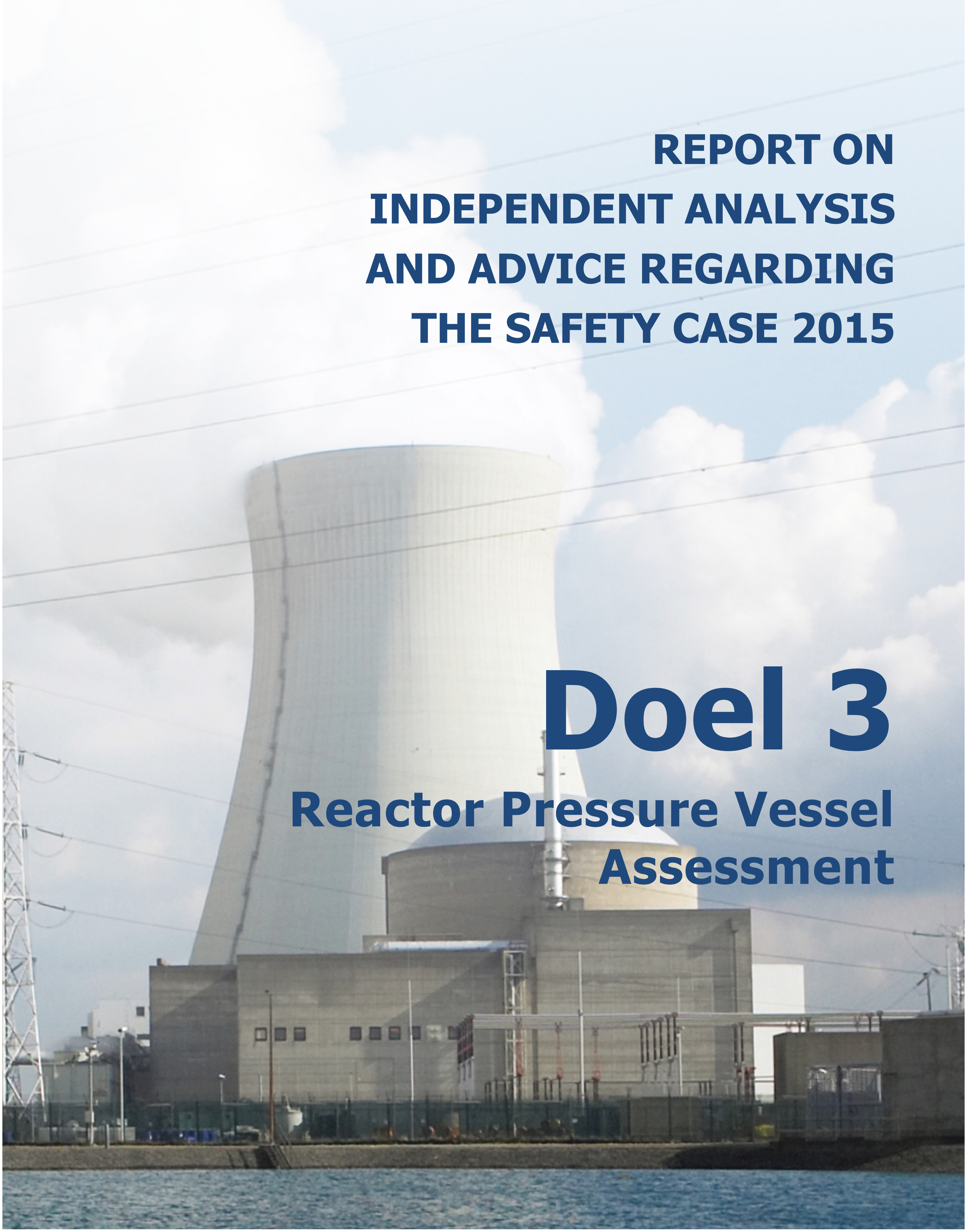
REPORT ON INDEPENDENT ANALYSIS AND ADVICE REGARDING THE SAFETY CASE 2015

Doel 3

Reactor Pressure Vessel Assessment



V1 03 November 2015 •

Electrabel

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2 Summary

2.1 Executive Summary

In 2012, Electrabel found indications (later identified as hydrogen flakes) in the reactor pressure vessel (RPV) of the Doel 3 and Tihange 2 Nuclear Power Plants. A series of inspections, tests and measurements were performed and synthesized in Safety Case Reports, which were submitted to the Federal Agency for Nuclear Control (FANC) in December 2012. Based on these reports, the FANC authorized the restart of both plants and issued a series of short- and midterm requirements, for which Electrabel developed an Action Plan.

As part of the midterm requirements, material properties were identified through tests on irradiated specimens containing flakes. These tests led to unexpected results in March 2014. Consequently, Electrabel decided to shut down the Doel 3 and Tihange 2 nuclear power plants as a preventive measure. Subsequently, the action plan was gradually extended and an updated Safety Case Report was submitted on 17 July 2015.

Electrabel's Service de Contrôle Physique (SCP), acting as an internal independent body, has been involved since the very beginning of the development of the Safety Case. Its objective has been to perform an independent review of the project deliverables issued by the Project Team. Hence, the SCP created an SCP Review Team consisting of internal experts (SCP corporate and site level) and external international experts (Sandia National Laboratories) and academics (Royal Academy of Engineering of Bristol University and Imperial College London).

The SCP Review Team challenged the Project Team's assumptions, analyses, and statements and suggested some improvements and modifications. It also assessed the conservativeness at all steps of the Project Team's justification strategy. During meetings with the Project Team (including participation in project meetings and independent assessment at testing laboratories), the SCP Review Team requested that the Project Team clarify certain issues.

The review and analyses have led the SCP Review Team to give a positive recommendation regarding the safe restart of the Doel 3 RPV, taking into account the advice given in this report. This advice is based on the Project Team's satisfactory consideration of all comments concerning the project deliverables and the final review of the 2015 Safety Case Report.

The present review is an extension of the review realized in 2012-2013 summarized in *'Report on independent analysis and advice regarding the Safety Case'* and its addendum. This review covers the full project scope (Safety Case 2015 Version1), ranging from the preliminary studies, proceedings of mechanical tests, and draft documents up to the final justification file that was delivered to the Safety Authorities on 28 October 2015.

2.2 Role of the SCP

Electrabel's Service de Contrôle Physique (SCP), acting as an internal independent body, has been involved since the very beginning of the development of the Safety Case. Its objective has been to perform an independent review of the project deliverables issued by the Project Team. In a letter addressed to Electrabel (2 August 2012), the FANC requested that the SCP conduct an independent analysis of the Doel 3 and Tihange 2 RPV Safety Cases and to provide an advice on the content and conclusions of the Safety Cases. Electrabel put together a SCP Review Team (see Chapter 2.4 Organization), which delivered two reports:

- *December 2012: positive advice and some recommendations*
- *April 2013: positive advice without recommendations*

Subsequently, the FANC agreed to a restart of both power plants, on the condition that an action plan is executed, which addresses the FANC's mid- and long-term requirements.

As part of the action plan, mechanical tests were performed on irradiated specimens containing flakes. This led to unexpected results for the VB395 material (a rejected portion of a steam generator known to contain flakes). Consequently, Electrabel decided to shut down the Doel 3 and Tihange 2 Nuclear Power Plants (March 2014) as a preventive measure.

After the preventive shutdown of both plants, the FANC sent a letter to Electrabel (27 March 2014), in which it requested the SCP to again conduct an independent analysis of the extended action plan to be developed by Electrabel and to provide an advice.

2.3 Methodology

The SCP Review Team took a two-way approach in its analysis of the Safety Case:

- **Follow-up of the development of the Safety Case** in order to get a deep understanding of the subject. Members of the SCP Review Team played an interactive role as 'participating review' and 'challenging interaction' with the Project Team.
- **Independent analysis of the project deliverables**: safety framework, characterization of hydrogen flakes, ultrasonic examinations, mechanical tests, root cause of the unexpected behaviour of the VB395 material under irradiation, proximity rules, calculations of the structural integrity, etc.

The SCP Review Team closely evaluated to what extent conservativeness, representativeness, validity and safety margins are taken into account in the roadmap and methodology applied in the Safety Case.

All comments regarding the project deliverables have been forwarded to the author of each deliverable. The most important comments have been formalized in review/advice sheets sent to the Head of the Project Team. The Project Team analysed the SCP Review Team's comments resulting from both internal and external reviews of the project deliverables and addressed all concerns properly.

2.4 Organization

In 2012, the SCP created a SCP Review Team to perform an independent review of the Doel 3 and Tihange 2 RPV Safety Cases. The SCP Review Team pursued its mission in 2014 and 2015 based on a similar organization, consisting of both internal and external experts.

Internal experts are:

- Members of CARE NS based at the nuclear plant site
- Members of the Electrabel Corporate Nuclear Safety Department (ECNSD)

External experts come from:

- Sandia National Laboratories (SNL), a US governmental multi-programme engineering and science laboratory, part of the US Department of Energy (DOE), reviewing the proximity rules.
- Two professors in Mechanical Engineering (Professor David Smith from the Royal Academy of Engineering of Bristol University, and Professor Kamran Nikbin from Imperial College London), reviewing the technical documents on metallurgical and structural integrity issues.

The SCP Review Team communicated systematically the outcomes of its reviews to the FANC, at its request. In addition, regular progress meetings between the SCP Review Team and the FANC have been held independently, closely after each progress meeting organized between the FANC and the Project Team.

2.5 Main Conclusions of the 2012 Safety Cases and their Addenda

A safety framework was defined at the beginning of the Project Team's investigations regarding the RPV issue. It gives an overview of the regulations and standards that apply to the Safety Case. The SCP Review Team has verified that the Project Team's safety demonstration is in compliance with the applicable international rules and standards.

In its *'Report on independent analysis and advice regarding the Safety Case'*, dated 19 December 2012, the SCP Review Team gave the following advice :

> *Although a lot of conservativeness has already been taken into account in the Safety Case, which supports confidence in the positive result of the structural integrity analysis, the SCP Review Team still advises the Project Team:*
>
> *• To adapt the Technical Specifications concerning minimum RWST water temperature taking into account its positive effect to reduce thermal shock knowing that a lot of indications are close to the inner surface of the Doel 3 RPV.*
>
> *• To carry out—before the next refuelling outage—the Action Plan's confirmatory test program on industrial material containing hydrogen flakes. It will enable the confirmation of the overall performance of the methods used in the Safety Case.*
>
> *• To perform—during the next refuelling outage—a UT inspection similar to the one that was performed during the summer of 2012 with additional one-to-one tracking of a small subset of selected indications. It will enable the confirmation of the Safety Case's conclusions regarding the absence of the indications' evolution in size, shape, and orientation. The extension of RPV inspection tool qualification foreseen in the Action Plan should include the ability to confirm such absence of evolution.*

The SCP Review Team followed the Action Plan's confirmation test programme and other short-term actions mandatory to correctly address the remaining issues identified by the FANC in its '*Provisional Evaluation Report'* of 30 January 2013.

On 23 April 2013, the SCP Review Team issued an addendum to its *'Report on independent analysis and advice regarding the Safety Case'* with a positive advice without recommendations.

3 Advice

Based on its independent analysis (see Chapter 4 Review) and the final review of the Safety Case, the SCP Review Team provided the following overall positive advice to the FANC.

In its Safety Case report, license holder Electrabel (the Project Team) demonstrated that the indications in the Doel 3 RPV do not jeopardize the equipment's structural integrity during normal operation, or during transient or accident conditions.

Electrabel's Service de Contrôle Physique (SCP) performed a thorough review of the project deliverables. This review has been conducted with the participation of internal and external experts (Sandia National Laboratories) and academics from British universities. Based on this review and analysis, the SCP Review Team gave recommendations, which have been adequately addressed by the Project Team.

The SCP Review Team is confident that the margins and conservativeness in the 2015 Safety Case Version 1 are high enough to cover the residual uncertainties. This confidence is primarily based on the sensitivity studies (performed by the Project Team to demonstrate the robustness of the applied approach), as well as the results of the assessment of the crack driving forces.

Consequently, the SCP Review Team's final opinion is positive regarding the content and general conclusions of the 2015 Safety Case Version 1 that was delivered to the FANC on 28 October 2015.

4 Review

The SCP Review Team took a two-way approach in its analysis of the Safety Case:

- **Follow-up of the development of the Safety Case** in order to get a deep understanding of the subject. Members of the SCP Review Team played an interactive role as 'participating review' and 'challenging interaction' with the Project Team.
- **Independent analysis of the project deliverables**: safety framework, characterization of hydrogen flakes, ultrasonic examinations, mechanical tests, root cause of the unexpected behaviour of the VB395 material under irradiation, proximity rules, calculations of the structural integrity, etc.

4.1 Roadmap

The SCP Review Team considers the Project Team's final roadmap as well as the methodology presented in the 2015 Safety Case to be appropriate to verify the integrity of the RPV. The SCP Review Team focused on the validity of the postulated statements and the adequacy of the safety margins identified in the proposed methodology.

4.1.1 Scope of the Review

The SCP Review Team assessed the roadmap developed by the Project Team and found that it demonstrated that the detected flaws do not impair the safety function of the Doel 3 RPV.

Based on the results of the inspections, tests and measurements conducted as part of the action plan, the roadmap was gradually extended to encompass all of these outcomes.

On 5 December 2014, the FANC issued a letter with 26 requirements and 14 suggestions after a workshop with an International Review Board (IRB) that took place in the first week of November 2014. The SCP Review Team followed the actions launched by the Project Team to address these requirements and suggestions.

In preparation of the second IRB workshop, which took place from 22 to 24 April 2015, the Project Team issued a Technical Summary note on 14 April 2015, synthesizing all of the actions taken to complete de roadmap and address the requirements and suggestions as stipulated in the FANC letter of 5 December 2014.

The Service Contrôle Physique accompanied the project during the completion of the extended action plan performed during 2013-2015 and reviewed the actions leading the project to conclude that the:

- Phenomenology of flaking is independent of the level of segregation in the material
- Hydrogen flakes are fully characterized and have a laminar orientation
- Qualified UT inspection procedure achieves high performance in detection and sizing
- Re-inspection of the vessel shells delivers a complete cartography of the indications which confirms that the flakes are stable
- Conservative material properties are derived for use in the SIA
- Structural integrity of the RPV is demonstrated with large safety margins, and has never been a concern during the whole operation of the plant since commissioning.

4.1.2 Analysis

The SCP Review Team examined the roadmap in accordance with a two-phased process presented by the FANC on 12 September 2014 in preparation of the IRB workshop that took place in the first week of November 2014:

- Phase 1: Methodology to set up the input data for Structural Integrity Assessment (SIA)
- Phase 2: New Safety Case to demonstrate that all safety criteria in the SIA are met

In the framework of Phase 1, the SCP Review Team issued a positive advice without reservation regarding the Technical Summary Note that was provided by the Project Team on 14 April 2015:

> *"The SCP participated to the review of the Technical Summary Note RPV assessment Do3/Ti2 on the basis of the results of the reviews/advices emitted between 2014 and 2015. After internal check, the SCP considers to have received satisfactory answers to all these reviews/advices and has no residual questions or comments".*

The FANC issued its position about Phase 1 in a letter dated 4 June 2015. This letter integrates the results of the second IRB workshop as well as the outcomes of the review performed by Bel V. In this letter, only one request has been introduced, to be solved before starting Phase 2. This request, copied hereafter, intends to cope with some uncertainties regarding the material properties in non-irradiated conditions :

> *« a term should be added to the initial RT_{NDT} to account for the potential lower fracture toughness of the material in the macro-segregated areas where the flakes are located. Justification of the assumed value of this additional term should be provided, e.g., by reference to published data."*

The FANC also requested complementary clarifications regarding the methodology proposed by the Project Team, but not concerning the SIA approach which is accepted for further use in the 2015 Safety Case.

The SCP Review Team followed the development of the answers to FANC's requests.
The Project Team addressed properly FANC's request before starting Phase 2 and summarized it in § 5.5.2 of the Safety Case 2015.
The SCP Review Team considers that its positive advice on Phase 1, issued on 14 April 2015, is still valid.

The FANC issued on 17 July 2015 a positive statement to close Phase 1.

For our advice on Phase 2, see Chapter 4.5 Structural Integrity Assessment.

4.2 Characterization of Hydrogen flakes

The SCP Review Team agrees with the main conclusions of the Project Team's analysis, i.e. the flakes are located in ghost lines and are inclined less than the maximum angle of the ghost lines.

The SCP also agrees with the Project Team's position that there is no correlation between the number of flakes in some areas of the RPV shells and the level of chemical enrichment inside the macro-segregation in those areas.

4.2.1 Scope of the Review

The SCP Review Team examined the completeness, consistency and reliability of the conclusions of the Safety Case regarding the characterization of hydrogen flakes.

4.2.2 Analysis

When analysing the deliverables issued by Laborelec, the SCP Review Team had only minor comments on the use and interpretation of statistics. The comments were taken into account by Laborelec. Therefore, the SCP Review Team can agree with the conclusion about the observation made on numerous samples coming from the AREVA shell VB395 as well as those coming from the Doel 3 nozzle shell cut-out (D3H1). In both sets of samples, the inclination of the ghost lines was measured and in VB395 samples the correlation between ghost line inclination and flake inclination has been confirmed.

Since the flakes are located in ghost lines whose maximum inclination do not exceed 16° and less than 5% of the flakes' inclination are between 10 and 15°, the SCP Review Team agrees with the Project Team's conclusion that the maximum expected inclination of the flakes is 15°.

The Project Team assessed the potentiality that the density of flakes found in some macro-segregated areas of the RPV shells might be correlated with a high level of chemical enrichment inside those areas. This correlation could have had an impact on the initial fracture toughness values for those zones. Therefore the Project Team has performed complementary assessments. It is clearly demonstrated that such a correlation does not exist.

4.3 Ultrasonic Inspection

The SCP Review Team was continuously involved in the review of the UT qualification process. The focus was primarily on the level of confidence in detection, the accuracy in sizing in the X and Y components and the reproducibility of the measurements. Regarding the sizing in the Z component, and according to the sensitivity study performed by the Project Team, the SCP Review Team does not request the application of the alternative DZ sizing methodology for the entire population.

The SCP Review Team also received and reviewed the *'Dossier de qualification de la MIS-B'* performed by Intercontrôle and Laborelec. As positive answers were received to all questions expressed during the qualification process, the SCP Review Team accepted the final UT qualification documents.

The SCP Review Team also assessed several of the Project Team's deliverables aiming at obtaining the new cartography for the indications (based on the methodology resulting from the qualification process) and also aiming at comparing this updated cartography with the 2012 cartography in order to show that there was no evolution of the indications during the 2013 operation cycle. As appropriate answers were received to all questions related to these items, the SCP Review Team accepts the new cartography as well as the Project Team's conclusion regarding the absence of evolution of the indications.

Although it is shown that the clad interface imperfections (in French: Défauts techniques de revêtement (DTR)) are not comparable to hydrogen flaking indications, the Project has conservatively decided to consider the DTRs as hydrogen flaking for the demonstration of the Structural Integrity Assessment (SIA). This approach is conservative and the SCP noted that even with the DTRs considered as hydrogen flakes, the SIA is not threatened which strengths the final conclusion.

4.3.1 Scope of the Review

The MIS-B device was initially not designed for the sizing and characterization of hydrogen flakes. Hence, the qualification of the tool needed to be extended for this particular purpose. In 2012 and 2013, several actions were undertaken to achieve this goal.

The SCP Review Team closely examined and followed all the developments along the extension of the MIS-B qualification for the detection, localization and sizing of hydrogen flakes in the RPVs. The following items have been reviewed :

1. Generalities about the UT examination and the accuracy expected
2. Selection of the sensors to perform the examination
3. Sizing of the indications in the X and Y dimensions
4. Re-analysis, complementary to the qualification of the MIS-B
5. DZ sizing and characterization
6. Clad interface imperfections (DTR) requalification for SIA analysis

4.3.2 Analysis

4.3.2.1 Generalities about the UT examination and the accuracy expected

During the qualification of the MIS-B, it appeared progressively that the selection of the **rejection threshold** was a key parameter that needed to be assessed. The rejection threshold changed multiple times in order to coincide with the destructive test results and to improve the confidence level.

It was also shown that the influence of the faceting of the flakes could have an adverse effect on the measurements as they tend to reduce the signal.

Rejection threshold

The threshold of rejection between the accepted measures and the normal measurement noise.

The SCP Review Team pointed out that the rejection threshold has to be selected in such a way that a high confidence level would be ensured for the detection, regardless of the effect of the faceting or other geometrical elements. The SCP Review Team requested that a confidence level of 95% should be reached corresponding to the best practices in that domain.

The Project Team answered positively to that request and consolidated the qualification process at a very high level of confidence (above the SCP Review Team's expectations).

4.3.2.2 Selection of the sensors to perform the examination

The SCP Review Team questioned the Project Team regarding the selection of the sensor used to perform the UT examination of the first mm of the core vessel, just behind the cladding. Two sensors could have been used: one MER and one EAR.

The aim of the Project Team was to challenge the selection of the sensor done by the Project Team and to check the completeness of the qualification performed by Intercontrôle.

The final consolidated results of the qualification confirmed that the MER sensor provided a level of performance similar to the EAR but that its response was better at near depths inside the material (especially <30 mm). At higher depths, the rejection threshold has been lowered to maintain the detection capability.

To illustrate the selection of the rejection threshold and the use of the sensors, Figure 1 shows clearly the old and new values used.

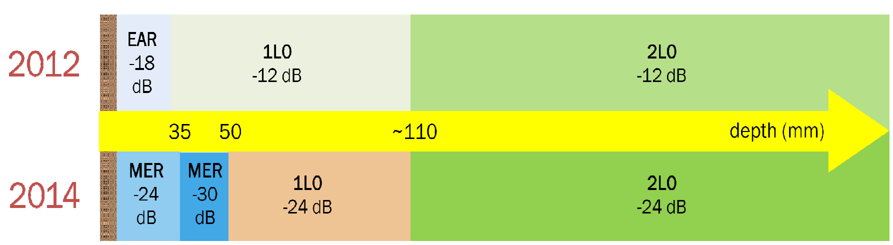

Figure 1: Evolution of the rejection thresholds between 2012 and 2014

4.3.2.3 Sizing of the indications in the X and Y dimensions

During the MIS-B qualification, several actions were taken by the Project Team in order to check the capability of the MIS-B to size the indications adequately.

The reference used when describing the flaws is depicted in Figure 2. The flaws are quasi-laminar, which means that their components are almost totally included in the XY plane, i.e. parallel to the cladding.

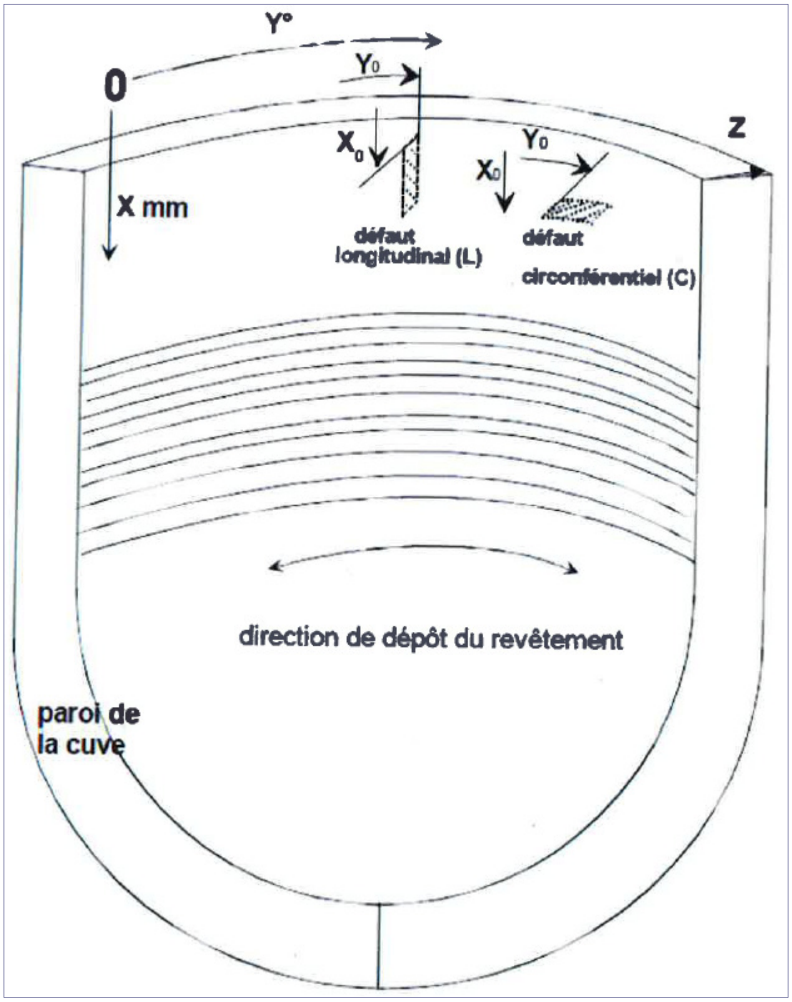

Figure 2: Axis system used in MIS-B Qualification

After the decision taken by the Project Team to select an **echo-dynamics-based methodology** to improve the sizing of the flaw in the XY plane and to correct the undersizing detected during the first measurements, the first action taken by the SCP Review Team was to challenge the adaptation of the methodology to the measurement in the Y component as was done by the Project Team on the X component.

The Project Team showed that there was an average over-estimation of the sizing in the Y direction, which is indeed conservative. The results of the qualification showed that the comparison between the destructive tests and the UT measurements were in accordance in the XY plane with the qualification criterion and good practices.

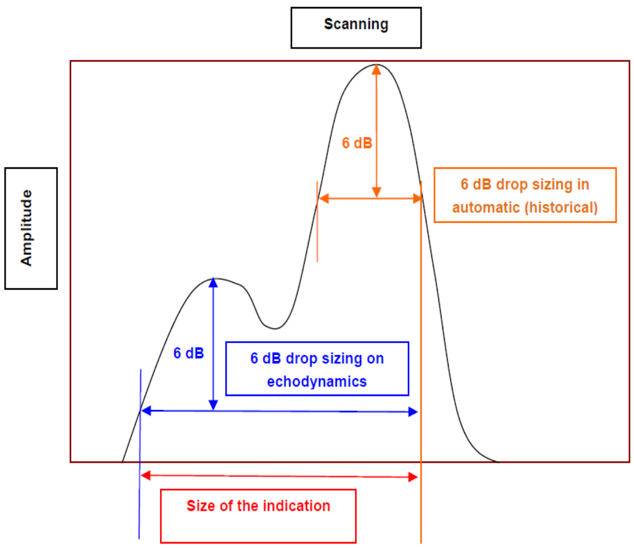

Figure 3: Representation of the echo-dynamics methodology

Echo-dynamics methodology

The principle of the echo-dynamics methodology is illustrated in Figure 3. When the UT sensor is placed along the surface, the usual sizing methodology aims at calculating a drop of 6 dB with respect to the maximum peak in amplitude. The size of the indication is then calculated as the distance between the two points from part and other of the maximum giving the -6dB loss of signal. This procedure is fully automated.

Destructive tests on the VB395 test blocks showed that sometimes this procedure led to the underestimation of the size of the actual flaw. Indeed, some part of the signal was considered as rejected noise because out of the 6db drop of the absolute maximum. The echo-dynamics procedure enables correction of this. It calculates the length of the indication by using the 6dB drop not only from the absolute maximum but also considering secondary (local) maxima that could be in the vicinity of the global maximum. As such, the sizing is improved.

4.3.2.4 Re-analysis, complementary to the qualification of the MIS-B

Since the continuous improvement of the qualification led to a new rejection threshold in the 2014 methodology, the SCP Review Team requested that the Project Team re-analyse the 2012 raw data set using the 2014 methodology (the echo-dynamic sizing), in addition to the analysis already performed with the 2012 methodology (the historical 6 dB drop sizing). On one hand, this action aimed at demonstrating that no evolution of the indications occurred between the inspection of 2012 and the inspection of 2014. On the other hand, it enabled establishing a better reference point (2012 inspection) for the comparison with any potential further examinations.

In answer to this request, the Project Team provided improved statistics summarized in Table 4 and illustrated in figures 5 and 6.

Unit	Core Shell	2012 methodology	2014 methodology	Variation
Doel 3	Upper	857	829	-3.3%
	Lower	7205	6936	-3.7%

Table 4: Number of indications reported in the core shells based on 2012 inspections raw data

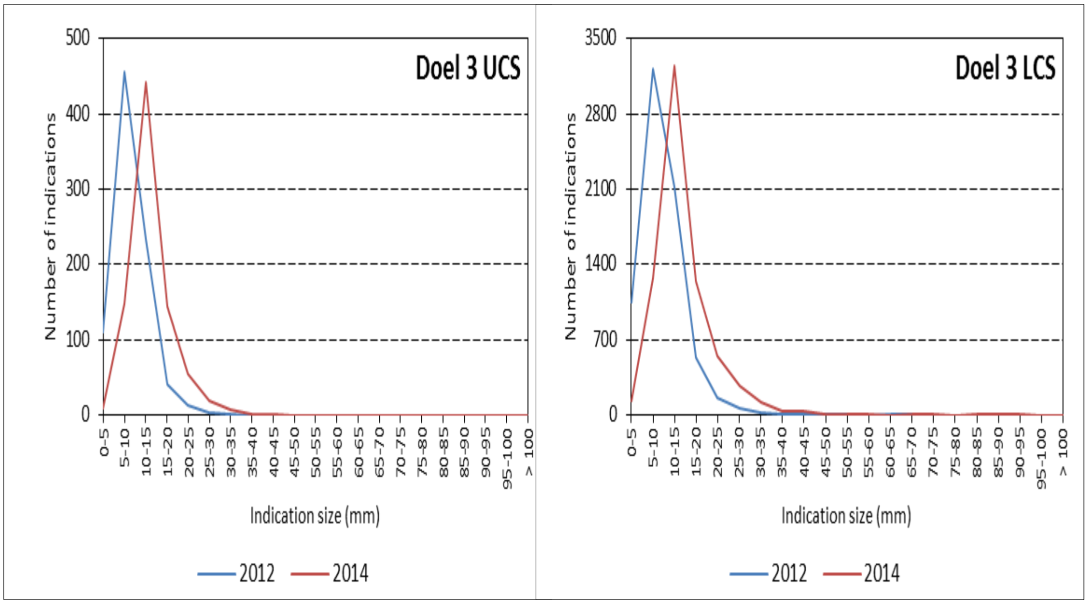

Figure 5: Indication size distributions (UCS: Upper Core Shell; LCS: Lower Core Shell) based on the 2012 or 2014 methodology with the 2012 raw data

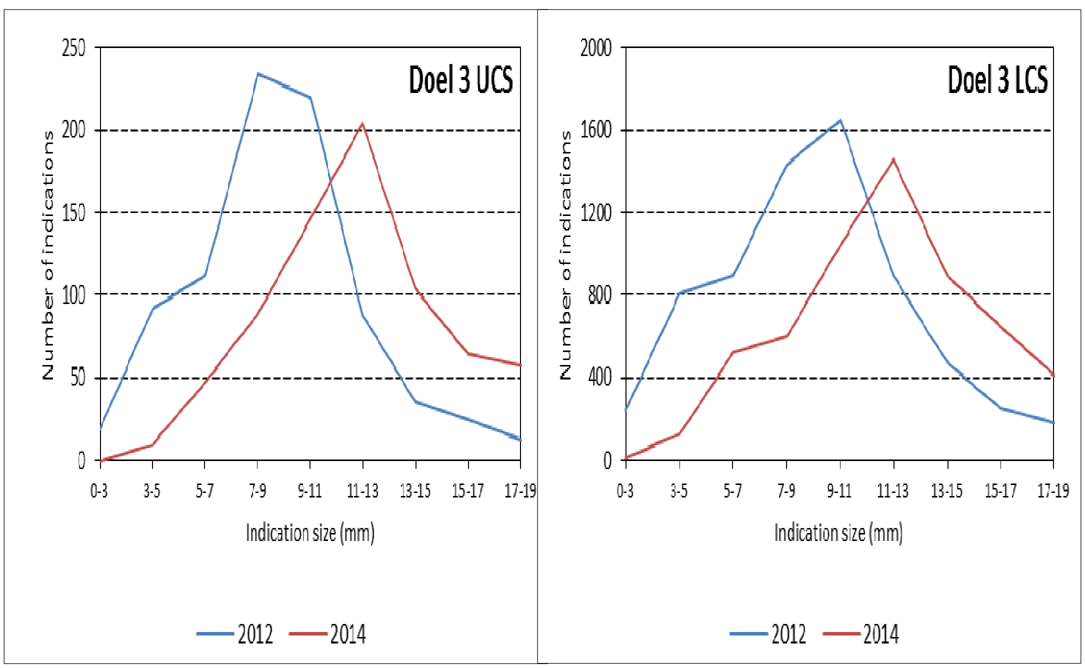

Figure 6: Small size distributions (UCS: Upper Core Shell; LCS: Lower Core Shell) based on the 2012 or 2014 methodology with the 2012 raw data

As illustrated in Figure 7, the increased sizes measured by the 2014 methodology (illustrated in pink) reduce in some cases the possibility of detecting sound metal between two indications (namely when the measured ligaments tends to zero) ; in such a case, only one larger indication is reported, thereby reducing the total number of flaw indications. The revised sizing methodology applied in 2014 resulted in a slight increase in the indication dimensions compared to 2012. However, the indication size distributions observed in the core shells remained unchanged.

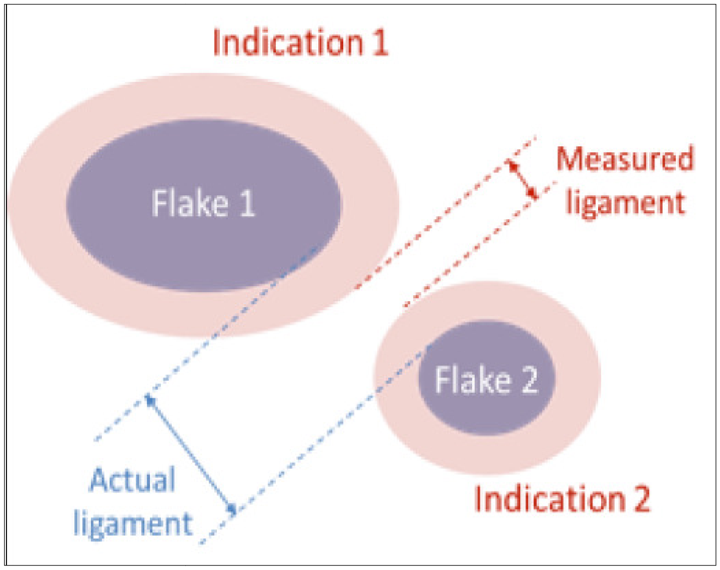

Figure 7: Undersizing the sound metal ligament between two oversized neighbouring flaws

After the presentation of those results, the FANC requested complementary information aiming at clarifying whether the same exercise of reanalysis with the 2014 methodology was done on the VB395/2A block used for the qualification and on which measurements were performed in 2012.

The reanalysis revealed that the same behaviour was observed on the VB395/2A block: a reduction of the number of indications but an increase in size (Figure 8, Table 9)[1].

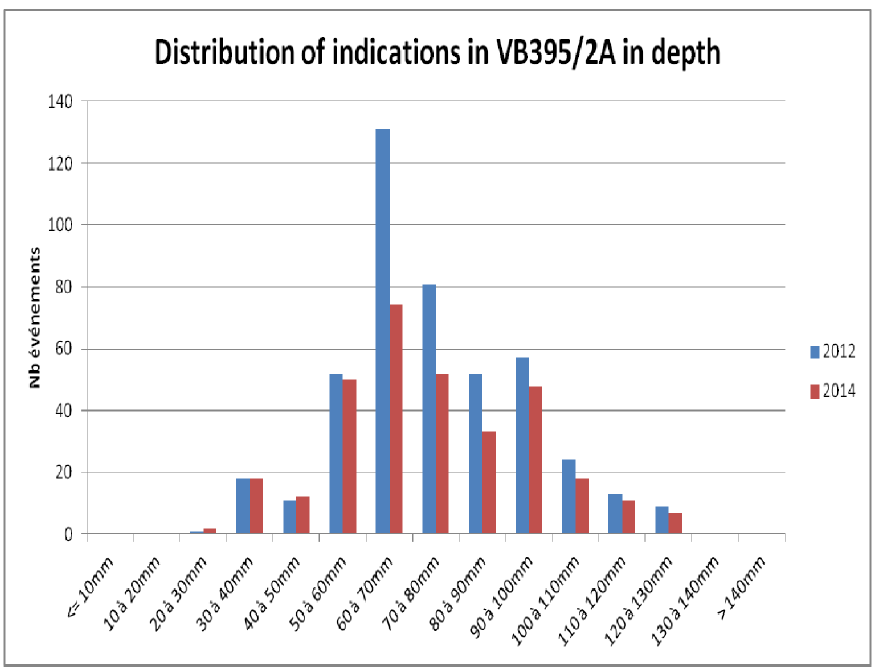

Figure 8: Distribution of the number of indications with respect to the depth—VB395/2A

[1] Note that the flaw density in both RPV KCD3/CNT2 and in the VB395/2A block differ; hence no direct comparison of the figures can be made.

Average indication size [mm] bloc VB395 /2A					
2012 procedure		Qualified procedure (2014)		Variation	
X	Y	X	Y	X	Y
15.3	11.6	32.8	25.1	53.4%	53.8%

Table 9: Size of the indications in VB395/2A block

4.3.2.5 DZ sizing and characterization

It is of utmost importance to remember that the hydrogen flaking defects are quasi-laminar defects. This means that, according to the reference that was used (Figure 2), they have their components in the XY plane and almost no Z (radial) component.

During the qualification process of the MIS-B, the detected undersizing of the X and Y components has been properly corrected by the new sizing methodology. In a later phase, it appeared that the Z sizing could also present some undersizing, if used with no adaptation with respect to the original procedure. (Reminder: the original procedure was not dedicated to the measurement of hydrogen flaking defects).

The methodology employed aims to size an indication by the determination of a loss of 6dB calculated on the maximum of the amplitude of the indication. If several local amplitude maxima exist, the loss of 6dB is calculated from the global maximum of the indication.

Hence, an 'alternative' methodology has been developed. This one aims at calculating a 6dB loss on each local maximum of an indication. The DZ values are then estimated by calculating the difference between Z_{max} and Z_{min}. This methodology avoids any potential underestimation.

In order to challenge this conclusion, AIA requested that complementary comparisons between the two methodologies be performed, with no destructive test, on the lower shell of the Doel 3 RPV. The following comparisons have been performed:

- 537 indications of DX and DY dimensions less than 30 mm have been randomly selected
- 541 indications of DX and DY dimensions between 30 mm and 40 mm have been selected (which is the entire population)
- 449 indications of DX and DY dimensions larger than 40 mm have been selected (which is the entire population)

In addition, complementary comparisons on the lower and upper shell of the Tihange 2 RPV and of the higher shell of the Doel 3 RPV have also been made. Nevertheless, only the Doel 3 lower shell results are presented in Figure 10, since they are the most representative and the conclusion regarding the other populations (Tihange 2 and Doel 3 upper shell) are similar.

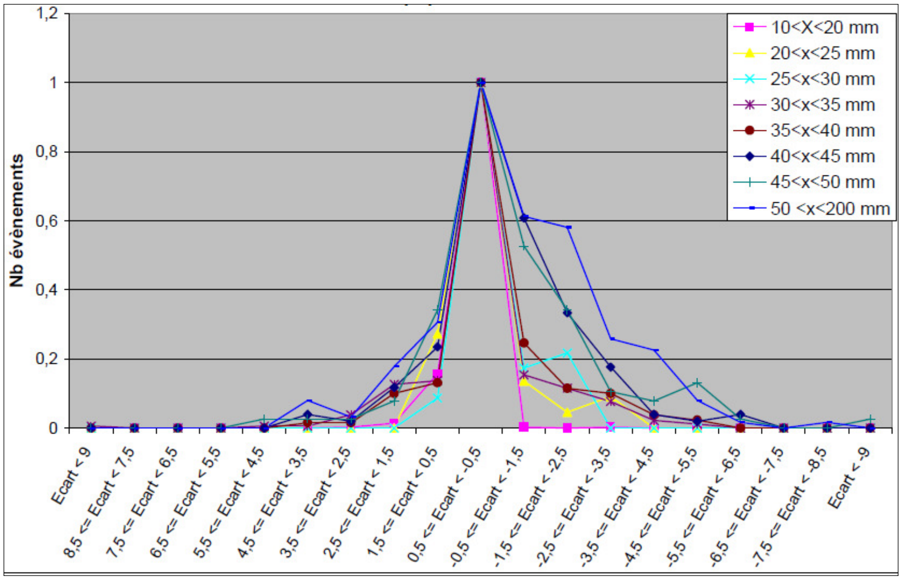

Figure 10: Normalized histogram of the delta in DZ sizing (usual sizing—alternative sizing)

It appears that the results are equivalent up to 20 mm. For the largest indications, it can also be concluded that the 'alternative' methodology gives statistically larger dimensions in DZ.

It must also be taken into consideration that the destructive tests on the VB395 samples analysed in the framework of the extension of the MIS-B qualification, have shown a trend to overestimate the sizing, even with the original methodology.

The Project Team performed a sensitivity study on the SIA with DZ inputs from the 'alternative' method for indications larger than 20mm in the DX or DY dimension (see § 4.6). As far as this sensitivity study shows that the SIA is not impacted, the SCP Review Team considers that the original 6 dB drop sizing methodology can be maintained for Z coordinates.

4.3.2.6 Clad interface imperfections requalification for SIA analysis

301 DTR indications were found in Doel 3: 268 such indications were found in the lower core shell and 33 in the upper core shell. The majority were thus located in the lower core shell, in the volume where the cloud of hydrogen flakes is situated close to the cladding-base metal interface.

As the DTRs could be close to area where hydrogen flakes (In French "défauts dus à l'hydrogène": DDHs) are present, it may not be evident to establish a clear distinction between those 2 categories of indications on some occasions. Therefore, a conservative approach has been used and the DTRs are considered as DDHs for the SIA. It is worth nothing that the penalizing inclusion of such indications did not modify the results of the SIA, showing robustness of this analysis. In addition, these indications will be included in future inspections of Doel 3 RPV and will be treated as hydrogen flakes in evolution checks. SCP agreed with that approach and its conclusion.

A **DTR** is any flaw located at the cladding-base metal interface, that does not penetrate the RPV core shell base metal itself. A DTR should not be confused with underclad cracks (French: défauts sous revêtement or DSR), which are planar flaws at the cladding-base metal interface, located in the base metal, oriented perpendicular to the RPV surface and generated by cold cracking. No underclad cracks were discovered during the 2012 inspections.

4.4 Material Properties

The SCP Review Team followed the test campaigns and requested complementary tests at low and medium fluence for specimens of the AREVA VB395 'between flakes' in order to validate the RSE-M prediction curve selected by the Project Team. It appeared that the RSE-M prediction curve for this VB395 material showed an important conservativeness at low and medium fluence, which encompasses most of the flakes.

However, the German KS 02 and Doel 3 D3H1 material behave as expected under irradiation. Hence, the SCP Review Team accepted the Project Team's approach to use the value of the shift in RT_{NDT} provided by the VB395 tests 'between flakes' as an upper boundary for the shift that the Doel 3 and Tihange 2 RPV steels would suffer under irradiation.

The SCP Review Team considers that transposing the shift of the VB395 to the Doel 3 and Tihange 2 RPV shells is based on strong engineering judgment and consistent test results. No formal demonstration of transposability has been given as the exact root cause of the unexpected atypical embrittlement of the VB395 has not been univocally identified.

4.4.1 Scope of the Review

The SCP Review Team closely examined the following items:

- Analysis of the unexpected results obtained in March 2014
- Review during the complementary test programmes set up in 2014 and 2015
- Review during the Root Cause Analysis (behaviour of VB395 under irradiation)
- Additional material investigations
- KS 02 material presentation and material properties
- Transposability
- Final selection of the material properties to be used for the Safety Case 2015

4.4.2 Analysis

4.4.2.1 Analysis of the unexpected results obtained in March 2014

Having seen the March 2014 test results, the SCP Review Team organized an audit at SCK•CEN to check the compliance between the test procedure and the effective execution of the Chivas-9 test campaign. The two-day audit covered various topics:

- The preparation of the samples tested in the BR2 irradiation facility of SCK•CEN, the link with subcontractors, the presence of the calibration certificate for the various applied tools, the qualification of the personnel
- The pre-crack method performed on different samples, the thermal treatment applied on the samples, the size of the samples used in the BR2 vs. the normally used dimensions of Charpy samples as required by the ASME Code, reconstitution of the samples
- Control of the dosimetry, check of the dose received and the flux homogeneity
- Boundary conditions, surrounding materials of the samples at the time of irradiation
- Destructive test examinations, storage of the samples, etc.

The result of the audit was that the tests were performed adequately and that no deviation was found which could explain the unexpected results. The reason of the unexpected behaviour was therefore not related to a human error or to a failing test procedure. The hypothesis that this behaviour is real and directly related to the tested material became stronger.

The Project Team decided to perform two additional irradiation test campaigns on BR2 irradiation facility of SCK•CEN (named Chivas-10 and Chivas-11) in order to confirm this statement. The results obtained were consistent with the values of the Chivas-9 campaign.

4.4.2.2 Review during the complementary test programmes set up in 2014 and 2015

The SCP Review Team provided some advice during the technical specification preparation of the test campaigns Chivas-10 and 11 as well as Chivas-12, as explained here after.

For instance, in preparation of the Chivas-12 campaign, the SCP Review Team asked the Project Team to perform irradiation tests on the VB395 material between flakes not only at high fluence (6 10^{19} n/cm², corresponding to a neutron dose of 40 years of reactor operation) but also at low/medium fluence (2 to 4 10^{19} n/cm²). The aim of this requirement was to have new points at lower fluence, which would help the SCP Review Team to challenge the correlation proposed by the Project Team to simulate the evolution of the RT_{NDT} in flaked areas. Indeed, this correlation was using the available library of points covering only high fluence zones and it was important to check its adequacy at lower neutron dose. Even more, as most part of the flakes inside the base metal are at a depth of several mm up to 10 cm, and as the fluence decreases exponentially in the RPV wall, those flakes will be affected by a lower fluence than 6 10^{19} n/cm² after 40 years of reactor operation. So, it was worth having these extra points to see if the correlation between RT_{NDT} and the fluence was indeed also conservative for low or intermediate fluence values. The results showed a clear conservativeness with the measured shift at these fluence levels, well below the predictive curve selected by the Project Team.

4.4.2.3 Review during the Root Cause Analysis (RCA)

In parallel with the preparation and execution of the new irradiation campaigns (Chivas-10 and 11), for which the results and outcomes will be discussed in the next chapter, discussions were held to try to investigate the root cause of the discovered atypical embrittlement under irradiation.

Several meetings took place between international experts of the Project Team and skilled personnel of Laborelec, Tractebel Engineering and SCK•CEN. The academics acted as experts for the SCP Review Team and actively participated during a plenary meeting (October 2014). They also met separately with experts of Tractebel Engineering and Laborelec.

These discussions resulted in the SCP Review Team's position that complementary measurements were needed. The SCP Review Team requested that the Project Team provide additional data regarding hardening measurements. The aim was to better evaluate the effect of the localized martensite on the material. Consequently, the cartography of the hardening of the VB395 shell was prepared by Laborelec. An answer was provided to the SCP Review Team and considered appropriate although no new element for the RCA could be extracted from the results of these hardening measurements.

Despite all the Project Team's efforts, it was not possible to isolate the univocal root cause of the unexpected atypical embrittlement of the VB395 material. The conclusions of the experts, shared by the SCP Review Team, are:

> *"Although the precise root cause(s) and microstructural mechanism(s) of the unexpected behaviour of VB395 after irradiation cannot be identified at this stage, several root causes and associated mechanisms can be excluded. In particular, hydrogen flaking or any other H related mechanism could be excluded as the cause of the unexpected behavior. The remaining two possible mechanisms (possibly interacting) are segregation of impurities and loss of strength of the martensitic segregation network. […] Since the larger than predicted shift in transition temperature after irradiation of VB395 is not linked with the hydrogen flaking and since none of the above mentioned other fabrication anomalies are reported for the D3/T2 shells, it is expected that the transition temperature shift after irradiation for the RPV shells will be in line of what is observed for typical RPV steels, i.e. comparable to the D3H1 shift."*

4.4.2.4 Additional material investigations

The potential influence of hydrogen from the primary water diffusing into the Reactor Pressure Vessel steel on the propagation of the hydrogen flakes was already studied in 2012 in the framework of the first Safety Case. However, at FANC's request, a re-evaluation of this work was carried out. The goal is to assess any potential risk of crack propagation due to accumulation of hydrogen coming from the primary water. This concern is known as "Hydrogen blistering" or "Hydrogen Induced Cracking" in the petrochemical industry.
The SCP Review Team has followed the discussion regarding the H2 blistering issue. Several meetings with international experts were held and aimed at exchanging about the possible mechanisms to investigate more deeply. The conclusions of those meetings, also covered by FANC and Bel V, were that the considered mechanisms were sufficiently investigated and that no doubt regarding H2 blistering issue subsists.

The SCP Review Team, in order to challenge the Project Team and experts conclusions, requested the support of Sandia National Laboratory to cross-check the conclusions. After analysis, Sandia National Laboratory concluded that the understanding of the phenomena and the Project's conclusions are correct.

Consequently, the SCP Review Team accepted the Project Team document dealing with H2 blistering.

4.4.2.5 KS 02 material presentation and material properties

KS 02 is made of German 22NiMoCr37 steel belonging to the family of NiMoCr RPV steel . The KS 02 flange is a half ring of which the forging started from a solid ingot without applying any piercing. The KS 02 was examined in the 1980s as part of a comprehensive German FKS (Forschungsvorhaben Komponenten Sicherheit) research programme with large forgings.

Summarizing the results and conclusions of the Chivas-12 test campaign performed on BR2 irradiation facility of SCK•CEN, it can be concluded that, as opposed to the results on the VB395, the KS 02 behaves according to the expected prediction defined by the models and shows no major modifications of the characteristics of the material due to the presence of the flakes. It must be noted that the chemical composition of the KS 02 component falls outside of the validity domain of the RSE-M prediction[2]. Strictly speaking, the RSE-M prediction formula may not be applied on this component to predict the RT_{NDT} shift. However, the measured values fall well in line with the prediction. While not a formal evidence of correctness, it is indeed a positive element.

Figure 11 shows the measured values of the shift which are in accordance with the RSE-M prediction and Figure 12 shows the results of the measured values of ΔT_0. For a proper understanding of the legend in this last figure, note that 'FKS non segregated' and 'AREVA segregated' are designating respectively the KS 02 out of the macro segregated area and the KS 02 broken specimens after Charpy tests reconstructed by AREVA Erlangen. Therefore, both are applicable for the KS 02 material.

Both figures show consistent results.

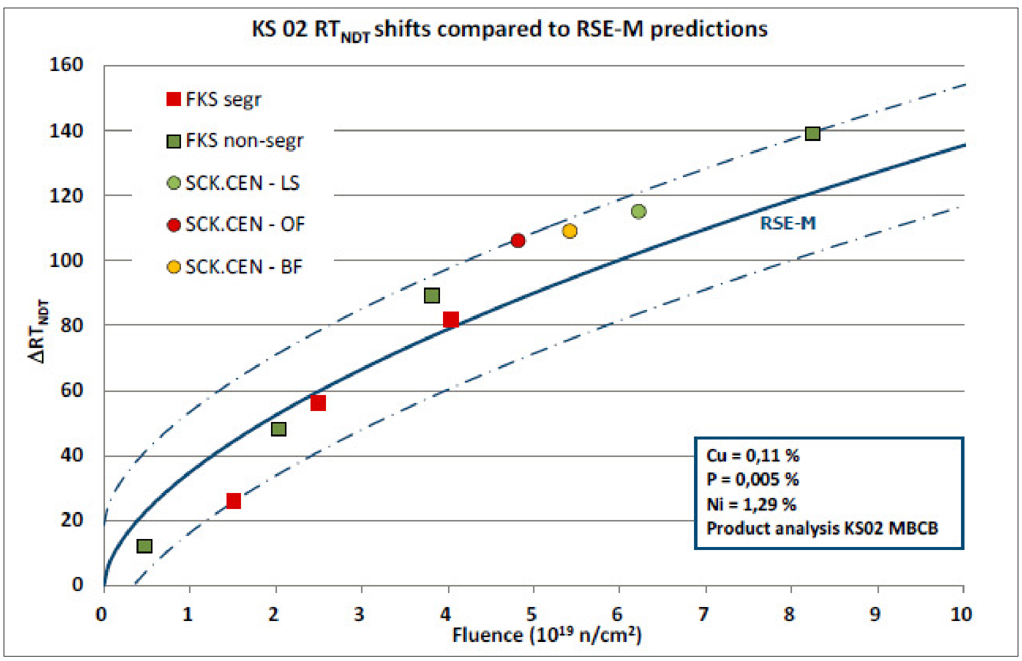

Figure 11: Shift in RT_{NDT} (ΔT=41J) versus fluence (LS = 'Less Segregated Zone', OF = 'out of flakes', BF = 'Between Flakes')

[2] The nickel content of KS02 is 1.29% and the limit of the RSE-M validity domain in Ni is 0.7%.

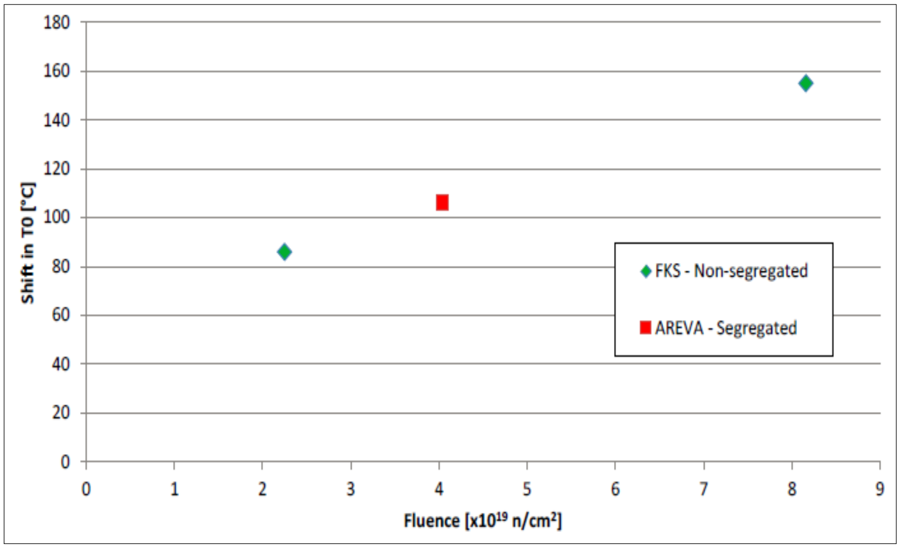

Figure 12: Shift in T_0 versus fluence for KS 02 B

For characterization of the KS 02 material, the SCP Review Team received the reports prepared by the Project Team for review.

The SCP Review Team had no questions or issues regarding the documentation provided by the Project Team and did not request any complementary information.

4.4.2.6 Transposability

One of the points studied for demonstrating the transposability of the VB395 under non-irradiated conditions on the Doel 3 and Tihange 2 RPV shells was "*to confirm the representativeness at local scale of the test materials VB395 and D3H1 in relation to the flaked Doel 3 and Tihange 2 RPVs*". This point was studied in the framework of 'Action 12: local properties'. The main objective of Action 12 was to "*identify the potential correlation between local material mechanical properties and local structural and chemical material characteristics (local microstructure, grain sizes, chemical composition of the ghost lines and on grain boundaries, fracture mode...)*".

The SCP Review Team followed discussions of the Project Team regarding this point and requested clarification about Laborelec's report dealing with the examination of the local material properties. This request challenged the statistics used by Laborelec and checked if the input data were not provided by the use of the MIS-B machine with a potentially inaccurate inspection procedure. The Project Team and Laborelec answered the SCP Review Team in order to clarify how the statistics presented in Laborelec's report were precisely carried out. They assured the SCP Review Team that the UT measurements were made using a phased array UT probe and should be considered as an inspection method that is commonly used in laboratory conditions. Therefore, criteria for the MIS-B qualification rejection threshold are not applicable in the present case.

On this basis, the SCP Review Team accepted the Laborelec deliverable dealing with Action 12.

The SCP Review Team required also the Project Team to provide additional elements to ensure that the VB395 material was representative for the Doel 3 and Tihange 2 RPV steels, in particular for its chemical composition and flake density.

The point dealing with the chemical composition comes from the fact that, as described above in the RSE-M prediction formula, the influence of phosphor has a major effect on the RT_{NDT} shift after irradiation. Hence, the chemical composition is a key parameter.

The Project Team answered that the chemical composition of the VB395 steel and the steel of the Doel 3 and Tihange 2 RPVs are quite similar and that the phosphorus content of the VB395 material is always lower than 0.08%. Hence, it does not change the outcome of the RSE-M prediction formula.
The Project Team excluded the chemical composition as a discriminating factor for the demonstration of the transposability but focused on the atypical embrittlement discovered. This atypical embrittlement of the VB395 material is not linked to the hydrogen flakes and is accordingly not transposable to the Doel 3 and Tihange 2 RPV steel.
The flake density of the VB395 material is of the same order of magnitude as that of the Doel 3 and Tihange 2 RPV steel. Regarding this point, the transposability is not threatened.
The Project Team prepared a complete argument for justifying the transposability and made a comparison between the mechanical and microstructural elements of the VB395 and the Doel 3 and Tihange 2 RPV steel.
Based on the Project Team's deliverables and the answer received, the SCP Review Team accepted the argument of the Project Team to justify the transposability.

4.4.2.7 Final selection of the material properties to be used for the Safety Case 2015

Table 13 shows the synthesis of the embrittlement properties of the materials tested. The VB395 shell acts as an outlier under irradiation, a fact that was consistently observed throughout the experiment campaign. It appears appropriate to use the value of the shift in RT_{NDT} provided by the tests on the VB395 material as an upper bound for the shift that the steel of Doel 3 and Tihange 2 RPV would undergo during irradiation. There is no technical basis for stating that the steel of the Doel 3 and Tihange 2 RPVs would react in any way worse than that of the VB395 regarding the embrittlement under irradiation in the flaked area.

Material	ΔRT_{NDT}	$\Delta T0$	Yield Stress Increase	Atypical embrittlement	Decrease of micro-cleavage fracture under stress
VB395 between flakes	>prediction	>prediction	OK	YES	YES
VB395 with flakes	>prediction	>prediction	OK	YES	YES
VB395 next to flakes	OK	>prediction	OK	YES	YES
VB395 far from flakes	OK	OK	OK	No	YES
D3H1 in segregation	OK	OK	OK	No	No
D3H1 out of segregation	OK	OK	OK	No	No
Doel 3 surveil. block	OK	OK	OK	No	No
KS 02 between flakes	OK	OK	OK	No	No
KS 02 out of flakes	OK	OK	OK	No	No
T2/D3 surveillance pg	OK	OK	OK	No	No

Table 13: Summary of the embrittlement behaviour of the different materials

Nevertheless, the Project Team concurred with "*the assumption that the Doel 3 and Tihange 2 RPV shells have an additional sensitivity to embrittlement under irradiation of the same magnitude as the VB395 material*". This extra shift has been used as input for the structural integrity assessment, providing a conservativeness that could not be quantified exactly (since we do not know the exact behaviour of the flaked areas in the Doel 3 and Tihange 2 RPV shells under irradiation).

The SCP Review Team considers that this transposability of the shift of the VB395 to the Doel 3 and Tihange 2 RPV shells is based on strong engineering judgment and consistent test results. As no univocal root cause of the VB395's unexpected behaviour has been identified, no formal demonstration of the transposability can be given.

Consequently, the behaviour of the final properties proposed by the Project Team for the Structural Integrity Assessment of the Doel 3 and Tihange 2 RPV shells has been accepted by the SCP Review Team as both a conservative and a state-of-the-art approach. In its advice, the SCP Review Team accepted the Project Team's deliverable covering this engineering judgment and giving the synthesis of the numerous tests done.

As mentioned in previous § 4.1.2 Analysis, the FANC issued in June 2015 a request to "*add a term to the initial RT_{NDT} to account for the potential lower fracture toughness of the material in the macro-segregated areas where the flakes are located* ".

This lead the Project Team to propose adapted embrittlement trend curves as described in § 5.5.2 of the Safety Case 2015. The proposed trend curves introduce, as requested, an additional term on the initial RT_{NDT} and adapt the margins for uncertainties taking into account the statement that the VB 395 is an outlier compared to similar steels.
These adapted trend curves are enveloped by the trend curves retained by the Project Team as input for the SIA. Therefore the SCP Review Team agrees with the position of the Project Team that the analysis performed with these inputs remain valid.

4.5 Structural Integrity Assessment

The SCP Review Team considers the approach that the Project Team developed for calculations and simulations to be a good theoretical development to demonstrate the RPV's structural integrity.

The SCP Review Team also considers that the results of the assessment of the crack driving forces as well as the conservativeness of the Structural Integrity Assessment provide enough confidence to cover the residual uncertainties.

4.5.1 Scope of the Review

The SCP Review Team closely examined the Structural Integrity Assessment (SIA) in particular with a focus on the following items:

- Updated grouping criteria used in the 2015 Safety Case (2D to 3D methodology)
- Determination of the acceptable flaw sizes
- ASME-III elastic-plastic analysis
- Assessment of the crack driving forces
- Conservativeness of the SIA

4.5.2 Analysis

4.5.2.1 The updated grouping criteria used in the Safety Case 2015

The setting up of the 3D methodology is based on a set of seven key assumptions, among which one may note that the flaw interaction between quasi-laminar elliptical flaws is calculated considering a uni-axial loading.

In order to challenge the Project Team's position, the SCP asked Sandia National Laboratory (SNL) to perform an independent review of this methodology. Sandia checked the consistency of the seven key assumptions and developed an alternate methodology to assess by its own the 3D methodology.

Sandia had some comments and remarks but none of them threatened the applicability of the 3D methodology. Finally, SNL concluded saying that: "*The good agreement between Tractebel Engineering's results and those of the alternate method provide independent verification of their methodology for determining regions of interaction between pairs of circular flaws.*"

SCP positioned itself vis-à-vis of the SNL comments and its own assessment in an advice. Complementary question regarding the boundary conditions for the 3D simulations for indications close to the cladding were communicated to the Project Team and properly answered.

In conclusion, the SCP admitted the use of the 3D methodology presented by the Project Team.

4.5.2.2 The determination of the acceptable flaw sizes

The methodology used by the Project Team can be summarized as follows:

- Introduction of the notion of stress intensity factor (independent of the material properties)
- Introduction of the notion of crack arrest/crack initiation toughness (depending on the material properties)

- Load cases: screening of the transients to find the most penalizing transients as a function of the ligament "S" in the base metal
- Definition of the acceptance criteria, according to ASME code
- Results of the calculations

The SCP Review Team has reviewed the methodology used by the Project Team to determine the admissible flaw sizes. An ASME Life Fellow of the SCP performed a check on the Project Team's deliverables without comments but with a suggestion to provide more description for the elastic-plastic behaviour.

Be reminded that the crack driving force is the stress intensity factor K, expressed in $\mathrm{MPA}\sqrt{\mathrm{m}}$. This stress intensity factor depends upon the geometry of the flaw but not on the properties of the material.

The initial requirement is the determination of the stress distribution. This distribution is calculated either by linear elastic theory or by elastic-plastic theory according to the yield limit (and so to the deepness of the considered indication inside the material).

With the stress distribution in hand, it is possible to calculate the equivalent stress intensity factor K_{eq}. In the framework of the review by SNL regarding the consistency of the seven key assumptions for the 3D methodology (see above) SNL retained its opinion that for mixed-mode loading the equation utilized by Tractebel Engineering may produce an equivalent stress intensity factor that is non-conservative for certain specific configurations (as already mentioned in their analysis of the original Safety Case in 2012). Based on clarifications, the SCP could conclude that SNL's statement is general. Indeed some non-conservative cases may occur, but in the configuration of the flaws of Doel 3 and Tihange 2 this would not happen.

Consequently, the SCP Review Team accepted the Project Team's methodology and calculation using this K_{eq} equivalent stress intensity factor.

4.5.2.3 The ASME-III elastic-plastic analysis

When a component is designed to become a part of a reactor pressure vessel, it must comply with the rules described in the ASME code, part III. The criteria expressed in this part of the code aim at ensuring that the component under pressure will not collapse under an excess of primary stress load. The criteria cover failure modes like excessive plastic deformation, plastic instability leading to incremental collapse, fatigue, etc.

Due to the presence of flakes in the Doel 3 and Tihange 2 RPVs, assurance was needed to ensure that the reduction of surface due to the presences of those voids could not threaten the original ASME III demonstration carried out at the time of the licensing of the units.

The SCP Review Team expressed its acceptance regarding the methodology developed by Tractebel Engineering since the final results of calculations were in line with ASME III requirements and as the assumptions taken (use of RSE-M code for part when the data were not available in the ASME) were consistent and robust.

4.5.2.4 Assessment of the crack driving forces

Methodology of the assessment

This part of the calculation chapter is very important because it deals with the assessment of the crack driving forces in the Doel 3 and Tihange 2 RPVs made by the Project Team in order to address the following requirement of FANC:

> *"Provide an assessment of the severity of the upgraded degraded condition of the Doel 3 and Tihange 2 RPVs by comparison to the condition assumed in the 2012 Safety Cases (estimation of the distribution of the driving force $K_{applied}$)"*

This part will make the link between the calculation of the stresses in the material (dependant of the transient considered and of the local stress distribution due to the flakes) and the material properties (dependant of T, RT_{NDT}, etc.).

In the study performed by the Project Team, 16 flaws are considered for Doel 3 (orange triangles on figures 16 and 17). They are spaced all along the RPV wall. The selected transients are the most penalizing ones. The criteria used to determine the most penalizing configuration of flaw is complex as it has to mix several consideration such as the Δ inclination angle of the flaw, its projection on the Z axis (radial dimension in the core vessel), its size (in term of 2a dimension), etc.

Then the considered flaws are modelled and adequate boundary conditions are imposed upon the model (pressure on the inner wall of the RPV wall). Finally, XFEM 3D calculations are performed to determine stress distribution in the material. Linear elastic theory is used (using equivalent K_{eq}) for flaws far from the cladding while elastic-plastic calculations (with J-integral) are employed for the flakes close to the cladding.

Then the influence of the material is taken into consideration via the fracture toughness curve K_{IR} (depending of both T and RT_{NDT}). As explained in the Safety Case :

> *"The fracture toughness K_{IR} is a function of temperature T and RT_{NDT} . For temperatures lower than the RT_{NDT}, the K_{IR} curve tends to a lower shelf (see figure 14 here after). Therefore, when the crack driving force K of a flaw is lower than the toughness lower shelf, no crack initiation is expected to occur regardless of T and RT_{NDT} values".*

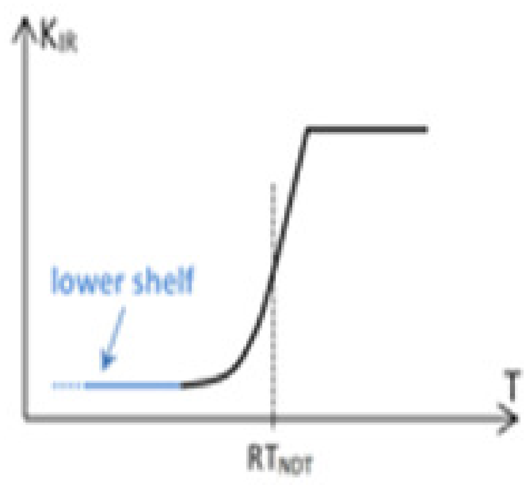

Figure 14: Fracture toughness lower shelf

Be reminded that safety factors are taken into consideration when adapting the value of the fracture toughness in a conservative manner. Those safety factors are dependent upon the transients considered (level A/B transients concern heat up/cool down and level C/D transients concern incidents like in case of small break LOCA).

One way to determine the margin on the RT_{NDT} is to shift the curve of the crack driving force to find its intersection (if any) with the fracture toughness (divided by the safety factor) curve. The value of the shift gives the RT_{NDT} margin. This is illustrated at the Figure 15.

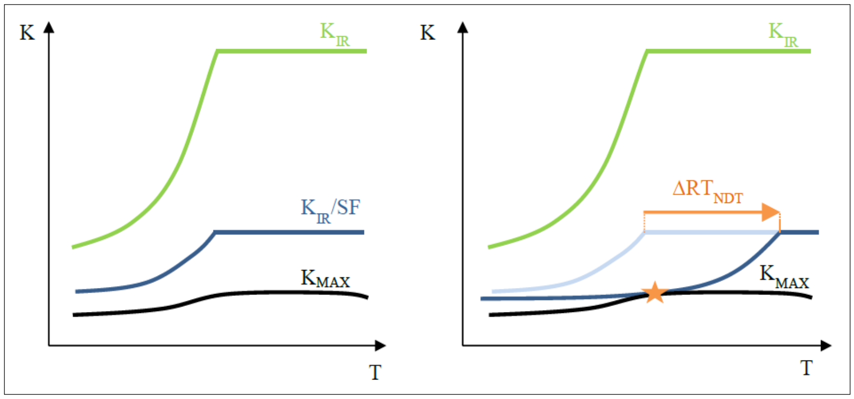

Figure 15: Determination of the RT_{NDT} margin

The results of the studies for the several criteria considered are numerous and differ from Doel 3 and Tihange 2.

Summary of Doel 3 results

As can be seen in Figure 16 and Figure 17, the results of the calculations to select most penalizing criterion (in this case the flaw with the highest radial projection Δz) give values which are always lower than the lower shelf. Nevertheless, some points slightly exceed the value of the lower shelf divided by the selected safety factor. For those configurations, the margin on the RT_{NDT}, assuming the temperature dependence of K_{Max} and K_{IC}, is 80 °C or more.

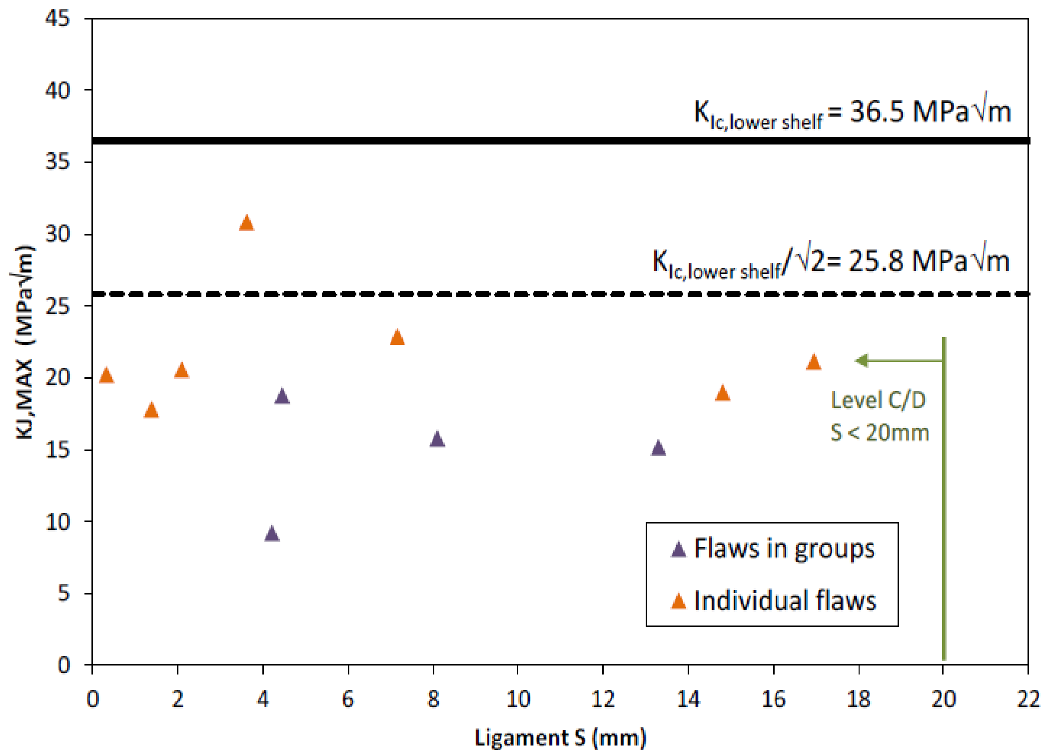

Figure 16: $K_{J,max}$ values compared to lower shelf toughness for flaws close to the cladding-base metal interface

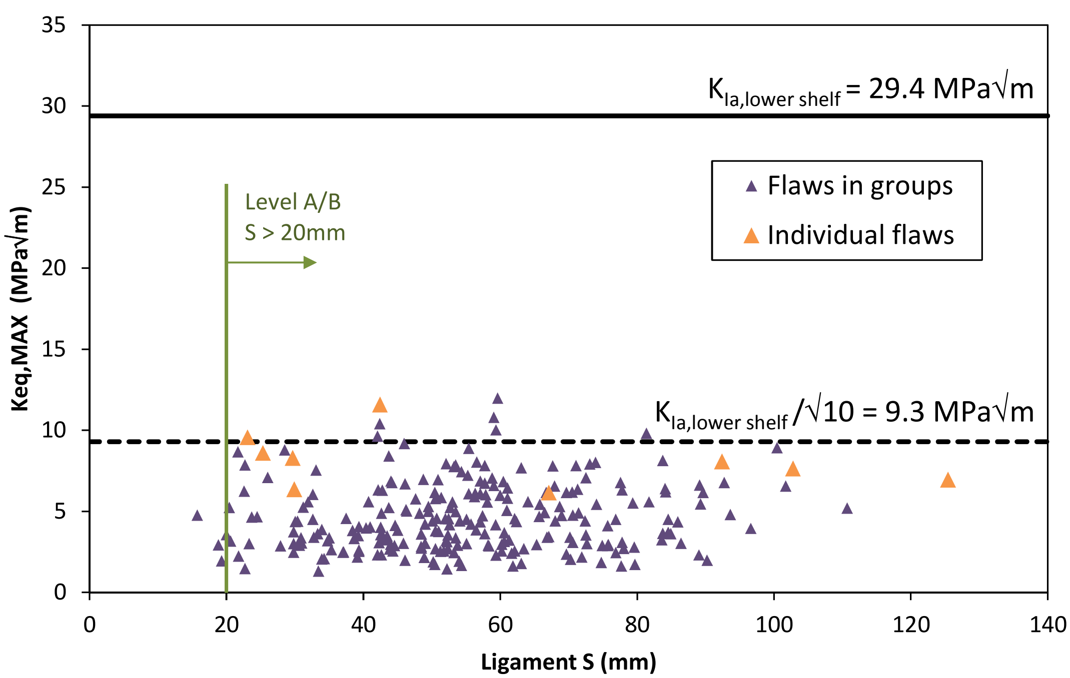

Figure 17: $K_{eq,max}$ values compared to lower shelf toughness for flaws far to the cladding-base metal interface

Conclusion of the assessment of the crack driving forces

In conclusion, the assessment of the crack driving forces show that, most of the time, the crack driving force is below of the lower shelf divided by the safety factor of the fracture toughness. In some rare cases (9 for Doel 3), the value of the lower shelf divided by the safety factor is slightly overtaken but in those cases strong margin in term of RT_{NDT} are still present (min 80 °C for Doel 3). The SCP Review Team considers that this is completely acceptable in term of safety approach assuming that it corresponds to the most penalizing flaws and the most penalizing transients.

4.5.2.5 Conservativeness of the SIA

The Safety Case relies indeed on some assumptions. In order to challenge the robustness of the structural integrity assessment, it was decided to perform a study on the conservativeness provided in the calculation/structural integrity assessment. It is important to note that the scope only focuses on the margin of the sole structural integrity assessment. So, other types of conservativeness may also exist.

The assessment was performed using several studies. Twenty-two types of conservativeness have been identified. The types of conservativeness deal with three families of topics:

- The UT inspection technique serving as an input for the calculations
- The load transients (acting as the load cases to take into consideration for the determination of the stresses imposed to the material)
- The ASME XI compliancy
    - Flaw acceptability analysis
    - Fatigue crack growth analysis
    - ASME III primary stress reassessment

Regarding the UT inspection techniques, the conservativeness concerns the general oversizing, demonstrated through destructive tests, which becomes higher for the smaller flakes. When a flake is smaller than the focal of the UT beam, this last is considered as the flake size. This oversizing reduces in some cases the possibility of detecting sound metal between two indications (namely when the measured ligament tends to zero). Only one larger indication is reported, which replaces sound material by void, which overly penalizes the calculation.

Concerning the load transients, several types of conservativeness are linked to the hypotheses (water injection flow rate, pressure and temperature, etc.), making the transients more severe than the potential ones. These hypotheses have an impact on the calculated maximum crack driving forces, which are overestimated.

Concerning the ASME XI compliancy, the larger conservativeness is linked to the grouping criteria as illustrated by the refined analyses performed on grouped flaws of the Doel 3 and Tihange 2 RPVs. Figure 18 shows that the conservativeness expressed in terms of the ratio flaw size to acceptable flaw size ($2a/2a_{acc}$) are very important. Indeed, this ratio calculated for a group of flaws is divided by a factor 6 to 54 (in the case of Doel 3) for each of the grouped flaws when the refined analysis of this group is performed.

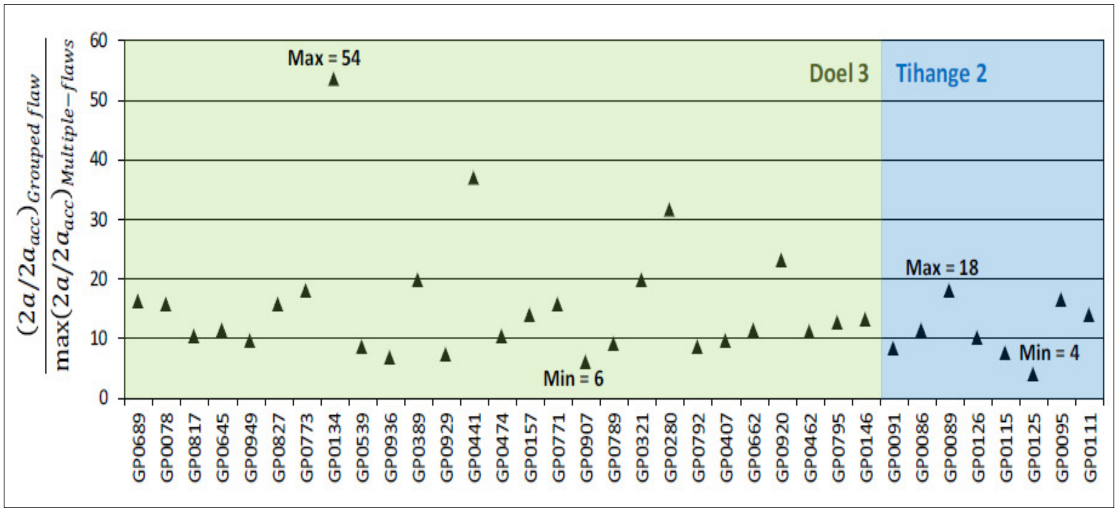

Figure 18: Impact on the refined analysis for the Doel 3 and Tihange 2 RPVs

The SCP Review Team participated in the Project Team's review committee related to the deliverable that summarizes the studies on the twenty-two types of conservativeness. Several SCP Review Team comments were discussed directly and taken into consideration.

Finally, the SCP Review Team accepted the study of the Project Team regarding the conservativeness of the Structural Integrity Assessment.

4.6 Sensitivity Studies

Sensitivity studies have been performed on three of the roadmap's key elements. They have demonstrated the robustness of the approach applied in the 2015 Safety Case 2015.

The SCP Review Team is confident that the margins and conservativeness in the 2015 Safety Case are high enough to cover the residual uncertainties. This confidence is primarily based on the sensitivity studies (performed by the Project Team to demonstrate the robustness of the applied approach), as well as the results of the assessment of the crack driving forces.

The SCP Review Team analysed the three sensitivity studies performed by the Project Team to assess the robustness of the 2015 Safety Case:

- Consideration of an alternative DZ sizing procedure for the indications (UT inspection)
- Impact of the KS 02-based RT_{NDT} curve on the margins of the SIA (Material properties)
- SIA analysis with 2012 methodology but 2014 cartography (SIA)

The SCP Review Team agrees with the conclusions given in the 2015 Safety Case Report regarding each sensitivity study.

Concerning the potential impact of an alternative DZ sizing procedure as discussed on previous § 4.3.2.5, a sensitivity study for the SIA was performed for all indications larger than 20 mm. in the DX or DY dimension, based on the 'alternative' DZ values.
As far as the results of the SIA in terms of $2a/2a_{acc}$ values (ratio flaw size to acceptable flaw size) are very similar to the ones based on the original DZ values, the SCP Review Team agrees with the Project Team's conclusions that "*the structural integrity of the core shells of Doel 3 and Tihange 2 is thus not impacted by the variation of the Z coordinates of indications bigger than 20 mm".* Hence, the SCP Review Team considers that the original "6db drop" sizing methodology can be maintained for Z coordinates.

Concerning the impact of the KS 02-based RT_{NDT} curve, the sensitivity study confirms that the original Safety Case assumption for the shift in RT_{NDT} (curve of Safety Case 2012 close to the KS 02-based RT_{NDT} curve) is more conservative than the VB395-based RT_{NDT} curve for most of the flakes (at low and medium fluence). Nevertheless the margins in RT_{NDT} based on the crack driving forces (as explained in Chapter 4.5.2) are almost not affected.

Concerning the SIA analysis with 2012 methodology and input parameters but applied with the 2014 cartography, the SCP Review Team underlines the fact that the structural integrity is still demonstrated for a SI water temperature of 7 °C. Thus, in addition to the demonstration that structural integrity has always been guaranteed, the modification aiming to bring this temperature at more than 40 °C for Doel 3 introduces a large margin for the flakes close to the inner surface of the vessel.

In addition to these sensitivity studies, the SCP Review Team considers the results of the assessment of the crack driving forces as the most important factor contributing to the SCP Review Team's confidence that the margins and conservativeness in the 2015 Safety Case are high enough to cover the residual uncertainties.

5 Abbreviations

Abbreviation	Meaning
AIA	Authorized Inspection Agency
ASME	American Society of Mechanical Engineers
BEST	Belgian Stress Tests
CARE NS	CARE Nuclear Safety Department of Doel/Tihange site Organization
D3H1	Doel 3 nozzle shell cut-out H1
DDH	Défaut Dû à l'Hydrogène
DOE	United States Department Of Energy
DSR	Défaut Sous Revêtement
DTR	Défaut Technique de Revêtement
EAR	Examen d'Accrochage du Revêtement (specific straight beam transducer)
ECNSD	Electrabel Corporate Nuclear Safety Department
FANC	(Belgian) Federal Agency on Nuclear Control
FIS	Fragilisation sous Irradiation Supérieure
IRB	International Review Board
LEFM	Linear Elastic Fracture Mechanics
LOCA	Loss of Coolant Accident
MER	Mesure d'Epaisseur du Revêtement (ultrasonic transducer)
MIS-B	Machine d'Inspection en Service Belge
Ppm	Parts per million
PTS	Pressurized Thermal Shock
RDM/RN	Rotterdamsche Droogdok Maatschappij/Rotterdam Nuclear
RF	Radio Frequency
RG	Regulatory Guide
RHRS	Residual Heat Removal System
RPV	Reactor Pressure Vessel
RSE-M	Règles de Surveillance en Exploitation des Matériels Mécaniques
RWST	Refuelling Water Storage Tank
RT_{NDT}	Reference Temperature for Nil Ductility Transition
SC	Steering Committee
SCK•CEN	StudieCentrum voor Kernenergie-Centre d'Etude de l'énergie Nucléaire
SCP	Service de Contrôle Physique of Electrabel
SI	Safety Injection
SIA	Safety Integrity Assessment
SNL	Sandia National Laboratories
TWCF	Through-Wall Cracking Frequency
UT	Ultrasonic Testing
XFEM	Extended Finite Element Modelling

Electrabel