authorized restart of the two nuclear power plants not understandable.

4. Attachment

Minority concern about the adequacy of the margins in the beginning of life toughness and other aspects of the safety case. [89] (page 29)

One member of the board does not fully support the IRB assessment, Section 3 and the conclusion, Section 4, on the basis of the following arguments and review of documents supplied after the IRB meeting in April 2015 in response to the minority concerns by Electrabel:

a) The initial fracture toughness values may be not conservative for the zones with a high density of UT indications because these are probably correlated with a high degree of segregation.

b) The content of phosphorus in the D3 and T2 shells is higher than VB395 and KS02 taking the product analysis, which may affect the extent of segregation and the irradiation response.

c) The distribution of near surface indications of the Lower Core Shell in D3 shows a type of truncation which differs considerably from the other shells and need to be explained in conjunction with the basic hypotheses of hydrogen flaking.

d) Based on the type of distribution mentioned above the expert sees no reason why the segregations would not be present up to the surface of the D3 Lower Core Shell affecting the cladding interface material properties. Furthermore it is possible that base metal repairs were made before cladding to remove surface defects in this region and, given the manufacturing practice at the time, not documented.

e) The distribution of indications of the 2014 inspection compared to the 2012 inspection show to some extent a more densely population in the axial direction which could result in a decrease of ligament sizes indicated in and would make it difficult to exclude non-detectable small defects or weak grain boundaries in the ligaments.

f) The expert understands that the stress intensity calculation does not consider residual stresses. These may be present due to manufacturing influences including: heat treatment; the different local microstructures; the formation of the hydrogen flakes; and for the near surface indications the heat affected zone of the weldment of the cladding. It is difficult to assess the values and direction (tensile/compression) during the transient loads.

g) The tilt angle may differ in the different segregation zones and basing the tilt angle on the UT measurements may be too demanding for the UT method for which the validation does not cover the whole spectrum of flake sizes and populations.

h) To rely on the visual inspection to support the assumption of an un-cracked cladding remains as a source of debate considering operating experience.

i) The areas of high density of near surface indications in D3 with the present interpretation of flake sizes could impact the local temperature distribution in transient conditions causing non-uniform stresses in the local ligaments.

j) Some IRB members gained some additional confidence in the case from a supporting crack arrest argument, which was not part of the Electrabel case, but had been suggested by one of the IRB experts. However the use of crack arrest condition may be difficult to validate for the shell areas with a high degree of segregation and flakes. To the knowledge of the expert large scale experiments (e. g. ORNL, MPA, NESC) simulating combined thermal-mechanical loads did not covered material conditions containing similar segregations and flakes and even under less complicated conditions was the extent of crack extension and number of re-initiation not sufficiently predicted.

[89] Doel 3 and Tihange 2 issue International Review Board Final Report, 2015 http://www.fanc.fgov.be/GED/00000000/4000/4029.pdf

Acronyms

DBTT	ductile-brittle transition temperature
EBL	Electrabel ENGIE Group
FANC	Federal Agency for Nuclear Control
FIS	Formule d'irradiation Supérieure
FKS	Forschungsvorhaben Komponentensicherheit
NDT	nil-ductility temperature
NSEG	National Scientific Expert Group
ORNL	Oak Ridge National Laboratory
RPV	reactor pressure vessel
RSE-M	Règles de Surveillance en Exploitation des Matérials Mécaniques
SCP	Service de Contrôle Physique
SI	Safety injection
SIA	structural integrity assessment
UT	ultrasonic testing
WPS	warm prestress