Note:
This is a translation of the RSK statement entitled
“Bewertung der Sicherheitsnachweise für die Reaktordruckbehälter der belgischen Kernkraftwerke Doel-3 / Tihange-2”

Appendix to the minutes of the 503rd RSK meeting on 23.05.2018

Assessment of the safety cases for the reactor pressure vessels of the Belgian nuclear power plants Doel-3/Tihange-2

STATEMENT

1 Background and proceeding

In June 2012, ultrasonic testing revealed a large number of flaw indications in the two core-near forged rings of the reactor pressure vessel (RPV) of the Belgian nuclear power plant Doel-3. In September 2012 similar flaw indications were also found in the RPV of the Belgian nuclear power plant Tihange-2, but in smaller numbers. These flaws have been attributed to hydrogen-induced cracks (“hydrogen flaking”) supposed to have been occurred during manufacturing. With preliminary IRS report no. 8244, the Belgian authority FANC reported on the flaw indications found by ultrasonic testing. On behalf of the BMU according to its advisory request of 23.08.2012, the RSK had discussed the facts and circumstances after preparatory work of the RSK Committee on PRESSURE-RETAINING COMPONENTS AND MATERIALS (DKW) and presented its statement on the applicability of the flaw indications to the reactor pressure vessels of German plants on 17.01.2013 [2].

An initial evaluation of the documents submitted by the operator of the Belgian plants Electrabel by FANC took place in January 2013, subject to a series of requirements, some of which were to be fulfilled shortly before restarting, and partly during operation in the medium term. Following fulfilment of the short-term requirements, FANC authorised the restart of the plants in May 2013. Both plants were shut down again in March 2014 due to unexpectedly unfavourable results regarding the behaviour of RPV material under irradiation with hydrogen flaking in the framework of the fulfilment of the med-term requirements. After further investigations and new safety case reports provided by Electrabel, FANC finally published its decision on 17.11.2015 to allow the two plants to be restarted.

Upon request of the BMU, the Committee DKW resumed its consultations at the 129th meeting on 28/29 May 2013. The Committee then has kept itself up to date with the developments on the subject. The consultations were based on the Electrabel reports on analysis results and safety case reports published by FANC and their review. At its 150th meeting on 16/17 December 2015, the RSK Committee DKW discussed the current status and identified a number of open issues. These open issues were submitted to the BMU in the form of a catalogue of 15 questions [3].

The BMU handed over the catalogue of questions to the Belgian regulatory authority FANC at a workshop organised by FANC on this topic on 11/12 January 2016. The questions contained in the catalogue were partly answered orally at the workshop. Written answers were sent by FANC to the BMU on 19.02.2016 [4].

The BMU requested the RSK Committee DKW to assess the soundness of the safety cases at its 152nd meeting on 17.03.2016 with respect to the integrity of the two reactor pressure vessels of the Doel-3 and Tihange-2 nuclear power plants. In this context, in-depth discussions were held on technical details of the safety cases at a bilateral meeting between the BMU and the Belgian authority with the participation of members of the RSK Committee DKW and GRS on 05./06.04.2016. The additional detailed information thus obtained has been considered in the assessment. At the 483rd RSK meeting on 13.04.2016, the RSK discussed and adopted the preliminary brief assessment of the safety cases for the reactor pressure vessels of the Belgian nuclear power plants Doel-3/Tihange-2 [5].

As a result, it was stated in the brief assessment that there was no concrete evidence that the safety margins were depleted. However, it could not be confirmed that these were safely maintained. The BMU was in agreement with the conclusion of the RSK and noted as a result of the bilateral meetings that both German and Belgian experts were in favour of conducting further investigations. According to a written request from FANC dated 04.05.2016, the BMU specified in a reply letter dated 02.06.2016 the open issues identified by the RSK [6]. In a reply dated 28.09.2016, FANC commented in writing on these open issues [7].

The BMU requested the RSK to review FANC's additional answers to determine whether the situation changed compared to the statement made on 13.04.2016 with regard to the soundness of the safety cases with respect to the integrity of the two reactor pressure vessels of the Doel-3 and Tihange-2 nuclear power plants and whether this could clarify some of the issues conclusively [8]. After several discussions in the RSK Committee DKW at the 157th and 158th meeting on 20.10. and 09./10.11.2016 and of the RSK at the 490th, 493rd, and 494th meeting on 25.01., 26.04., and 18.05.2017, the RSK stated that another meeting with FANC would be useful for the discussion of the remaining questions of the RSK and prepared a paper to inform FANC about the remaining issues that it considers open, which was submitted to FANC by the BMU by letter of 28 August 2017 [9].

At a bilateral expert meeting of representatives of the RSK and Belgian expert and operator organisations with the participation of representatives of the BMU and the Belgian authority FANC on 02.02.2018, the remaining questions of the RSK were discussed. On the part of the Belgian side, additional arguments and calculations were presented, which could be taken into account in the further consultations. After preparation of a report at the 170th meeting of the RSK Committee DKW, the BMU's advisory request [8] was finally discussed at the 503rd meeting of the RSK on 23.05.2018 and this statement adopted.

2 Facts

2.1 Detection, characterisation and cause of the indications

In June 2012, the two core shells of the reactor pressure vessel of the Belgian plant Doel-3 were subjected to a newly introduced ultrasonic test. This test was developed and introduced in France to detect possible underclad cracks. Indications of underclad cracks were not found in Doel-3, but a large number of indications pointing to a different type of defect at greater depth in the base metal. This was confirmed in 2012 with the testing technique otherwise used for the examination of welds. The defects were characterised as laminar material separations approximately parallel to the surfaces. The flaw indications were attributed to hydrogen-induced cracks (“hydrogen flaking”) that occurred during manufacturing [10].

Further, optimised ultrasonic tests were carried out in 2014 with straight beam (0°) and 45° angle beam, focusing on different depth ranges and an additional transducer with a 15° angle beam. The signal reporting thresholds of 0° transducers were lowered to ensure the detection of smaller flakes, flakes inclined up to 16° with respect to the surface parallel orientation, and to ensure a conservative flaw sizing. The objective of using a transducer with a 15° angle beam was to detect cracks with even larger angles whereas transducers under a 45° angle from 4 orthogonal directions were to detect radial connections between cracks at different depths. There were neither indications of cracks with angles >16° nor of radial connections [12].

The ultrasonic tests were qualified on a test block with hydrogen flakes from a rejected steam generator shell from French production designated as VB395, which had been additionally cladded for this qualification. For the qualification, geometry, position and orientation of approximately 100 indications from the UT inspection data were subjected to destructive tests. [12] The targeted examination of four cracks partially hidden by other cracks revealed that these were also detected by the 0° transducers and their size were determined correctly [14], [15].

Both at Doel-3 and Tihange-2, the central areas of both core shells outside the heat-affected zone of the weld are affected by flaw indications, with by far the largest number of indications found in the lower core shell of Doel-3, followed by the upper core shell of Tihange-2. After the tests in 2014, more than 10,000 indications were counted in the lower core shell of Doel-3 and more than 3,000 in the upper core shell of Tihange-2 with dimensions of 15 mm on average. Due to the lower reporting threshold compared to the previous tests in 2012 and the changed testing techniques, the number of reportable flaw indications had increased significantly. In addition, indications located closely together were merged to significantly larger indications, resulting in a maximum dimension of an indication of about 180 mm. The interpretation of both test results by the Belgian side led to the statement that no growth was found [12, 13]. Both plants had been in operation meanwhile for 10 months.

According to a requirement of FANC, tests were again carried out in both plants in 2017 after another year of operation. These tests did not reveal any indications of growth of existing or of new cracks [16], [17].

The laminar flaw indications concentrate near one end of the forged ring, beginning near the clad/base metal interface and extend to near the other end to a depth of max. 120 mm. The spatial distribution of the indications corresponds to the typical distribution of the macro-segregations of a forged ring. This distribution as well as the geometry (flat, almost elliptical, typical dimensions ranging from 10 to 15 mm) and orientation of the indications support the hypothesis on the cause that these are hydrogen flakes generated by hydrogen accumulation in segregation zones. The formation of cracks due to radiolysis, corrosion and injected hydrogen during operation is ruled out because of the low concentration (more precisely: chemical activity) of the hydrogen in the coolant. Growth of existing flakes by diffusing hydrogen is also considered very unlikely. Fatigue could be the only mechanism leading to a minor growth of the cracks during operation. Therefore, FANC required the licensee to conduct follow-up ultrasonic inspections every three years [10], [12], [18].

This hypothesis on the cause also corresponds to the test results of the material block VB395 examined ultrasonically and also destructively, which was already rejected during the manufacturing process and where the flakes are always located in the so-called ghost lines. These dark lines in micrographs are the cuts through small, flat segregation zones, which are found in a forged ring globally following the spatial distribution described above and, after forging, only form a small angle to the surfaces. An evaluation of 152 flakes in VB395 revealed an average inclination of 4° and 5 flakes showed an inclination above 10° with a maximum value of 15° [10], [12].

2.2 Safety assessment of the indications by FANC

2.2.1 Investigation of material properties

By means of several destructive tests on three different materials it was examined how far their behaviour in segregation zones without and with hydrogen flakes deviates from that of non-segregated material. The properties after accelerated irradiation in a research reactor were also examined. These are the materials tested [12]:

- Archive material from Doel-3 and Tihange-2 in the form of nozzle cut-outs from the RPV nozzle shell designated D3H1 and T2H2. Their material SA508 Cl.3 is virtually identical to that of core shells and similar to German steel 20 MnMoNi 5 5. D3H1 and T2H2 also contain segregation zones and ghost lines, but no flakes.

- A block from a steam generator shell from French production designated VB395, containing both segregations and flakes. This material 18MND5 has a chemical composition very similar to the forged rings of Doel-3 and Tihange-2, but it contains impurities of about 0.25% chromium, was poured as hollow ingot and thus no piercing was performed, and it was subjected to an unusual heat treatment. Compared to the forged rings of Doel-3 and Tihange-2, VB395 has a slightly higher hardness, the structure is inhomogeneous and it contains larger amounts of tempered martensite.

- A block from a rejected half ring for a RPV flange of a German PWR designated KS02 made of 22 NiMoCr 3 7. KS02 has a slightly different chemical composition, was forged from an ingot without piercing and therefore has segregation zones in the centre, partially with flakes. The structure and hardness are similar to the forged rings of Doel-3 and Tihange-2. Other parts of KS02 have already been intensively examined in the framework of the German research programme on component safety (Forschungsvorhaben Komponentensicherheit – FKS).

Tests on tensile, Charpy and fracture mechanics specimens were carried out to investigate the local toughness at the flakes and the local strength and toughness of the material between the flakes. Tests were carried out on large-scale tensile specimens of 25 mm diameter and flakes or notches with an inclination lower than 20° with respect to the longitudinal axis to determine strength and ductility of the RPV wall with flakes in the upper shelf of the toughness curve.

From the evaluation of the results FANC concluded that the mechanical behaviour of VB395 and KS02 is macroscopically representative of unirradiated material with flakes. The influence of segregations on ductility and toughness is limited. The ductility is further reduced by flakes, but remains sufficient and toughness is not further affected by the presence of flakes. These deviations from the behaviour of the non-segregated material can be adequately taken into account by a shift in the reference temperature for nil ductility transition RT_{NDT}. An additional shift in RT_{NDT} of 50 K after irradiation was to also cover a possibly higher embrittlement of the segregation zones due to the enrichment in Cu, Ni and P.

In order to also determine the irradiation behaviour of these materials in segregation zones and with flakes, these were irradiated in several campaigns in the Belgian research reactor BR2. Under PWR operating conditions, but with a very high flux density, fluence levels were achieved within one to two months corresponding to 40 years of operation of Doel-3 and Tihange-2, i.e. about $6 \cdot 10^{19}$ n/cm² (E > 1 MeV).

In the first irradiation campaign, only specimens from VB395 were irradiated. The subsequent tests showed a very inhomogeneous behaviour, with a shift ΔRT_{NDT} that was significantly higher than the predictions and an even stronger shift ΔT_0 of the Master Curve in the segregated areas. However, the increase in yield strength and hardening is not higher than expected and is in agreement with the predictions. This effect is associated with a decrease in the micro-cleavage fracture stress. By contrast, the behaviour of the non-segregated areas is in the typical range of the predictions in terms of all aspects. The flakes themselves had no influence on the irradiation reaction. These results were considered as outliers by FANC. The results have not been explained until today and are not covered by the additional shift in RT_{NDT} of 50 K in the area of higher fluences.

Therefore, the originally planned irradiation programme was extended to the other two above-mentioned materials as well as to archive specimens from the Doel-3 RPV surveillance programme. All these other materials show the expected irradiation behaviour and no deviations in the segregation zones. In particular, the shift ΔRT_{NDT} as a function of the concentration of the chemical elements Cu, Ni and P in the materials and fluence f is within the typical range of the prediction formula from the French nuclear code RSE-M. This formula is based on the results of RPV surveillance programmes of the French reactors[1].

After the investigations, the behaviour of VB395 was considered atypical and not representative, but its transferability to the Doel-3 and Tihange-2 materials could not be completely ruled out after tests on only two materials with flakes (VB395 and KS02). Therefore, for a conservative estimate of the RT_{NDT} at the end of the 40-year operating time, further terms were added to the RT_{NDT} compared to the usual procedure. These take into account the effect of segregation in the unirradiated state and the deviant behaviour of the segregation zones of VB395 compared to the prediction formula according to RSE-M and the dispersion of these two terms. Finally, increased concentrations of the elements Cu, Ni and P are considered in the prediction formula for the calculation of ΔRT_{NDT}, which correspond to experimentally determined enrichments in segregation zones. At a fluence of $6 \cdot 10^{19}$ n/cm² (E > 1 MeV), this results in an additional shift

[1] It reads as follows: $\Delta RT_{RSE} = 2\sigma + A(1 + 35.7\,(P - 0.008) + 6.6\,(Cu - 0.08) + 5.8\,Ni^2Cu)\,\mathbf{f^{0,59}}$

of about 85 K and absolute values for RT_{NDT} of about 120 K* as a maximum for the forged rings most affected by flakes of both plants [12].

This proceeding was considered adequate by FANC and accepted as a conservative approach [18].

2.2.2 Structural integrity assessment

The structural integrity assessments for the RPV have largely been based on the US regulatory framework in force in Belgium, i.e. the Code of Federal Regulations (CFR) and the Boiler and Pressure Vessel Code of the American Society for Mechanical Engineers (ASME). In particular, these were conducted

a) to rule out crack initiation for individual flakes under all conditions of normal operation, i.e. stress levels A and B, and the design basis accidents, i.e. stress levels C and D, with the corresponding safety factors $\sqrt{10}$ for levels A and B, and $\sqrt{2}$ for levels C and D of the ASME XI code,
b) to demonstrate the stability of the flakes against fatigue crack growth,
c) to demonstrate compliance with the ASME III primary stress intensity acceptance criteria for the forged rings with flakes,
d) to meet the fracture toughness requirements according to 10CFR50, Appendix G,
e) to demonstrate compliance with RT_{NDT} limits for protection against pressurised thermal shock events according to 10CFR50.61 ("PTS screening criterion"), i.e. RT_{NDT} < 132°C for core shells and 149°C for circumferential welds. This criterion is met for the forged rings with the determined values for RT_{NDT} of about 120°C.

2.2.3 Methodology

Ref. point a) For the brittle fracture safety analysis according to ASME XI, the flaw indications are to be represented by circles that conservatively cover the flakes in size, angle to surface and distance from the surface (i.e. the clad/base metal interface). Indications classified as clad interface imperfections were also treated as flakes. For this purpose, the flaws measured by the UT inspection equipment are represented by rectangular 3D boxes according to their dimensions in the three orthogonal directions x, y and z, where x is parallel to the vertical axis of the RPV, y lies in the circumferential direction and z in the direction of wall depth. The diameter 2a of the circle then corresponds to the larger of the box face diagonals in the x-z and the y-z plane. The angle of the circle to the surface is the larger of the two angles of these two diagonals. It thus tends to be larger than the angle of the flaw to the wall surface, but is limited to a maximum of 20° (see p. 78 et seq. in [12]).

If several flaw indications are very close to each other so that an elastic interaction is postulated, their boxes are to be encompassed by a larger box and the circle has to encompass this group of indications analogously in this larger box. This eliminates the limitation of the angle to 20°, so that larger angles can also occur.

* *Translator's note: in the German original erroneously 120 K (see also 2.2.2 e) where it reads 120°C)*

Based on the design data, all transients were evaluated for their stresses on flakes. Accordingly, loss-of-coolant accidents (LOCAs) are the leading transients for distances $s < 20$ mm from the surface, cool-down transients leading for 20 mm $< s <$ 30 mm and heat-up transients for greater depths up to 120 mm. For LOCAs, a rotationally symmetric, abrupt thermal shock with cooling to the feed temperature of the emergency cooling system at the inner surface of the RPV is assumed in a simplified 1D analysis with a conservatively high heat transfer coefficient.

In a multi-step procedure to demonstrate the acceptability of the flakes, the first step was to calculate the maximum acceptable size of circular flaws using 3D finite element (FE) analyses as a function of their diameter 2a, distance s to the surface, local RT_{NDT} at the flaw position, and angle α to the surface according to the provisions of the ASME XI code, also taking into account safety factors √10 and √2 required therein. This resulted in 24 curves for the acceptable size $2a_{acc}$ as a function of the distance s for four different tilt angles α (10°, 20°, 30° and 45°) and in each case six different values of local RT_{NDT}. For every flaw with the parameters s, RT_{NDT} and α, the acceptable size $2a_{acc}$ can thus be determined by interpolation. In a first step, all flaws were classified as "harmless" that are smaller than half the acceptable size. This concerns 99.75% of all registered flaws or groups of flaws in the case of Doel-3 forged rings [12] and 99.7% of the flaws or groups of flaws in Tihange-2 [13].

The remaining 0.25% or 28 flaws or groups of flaws at Doel-3 and 0.3% or 11 flaws/groups of flaws at Tihange-2 were subjected to a more detailed but less conservative assessment. These are groups of flaws, with only one exception each of a near-surface crack. For this analysis, the identical load assumptions were made and the individual flaws modelled as largest possible ellipses instead of circles, fitting into the same rectangular UT boxes. In addition, closely spaced flaws were no longer grouped into one combined flaw but modelled using an extended finite element model (XFEM) accounting for their interactions. All flaws modelled accordingly meet the same acceptance criteria as above with a considerable safety margin. The maximum value for $2a/2a_{acc}$ is 0.32 for Doel-3 [12] and 0.52 for Tihange-2. The flaw indication concerned there is a single crack very close to the inner surface. All other analyses for Tihange-2 result in values of less than 0.2 for $2a/2a_{acc}$ [13].

In a further step, the calculated curves of the stress intensity factor $K_I(T)$ during the transients for flaws considered as enveloping were compared to the acceptable fracture toughness at the lower shelf according to the regulations, applying the respective safety factor $SF=\sqrt{10}$ or $SF=\sqrt{2}$. In most cases, the stress intensity factor $K_I(T)_{max}$ is below the lower shelf of the curve of the applicable regulations, i.e. the value of the acceptable fracture toughness at low temperatures, divided by SF. Thus, these loads are acceptable regardless of the actual value of RT_{NDT}. In the few cases in which $K_I(T)_{max}$ exceeds the lower shelf of the curve $K_{IR}(T - RT_{NDT})/SF$, the distance of the maximum $K_I(T)_{max}$ to the curve $K_{IR}(T - RT_{NDT})/SF$ defined as a margin on the temperature axis. For Doel-3, the smallest margin for a single flake near the surface ($s = 3.6$ mm) was determined to be $\Delta T = 80K$. All other values are between $\Delta T = 105$ K and 190 K [12]. For Tihange-2, loads exceeding the lower shelf of the applicable curve were only calculated for two flakes. The margins for these flakes are 110 K and 130 K, respectively [13].

From these analyses, FANC concludes that most flakes are harmless. With the refined analysis of the few remaining cracks, Electrabel demonstrates that the crack driving forces are very low and thus all flakes meet the acceptance criterion according to ASME XI [18].

Ref. point b) The stability of the flakes against fatigue crack growth was demonstrated by conducting a crack growth analysis based on linear-elastic fracture mechanics according to Appendix A of ASME XI. Again, the flakes were first classified according to angle α and distance s to the surface. Subsequently, a growth analysis was performed for conservatively determined reference flakes. Here, the projection of the flakes modelled as circles or ellipses onto the axial-radial plane (spanned by the radius and the longitudinal axis of the RPV) is taken into account for the range of the stress intensity factor ΔK_I. With this simplified conservative analysis, a maximum flake growth of about 3.2% was calculated until the end of service life [12].

From this analysis, FANC concludes that flakes could not grow significantly due to fatigue since the plant started operation and will not do so for the remaining operating time [18].

Ref. point c) It was to be demonstrated by means of an elasto-plastic analysis according to ASME III, NB 3228.3 that the forged rings with flakes are still in compliance with design basis conditions. According to NB 3228.3, it must be demonstrated that the sum of the primary stresses in a plastic analysis does not exceed the collapse load. For this purpose, the actual stress-strain behaviour of the material including work-hardening can be applied. A reduction of the load-bearing cross section by the flakes was taken into account by modelling the cross-sections of the flakes in a horizontal section through the forged ring as crack-like separations in a 2D analysis. The density of the flakes in the sector most affected by flakes was transferred to the entire cross-section of the ring. Since in the load-bearing capacity analysis according to ASME III only the primary stresses for the design pressure load case are to be assessed, the internal pressure was increased in the FE calculation until plastic instability was reached in the structure of the cylindrical ring modelled with flaws. The analysis showed that the flawed rings withstand at least 1.5 times the design pressure [12].

From this analysis, FANC concludes that the collapse load is only slightly reduced by the flakes and that the primary stress criteria according to ASME III are met [18].

Ref. point d) To meet the fracture toughness requirements according to Appendix G of 10CFR50, the pressure-temperature limits for normal operation are to be redefined in accordance with the recalculated RT_{NDT} at the end of service life and included in the Technical Specifications. This also ensures protection against cold overpressure.

FANC states that these measures have already been implemented as part of the 2012 Safety Case. The RT_{NDT} according to the 2015 Safety Case is lower in the fluence range of approximately $3.8 \cdot 10^{19}$ n/cm², so that the measure of 2012 is enveloping for the new safety case of 2015.

Ref. point e) The “PTS screening criterion” according to 10CFR50.61 requires $RT_{NDT} < 132°C$ for core shells at the end of service life. This criterion is met for the forged rings with the determined values for RT_{NDT} of about 120°C.

From the PTS analyses, FANC concludes that the RT_{NDT} values for the base metal will remain below 132°C after 40 years of operation.

3 Preliminary brief assessment of the safety cases by the RSK in April 2016 and open issues

On 13.04.2016 the RSK adopted a brief assessment of the safety cases [5]. Accordingly, the RSK considered the described cause of the indications to be comprehensible and plausible and the state of flaws in the forged rings to be largely covered by the non-destructive examinations. In addition, the proceeding applied for the determination of material properties is largely comprehensible. The uncertainties were accounted for by additional margins with regard to the reference temperature for the brittle-ductile transition RT_{NDT}. As a conclusion, the RSK assumed that a loss of integrity of the RPV wall under operating conditions is not to be postulated. From the point of view of the RSK, however, additional evidence and the validation of some methods were needed to confirm compliance with the required safety margins in case of accident conditions.

This was followed by the correspondence between BMU and FANC described in Chapter 1 with questions of the RSK and answers by FANC. After further consultations by the RSK Committee DKW and the RSK, four open issues remained considered to be essential for the assessment, which were formulated in a further letter from the BMU to FANC [9] and used to prepare another expert meeting on 02.02.2018. These open issues can be summarised as follows:

1. The RSK considers the experimental validation of the methods used for the fracture mechanics analysis not to be sufficient. This concerns several aspects:

   a) The behaviour of many closely spaced flaws with their potential interaction under multiaxial transient loads. The validity of two four-point bending tests carried out to validate the calculation method is questioned in this respect. Here, essentially, only a single crack was subjected to a high load and this had a greater inclination angle of about 32° to the surface relative to the flakes in the forged rings. In addition, the experiments could not show the conservatism of the calculation model because the failure load was calculated with a fracture toughness corresponding to a low value of the characteristic material property (1% percentile of the Master Curve). This inevitably results in a low calculated failure load that is below the experimental value.

   b) The "effective stress intensity factor" method used to calculate the stresses on flakes within segregation zones under "mixed-mode" loading conditions. In particular, the crack propagation direction could have a significant influence on the crack driving forces.

   c) The influence of hidden cracks. The RSK accepts the argument of the Belgian experts that the probability of undetected radial connections between flakes is very low due to the ultrasonic methods used. However, the RSK cannot rule out smaller cracks hidden behind larger flakes and therefore proposes to analyse the potential influence of such hidden cracks.

2. For the RSK, doubts remain as to whether the simplified 1D analysis of the LOCAs actually provides results which conservatively cover crack driving forces for the specific situation in Doel-3 and Tihange-2 with the multitude of flakes or whether cold plumes or strip-like cooling would have to be considered with a 3D analysis.

3. From the point of view of the RSK, moderate residual tensile stresses over a range approximately equivalent to the depth of the heat-affected zone should be considered in a conservative safety analysis for the assessment of sub-clad cracks.

4. From the point of view of the RSK, the fracture-mechanical behaviour of a flawed RPV has not been considered adequately in the analysis of the load-bearing capacity according to ASME III, NB-3228.3 described by FANC. The tensile tests carried out with inclined flakes show a reduced ductility and load-bearing capacity. Thus, it cannot be assumed without doubt that the required safety factor of 1.5 is maintained regarding the plastic collapse load.

4 Final assessment of the open issues

As agreed upon by the BMU and FANC, another expert meeting between representatives of the RSK and Belgian experts took place on 02.02.2018. At this meeting, the four above-mentioned open issues of the RSK were again presented in detail as well as the respective position of the expert organisation BelV and further arguments and calculations of operator representatives [19].

As regards the overall question concerning the experimental validation of methods for the integrity assessment of crack fields, a representative of the RSK delegation presented a joint research project of several German university institutes, which is supported by the Federal Ministry for Economic Affairs and Energy and comprises three coordinated research projects. In these projects, experimental and numerical investigations were carried out to describe the behaviour of crack fields in components based on damage-mechanical (local approach) models and to validate them. The Belgian institutions were invited to participate in this project and to contribute their experiences to date.

BelV also presented a project to validate the methods for the assessment of crack fields under multiaxial loading conditions, including bending tests with cruciform-type specimens from the flawed VB395 material. This project in cooperation with the French institutions IRSN and CEA has also already begun. From the point of view of BelV and the RSK, an exchange with German institutions would be desirable.

In the further discussions with FANC, the Belgian side commented on the individual open issues (OIs) mentioned in Chapter 3. The additional arguments and analyses presented and the corresponding position of the RSK are summarised as follows.

OI 1a Four-point bending tests were used to validate the assessment method applied to demonstrate the resistance to brittle fracture by means of experiments. Two four-point bending specimens from the flawed VB395 material were used to demonstrate that the calculated failure load is in agreement with the experimental failure load using fracture toughness values exceeding the fracture toughness values described by the 50% percentile of the Master Curve. This was to demonstrate the conservatism of the calculation method.

- Position of the RSK:
  In the opinion of the RSK, these experiments only show that the calculation and the experiment are in agreement within the range of values of the characteristic material property for the two specific cases examined here, but not the conservatism of the method. The RSK holds the view that it has to be taken into consideration that with the brittle material behaviour present here, the fracture toughness values exhibit a large scatter so that only two tests do not provide sufficient data. In addition, the load and crack configuration in these experiments cannot be considered representative with regard to the interaction of flakes in the RPV under multiaxial loading conditions.

OI 1b It should be noted that the equivalent stress intensity factor K_{eq} as used in the safety case is a common reference value for mixed-mode loading conditions in linear elastic fracture mechanics and is applied in various fitness for service (FFS) procedures. The use of the virtual crack extension (VCE) method to determine a $K_{eq,\theta}$ maximised as a function of the crack propagation direction would require a mixed-mode fracture toughness associated with this direction. For this, however, there are no experimental values that could be used for the assessment in analogy to K_{Ic}. In addition, this procedure was not implemented in any FFS procedure.

As regards elastic-plastic fracture mechanics, experimental results show a transition from Mode I (crack opening under tensile stresses applied normal to the crack plane) to Mode II (crack extension by shear stress applied parallel to the crack plane and normal to the crack front) for angles α less than 45° between crack plane and main stress direction. For the flakes with an angle $\alpha < 20°$ crack extension is expected by in-plane shear stress. The VCE method would therefore not be applicable. With elastic-plastic material behaviour, it is only possible to convert the J-integral into a fictitious fracture toughness K_J by means of an equation valid for elastic material behaviour and to compare it with fracture toughness K_{Ic}.

- Position of the RSK:

The presentation of Tractebel is based on the consideration of a single crack. In this case, the crack propagation direction is of lesser importance as long as it can be shown that the calculated crack driving force (K- or J-integral) is enveloping for all possible crack propagation directions. In the area of application of the linear-elastic fracture mechanics (LEFM) – i.e. in the brittle fracture region – this is the case if the stress intensity factors (K_I, K_{II}, K_{III}) determined for the different crack opening modes (I, II, III) are superimposed in such a way that an equivalent stress intensity factor K_{eq} comparable with Mode I stress condition is defined which can be compared with fracture toughness K_{Ic} (determined under Mode I load). In this respect, Tractebel uses an equation established in fracture mechanics. However, Tractebel's statement that this equation always gives a conservative value cannot be confirmed (e.g. in the FKM guideline on fracture mechanics proof of strength for engineering components, a ratio of $K_{IIc}/K_{Ic} = 0.87$ is given as conservative, in the equation of Tractebel, a ratio of $K_{IIc}/K_{Ic} = 1.0$ is postulated).

This approach, however, is based on the "a priori" assumption that the fracture-mechanical behaviour of a crack field (arrangement of several cracks whose stress fields influence one another) can be described by the equivalent flaw defined according to the ASME Code Case. On the other hand, if a single crack in a crack field is considered, the crack driving force is influenced by the surrounding cracks and the solutions valid for a single crack are no longer fully valid. In this case, characterisation of the crack driving force based on the J-integral using the VCE method provides a way to quantify this influence. However, such an analysis has not been performed by Tractebel. This makes it clear that the computational assessment of the flaw pattern in the affected plants is outside the area of scientifically proven fracture mechanics methods. As shown above, it therefore would be appropriate to further qualify the calculation methods through specific research.

OI 1c Due to the applied ultrasonic technique with focused sound, cracks at greater depths can only be covered by larger cracks at lower depths. The most adverse limiting case would be two equally large parallel cracks one behind the other, close to the inner surface. Using the example of the flake near the inner surface with the highest stress intensity factor under LOCA loads, the maximum interaction energy was calculated for different distances between the cracks. Accordingly, the stress intensity factor for the parallel cracks would increase by a maximum of almost 5% compared with the single crack. From this it can be deduced that the influence of potentially hidden cracks can be neglected.

- Position of the RSK:
  The presented analysis corresponds to the suggestion of the RSK. It shows that potentially hidden flakes have only a minor influence on the maximum occurring stress intensity factor and that this influence can be assumed to be covered by the conservative assumptions and safety factors considered in the safety case. This open issue has therefore been clarified from the point of view of the RSK.

OI 2 On request, both the operator representatives and BelV confirm that the Doel-3 and Tihange-2 systems are in line with Westinghouse's standard design for LOCA conditions. Thus, the results on emergency cooling analyses from France and the USA for this design were transferable to the Belgian plants with regard to the loads for the brittle fracture analyses.

- Position of the RSK:
  With the confirmation of BelV regarding the design of the plants Doel-3 and Tihange-2, the RSK sees a basis for assessing the Belgian side's approach to thermal shock loading. Earlier research projects [20] have already shown that the assumption of a rotationally symmetric temperature distribution and the neglect of plume/strip cooling are justified for plants of the Westinghouse design. Thus, the RSK considers the approach of the Belgian institutions to the thermal shock loads as comprehensible and this open issue as clarified.

OI 3 Residual tensile stresses exist only within a few millimetres below the cladding. Assuming a constant tensile residual stress of 100 MPa within the first 25 mm below the cladding, the influence on the margin to the acceptable size and the increase of the stress intensity factor is calculated for the two most unfavourable flakes in this zone. This results in a moderate influence of the residual stresses where these two most unfavourable flakes still remain acceptable with a large margin. For all other flakes, the influence of residual stress is significantly lower and can be neglected here.

- Position of the RSK:
  The analysis presented shows that the influence of the residual stress on the flakes close to the cladding is too small to question the acceptability of the flakes. This open issue has therefore been clarified from the point of view of the RSK.

OI 4 With regard to the load-bearing capacity analysis according to ASME III, NB-3228.3 for RPV sections containing flaws, additional fracture mechanics analyses were conducted by the Belgian side for 1.5 times the design pressure. Thus, it could be demonstrated that at 1.5 times the design pressure there are sufficient margins with regard to a global plastic collapse. In addition, a representative accumulation of flakes has been modelled in 3D in an elasto-plastic finite element analysis and it was demonstrated that also the local plastic strains remain limited below 1.5 times the design pressure and no plastic ligaments will develop between the individual cracks. Accordingly, no local plastic failure will occur.

- Position of the RSK:
  The Belgian side has responded to the question of the RSK with the new analyses. The approach is comprehensible. It was thus confirmed that the requirements of the ASME code for the load-bearing capacity analysis are met and that there is a safety factor of 1.5 with regard to the plastic collapse load. This issue has thus been clarified.

Subsequent to the meeting, FANC confirmed that the Belgian institutions will become involved in German research projects. How this will be organised in practice, is still to be agreed upon.

5 Summary assessment

Since 2012, the detection of the flakes, the RSK and its RSK Committee on PRESSURE-RETAINING COMPONENTS AND MATERIALS (DKW) have been dealing intensively with the flaw indications in the RPV of the nuclear power plants Doel-3 and Tihange-2. They analysed the extensive safety cases and further work results on the questions published by the Belgian side. Three packages of questions were sent to the Belgian side in order to clarify issues considered open from the point of view of the RSK. There were several expert meetings between German and Belgian experts, most recently on 02.02.2018 in Brussels.

The RSK wishes to thank the Belgian nuclear regulatory authority FANC, the expert organisation BelV and the operators for providing detailed information and answering questions from the German side. This transparency made an assessment by the RSK possible.

On the basis of the publications, the expert meetings, the written answers of FANC as well as the knowledge and considerations of its members, the RSK draws the following conclusions:

- It is comprehensible and plausible that the flaw indications are due to flakes originating from manufacturing. This hypothesis is consistent with the results of non-destructive testing, the assessment of the manufacturing process (the formation of flakes by hydrogen dissolved in steel is a well-known phenomenon) and the indications on other forged components which were rejected during manufacture due to imperfections identified. These forgings were subjected both to non-destructive and destructive testing.

- The non-destructive examinations and complementary analyses showed no service-induced crack growth. This result should be confirmed by the further in-service inspection in the next years.

- The non-destructive examinations to determine the flaw state have been qualified. By using ultrasound beams with different angles and focal depths, the flaw state could be reliably determined. In no case have radial connections between flakes been identified. The influence of any hidden cracks has been examined analytically to show that such postulated hidden cracks have only a negligible influence on the stresses. The non-destructive examinations are thus suitable for providing the basis for the safety analyses.

- The proceeding applied for the determination of material properties is largely comprehensible. The transfer chain of terms determining the nil ductility temperature after irradiation represents a pragmatic approach. The currently known uncertainties regarding the material condition due to the extent of the segregation zones of the two RPVs are accounted for by additional margins with regard to the nil ductility temperature.

- For the validation of the calculation model, the Belgian side carried out or initiated different tests. In the opinion of the RSK, these experiments only show that the calculation and the experiment are in agreement within the range of values of the characteristic material property for the two specific cases

examined here, but not the conservatism of the method. From the point of view of the RSK, the validation does not cover all loading conditions – in particular not the multiaxial loads to be postulated – and the complex interaction between closely spaced cracks in a crack field. In addition, only a small number of experiments were performed to validate the calculation model.
Against this background, the RSK welcomes the fact that experiments are being carried out by the Belgian side in cooperation with the French CEA in France under multiaxial loads on comparable, flawed material. The RSK also welcomes the readiness of the Belgian side to get involved in German research projects. This contributes to further improving the validation of the computational models.

- The Belgian side investigated the influence of potential residual tensile stresses on the inner surface of the RPV. For the RSK, the results are comprehensible, which show that such residual tensile stresses have only a minor influence on the stresses on flakes.

- The thermal shock analyses in case of a loss-of-coolant accident is based on generic analysis for French and American plants with a rotationally symmetric temperature distribution in the RPV. According to the results of international research projects, this represents the enveloping load case for plants of the Westinghouse design.

- From the point of view of the RSK, the requirements of the ASME code for demonstrating a safety factor of 1.5 with regard to the plastic collapse load are met for the RPVs of the two plants.

Overall, most of the open questions of the RSK could be clarified in exchange with the Belgian side. However, there remains the question of adequate experimental validation of the calculation methods for crack fields. The research projects initiated in Germany and Belgium in cooperation with the French CEA can contribute to further improving the validation of the calculation methods.

6 References

[1] IAEA report, IRS-8244, of 31.07.2012 "Flaw Indications in the Reactor Pressure Vessel"

[2] Ultraschallanzeigen am Reaktordruckbehälter des belgischen Kernkraftwerks Doel, Block 3 (Doel-3)
RSK-Stellungnahme of 17.01.2013

[3] Fragen zum Sicherheitsnachweis für die Reaktordruckbehälter der belgischen Kernkraftwerke Doel-3 / Tihange-2
Anlage zum Ergebnisprotokoll der 150. Sitzung des RSK-Ausschusses DRUCKFÜHRENDE KOMPONENTEN UND WERKSTOFFE (DKW) am 17.12.2015

[4] FANC - federaal agentschap voor nucleaire controle
Letter of 18.02.2016 to the Federal Ministry for the Environment, Nature Conservation, Building and Reactor Safety, Appendix 1
http://www.bmu.bund.de/fileadmin/Daten_BMU/Download_PDF/Nukleare_Sicherheit/belgische_kernkraftwerke_antworten_en_bf.pdf

[5] Vorläufige Kurzbewertung der Sicherheitsnachweise für die Reaktordruckbehälter der belgischen Kernkraftwerke Doel-3 / Tihange-2
Anlage zum Ergebnisprotokoll der 483. Sitzung der Reaktor-Sicherheitskommission (RSK) am 13.04.2016

[6] Anlage zum Schreiben des Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB) vom 02.06.2016 „Befunde in den Reaktordruckbehältern der Kernkraftwerke Doel-3 und Tihange-2"

[7] Anlage zum Schreiben der föderalen Agentschaft für nukleare Kontrolle (FANK) vom 28.09.2016 "Reaktordruckbehältern der Kernzentralen Doel 3 und Tihange 2"

[8] Beratungsauftrag des BMUB (Az.: RS I 3 17018/1; RS I 5 18 231 BE) vom 13.10.2016 an die Reaktor-Sicherheitskommission „Ultraschallanzeigen in den Reaktordruckbehältern (RDB) der belgischen Kernkraftwerke Doel-3 und Tihange 2"

[9] Annex to the letter from the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) of 28 August 2017 “Information for FANC and Belgian experts for the preparation of an expert meeting on the RPV issue Doel-3/Tihange-2”

[10] Doel 3, Reactor Pressure Vessel, Safety Case Report
Electrabel, Brussels, 05.12.2012

[11] Tihange 2, Reactor Pressure Vessel, Safety Case Report
Electrabel, Brussels, 05.12.2012

[12] Doel 3, Reactor Pressure Vessel, Safety Case Report 2015
Electrabel, Brussels, 28.10.2015

[13] Tihange 2, Reactor Pressure Vessel, Safety Case Report 2015
Electrabel, Brussels, 28.10.2015

[14] Doel 3, Reactor Pressure Vessel, Safety Case Report Addendum
Electrabel, Brussels, 26.04.2013

[15] Tihange 2, Reactor Pressure Vessel, Safety Case Report Addendum
Electrabel, Brussels, 15.04.2013

[16] Indications de défauts dans les cuves des réacteurs de Doel 3 et Tihange 2
Chronologie et contexte scientifique du dossier
https://afcn.fgov.be/fr/dossiers-dinformation/centrales-nucleaires-en-belgique/actualite/indications-de-defauts-dans-les

[17] Examen des cuves PWR, Doel 3 VP-2016, Rapport de synthèse
Rapport Areva DI 33943, Rev. 0, 06.12.2016

[18] Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2 Final Evaluation Report 2015
FANC-AFCN, 12.11.2015

[19] Doel 3/Tihange 2 Reactor Pressure Vessel Expert Meeting, 02.02.2018
Slides of the Belgian experts presented at the meeting

[20] Reactor Safety Issues Resolved by the 2D/3D Program
NUREG/IA-0127, GRS-101, MPR—1364
July 1993
http://www.nrc.gov/docs/ML0625/ML062560279.pdf

[21] MPA Universität Stuttgart
Untersuchungsbericht zu den Prüfberichten der Ultraschallprüfungen an den RDB der Anlagen Doel-3 (2016) und Tihange-2 (2017)
31.07.2017

[22] C. Boyd, U.S. NRC
Pressurized Thermal Shock, PTS
Thicket 2008
https://www.iaea.org/inis/collection/nclcollectionstore/_public/42/101/42101996.pdf