Nuclear Risk Report

Excerpt:

I. Tweer / W. Renneberg:

Material Problems in Reactor Pressure Vessels: Doel 3/Tihange 2

iNRAG International Nuclear Risk Assessment Group

Material Problems in Reactor Pressure Vessels: Doel 3/Tihange 2

The Safety Cases performed by the licensee as a consequence of the detection of thousands of flaws in the reactor pressure vessels in Doel 3 and Tihange 2 were analyzed, the deficiencies of the structural assessment in the safety case reports published by the Belgian Nuclear Authority FANC were identified and discussed. There exist considerable doubts on the Safety Cases as accepted by FANC with respect to the methodology concerning number, size and origin/nature of the flaws, the radiation embrittlement trend curves and the performed structural integrity assessment for the reactor pressure vessels.

Ilse Tweer / W. Renneberg

1. Introduction

The PWR nuclear power plants Doel 3 and Tihange 2 in Belgium are operated by Engie Electrabel S.A. part of GDF Suez; NPP Doel 3 started operation in 1982, Tihange 2 started operation in 1983.

The reactor pressure vessel (RPV) of a nuclear reactor is the central component enclosing the reactor core where the nuclear reactions occur. The RPV's integrity is therefore the key barrier for fission product retention; structural integrity of the RPV during service life is the primary requirement for safe operation of the nuclear power plant. The RPV steel has to be of superior quality without inacceptable defects.

For the demonstration of the RPV structural integrity throughout service life it is crucial to consider material aging phenomena due to radiation, thermomechanical fatigue and corrosion. Scheduled in-service inspections using nondestructive techniques are supposed to survey the defect-free status and the stability of detected flaws.

In addition to the regular recurring in-service inspections specific inspections carried out in Doel 3 in June 2012 to detect possible underclad defects in the base material of the entire cylindrical part of the RPV, unexpected flaws in the forged rings (SA-508-cl.3) of the reactor core area were detected.

A total of 7,776 indications were found in the core lower shell, and 931 indications in the core upper shell [1]. Similar flaws were revealed in September 2012 in the reactor pressure vessel of the nuclear power plant Tihange 2: in the upper core shell 1,931 indications, in the lower core shell 80 indications. In the transition ring no indications have been reported, in the flange 19 indications have been identified.

Based on the Safety Case in 2012 experts from the Federal Agency for Nuclear Control (FANC) issued a positive opinion to restart the Doel 3 & Tihange 2 reactor units on May 17, 2013.[2]

[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

FANC imposed requirements concerning further studies and experiments on the licensee[3]. 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 on its decision to advance the planned outage of its nuclear reactors Doel 3 and Tihange 2 due to unexpected results of irradiation experiments.[4]

November 17th, 2015 FANC authorized the licensee Electrabel to restart the Doel 3 and Tihange 2 reactor units based on the Safety Case 2015 documents.[5] These documents were published on the FANC web side.[6]

2. Detected flaws - characterization – basic safety

The Belgian nuclear authority FANC informed the public in the Provisional Evaluation Report[7] (page 23/24) that the flaws in the depth ranges up to 120 mm from the inner clad surface have mean sizes of 10-14 mm, "some exceeding 20-25 mm" in the case of Doel 3, and "maximum size 24 mm" 2 in the case of Tihange. This statement is a clear contradiction to the figure published by Electrabel[8] (fig. 1): the number of flaws with sizes above 25 mm is significantly more than "some". The observed flaws were describes as quasi-laminar, i.e. parallel to the inner surface in about 100 mm depth.

In February 2015 FANC published revised data of the number of flaws and their sizes[9]: According to FANC the operator of the two power plants 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 hardly understandable fact that indications with sizes up to 179 mm have not been detected during acceptance testing after manufacture has not be explained by the Electrabel and FANC. In spite of this fact Electrabel claims that no growth of the flaws has occurred during operation. There is also no unquestionable explanation for the increase of number and sizes of flaws between 2012 and 2014. "*Bel V concludes that the updated condition of the Doel 3 and Tihange 2 RPV core shells as revealed by the examination performed in 2014 using the qualified UT inspection procedure is to be considered as having a substantially increased structural significance when compared to the condition determined in 2012.*"[10]

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[3] FANC, Doel 3 and Tihange 2 reactor pressure vessels. Final evaluation report, http://www.afcn.fgov.be/GED/00000000/3400/3429.pdf

[4] 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

[5] http://www.fanc.fgov.be/GED/00000000/4000/4032.pdf

[6] For summarizing comments on the safety Case 2015 see: Ilse Tweer, Flawed Reactor Pressure Vessels in the Belgian NPPs Doel 3 and Tihange 2. Comments on the FANC Final Evaluation Report 2015, January 2016, https://www.greens-efa.eu/legacy/fileadmin/dam/Documents/Studies/Nuclear_issues/Report_Flawed_Reactor_Pressure_Vessels_Doel-3_and_Tihange-2.pdf

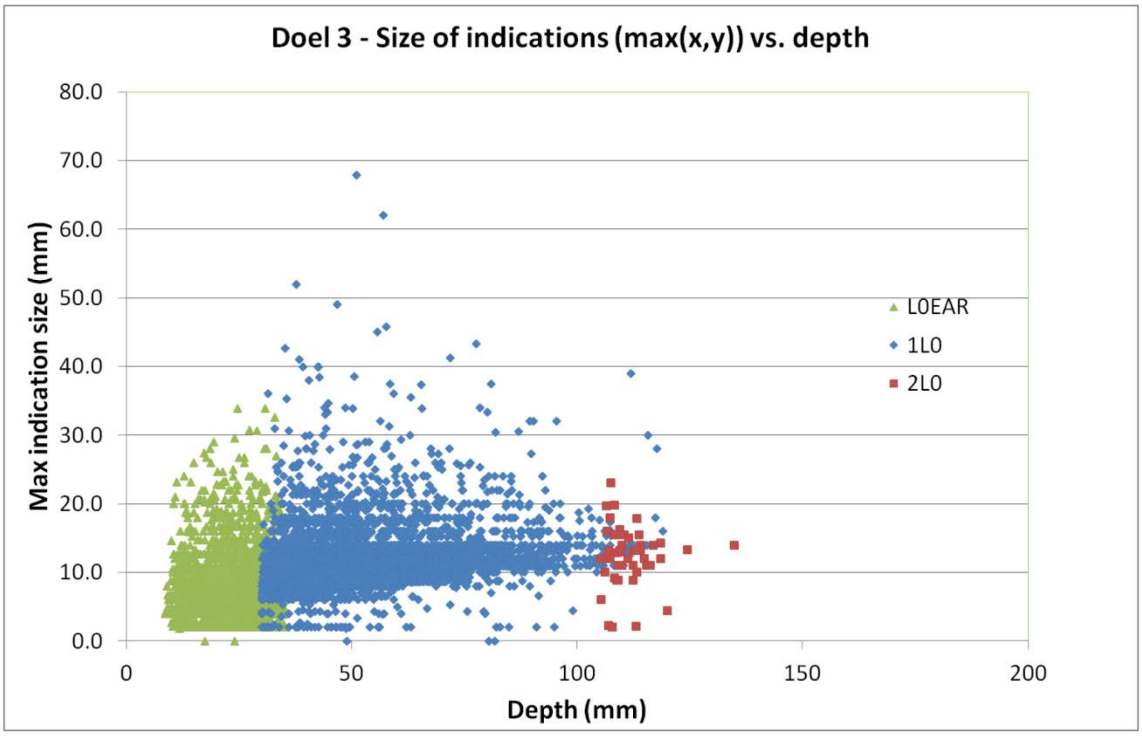
[7] FANC, Doel 3 and Tihange 2 reactor pressure vessels. Provisional evaluation report, http://www.afcn.fgov.be/GED/00000000/3300/3391.pdf

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

Doel 3/Tihange 2: clarifications regarding the detection, the position and the size of the flaw indications, 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

[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, http://www.fanc.fgov.be/GED/00000000/4000/4028.pdf

Figure 1: Indication sizes at Doel 3



Source: Electrabel

On a parliamentarian request of the Green Party, the German Government answered that the Belgian Nuclear Authority FANC is not able to reconstruct from the manufacturing documentation, why the flaws have not been detected before operation.[11]

FANC informed on May 5th, 2017 that the recent ultrasonic testing in Doel 3 (November 2016) and Tihange 2 (April 2017) has shown that no new indications were recorded and no growth of the flaws was observed.[12]

In June 2017 FANC revealed that 300 new indications were recorded in the RPV of Doel 3 and 70 new indications in the RPV of Tihange 2[13]. At the same time FANC confirms: "*Since we have been able to find scientific explanations for all these newly reported hydrogen flakes, or they have been accounted for by signals recorded in previous inspections, the analysis of these results allows us to conclude that no new hydrogen flakes have appeared and that there has been no change in the size of the hydrogen flakes already detected*". There is no explanation or justification for the exclusion of growth processes that could also contribute to the larger size of indications.

The statement indicates that the uncertainty in size estimates is rather large so that a possible growth of the flaws in the range of this uncertainty would not be considered as growth by FANC. The same is true for possible radial connections between the flaws. FANC does not quantify this uncertainty. The clear statement by FANC does not comply with its requirement of further confirmation by structural integrity assessment (SIA) and indicates FANC's unsureness.

[11] Bundesregierung, 08.05.2017, Drucksache 18/12057, Antwort der Bundesregierung auf die kleine Anfrage zum aktuellen Sachstand zu den belgischen Kernkraftwerken

[12] FANC, 05.05.2017, Pas d'évolution des flocons d'hydrogèneà Tihange 2, http://www.fanc.fgov.be/fr/news/pas-d-evolution-des-flocons-d-hydrogenea-tihange-2/878.aspx

[13] June 2017: No evolution of hydrogen flakes: Full Tihange 2 inspection report, http://www.fanc.fgov.be/fr/page/doel-3-tihange-2-flaw-indications-in-the-reactor-pressure-vessel-steel/1989.aspx

Table 1: Indications Doel-3

Doel-3	Upper Shell 2012	Upper Shell 2012_reint erpr.	Upper Shell 2014	Lower Shell 2012	Lower Shell 2012_reint erpr.	Lower Shell 2014
Nr. of indications	857	829	1440	7205	6936	11607
Mean axial length	8,8	12	13,7	9,6	13,2	16
Mean azimuthal length	7,6	11,6	12,3	7,6	11,7	12,7
Max axial length	31	40,6	56,4	67,9	90,6	179
Max azimuthal length	26,4	32,8	45,3	38,4	47,2	72,3

Source: Electrabel

Table 2: Indications Tihange-2

Doel-3	Upper Shell 2012	Upper Shell 2012_reint erpr.	Upper Shell 2014	Lower Shell 2012	Lower Shell 2012_reint erpr.	Lower Shell 2014
Nr. of indications	1931	1901	3064	80	76	85
Mean axial length	9,8	13,4	14,8	10,2	14,8	15,5
Mean azimuthal length	7,9	12	13,8	9,3	14,3	15,4
Max axial length	38	61,8	154,5	27,4		33,1
Max azimuthal length	25,4	34,2	70,9	19,1		27,6

Source: Electrabel

Nature and origin of the flaws

Shortly after the detection of the large amount of flaws Electrabel stated that these flaws are "hydrogen flakes" originating from the manufacturing process. "*The full screening of all potential forming mechanisms confirms the hydrogen flaking as the most likely origin of the indications*"[14]. FANC adopted this explanation[15]. This root cause analysis cannot explain why not all the forged shells are affected by hydrogen flaking (the flaking is only found in the core neighboring shells) – this fact was already mentioned by the Belgian Bel V in 2012[16].

Excessive hydrogen in the steel cannot be excluded, because the required manufacture documentation of the RPVs in Doel 3 and Tihange 2 is not complete[17], especially with respect to the heat treatment (dehydrogenation treatment) of the steel.

[14] Electrabel, Safety Case Report: Doel 3 - Reactor Pressure Vessel Assessment, December 2012 (page 88)..
[15] 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
[16] 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
[17] 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

On the other hand Bel V notices: "*The identification of indications with large size (> 25 to 30mm) raises an important issue because "elementary" flakes of such a size are practically excluded due to metallurgical considerations.*"[18] This implies that either growth of hydrogen flakes during operation had occurred or the flaws cannot be considered to be hydrogen flakes.

One expert of the International Review Board (IRB) referred to the fact of a truncation in the indication distribution close to the cladding interface in one of the shells that causes doubts concerning the flaking hypothesis[19].

The possibility of other defects/introduced impurities caused before or during the cladding process that could have grown during operation was not discussed by Electrabel and FANC, although they were mentioned by the member of the IRB and one of the authors of this paper[20].

In 2015, the corrosion experts W. Bogaerts and D.D. MacDonald discussed the hypothesis that hydrogen is produced by electrolytic processes (corrosion) during operation and could diffuse into the reactor pressure vessel wall and agglomerate with hydrogen flakes, which could then induce dangerous blistering.[21] FANC rejected this hypothesis referring to "*comments stated by three international experts who are worldly recognized as specialists in hydrogen induced corrosion*" [22].

The growth of defects due to radiation-induced processes, esp. radiation-enhanced diffusion and radiation induced segregation is not taken into account by Electrabel and FANC although this is a known characteristic in the context of material aging of reactor pressure vessel steels during operation[23]. To the knowledge of the authors there is literature on radiation effects in materials with high density defects.

Defense in depth (basic safety)

The acceptance of a high-risk technology is based on the precondition of superior materials according the specifications and the state of the art (basic safety). The reactor pressure vessel enclosing the reactor core, where the nuclear reactions occur, is the most important barrier against the release of fission products into the environment. Thus the failure of the reactor pressure vessel must be excluded, a replacement is not possible.

Bel V states in the introduction of the Safety Case 2015 evaluation (page 4): "*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.*"[24]

Steels with thousands of flaws with sizes up to 170 mm cannot be considered to be superior quality materials for the manufacture of reactor pressure vessels. At the time of construction appropriate ultrasonic testing equipment was available so that defects as detected in 2012 should have been found. In this context the acceptance of the respective core shells in Doel 3 and Ti-

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[18] BelV 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, (page 15) http://www.fanc.fgov.be/GED/00000000/4000/4028.pdf

[19] Doel 3 – Tihange 2: RPV issue - International Expert Review Board - Final Report (page 29), http://www.fanc.fgov.be/GED/00000000/4000/4029.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, (page 14) http://www.greens-efa.eu/fileadmin/dam/Documents/Studies/Flawed%20Reactor%20Pressure%20Vessels.pdf

[21] 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

[22] FANC, Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2 Final Evaluation Report 2015 (page 41ff), http://www.fanc.fgov.be/GED/00000000/4000/4027.pdf

[23] G.R. Odette, G.E. Lucas, JOM, 53 (7) (2001), Embrittlement of nuclear pressure vessels (pp. 18-22).

[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

hange is inapprehensible. „*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.*"[25]

The first level of the defense-in-depth philosophy is basically violated - the reactor pressure vessel is not licensable, neither today nor at the time of manufacture.

Summarizing remarks – remaining open questions

The core shells of the reactor pressure vessels Doel 3 and Tihange 2 do not correspond to the basic safety requirements – the reactor pressure vessels are not licensable. The late detection of large flaws cannot be explained - the possibility of counterfeits/frauds cannot be excluded. Growth of defects during operation might be an explanation but is strictly excluded by the licensee and the Regulatory Authority FANC. The characterization of the flaws as hydrogen flakes is only based on plausibility arguments; an experimental proof would need destruction of the reactor pressure vessels.

Open questions:

- The size of the flaws is contradicting the hydrogen flaking hypotheses - thus the nature of the flaws is still not clarified.
- There is still no explanation why the large number of flaws was not detected at the time of manufacture although the testing technology was appropriate.
- There is no explanation why only the core shells are affected.
- The possible growth of flaws during operation – as negated by Electrabel - cannot be excluded especially in the frame of new indications exceeding the recording threshold in the last inspection (2016/2017).

3. Aging of the reactor pressure vessel steel

The first level of the defense-in-depth philosophy requests superior quality of the RPV materials – steel and welding metal. Besides the in-service inspections including visible inspections, dye penetration tests and ultrasonic testing material focused on possible evolution or growth of flaws the mechanical properties of the materials are of predominant interest with respect to the maintenance of the structural integrity.

Mechanical properties of the steel

In the frame of the demonstration of structural integrity for reactor pressure vessels the fracture toughness (ductility) of the steel is of predominant importance. The steel has to be ductile in the complete temperature range of operational procedures. Neutron (and gamma) irradiation cause an embrittlement of the steel, i.e. the ductile-brittle transition temperature increases with increasing fluence.[26] The reference temperature for this transition RT_{NDT}[27] is defined either by Charpy tests (RT_{NDT} is the temperature at 41 J) or by direct fracture toughness measurements (T_0 is the temperature at 100 MPa√m).

[25] 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

[26] At low temperatures the steel is brittle - the temperature of transition to the ductile state is the so called ductile-brittle transition temperature.

[27] NDT stands for nil-ductility temperature.

The fulfillment of design specifications for the mechanical materials' quality has to be demonstrated using samples of identical charges with identical manufacture and heat treatment history as the RPV shells. Equivalent samples are necessary for the so called irradiation surveillance program designed for radiation effect monitoring.

The initial ductility and RT_{NDT} values (unirradiated) were measured in faultless samples (without a high density of flaws as observed thirty years later). This implies that the ductility of flaw containing material is not known.

In the safety Case 2012 Electrabel proposed a shift of 25°C to the reference temperature RT_{NDT} to cover possible effects of macrosegregation and hydrogen flakes on fracture toughness of the material – as reported by Bel V[28]. FANC stated in the Final evaluation Report in 2015 that "*the presence of flakes has no direct effect on fracture toughness*"[29]. This conclusion is based on experiments performed by Electrabel using samples from a rejected steam generator block (VB395) containing hydrogen flakes and a German block KS02 (Forschungsvorhaben Komponentensicherheit). These samples can certainly not be considered to be representative with respect to steel production, manufacture and heat treatment history.[30]

Radiation effects

As mentioned above the fracture toughness is reduced by neutron irradiation – the so called neutron embrittlement of the steel - i.e. the reference temperature RT_{NDT} is increased with neutron fluence. In order to predict the embrittlement of the RPV steel the increase of RT_{NDT} with neutron fluence is calculated using predictive trend formulae based on a large number of irradiation experiments of comparable steels. These trend curves are supposed to be an enveloping upper bound curve (in the French standards the FIS formula - Formule d'irradiation Supérieure). The formula includes a term considering the chemical composition of the steel; this allows adjusting the trend curve for the considered steel.

The plant-specific surveillance program is designed to monitor neutron embrittlement with RPV representative samples that are positioned during operation close to the inner RPV wall. The higher neutron flux at the surveillance capsules with respect to the RPV wall defines the "lead factor"; the accelerated embrittlement behavior may be used for experimental control of the predictive calculations.

Due to the lack of archive material representative for flaw-containing steel, FANC imposed for the restart in May 2013 the requirement of irradiation experiments using samples from the rejected steam generator block AREVA VB395 that contain hydrogen flakes. The irradiation was performed in the BR2 test reactor.

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

Predictive trend curves for radiation embrittlement

In the safety Case 2012 Electrabel had proposed to add an extra shift of RT_{NDT} in the predictive trend curves in order to cover the effect of hydrogen flaking and macrosegregation and the un-

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[28] 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 (page 9)

[29] 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 (page 53)

[30] For a more comprehensive overview on official statements on this issue see [30] Ilse Tweer, Flawed Reactor Pressure Vessels in the Belgian NPPS Doel 3 and Tihange 2. Comments on the FANC Final Evaluation Report 2015, January 2016, https://www.greens-efa.eu/legacy/fileadmin/dam/Documents/Studies/Nuclear_issues/Report_Flawed_Reactor_Pressure_Vessels_Doel-3_and_Tihange-2.pdf

known radiation effects on the flaw-containing material. As the experimental irradiation results from the VB395 samples could not be described by this assumption Electrabel decided to replace the FIS curves by newly designed trend curves.

In the Safety Case 2015 Electrabel replaced the enveloping FIS curves as applied until 2012 by these trend curves that include the composition dependent term from the French standards[31] and a fluence dependent term that is supposed to reflect the radiation effects observed using the VB395 samples[32]. Figure 3 shows the old and new trend curves (shift of the reference temperature RT_{NDT}). The new trend curves are no more enveloping curves but average value curves with standard deviation margins (M): $RT_{NDT\ SIA} = RT_{NDT,init} + \Delta RT_{NDT,RSE\text{-}M} + \Delta RT_{NDT,VB395} + M$

At first sight the new trend curves seem to be more conservative than the former FIS curves in the end-of-life fluence range. But since the fluence at the position of the flaws within the RPV wall is lower than at the inner surface of the wall the lower frequency range (3-4 x 10^{19} n/cm^2) is relevant[33].

Figure 3: Trend curves for shift of reference temperature RT_{NDT}

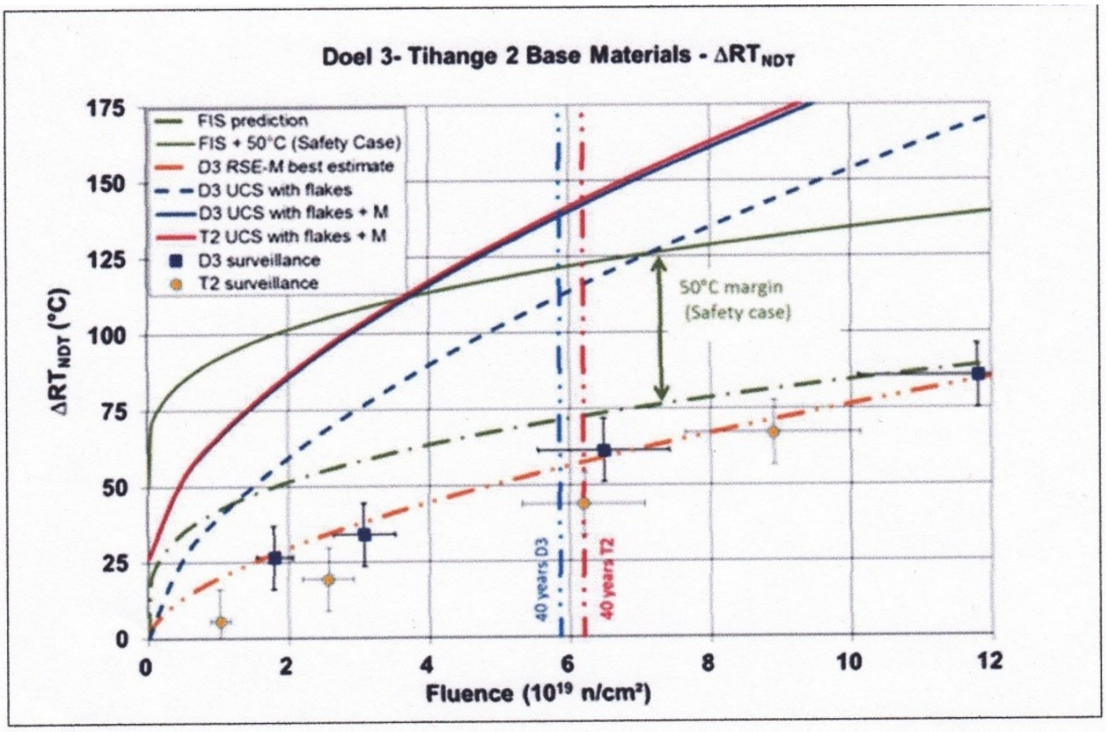


Figure 5.26: ΔRT_{NDT} for flaked D3T2 upper core shells as a function of fluence.

The lowest curve is the new trend curve without standard deviations (average value through surveillance program data). The curve above (dotted green) is the old FIS curve showing to be an envelope with respect to the surveillance data. The green curve is the FIS curve + 50°C as proposed in the Safety Case 2012. The red-blue curve is the new trend curve including the standard deviation margins (in the range of 3-4 x 10^{19} n/cm^2 the new trend curve is less conservative than the trend curves as proposed in the Safety Case 2012). Source: Electrabel Safety Case 2015[34]

[31] RSE-M[31] (Ed.2010) (page 69). RSE-M: Règles de Surveillance en Exploitation des Matérials Mécaniques.

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

[33] The EOL fluence values for the serious flaws are listed in ORNL Evaluation of Electrabel Safety Cases for Doel 3 / Tihange 2: Final Report, page 44/45 http://www.fanc.fgov.be/GED/00000000/4000/4030.pdf

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

It is interesting to look at the definition of the margin M[35]: *"two times the quadratic combination of the following uncertainties (1σ):*
3°C for $RT_{NDT,init}$
9.3°C for $RT_{NDT,RES.M}$ *for D3/T2 lower core shells, 0° for the upper core shells*
13.5°C for $\Delta RT_{NDT,VB395}$ *(combination of 9.3° for irradiation and 9.3°C for prediction of VB395)"*

Bel V had requested to consider macrosegregation by adding 10°C in the trend curve for the pressurized thermal shock (PTS) screening criterion. Electrabel included the segregation term $\Delta RT_{NDT,init,segr}$ (10°C) with $\sigma = 5°C$, *and* eliminated the standard deviation *for* $RT_{NDT,init}$ "*in agreement with international practice*". At the end the trend curve is "*slightly lower than that for SIA*".

The PTS screening criterion (US NRC Reg. Guide 1.99, rev 2)[36] limits the value of RT_{NDT} for end-of life for the base metal: RT_{NDT} (EOL) = 132°C.

Table 3: RT_{NDT} Values for EOL and for the initial state

	EOL-values for RT_{NDT}	RT_{NDT} values for the initial (unirradiated) state
Doel 3 (upper core shell)	120°C	-22°C
Doel 3 (lower core shell)	119°C	-22,2°C
Tihange 2 (upper core shell)	123°C	-25,4°C
Tihange 2 (lower core shell)	118°C	-27,2°C

Using the new Electrabel trend curves the EOL-values for RT_{NDT} can be calculated (the respective numerical data for $RT_{NDT(init)}$ and M can be found in the ORNL paper [37].

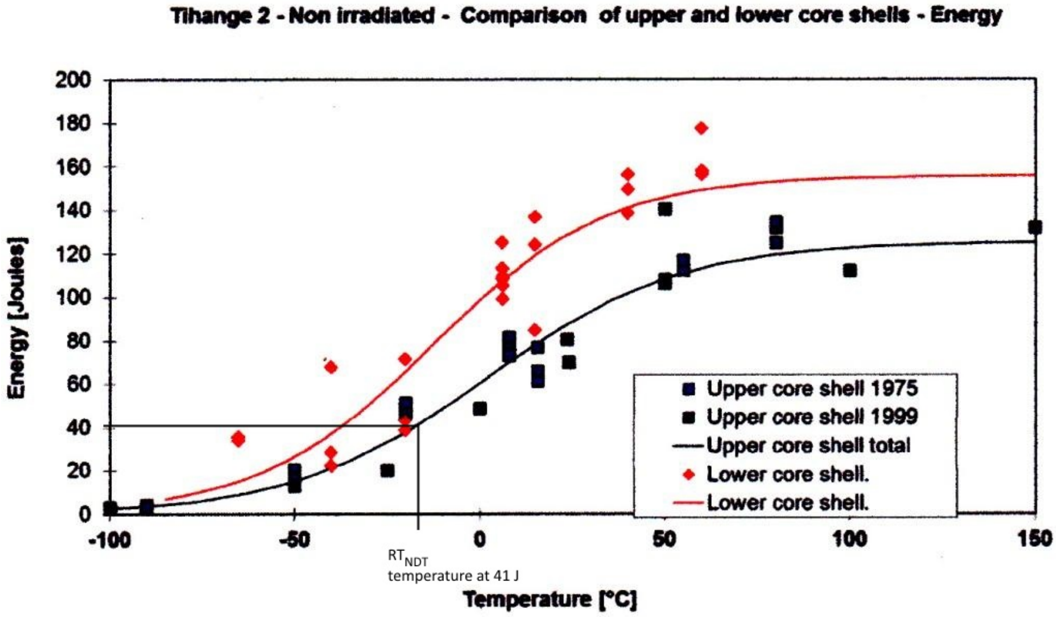
RT_{NDT} values for the initial (unirradiated) state of the base metal as used by ORNL.

Comparing the RT_{NDT} values for the initial (unirradiated) state of the base metal as used by Oak Ridge National Laboratory - ORNL (table 3) with experimental data sheets[38] for Tihange 2 upper core shell (black curve in figure 4) the following can be observed:

The figure shows that $RT_{NDT(init)}$ for the upper core shell cannot be -25,4°C. The figure also shows that the there is a large scatter of the experimental data so that the reduction of the standard deviation for $RT_{NDT(init)}$ to zero is not justified. Both facts indicate that it is doubtful that the PTS screening criterion is met.

[35] CNT-KCD_4NT_20729_000_03 (2015/10/21) page 14/15
[36] Fracture toughness requirements for protection against pressurized thermal shock events, 10 CFR 50.61
[37] ORNL Evaluation of Electrabel Safety Cases for Doel 3 / Tihange 2: Final Report, page 66
http://www.fanc.fgov.be/GED/00000000/4000/4030.pdf
[38] CNT-KCD_4NT_20729_000_03 (2015/10/21) page 65/66

Figure 4: Temperature at 41 J in comparison to Tihange 2 core shell experimental data sheets



(RT_{NDT}: temperature at 41 J)

Source: CNT-KCD_4NT_20729_000_03 (2015/10/21) page 65/66

Irradiation campaigns

The results from different irradiation campaigns using samples from VB395 showed remarkable higher embrittlement than predicted by the new predictive trend curves. As mentioned above the rejected steam generator block VB395 (AREVA) is certainly not representative for the RPC material but has been selected due to the proven hydrogen flakes.

The last irradiation campaign was performed with samples from a similar German steel containing hydrogen flakes (FKS: Forschungsvorhaben Komponentensicherheit) for further comparison. The measured RT_{NDT} shifts of this campaign also exceeded the trend curves by up to 20°C[39].

Doel 3 nozzle cuts used for Irradiation experiments can be considered representative for the defect-free material but certainly not for the actual RPV base material.

The irradiation experiments included Charpy tests and direct fracture toughness measurements (Master curve approach). The direct fracture toughness measurements of irradiated VB395 samples (Master Curve) showed fracture toughness shifts (ΔT_0) for VB395 samples remarkably higher than the RT_{NDT} shifts measured by Charpy tests[40], the difference estimated from the figures is about 40 °C.

In the Safety Case 2015 Electrabel argues that the observed embrittlement of the VB395 samples does not imply high embrittlement of the Doel3 /Tihange 2 RPV base metal. 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*

[39] Service de Contrôle Physique - SCP report on Safety Case 2015 RPV Doel,(figure 11, page 21), http://www.fanc.fgov.be/GED/00000000/4000/4025.pdf

[40] Electrabel, Safety Case 2015, Doel 3 reactor pressure vessel assessment (see figure 5.18 and 5.19, pages 53/54), http://www.fanc.fgov.be/GED/00000000/4000/4023.pdf

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."[41]

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[42] high-flux irradiation results might underestimate the real embrittlement. The dose rate effect has been observed in Western RPV steels[43] and Russian RPV steels[44,45].

Summarizing remarks – remaining open questions

The effect of the high density of flaws on the initial (unirradiated state) fracture toughness has not been clarified; the comparison of experimental data and numerical values used for the structural integrity assessment indicates at least for Tihange 2 (upper core shell) significant inconsistencies. The elimination of a standard deviation for the initial fracture toughness cannot be justified in face of the large scatter of the experimental data points. This implies that the PTS criterion is not met in spite of the significant reduction of conservatism.

The new predictive trend curves (Safety Case 2015) are less conservative in the fluence range relevant for the large flaws than the FIS curve with 50°C extra shift as proposed in the Safety Case 2012. This is a reduction of conservativeness canceling the arguments concerning effects of hydrogen flaking + macrosegregation based on experiments as described in the Safety Case 2012.

The effect of neutron irradiation on defect-containing material is also not clarified; the observed strong embrittlement was declared to be "abnormal" (or "atypical") due to an unknown embrittlement mechanism in the VB395 samples. It has to be recalled that the irradiation experiments with VB305 samples were requested by FANC to approve that radiation effects are not enhanced by hydrogen flaking.

Open questions:

- The initial (unirradiated state) fracture toughness of the RPV base metal containing a high density of defects is still uncertain.
- The radiation effects on RPV base metal containing a high density of defects is also still uncertain.

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[41] Electrabel, Safety Case 2015, Doel 3 reactor pressure vessel assessment, (page 67) http://www.fanc.fgov.be/GED/00000000/4000/4023.pdf

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

[43] 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

[44] 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)

[45] 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

4. Structural integrity assessment (SIA) of the reactor pressure vessel

The structural integrity of the reactor pressure vessel containing the complete radioactive inventory has to be maintained throughout operation. Failure of the reactor pressure vessel would initiate fission product release into the environment. A replacement in case of structural deficiencies is not possible.

Load bearing capacity

The structure mechanical assessment of the load-bearing capacity according ASME III cannot be performed because defect-free material is assumed. The RSK concludes that the material model used by Electrabel does not consider the fracture mechanical behavior of a component with cracks so that the load bearing capacity might by overestimated.[46]

The BMUB concludes that is questionable that the safety margin calculates by Electrabel is realistic for the crack containing reactor pressure vessel.[47]

Pressurized thermal shock (PTS) screening criterion

The PTS screening criterion (according 10 CFR 50.61)[48] requires that the ductile-brittle transition temperature RTNDT may not reach 132°C for the base metal until end-of-life (EOL). As described in above in section 3, it is doubtful that the PTS screening criterion is met (at least for the upper shell in Tihange 2).

Fracture mechanical PTS-analysis

The demonstration of the RPV structural integrity throughout service life is usually performed by a PTS (pressurized thermal shock) analysis. The temperature distribution in the RPV wall due to normal and accidental transients is calculated using thermohydraulic codes. The experts of the German Federal Ministry of Environment, Nature Conservation and Nuclear Safety (BMUB) remark that there are open questions with respect to the boundary conditions of the transients[49].

The induced thermal stress field on an assumed crack in the RPV wall is calculated with fracture mechanical methods for the progressing accident transient. The fracture mechanical codes used for quasi-laminar flaws under mixed-mode loading is not yet sufficiently verified as the experts of the BMUB state in their preliminary evaluation[50]. The BMUB experts question also whether the residual stresses below the cladding interface have been adequately considered.

The calculated load path for each assumed crack is than compared with the fracture toughness curve based on embrittlement assumption by predictive trend curves and the respective fluence at the crack position (see the preceding sections) as shown in figure 5. The load path may not intersect the fracture toughness curve (the diagram is equivalent to the ASME acceptance criterion describes below).

46 Preliminary brief assessment of the safety cases for the reactor pressure vessels of the Belgian nuclear Power Plants Doel 3 and Tihange 2, 483th Meeting of the Reactor Safety Commission (RSK), 13.04.2016

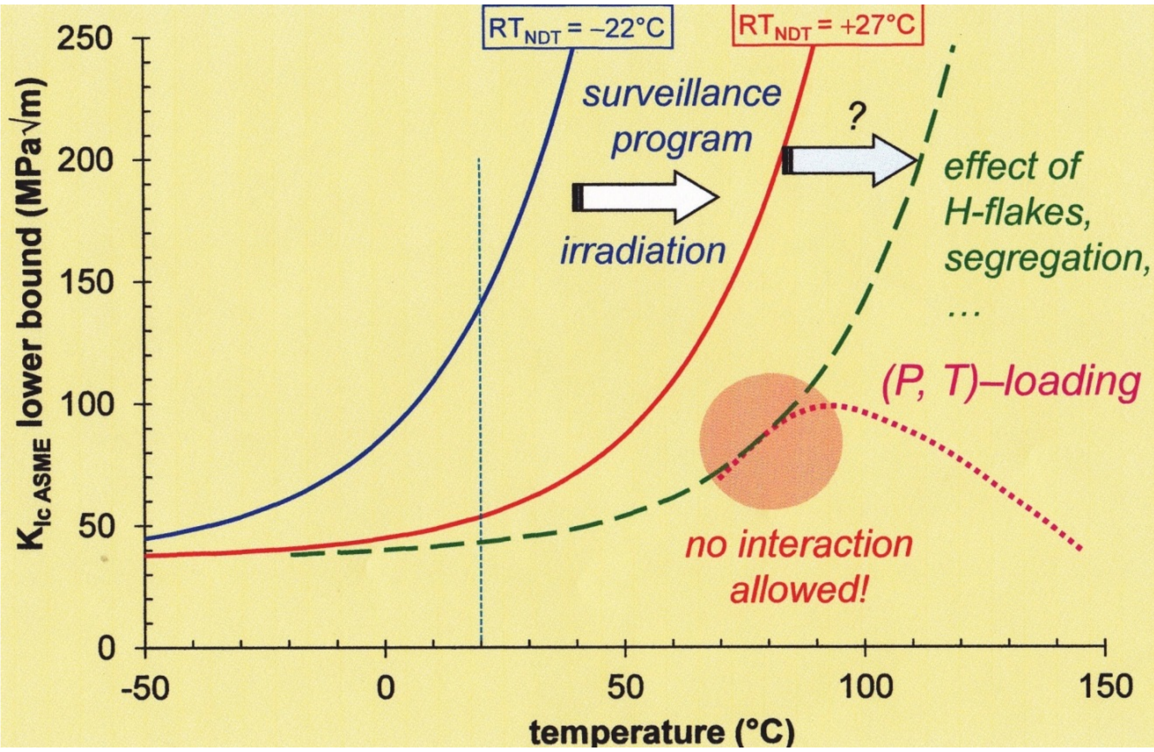
47 Aktualisierter Bericht des BMUB zu TOP 20 der 81. Sitzung des Bundestags-Ausschusses für Umwelt, Naturschutz, Bau und Reaktorsicherheit zum aktuellen Stand der belgischen Atomkraftwerke Doel 3 und Tihange 2, 25.04,2016

48 "The screening limits provided in 10 CFR 50.61 restrict the maximum values of RTNDT permitted during the plant's operational life to +270 °F (132 °C) for axial welds, plates, and forgings, and +300 °F (149 °C) for circumferential welds". US NRC NUREG 1874,

49 Vorläufige Kurzbewertung der Sicherheitsnachweise für die Reaktordruckbehälter der belgischen Kernkraftwerke Doel-3 / Tihange-2, 13.04.2016, Seite 2

50 Aktualisierter Bericht des BMUB zu TOP 20 der 81. Sitzung des Bundestags-Ausschusses für Umwelt, Naturschutz, Bau und Reaktorsicherheit, 25.04.2016, Seite 27

Figure 5: Fracture toughness curve



Source: Source: E.van Walle[51]

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

The ORNL[52] report lists the flaws that are not compliant with the ASME criterion for both RPVs[53].

Electrabel performed further fracture mechanical computer calculations using a commercial crack propagation code (MORFEO Crack XFEM)[54] that was developed for commercial weld structures. It is not clear whether the code was validated for the application for PTS analysis of reactor pressure vessels. It is remarkable that fracture mechanical experiments with VB395 samples could not be sufficiently simulated using this code[55]. By application of this so called "*more*

[51] SCK-CEN E. van Walle, The Detection of Hydrogen Flakes in the Belgian Doel3/Tihange2 Reactor Pressure Vessels, NENE 2013, Bled, Slovenia, September 11, 2013, http://www.djs.si/proc/nene2013/pdf/NENE2013_106.pdf

[52] ORNL was assigned 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".

[53] ORNL Evaluation of Electrabel Safety Cases for Doel 3 / Tihange 2: Final Report, page 44/45 http://www.fanc.fgov.be/GED/00000000/4000/4030.pdf

[54] BelV 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 (page 35). http://www.fanc.fgov.be/GED/00000000/4000/4028.pdf

[55] "Although they shed an additional light on the interpretation of the tests, the calculations have not allowed to predict the fracture mode." (Bel V Seite 44)

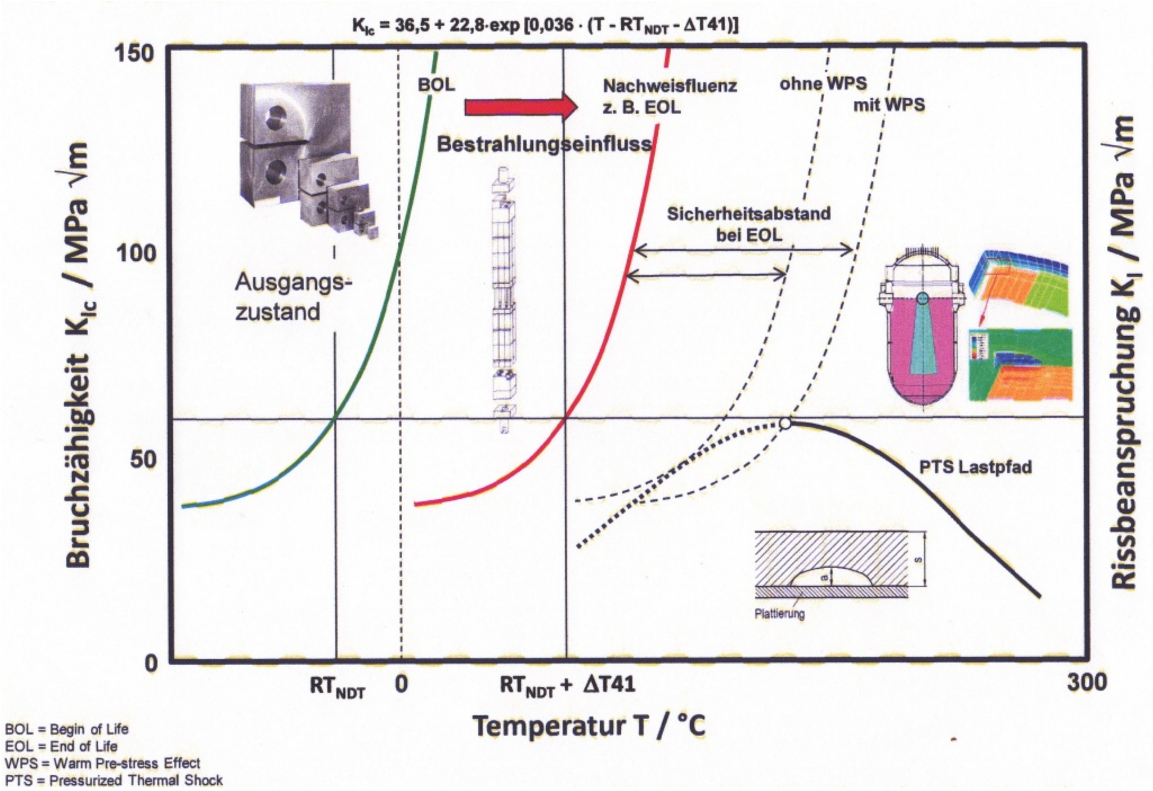
realistic modeling" Electrabel states that these calculations showed that all detected flaws are compliant with the ASME criterion.

ORNL followed another strategy applying the so called warm prestress (WPS) effect. The application of the WPS effect in the PTS analysis is allowed in the US Regulatory environment but not in the French standard. As the above figure indicates ("*no interaction allowed*") the application of the WPS effect is also not allowed in Belgium. It is not clear why ORNL nevertheless has adopted the WPS effect for its safety margin assessment.

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.[56] The experiments were performed with small and component-like samples but not with complete pressure vessels.

The application of the WPS effect means that the tangency of the load path with the fracture toughness curve occurs after the reaching the maximum of the load path as can be seen in the figure 6.

Figure 6: Fracture toughness curve and WPS effect



Source: Xaver Schuller, Kerntechnisches Kolloquium, 21.06.2016, RWTH Aachen LRST, page 52

Nevertheless, the ORNL calculations including the WPS effect could not show compliance for all flaws. For the flaw #1660 (Tihange 2) ORNL finally adopted also a 3D-XFEM approach ("*more realistic modeling*") to reach compliance.

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

In order to reduce the load the warming-up of the safety injection water (for emergency cooling) was implemented for Doel 3 ("*Safety Injection System water temperature: 40°C (2014) vs. 7°C* in 2012)."[57] No information exists why the warming-up was not implemented in Tihange 2

Summarizing remarks and open questions

Several deficiencies have been identified in the demonstration of the structural integrity of the reactor pressure vessel in the safety cases 2015:

- The assessment of the load bearing capacity as performed by Electrabel might be overestimated due to missing validation of the applied methodology.
- The fulfillment of the PTS screening criterion is doubtful at least for the upper core shell of Tihange 2.
- The PTS analysis as performed by Electrabel includes the application of fracture mechanical methods that are not sufficiently validated for the quasi-laminar type of flaws; the safety margins in the assumed radiation effects on the fracture toughness of the material have been significantly reduced.

Open questions:

- It has not been clarified whether the most penalizing transients have been used for the PTS analysis.
- The validation of the applied fracture mechanical codes for the specific flaw orientation - especially the XFEM code MORFEO – has not been demonstrated.

[57] Electrabel, Safety Case 2015, Doel 3 reactor pressure vessel assessment, (page 105) http://www.fanc.fgov.be/GED/00000000/4000/4023.pdf

5. Conclusions

The thousands of flaws detected 2012 in the core shells of the reactor pressure vessels in Doel 3 and Tihange 2 have to be considered as severe violation of the defense-in-depth approach. The statement of the licensee Electrabel (accepted by the national nuclear authority FANC) that no evolution of the flaws has occurred during operation is doubtful because no not-acceptable defects were documented before start-up of the reactors. The increase of detected flaws and their size during in-service inspections in 2014 and 2016/17 have aggravated the doubts. It is obvious that no credible basis for comparative evaluation of the ultrasonic test results exists - thus the growth of flaws during operation cannot be excluded.

Due to the lack of representative materials for tests the effect of the high density of defects on the mechanical properties of the RPV material can only be estimated. The definition of a new predictive trend curve for the radiation effects includes significant reductions of conservatism with respect to the structural integrity assessment. The applied fracture mechanical methodology is partially not validated. Deficiencies in the demonstration of the PTS screening criterion fulfillment have been identified in the course of this study.

The forthcoming 1st edition of the

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will contain the following articles:

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- **Compensating for Nuclear Disaster?** by Sonja D. Schmid
- **Beznau 1: Safety Case of Reactor Pressure Vessel Integrity** by Simone Mohr
- **The British nuclear programme** by Steve Thomas
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