

**REPORT ON INDEPENDENT  
ANALYSIS AND ADVICE  
REGARDING THE SAFETY CASE  
ADDENDUM**

**FINAL VERSION**

**Doel 3**  
**Reactor Pressure Vessel  
Assessment**

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# 1 Executive Summary and Advice

In the summer of 2012, Electrabel found indications in the reactor pressure vessel (RPV) of the Doel 3 Nuclear Power Plant (NPP). It was decided to keep the Doel 3 reactor in cold shutdown, core unloaded, until it could be demonstrated that the identified indications did not jeopardize the structural integrity of the RPV during normal operation, as well as during transient or accident conditions.

The results of the investigations were synthesised in a comprehensive Safety Case Report, and submitted to the Federal Agency for Nuclear Control (FANC) on 5 December 2012, complemented by a Report on Independent Analysis and Advice on 19 December 2012.

On 30 January 2013, the FANC provided Electrabel with a Provisional Evaluation Report stating that there is no need for a definitive shutdown of the units, but that some open issues remain to be addressed before being able to restart the reactors. In response, Electrabel put together an Action Plan.

On 26 April 2013, Electrabel provided the FANC with a Safety Case Report Addendum for the Doel 3 RPV, answering each requirement of the FANC. In this addendum, license holder Electrabel (the Project Team) demonstrated that the indications in the Doel 3 RPV do not jeopardize the structural integrity of the equipment during normal operation, as well as during transient or accident conditions.

Electrabel's Service de Contrôle Physique (the SCP Review Team) performed a thorough review of the project deliverables. This review was conducted in collaboration with internal and external experts, including academics from British universities. The results of this evaluation are summarized in this Report on Independent Analysis and Advice Regarding the Safety Case Report Addendum.

The review and analyses have led the SCP Review Team to give an overall positive advice regarding the immediate and safe restart of the Doel 3 NPP. This advice is based on the Project Team's satisfactory consideration of all comments concerning the project deliverables and the final review of the Project Team's Safety Case Report.

## 1.1 Review of the Project Deliverables

The Project Team built an Action Plan to answer the requirements of the FANC as stated in the Provisional Evaluation Report of 30 January 2013. The present document summarizes the evaluation, analyses, and assessments of the SCP Review Team regarding the deliverable that the Project Team produced in the framework of this Action Plan.

The major topics assessed are:

- The accuracy of the UT inspections, specifically the accuracy of the applied method, as well as the determination of a boundary curve to encompass the potential for unreported flaws.
- A sensitivity study based on this boundary curve, to ensure that even if some indications were potentially not reported, their effect would be negligible.
- The small-scale test program regarding the local characterization of mechanical properties inside the ligaments between flakes and the characterization of ghost lines.
- The large-scale test program, i.e. the test performed to assess the global behaviour of the material affected with flakes.
- The hydrogen content left in the material, to ensure that no adverse effect is to be expected due to the residual presence (if any) of hydrogen in the RPV's base metal.
- The assessment of non-inspectable areas.
- The assessment of the load test followed by UT inspections of the RPV.
- Other points with a lower impact on the studies.

The SCP Review Team took a similar approach as the one used in its analysis of the 2012 Doel 3 RPV Safety Case. However, its review was limited to two steps:

- **Follow-up of the development of the safety cases** in order to gain a deeper understanding of the subject: members of the SCP Review Team played an interactive role as participating reviewers and challenging parties of the analyses performed and the decisions taken by the Project Team.
- **Independent analysis of the project deliverables:** ultrasonic examinations, RPV manufacturing documentation, mechanical tests, metallurgical origin of the indications, calculations of the structural integrity (deterministic and probabilistic), safety framework, et cetera. British academics contributed to the analysis of some of these deliverables.

# 2 Ultrasonic Inspection

## 2.1 Inspection Results

### 2.1.1 Flaw distribution statistics

#### Requirement

During the discussion of the Safety Case Report, the need was expressed for a better understanding of how the flaws are distributed in the RPV shells.

#### Steps taken

The Project Team has reprocessed the collected data. It presented the results, including flaw density, distance between flaws, potential correlation with fluence distribution, and trends between the inclination and position of flaws.

#### Conclusion of the Project Team

During the 2012 UT inspection, precise and complete data about each individual flaw's position and dimensions were collected. In order to provide a good understanding of the flaw distribution, the data have been processed in different ways. The conclusion is that the Project Team believes that the FANC's requirements are met by the additional elements given.

#### Review by the SCP

As explained in the previous Report on Independent Analysis and Advice Regarding the Safety Case, Sandia National Laboratories (SNL) performed their own evaluation of flaw density in order to investigate the role of flaw configuration and spacing on fracture criticality, as well as to identify the more penalizing flaw configurations for the three dimensional finite element analyses they made. In order to ensure a conservative evaluation, the upper bound configuration used by SNL considered a flaw diameter of 25 mm, a density of 35 flaws/litre, and an out-of-laminar flaw angle of 20°, which largely covers the described flaw distribution statistics.

#### Conclusion of the SCP

The SCP Review Team has no residual comment regarding this valuable complementary information of the Project Team.

### 2.1.2 Cladding and Internal Surface of Forgings

#### Requirement

During the discussion of the Safety Case Report, the question was raised as to whether or not the cladding affects the Safety Case and whether or not it is sound.

#### Conclusion of the Project Team

The cladding was not taken into consideration in the Structural Integrity Assessment, in conformance to the ASME code. Periodic in-service inspections confirm that the cladding is sound.

#### Conclusion of the SCP

The SCP Review Team has no further comment on this complementary information in the Safety Case Report Addendum.

## 2.1.3 Non-Inspectable Areas

### Requirement

The FANC asked the Project Team to determine the zones where the UT examination could potentially have been inaccurate or inefficient due to physical constraints, and to demonstrate that no critical hydrogen flakes are expected in the non-inspectable areas.

### Steps taken

The geometry of the Doel 3 RPV is slightly different from the circular, cylindrical form that it has elsewhere at four locations on its inner surface. This has an effect on the capability of the UT inspection technique to detect flaws in four specific areas. The Project Team compared the location of the observed flaws with the location of the non-inspectable areas. For Doel 3, no flaws were detected in three of the four areas: near the RPV flange diameter step, the flange tapered transition, and the nozzle shell tapered transition.

It cannot be excluded that some indications are present in the fourth area, corresponding to the four brackets that support the lower internal structure. However, the presence of the brackets could be seen as beneficial as they protect the base metal from neutron interaction (reduction of the exposure to the fluence) and they add a thermal resistance that will reduce the thermal gradient in the metal of the core. In addition, the brackets were welded onto the shell before RPV heat treatment. So, no residual stress needs to be taken into consideration.

### Conclusion of the Project Team

The capability of the UT inspection technique is to some extent affected by the geometrical features of specific areas of the RPV inner surface. The Doel 3 RPV has four of these areas on its inner surface. Near three of these areas, no clusters of flaws are detected. Therefore, no hydrogen flakes are expected there. In the fourth area—behind the brackets—the presence of flakes cannot be excluded. However, the brackets would protect potentially hidden flakes in terms of stress and toughness. Hence, such potentially hidden flakes are not considered to be critical.

### Conclusion of the SCP

The SCP Review Team accepts the argument of the Project Team. Since no clusters of flaws were detected near three of the non-inspectable areas and since the brackets in the fourth area introduce a protection in terms of stress and toughness, no harmful flaw is expected to be present inside the non-inspectable areas.

## 2.1.4 Potentially Unreported Higher Tilted Flaws

### Requirement

The FANC asked for assurance that the applied UT technique demonstrates the detection of higher tilted defects in the Doel 3/Tihange 2 data (2012 inspections) with a high level of confidence.

### Steps taken

The Project Team thereupon:

- Ordered additional UT and destructive examinations on higher tilted flaws.
- Evaluated the UT inspection sensitivity.
- Carried out a UT sensitivity study.

### Conclusion of the Project Team

Additional examinations on higher tilted flaws confirm that the 2012 straight beam UT inspections correctly detected and sized all hydrogen flakes in the VB395/1 block. Flaws with an inclination up to 20°, which would potentially not have been reported, have been determined as a function of the position in the RPV wall. These potential flaws are considered in the Structural Integrity Assessment (SIA).

### Review by the SCP

The SCP Review Team has followed each step of the following examinations and studies.

- **Additional examinations on higher tilted flaws**

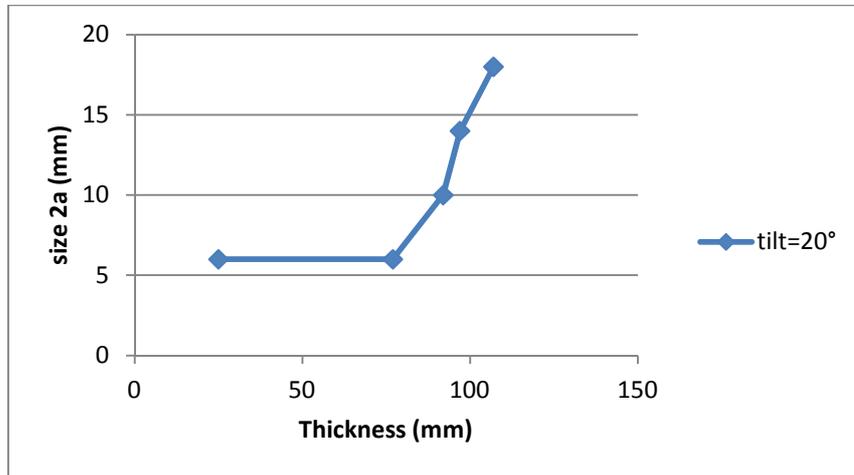
The Project Team re-analyzed the results of the UT inspections on the AREVA VB395/1 block. Several destructive examinations on higher tilted flaws showed a strong correspondence between the data from the UT characterization and the physical observations. This good correlation confirms that the 2012 UT inspections correctly detected and sized this kind of flaw.

- **Experimental evaluation of the inspection sensitivity**

The reference reflectors used in the analysis of the AREVA VB395/1 block and the RPVs had a different sensitivity level. Applying the same inspection sensitivity to the VB395/1 block demonstrates that all indications are adequately detected, sized, and reported using the 2012 UT-reporting threshold.

- **UT sensitivity study as input for the Structural Integrity Assessment**

The Safety Authorities requested the performance of a sensitivity study of mechanical integrity. An envelope curve for the size of a potentially unreported flaw was determined in order to obtain a realistic basis to add potentially unreported flaws. Based on that input, the Project Team simulated various flaw configurations (orientation, size, tilt). The curve below represents the maximum size of a potentially unreported flaw with a conservative 20° tilt. This is the main input for the sensitivity analyses (see Chapter 5.3).



**Figure 2.1: Size of the largest flaws with 20° inclination potentially not reported by UT inspection**

**Conclusion of the SCP**

The SCP Review Team endorses the conclusion of the Project Team that the 2012 straight beam UT inspections correctly detected and sized all hydrogen flakes in the VB395/1 block.

## 2.2 Ultrasonic Testing Validation (UT Validation)

### 2.2.1 Indications with 45° T Shear Wave Response

#### Requirement

The FANC asked the Project Team to present the detailed report of all macro-graphical examinations including the sample with the 45° T reflections and to analyze and report additional samples with 45° T reflectivity.

#### Steps taken

The Project Team carried out UT Tests with a 45° T probe followed by macro-graphical examination of samples from the AREVA VB395/1 block.

#### Conclusion of the Project Team

During the 2012 in-service inspection of the RPVs, a number of very weak 45° T shear wave UT responses were observed. The macro-graphical examination of three samples of block VB395/1 showed that there is no correlation between the 45° T UT responses and any radial or volumetric component.

#### Review by the SCP

The macro-graphical examination of three samples indicated that the low amplitude signals recorded at 45° T were not linked to any radial or volumetric component.

#### Conclusion of the SCP

The SCP Review Team endorses the conclusion of the Project Team that there is no correlation between the 45° T UT responses and any radial or volumetric component.

## 2.2.2 Partially Hidden Indications

### Requirement

The FANC asked that the set of defects partially hidden by other defects was examined, including macro-graphical examination, to confirm that the sizing method continues to function well.

### Steps taken

The Project Team performed straight beam UT on samples extracted from the AREVA VB395/1 block. The UT results were then compared with the results of destructive tests.

### Conclusion of the Project Team

Two samples with multiple hydrogen flakes were taken from block VB395/1 and examined. The dimensions resulting from their ultrasonic examination were compared with the results of their destructive examination. The comparison confirms the capability of straight beam UT to correctly detect and size hydrogen flakes that are partially hidden by others.

### Review by the SCP

The investigation of the Project Team confirmed that no partially hidden flaw was wrongly characterized. The SCP reviewed and accepted the approach used by the Project Team, as well as its straightforward methodology, measurement campaign, and the results obtained.

### Conclusion of the SCP

The SCP Review Team concurs that the Project Team demonstrated that straight beam UT correctly detects and sizes hydrogen flaws that are partially hidden by others.

## 2.2.3 Inclination of Flaws Detected by Ultrasonic Testing

### Requirement

The FANC noted that the 2012 onsite in-service inspection and the UT validation on the AREVA VB395/1 block were carried out using different UT inspection methods. The Project Team was therefore asked to re-analyze the tilts of the defects in the AREVA block with the same method as applied on site.

### Steps taken

The Project Team re-analyzed the AREVA VB395/1 block with the straight beam method. The results confirmed those obtained with the phased array method. Moreover, the results were corroborated by destructive tests carried out on the AREVA VB395/1 block.

### Conclusion of the Project Team

During the 2012 in-service inspection, UT was performed using a straight ultrasonic beam. The results contained a number of indications with tilts that were evaluated based on the straight beam information. Regarding the UT validation, the tilts of the indications in block VB395/1 were determined using a phased array inspection.

The tilts of the flaws in block VB395/1 were re-evaluated using the same straight beam UT method as applied on site. The results confirm a very good correlation between both methods.

### Review by the SCP

The SCP reviewed the results of the re-analysis carried out by the Project Team. The SCP Review Team agrees that the results indicate a very good correlation between both methods. The analyses did not modify the measured angle results.

### Conclusion of the SCP

The SCP Review Team endorses the conclusion of the Project Team that the straight beam and the phased array UT methods give similar results regarding flaw inclination.

# 3 Origin and Evolution of the Indications

## 3.1 Link between Manufacturing and Flake Occurrence

### Requirement

During the discussion of the Safety Case Report, it was noted that the root cause analysis did not explain why the hydrogen-induced degradation did not evenly affect all forged components of the Doel 3 and Tihange 2 RPVs, though their hydrogen content is comparable.

### Steps taken

The Project Team performed a literature review. This revealed the factors that are necessary for the creation of hydrogen flakes. The Project Team then correlated the presence of indications with those factors.

### Conclusion of the Project Team

Based on an analysis of the ingot size and the combined sulphur and hydrogen content, the forgings were ranked according to their susceptibility to hydrogen flaking. This revealed a good correlation with the amount of flakes found in each forged component.

### Review by the SCP

The previous Report on Independent Analysis and Advice Regarding the Safety Case mentioned the potential impact that the combined sulphur and hydrogen content could have on the susceptibility of a forging to hydrogen flaking. This is confirmed by the deeper analysis presented in the Safety Case Report Addendum, which takes into account the ingot size. It explains the fact that the hydrogen-induced degradation did not evenly affect all the forged components of the Doel 3 RPV, although their hydrogen content is comparable.

### Conclusion of the SCP

The SCP Review Team endorses the qualitative demonstration by the Project Team of the different amounts of hydrogen flakes in the forgings.

## 3.2 Phenomenology of Hydrogen Flaking

### Requirement

In the Safety Case Report, the flaking mechanism, its influencing factors, and root cause analysis were described based on the literature. The Project Team was asked to conduct additional investigations to confirm this.

### Steps taken

Tests were carried out on samples of the VB395/1 block, investigating several aspects including the flake position, size, inclination, morphology, and their position with respect to the macro-segregation in the material, among others.

In addition, a carbon mapping of the VB395/62 block was made.

### Conclusion of the Project Team

As mentioned in the Safety Case Report, the literature shows that the indications in the RPV shell could be associated with a zone of macro-segregations, originating from the fabrication process. This was confirmed by new tests on reference block VB395/1.

Moreover, the flaws are situated in very specific locations: the so-called ghost lines, which correspond to the residual features of the ingot after forging. In addition, the representativeness of the reference block VB395/1 and the flaking mechanism have been confirmed. Bridging was found to occur only between flakes that are very close to each other, under circumstances that exclusively exist during manufacturing.

### Review by the SCP

In its previous Report on Independent Analysis and Advice Regarding the Safety Case the SCP Review Team already mentioned the importance of analyzing the material properties of the Doel 3 RPV H1 nozzle shell cut-out in the segregated zones. The SCP Review Team asked for additional tests in the ghost lines to confirm the limited impact of the different mechanical characteristics in the ligaments inside these ghost lines with respect to sound material.

### Conclusion of the SCP

The SCP Review Team endorses that the investigations carried out by the Project Team on the AREVA VB395 shell and reported in the Safety Case Report Addendum confirm the importance of ghost lines with regard to hydrogen flaking. The tests performed by SCK•CEN also revealed a limited impact on the properties of the material between flakes versus that of zones without flakes (see Chapter 4). The micro-fractographic examinations confirm that the material between two flakes is sound.

## 3.3 Residual Hydrogen

### Requirement

The FANC asked that additional measurements be taken of the current residual hydrogen content in specimens with hydrogen flakes, to confirm the results of the limited number of tests achieved so far, and to determine whether the hydrogen that caused the hydrogen flakes could potentially form new flakes.

### Steps taken

The Project Team compared samples of the AREVA VB395/1 block with the Doel 3 RPV H1 nozzle shell base metal. Both types of samples were heated and the hydrogen content was measured. The level of hydrogen in each sample was similar.

The amount of hydrogen present inside flakes has been investigated using hot extraction. This confirmed that there is no significant amount of hydrogen present inside flakes.

### Conclusion of the Project Team

Additional tests confirm that there is no significant amount of residual hydrogen present inside the metal, nor in the flakes. Therefore, the material properties are unaffected.

### Review by the SCP

The SCP reviewed the process and challenged the statistical representativeness of the tests performed, especially with regard to the test material and the effect of irradiation. Tests indicated that hydrogen is not released easily during the heating process, so it cannot be put in motion easily inside the metal.

### Conclusion of the SCP

Based on the available results and provided answers, the SCP Review Team agrees with the results and conclusion of the Project Team that no adverse effect of original hydrogen on material properties is to be expected.

## 3.4 Representativeness of the AREVA Shell with regard to RPV Flaking

### Steps taken

The investigations conducted by the Project Team on both the Doel 3 RPV H1 nozzle shell cut-out and the AREVA VB395 shell demonstrate the good correlation between the micro-structural and chemical characteristics of both materials.

### Conclusion of the Project Team

The representativeness of the AREVA shell VB395 regarding hydrogen flaking has been confirmed. Therefore, the findings and conclusions of the tests on the AREVA shell can be transferred to the RPVs.

### Review by the SCP

In its previous Report on Independent Analysis and Advice Regarding the Safety Case the SCP Review Team mentioned the strong correlation—identified by SNL on UT inspection data—between the radio frequency signals from the Doel 3 RPV H1 nozzle shell cut-out and the AREVA VB395 shell.

In addition, the average density and size of flaws inside the VB395 shell are larger than the actual ones present in both RPVs. Hence, the representativeness of the VB 395 is granted.

### Conclusion of the SCP

The SCP Review Team endorses the statement made by the Project Team that hydrogen flaking in the AREVA shell is representative for the flaking in both RPVs.

# 4 Material Properties

## 4.1 Effect of Ghost Lines on Mechanical Properties

### Requirement

The Project Team was asked to further investigate experimentally the local (micro-scale) material properties of specimens with ghost lines and hydrogen flakes (for example, local chemical composition). Depending on these results, the effect of composition on the local mechanical properties (i.e. fracture toughness) shall be quantified.

### Steps taken

The following tests have been performed on specimens taken from the Doel 3 RPV H1 nozzle cut-out in order to assess the local properties in the zones containing ghost lines:

- Charpy tests
- Fracture toughness tests
- Tensile tests

The tests were followed by microscopic examinations on the destroyed samples.

### Conclusion of the Project Team

Two sets of three tensile tests were performed. The tests confirmed the expected behaviour of the material in terms of elongation. The twelve Charpy and eighteen fracture toughness tests performed on specimens from the Doel 3 H1 nozzle cut-out show that the ghost lines have no significant effect on the Charpy impact or fracture toughness properties.

### Review by the SCP

The conclusion of the Project Team is in contrast with French literature on the subject. However, the tests were performed on the metal of the H1 nozzle shell cut-out of the Doel 3 RPV. Therefore, the material is representative and the results, regarding the un-flaked ghost lines, can be transferred to the RPV.

### Conclusion of the SCP

The SCP Review Team endorses the conclusion of the Project Team that the ghost lines have no significant effect on the Charpy impact or fracture toughness properties compared with RPV material that was not subjected to irradiation.

## 4.2 Effect of Hydrogen Flakes on Material Properties

### Requirement

The Project Team was asked to complete the material testing program using samples with macro-segregations containing hydrogen flakes. This experimental program needed to include:

- Small-scale specimen tests:
  - Local toughness tests taking an hydrogen flake at the crack tip instead of a pre-fatigue crack.
  - Local tensile tests on ligament material near the flakes.
- Large-scale (tensile) specimen tests (see Chapter 5.5).

### Steps taken

In the ligaments between the zones affected by hydrogen flakes, the following tests were carried out on the only flaked material available (the AREVA VB395 block):

- Four tensile tests in each orientation (L,T,S).
- Seventeen fracture toughness tests.

### Conclusion of the Project Team

Tensile tests on specimens taken from the VB395 shell show that the ductility of the material in the ligaments between flakes is similar to the ductility of the material free of flakes. Large-scale tests on material containing flakes confirm the good ductility and load bearing capacity.

The fracture toughness tests confirm that the original margin (50 °C shift on the  $RT_{NDT}$ ) considered in the Safety Case is appropriate to cover the potential deterioration of the local fracture toughness properties in the vicinity of the hydrogen-induced flaws.

### Review by the SCP

The SCP Review Team performed a critical analysis of the methodology applied by the Project Team and underlined its conservative nature:

- Fracture toughness on the ligaments between the affected zones: An impact on the  $RT_{NDT}$  of 11 °C has been taken into account to envelope the potentially small reduction on the toughness of the ligament, although this difference of 11 °C is comparable to the experimental scatter.
- Fracture toughness on specimens with a hydrogen flake as crack initiator: The tests do not fulfil the standard requirements in terms of crack front regularity. However, the measured values of fracture toughness have been confirmed by 3D Finite Element Analysis. This gives more confidence that the 14 °C shift in  $T_0$  temperature (obtained by application of the Master Curve on the confirmed values) covers a real effect (a combination of both fracture toughness scatter and crack front irregularity).
- The 4 °C to 17 °C range accounting for a possibly higher irradiation embrittlement sensitivity of the macro-segregated zone (as already mentioned in the Safety Case): The SCP Review Team endorses the statement made by the Project Team that this irradiation effect could be reduced to 4 °C to 12 °C. Indeed, 17 °C corresponds to the highest fluence peak in the core vessel. However no critical flaw is present at that level. The conservative 12 °C value that was used, corresponds to the spatial fluence variation in the RPV for the most critical flaw locations of the Doel 3 RPV.

According to the fact that segregation, orientation, and ghost lines effects have no impact on the  $RT_{NDT}$ , the global impact is limited to the sum of 11 + 14 + (4 to 12) °C or 29 °C to 37°C. This is well below the 50 °C original margin on the  $RT_{NDT}$  considered in the Structural Integrity Assessment.

In addition, the surveillance results for the Doel 3 RPV have shown that the effect of embrittlement, as evaluated by the Formule d'irradiation Supérieure (FIS) formula, is conservative. This led to an additional margin of 10 to 25 °C on the  $RT_{NDT}$ , not taken into account in the evaluation

### Conclusion of the SCP

The SCP Review Team endorses the methodology used by the Project Team, as well as the conclusions made. The SCP Review Team underlines the conservative nature of the methodology. The original margin of 50 °C on the  $RT_{NDT}$  (as considered in the Safety Case) is deemed appropriate — with a high level of confidence — to cover the potential deterioration of the local fracture toughness properties near the hydrogen-induced flaws.

# 5 Structural Integrity Assessment

## 5.1 ASME III Elastic-Plastic Analysis

### Requirement

During the discussions of the Safety Case, it was decided to add an elastic-plastic analysis according to the ASME III NB-3228.3.

### Steps taken

In order to determine the collapse load, an elastic-plastic analysis according to the ASME III NB-3228.3 was performed.

### Conclusion of the Project Team

After the ASME III NB-3228.3 elastic-plastic analysis, it is shown that the collapse load evaluated for the most penalizing flaw configuration meets the acceptance criterion.

### Review by the SCP

The SCP has reviewed the deliverable of the project and has no further questions.

### Conclusion of the SCP

The SCP Review Team endorses the conclusion of the Project Team that the collapse load for the most penalizing flaw configuration meets the acceptance criterion.

## 5.2 Flaw Acceptability Analysis

### Requirement

To assess the effects of the high number of detected flaws, Bel V proposed the use of a deterministic screening criterion approach. The objective of this approach is to determine whether:

- The hydrogen-induced degradation significantly affects the safety level of the RPVs.
- Only a limited number of flaws require a more in-depth analytical evaluation.

### Steps taken

The screening criterion proposed in the FANC's Provisional Evaluation Report was applied. The screening is a graded approach that identifies only a limited number of flaws requiring a more in-depth analytical evaluation. The flaws are screened as follows:

- Closely spaced flaws are grouped based on grouping rules, as in the Safety Case Report.
- Each individual flaw or group of flaws is submitted to the flaw-screening criterion:
  - **If flaw size  $2a$  is less than half of the acceptable flaw size  $2a_{acc}$** , then the flaw is considered to be harmless and no further analysis is required.
  - **If flaw size  $2a$  is larger than half of the acceptable flaw size  $2a_{acc}$**  further analysis is required.

Applying the flaw-screening criterion to the flaws detected in the RPV core shells of Doel 3 shows that eleven flaws (isolated or grouped) exceed the flaw-screening criterion, as illustrated in Figure 5.1:

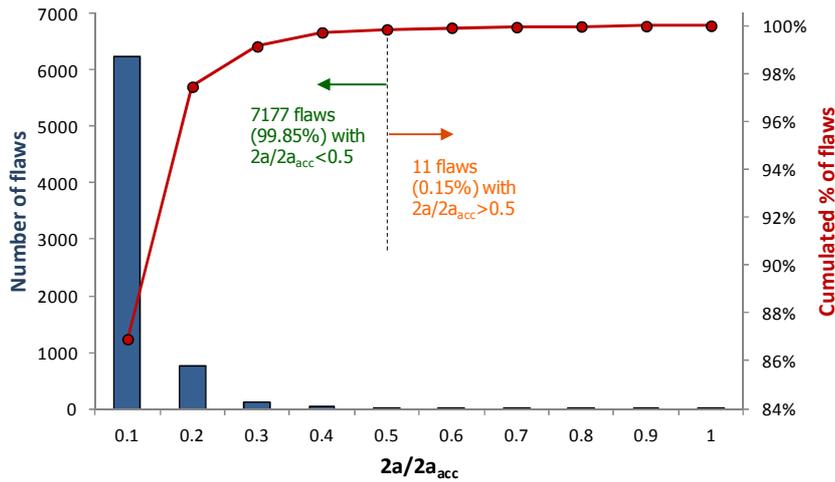


Figure 5.1: Flaw-screening criterion applied to core shells of Doel 3

However, as Figure 5.2 shows, these flaws or groups of flaws meet the acceptability criterion (i.e. the ratio  $2a/2a_{acc} < 1$ ). In conformity with the flaw-screening approach, refined analyses were performed. They revealed substantial margins: the margin with respect to the  $2a/2a_{acc}$  ratio increases from 40% to more than 70% according to the six 3D-analyses that were performed on six configurations representative of the eleven considered here.

Figure 5.2 visualizes the flaws or groups of flaws taken into account in the analysis. The acceptability criterion (i.e. the ratio  $2a/2a_{acc} < 1$ ) is respected in every case, as shown in Table 5.1.

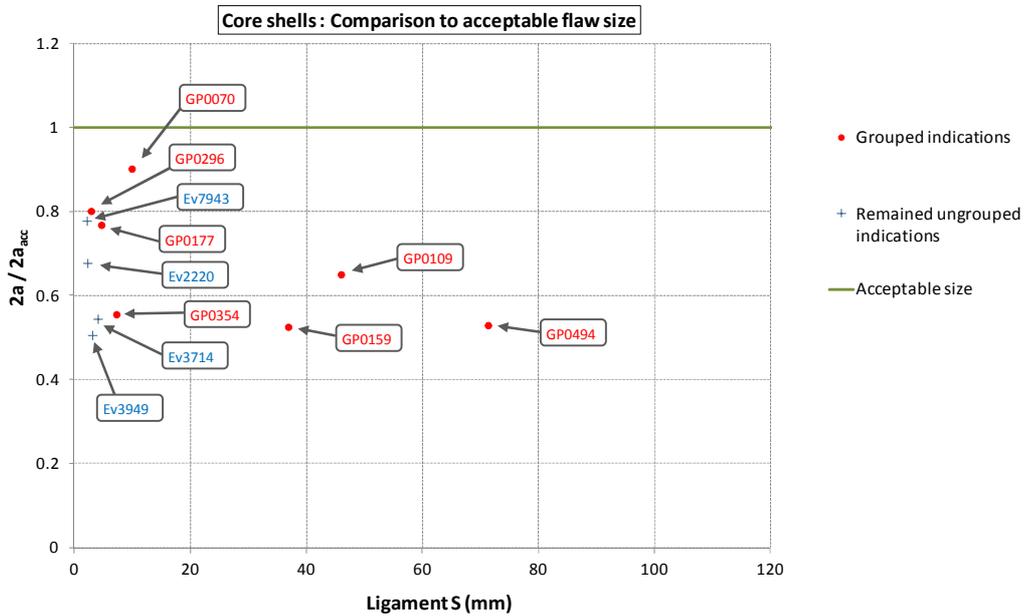


Figure 5.2: Ratio  $2a/2a_{acc}$  as a function of ligament for flaws exceeding the screening criterion

Nr.	$2a/2a_{acc}$	Refined $2a/2a_{acc}$	$K_{eq,max}$ (MPa√m)
GP0070	0.90	0.22	19.3
GP0296	0.80	0.28	20.5
EV7943	0.78	0.44	25.0
GP0177	0.77	0.27	20.5
EV2220	0.68	0.39	29.2
GP0494	0.53	0.09	4.6

**Table 5.1: Refined analysis of flaw configurations exceeding the flaw-screening criterion**

### Conclusion of the Project Team

The Flaw Acceptability Analysis was expanded with a flaw-screening criterion approach. Only eleven flaws or groups of flaws in the Doel 3 RPV exceed this screening criterion. However, they meet the acceptability criterion. Additional refined analyses show substantial margins.

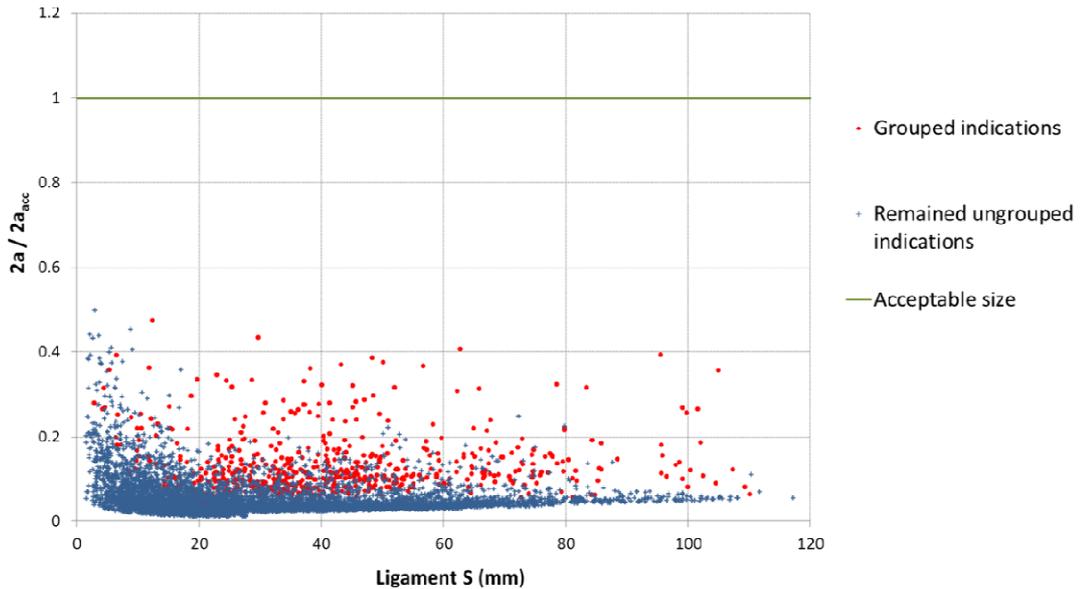
### Review by the SCP

The flaw-screening criterion approach proposed in the FANC's Provisional Evaluation Report is in line with the request made in 2012 by the SCP Review Team to perform 3D calculations for all grouped and isolated flaws close to the acceptable flaw size. This request was based on the critical review by Sandia National Laboratories (SNL) regarding the proposed grouping criteria and their concern about the way to take into account the effect of the surrounding flaws on an isolated flaw.

The refined analyses performed by the Project Team are relevant and demonstrate the conservativeness of the Structural Integrity Assessment. It correctly addresses the concerns expressed by SNL.

The refined analyses also take into account an increase in the Safety Injection (SI) water temperature, foreseen as an operational measure for the Doel 3 RPV in the 2012 Safety Case. This Defense-in-Depth decision was already supported by the SCP in its 2012 advice report regarding the Doel 3 RPV Safety Case. Indeed, in the Doel 3 RPV, most of the flaws close to the acceptable flaw size are located near the inner surface, which is not the case for the Tihange 2 RPV.

Finally, the SCP Review Team confirms its confidence in the demonstration of the structural integrity of the Doel 3 RPV, since the results of the refined analyses (see Figure 5.3), show a margin higher than 50 % with respect to the acceptability criterion ( $2a/2a_{acc} < 1$ ).



**Figure 5.3: Doel 3 core shells, comparison to acceptable flaw size (SI water at 30 °C)**

### Conclusion of the SCP

The SCP Review Team has no comment or remark regarding the Flaw Acceptability Analysis.

## 5.3 Sensitivity Analyses

### 5.3.1 Sensitivity Analysis of the Structural Integrity Assessment (SIA) with respect to Ligament

#### Requirement

The International Expert Review Board (IERB) required a sensitivity analysis for the location of the flaws in the structural analysis. More specifically, the IERB suggested considering the most critical flaw of the analysis: the Doel 3 flaw Ev2220, with the corresponding Stress Intensity Factor (SIF) of  $30.9 \text{ MPa}\sqrt{\text{m}}$ . It also asked to investigate how the results of the SIA might change if the ligament  $S$  of the flaw tends to zero.

#### Steps taken

A sensitivity study was performed on the most penalizing flaw for the two RPVs: the Doel 3 flaw Ev2220. The distance between the surface and the flaw (called the ligament) was modified and the flaw was moved towards the surface. Hence, the effect of the ligament on the  $2a/2a_{acc}$  criterion has been evaluated.

#### Conclusion of the Project Team

A number of sensitivity analyses were performed on the most penalizing flaw of the two RPVs (Doel 3 flaw Ev2220), considering effects such as the ligament tending to zero, a  $5^\circ$  larger inclination, the actual fluence, the flaw shape, and the safety injection water temperature. Results confirm that a significant margin remains in all cases.

#### Review by the SCP

The SCP reviewed the deliverable of the Project Team. Using the most penalizing situation (i.e. the Doel 3 flaw Ev2220) ensures that the Doel 3 set of flaws is covered.

#### Conclusion of the SCP

The SCP Review Team endorses this analysis and has no further questions regarding the conclusion of the Project Team.

## 5.3.2 Sensitivity Study of Higher Tilted Flaws

### Requirement

Taking into account the results of the actions related to the previous requirement on the detection of higher tilt defects during in-service inspections, the Project Team was asked to evaluate the impact of the possible non-reporting of flaws with higher tilts on the results of the structural integrity assessment.

### Steps taken

The Project Team used the actual distribution of Doel 3 lower core shell flaws in order to determine the most penalizing situation. Postulated flaws were added according to the physical distributions and considering a penalizing tilt of 20°. A random size was determined according to the input provided by the curve presented in Figure 2.1, Chapter 2.1.4 (maximum size of a potentially unreported flaw) as described by the UT study. In total, 1045 flaws were added, mainly in the area with maximum flaw density. The latter ensures a penalty as the postulated flaws are mainly set where the material is highly affected.

Finally, a Flaw Acceptability Analysis was performed on the entire population of reported and potentially unreported flaws. According to 3D-analysis, the  $2a/2a_{acc}$  value obtained for the most penalizing group of flaws remains acceptable ( $2a/2a_{acc} < 1$ ) when the flaws are ungrouped. For the two most critical configurations (group of flaws with the highest  $2a/2a_{acc}$  value and group of flaws containing the individual flaw with the highest  $2a/2a_{acc}$  value), the  $2a/2a_{acc}$  value obtained for each of the constitutive flaws after execution of the 3D-analysis remains well below the flaw acceptability criterion  $2a/2a_{acc} < 1$  (more specifically below 0.3).

### Conclusion of the Project Team

The integration of potentially unreported flaws with up to 20° inclination in the Structural Integrity Assessment of the Doel 3 lower core shell does not affect its structural integrity.

### Review by the SCP

The analysis was performed based on data from the lower core shell of Doel 3, the component that is most affected by hydrogen flaking. The Project Team added a population of potentially unreported flaws (1045), distributed in the shell similar to the reported flaws in the lower core shell of Doel 3. The depth range of 25 to 120 mm is divided into several intervals; potentially unreported flaws do not concern the zone below 25 mm.

The SCP Review Team followed and challenged the Project Team's methodology. Two parts could clearly be distinguished:

- The calculation of an envelope curve to define the size of the largest flaws with respect to the depth inside the material that would potentially not have been reported (see Figure 2.1). This relies on a deterministic approach and does not need to be penalized again.
- The use of a statistical and probabilistic tool in order to define the distribution of the additional postulated flaws.

The application of the conservative grouping methodology reveals that only a very small amount of grouped flaws exceed the flaw acceptability criterion  $2a/2a_{acc} < 1$ . However, application of the 3D-analysis again demonstrates significant margins with respect to the flaw acceptability criterion regarding ungrouped flaws.

### Conclusion of the SCP

The SCP Review Team endorses the methodology and conclusions of the Project Team regarding the sensitivity study of higher tilted flaws.

## 5.4 Flaw Acceptability Analysis including DTRs of Doel 3

### Requirement

Since 320 *Défauts Techniques de Revêtement* (DTR) have been located close to the hydrogen flaws, the Project Team was asked to consider all of the DTRs as hydrogen flaws to ensure that even if they would be hydrogen flakes, they would not have any negative impact on the safety assessment performed.

### Steps taken

The Project Team has taken all of the 320 DTRs into consideration and performed complementary analyses when the flaw-screening criterion was exceeded. The analyses revealed that the acceptability criterion was respected in every case. Hence, no adverse effect should be expected from the DTRs.

### Conclusion of the Project Team

The integration of DTRs (clad interface imperfections) as hydrogen flakes in the Structural Integrity Assessment of the Doel 3 RPV does not affect its structural integrity.

### Conclusion of the SCP

The SCP Review Team endorses the methodology and conclusions of the Project Team regarding the harmless character of the DTRs.

A **DTR** is any flaw located at the cladding-base metal interface, parallel to the vessel surface, that does not penetrate the 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, oriented perpendicular to the RPV surface and generated by cold cracking. No underclad cracks were discovered during the 2012 inspections.

## 5.5 Large-Scale Validation Testing

### Requirement

The Project Team was asked to complete the ongoing test program by testing larger specimens containing hydrogen flakes, with the following objectives:

- Objective 1: Tensile tests on samples with (inclined) multiple hydrogen flake defects, which shall in particular demonstrate that the material has sufficient ductility and load bearing capacity, and that there is no premature brittle fracture.
- Objective 2: An experimental confirmation of the suitability and conservatism of the 3D finite elements analysis.

### Steps taken

The Project Team proposed the following sets of large-scale tests to meet the requirements of the FANC:

- **Objective 1: Large-scale tensile tests on samples taken from the AREVA VB395 block containing hydrogen flakes (for ductile behaviour and load bearing capacity)**

The Project Team performed tensile tests on bars including flakes oriented at 0° (at room temperature and at 290 °C) and four tests with flakes oriented at 20° (at room temperature and at -80 °C). The latter was added at the request of Bel V and the AIA.

- **Load bearing capacity:** All tests have shown an adequate load bearing capacity as no rupture occurred before the yield stress. This is especially true for the specimen with flakes oriented at 20°.
- **Ductility:** Tests of flakes with a 0° inclination have shown an adequate ductile behaviour of the specimen. Tests with flakes with a 20° inclination evidenced rupture with less total elongation of the specimen. This is due to the fact that the specimens were actually governed by fracture mechanics laws. The broken specimens show that the break initiated at a flake location. The SCP Review Team also noted that the structural integrity calculations performed for both specimens tested at -80 °C have confirmed that the actual fracture loads were higher than the calculated fracture load required for brittle initiation of the flake (responsible for the rupture). In addition, the results of the four tests show a scatter, which is typical of fracture mechanics and not representative of tensile tests.

Fractographic examination of both specimens put in evidence the ductile behaviour of the flaked steel, as they showed that areas around the flakes exhibiting ductile aspects and the flakes inside the specimens behaved in a ductile manner (displacement of the edges of the flakes submitted to stresses).

- **Objective 2: Large-scale four-point bending test on samples from the AREVA VB395 block (fracture toughness, UT inspection, and structural integrity demonstration tests)**

The Project Team performed two bending tests on two different specimens including flakes at a temperature of -130 °C. Test conditions were set to maximize the probability of obtaining a brittle initiation of the flakes. Each specimen underwent UT examination and the flakes were characterized according to the Safety Case method. The Project Team used the input to assess the range of loads where initiation of flakes (and breaking of specimen) would occur.

Tests were performed on two specimens. Eight flakes were detected in the first specimen, seven in the second one. A 3D model of the block was made and used for computation of stress intensity factors where only relevant flakes have been modelled. The interaction with other flakes was not taken into account.

Both blocks broke at a load higher than the minimum fracture load predicted by the calculations.

Specimen	Calculated Failure Load	Experimental Failure Load
Specimen 1	111 kN	209 kN
Specimen 2	79 kN	489 kN

**Table 5.2: Comparison of predicted and experimental failure load**

Post-calculations (2D instead of 3D in this case) were carried out using the actual flake profile (size and inclination) to re-assess the predicted fracture load range.

The results show the conservative nature of the safety case methodologies (UT inspection, 3D modelling of flakes, 3D structural integrity calculations).

### Conclusion of the Project Team

The good ductility and load bearing capacity of the material was demonstrated by the tensile tests described in the previous chapter. These tests confirmed that the ductility of the material in the ligaments between flakes is similar to the ductility of material free of flakes.

The two large-scale tensile specimens with inclined flakes tested at room temperature exhibited significant uniform elongation and local plasticity at crack tips. The results clearly indicate the good ductility and load bearing capacity.

The 3D Finite Element analysis on two large-scale tensile specimens with inclined flakes tested at -80 °C, demonstrated that the specimen failure was as predicted by fracture mechanics, and that there is no premature brittle fracture.

The 3D Finite Element simulation of two large-scale bend bars with flakes tested in four-point bending demonstrated that the failure load calculated according to the same methodology as applied in the Structural Integrity Assessment of the RPVs was significantly lower than the actual failure load.

### Review by the SCP

Large-scale tests are useful to validate the global assessment of the flaked steel used in the Safety Case. Such assessment is based on a series of methodologies, mechanical properties, non-destructive examination, characterization of hydrogen flakes, and 3D calculation tools.

The SCP has reviewed the large-scale tests proposed by the Project Team to make sure that the elements above are assembled satisfactorily to predict the global mechanical resistance and the behaviour of hydrogen-flaked steels in normal and accident design conditions.

In addition, the microscopic examination of the fractured test samples provided valuable information to confirm the hypotheses of the Project Team regarding both the ductile behaviour of flaked steel (which has clearly been demonstrated) and the fracture mechanism of the test samples (satisfactorily correlated to test conditions and hydrogen flake position).

### Conclusion of the SCP

The SCP Review Team endorses the conclusions of the Project Team and has no further comments regarding the large-scale validation tests.

# 6 Load Test

## Requirement

In addition to the actions proposed by the licensee and the additional requirements specified by the FANC in the previous sections, the Project Team was asked to perform a load test of both reactor pressure vessels. The objective of the load test is not to validate the analytical demonstration on the reactor pressure vessel itself, but to demonstrate that no unexpected condition is present in the reactor pressure vessels. The methodology and associated tests (acoustic emission and ultrasonic testing among others) will be defined by the licensee and submitted to the nuclear safety authority for approval. The acceptance criterion will be that neither crack initiation nor crack propagation is recorded under the pressure loading.

## Steps taken

- The load test was performed above 175 bar abs with the reactor internals in place but without any fuel elements in the RPV. Throughout the test, the RPV wall temperature was heated up to about 140 °C. The lower temperature limit takes into account the minimum required wall temperature of 117 °C imposed by the RPV structural integrity analysis. The upper temperature limit considers the maximum allowable temperature of 150 °C for the Acoustic Emission (AE) sensors mounted on the RPV. The test was performed with the primary system operating in solid mode (liquid water phase). The reactor coolant was heated through the reactor coolant pumps and the pressure was increased through the charging pump of the Chemical and Volumetric Control System (CVCS). The reactor coolant pumps were inactive during the AE measurements.
- The AE measurements were performed during the load test. The technique is based on the principle that flaws propagating under mechanical stress (e.g. due to internal pressure) undergo local micro-displacements that release energy in the form of transient elastic waves. These waves can be captured by sensors installed on the surface of the component.
- After the load test, a UT inspection was carried out on both core shells of the Doel 3 RPV using MIS-B in a similar fashion as during the 2012 UT inspections under the same conditions. The results of the UT inspections demonstrate that the flaws detected during the 2012 inspection did not evolve because of the load test.

## Conclusion of the Project Team

The Doel 3 RPV was subjected to a load test with acoustic emission (AE) measurements, followed by a post-load UT inspection.

The AE measurements performed did not reveal any source or area for which complementary investigations would be required.

The number of flaw indications reported by the post-load test inspection is fully consistent with the findings of the 2012 RPV inspection. The peak amplitude and dimensions of every indication reported by the post-load test inspection match those of the 2012 RPV inspection.

All examination results confirm that the load test did not modify the condition of the material.

### Review by the SCP

The preparation and execution of the load test, the AE measurements, and the post-load UT inspection were closely monitored by the SCP (required permissions, modifications, procedures, preconditions, et cetera). The AE tests resulted in a Category II classification of the investigated zones. This means that no mandatory inspection is requested but that additional investigation is only recommended (the UT might be considered as such). However, the conditions in which the load test took place differed significantly from normal AE test conditions (e.g. in the petrochemical sector) with respect to:

- Intensive acoustic activity related to operating conditions.
- RPV not isolated from primary circuit that is also pressurized.
- Localization of AE sources limited due to core vessel shell unreachable for the fixation of the sensors.

Standard AE test condition could not be duly met in the RPV of Doel 3 where the test was used to detect any possible crack propagation. Hence, the conclusions of the AE measurements need to be interpreted with care. Nevertheless, no zone was declared as Category III that would have required complementary examination.

The results gathered during and after the load test confirm that the load test did not modify the conditions of the material.

### Conclusion of the SCP

The examination results gathered during and after the load test confirm that the load test did not modify the conditions of the material. The SCP Review Team closely monitored the load test and points out that the test conditions during the Acoustic Emission measurements did not enable the accomplishment of the objective of the load test, even if no Category III zone was detected. However, comparing the data from the UT performed in 2012 and the UT carried out after the load test did not induce any modification in the condition of the RPV material; this point is important to be underlined.

The most fundamental conclusion that may be drawn is that there has been no evolution of the flaws between the UT inspections of 2012 and 2013. All indications were investigated and a one-to-one correspondence has been observed for each indication between the 2012 and 2013 UT results.

The SCP Review Team is convinced that these results demonstrate that no crack initiation or propagation took place during the load test.

# 7 List of Abbreviations

<b>Abbreviation</b>	<b>Meaning</b>
AIA	Approved Inspection Authority
AE	Acoustic Emission
ASME	American Society of Mechanical Engineers
CVCS	Chemical and Volumetric Control System
DTR	Défaut Technique de Revêtement
FANC	(Belgian) Federal Agency on Nuclear Control
FIS	Formule d'Irradiation Supérieure
IERB	International Expert Review Board
MIS-B	Machine d'Inspection en Service Belge
NPP	Nuclear Power Plant
RPV	Reactor Pressure Vessel
RT <sub>NDT</sub>	Reference Temperature for Nil Ductility Transition
SCK•CEN	StudieCentrum voor Kernenergie-Centre d'Etude de l'énergie Nucléaire
SCP	Service de Contrôle Physique
SI	Safety Injection
SIA	Safety Integrity Assessment
SIF	Stress Intensity Factor
SNL	Sandia National Laboratories
UT	Ultrasonic Testing