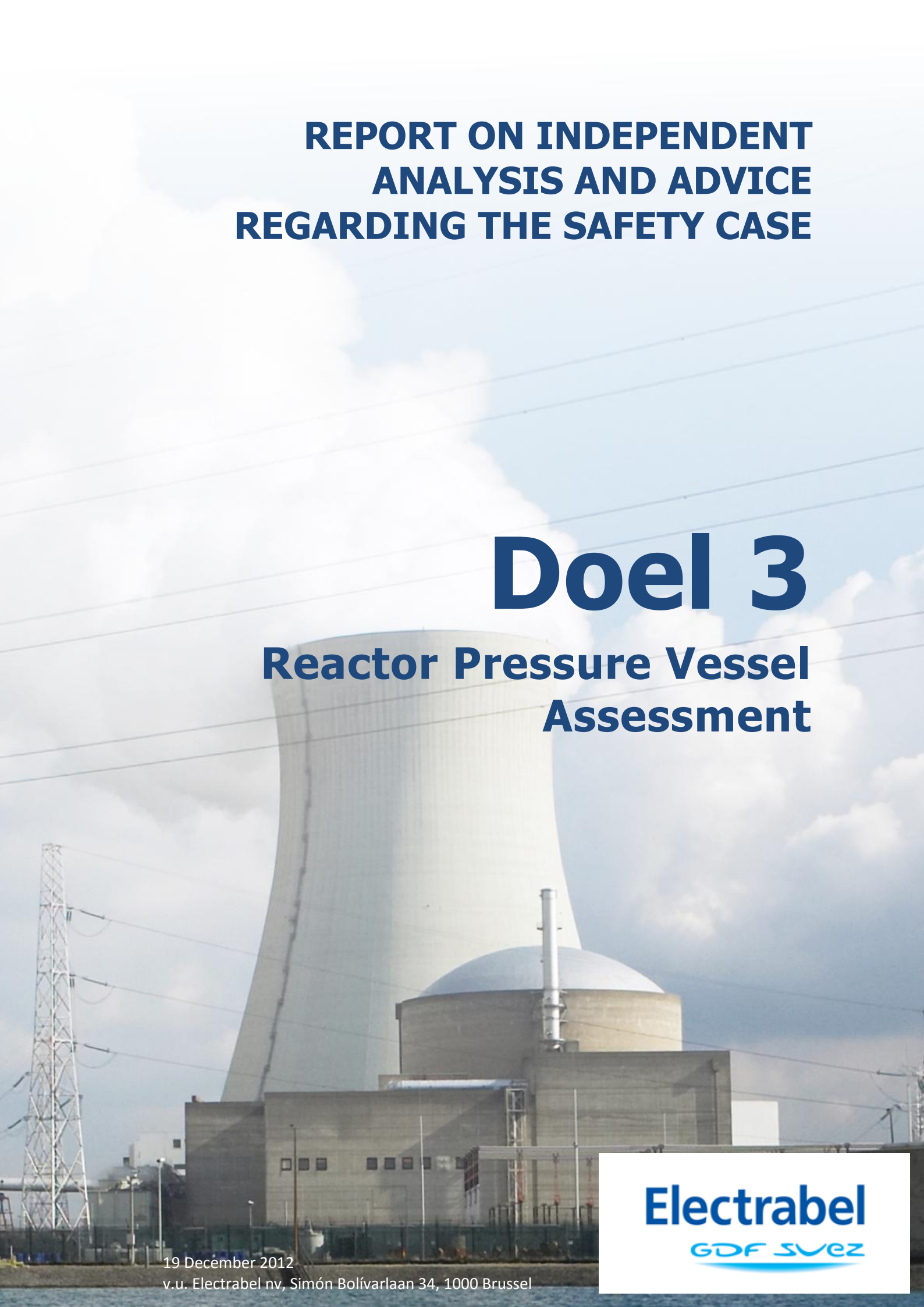
REPORT ON INDEPENDENT ANALYSIS AND ADVICE REGARDING THE SAFETY CASE

Doel 3

Reactor Pressure Vessel Assessment



19 December 2012
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Electrabel
GDF SUEZ

Contents

1 Executive Summary

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

Subsequently, Electrabel created a Project Team to thoroughly investigate the nature, origin, and possible evolution of the indications and their potential impact on the structural integrity of the RPV.

At the same time, Electrabel Service de Contrôle Physique (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 purpose of the SCP Review Team is to perform an independent review of the project deliverables issued by the Project Team.

Separately, Sandia National Laboratories (SNL) has also been requested to perform an additional independent analysis, based on raw data from the ultrasonic inspection of the Doel 3 RPV material.

The review and analyses have led the SCP Review Team to giving an overall positive recommendation regarding the immediate and safe restart of the Doel 3 RPV taking into account the advice given in this report. This advice is based on the Project Team satisfactory consideration of all comments concerning the project deliverables, the outcomes of the additional independent analysis, and the final review of the Safety Case.

1.1 Review of Project Deliverables

The SCP Review Team thoroughly analyzed the project deliverables. It challenged the Project Team assumptions, analyses, and statements and suggested some clarifications. It also assessed the conservativeness at all steps of the Project Team 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 contribution of external experts to the review of Project Deliverables has been integrated in the overall review process of the SCP Review Team and their main comments have been added in the final version of the advice sheets sent to the Head of the Project Team (see § 2.1).

Several quotes of SNL are mentioned in some chapters of the present report in italics. Concerning the two professors in Mechanical Engineering, we will keep on the following quotation from their final report on review: "*Overall it is possible to conclude on the findings with confidence taking into account the stringent safety concerns that a restart of the nuclear plant would entail. It is clear that a detailed and accurate testing and analysis programme has been carried out to resolve the important issues of the safety case. Hence the relevant authorities should now be in a confident position to reach appropriate decisions as to the next line of action based on the information provided*".

1.2 Additional Independent Analysis

At the request of the SCP Review Team, Sandia National Laboratories (SNL) provided an additional independent analysis of two topics:

- The nature and origin of the indications
- The structural integrity of the Doel 3 RPV

Nature and origin of the indications

Based on its assessment of the nature and origin of the indications found in the Doel 3 RPV, SNL came to the following conclusion:

> "*The observed indications present in the Doel 3 RPV are not related to open metal-to-air interfaces or voids based on the characteristics of the UT signals. Instead, there are a number of observations that support the theory of hydrogen flaking as a plausible explanation for the observed discontinuities within the structure*".

Structural integrity of the RPV

For the second topic, SNL conducted analyses on their own resources. This led to the following conclusions:

"*The results of these analyses would tend to indicate that configurations of cracks within the Doel 3 RPV that have similar characteristics to those investigated here, with crack size up to 25 mm, crack out-of-laminar angle up to 20 degrees, and crack density up to 35 cracks/litre, will likely have sufficient margin against brittle fracture initiation under A/B transients. In addition, the same statement can be made for the cracks in those configurations that exist within the region of the RPV wall in which LEFM applies, under C/D transients."*
(LEFM: Linear Elastic Fracture Mechanics, transients A/B: heat-up and cool-down, C/D: small/large Loss Of Coolant Accident (LOCA))

2 Introduction

In a letter addressed to Electrabel (2 August 2012), the FANC requested the Electrabel Service de Contrôle Physique (SCP) to conduct an independent analysis of the Safety Case and provide an advice. Electrabel puts together an SCP Review Team, consisting of the Electrabel Corporate Nuclear Safety Department (SCP corporate level) and the CARE Doel and Tihange Department (SCP site level), as well as external international experts and academics.

The review covered the full project scope, 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.

2.1 Methodology

The SCP Review Team took a three-way approach in its analysis of the Doel 3 RPV 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**: ultrasonic examinations, RPV manufacturing documentation, mechanical tests, metallurgical origin of the indications, calculations of the structural integrity (deterministic and probabilistic), safety framework, et cetera.
- **Additional independent analysis** performed by Sandia National Laboratory (SNL) on their own resources. This analysis is based on available raw data from the ultrasonic inspection of the Doel 3 RPV, as well as on RPV design and the applicable transients, in order to assess:
  - The nature and origin of the indications
  - The structural integrity of the RPV

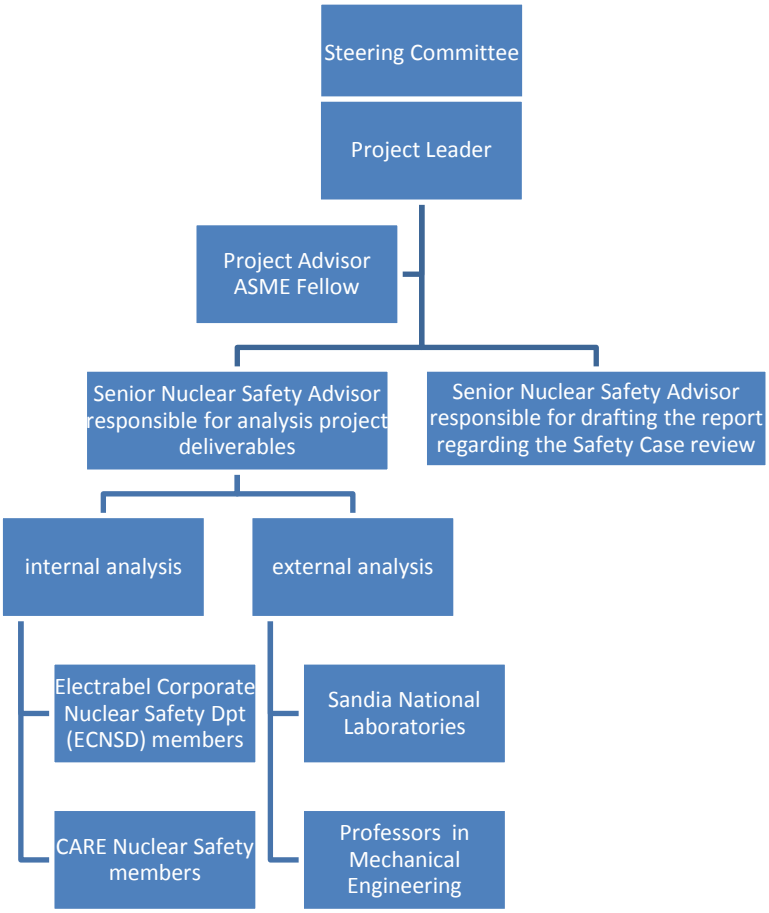
All comments on the project deliverables have been forwarded to the author of each deliverable. The most important comments, as well as the outcome of the additional independent analysis performed by SNL, have been formalized in advice sheets sent to the Head of the Project Team. The Project Team analyzed the SCP Review Team comments resulting from both internal and external reviews of the project deliverables and addressed all concerns adequately.

Based on this conclusion, the outcomes of SNL additional independent analysis, and the final review of the Safety Case, the SCP Review Team provided an overall positive advice to the FANC (see Chapter 3).

2.2 Organization

Electrabel Service de Contrôle Physique (SCP) created a SCP Review Team to perform an independent review of the Doel 3 RPV Safety Case. It consists of both internal and external experts.

SCP Review Team organization chart



Sandia National Laboratories

A US governmental multi-program engineering and science laboratory, part of the US Department of Energy (DOE), was also involved in the aircraft crash studies performed as part of the BEST program (Belgium Stress Tests program following the Fukushima accident). Thanks to its experience in the nuclear field, this laboratory is well placed to provide an independent analysis.

ASME fellow

The ASME Board of Governors confers the Fellow grade of membership on worthy candidates to recognize their outstanding engineering achievements. Nominated by their peers, ASME Fellows have had 10 or more years of active work experience and at least 10 years of continuous active corporate membership in ASME.

Professors in Mechanical Engineering

One from the Royal Academy of Engineering of Bristol University and one from Imperial College London

Role description

The SCP Review Team is organized as follows:

- The Steering Committee (SC) takes strategic decisions and defines the main focus areas of the analysis, up to the endorsement of the preliminary and final recommendations.
- The Project Leader implements the directives of the SC and coordinates all activities of the SCP Review Team for the RPV Safety Case review.
- The Project Advisor, an ASME fellow (see sidebar above), supports the SCP Review Team with his experience and challenges the external analysis.
- Two Senior Nuclear Safety Advisors:
  - One coordinates the analysis of the selected deliverables up to the communication of the resulting comments to the Project Team. He also organizes internal and/or external reviews. He is assisted by two engineers, one focusing on the coordination of the exchanges with external experts and the other on coordination of the exchanges with the Doel 3 Nuclear Power Plant.
  - The other Senior Nuclear Safety Advisor oversees the drafting of the report on the Independent Analysis and Advice regarding the Safety Case.
- The CARE NS members review the technical documents from a site-level point of view and design modifications proposed by the Project Team.
- The ECNSD members review the technical documents on the corporate level.
- Sandia National Laboratories (SNL – see sidebar above) provides an additional independent analysis of flaws spotted in the reactor pressure vessels and on the structural integrity issue.
- Two professors in Mechanical Engineering (see sidebar above) review the technical documents on metallurgical and structural integrity issues.

3 Advice

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 structural integrity during normal operation, as well as during transient or accident conditions.

Electrabel Service de Contrôle Physique (SCP Review Team) performed a thorough review of the project deliverables. This review has been conducted with the participation of internal and external experts (Sandia National Laboratories (SNL) and academics from British universities). SNL also performed an additional independent analysis.

Based on this review and analysis, the SCP Review Team gave recommendations, which were then adequately addressed by the Project Team. Consequently, the SCP Review Team final opinion is positive regarding the content, general conclusions, and Action Plan of the Doel 3 Safety Case Report that was delivered to the FANC (Federal Agency for Nuclear Control) on 5 December 2012.

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 confirmatory test program on industrial material containing hydrogen flakes. It will enable the confirmation of the Safety Case method overall performance.**
- **To perform—during the next and some further refuelling outages—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 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.**

4 Review

The SCP Review Team used a three-way approach in its analysis of the Doel 3 RPV Safety Case (see Chapter 2.1):

- Follow-up of the development of the safety cases. This consists mainly of "participating review" and "challenging interaction" with the Project Team.
- Independent analysis of the project deliverables summarized in this Chapter.
- Additional independent analysis performed by SNL (see Chapter 5).

4.1 Safety Framework

The Safety Framework gives an overview of the regulations and standards that apply to the Safety Case. The SCP Review Team has verified that the Project Team safety demonstration is in line with Belgian legislation and in compliance with the applicable international rules and standards.

4.1.1 Scope of the Review

The SCP Review Team analyzed the completeness and validity of the Safety Framework, the list of international rules and standards that apply to the Safety Case.

4.1.2 Conclusions

The Safety Framework used for the evaluation of the Tihange 2 RPV Safety Case is in line with Belgian legislation and is in compliance with the applicable international rules and standards.

The Project Team demonstrated the compliance of the Safety Case with Belgian legislation and the following international rules and standards:

- ASME Section III
- ASME Section XI including Appendix G
- Supporting ASME Sections
- European Methodology for NDT qualification
- 10CFR50 Appendix G
- 10CFR50.61
- 10CFR50.61a

The SCP Review Team assessed the Project Team compliance evaluation. When the SCP Review Team indicated that additional standards or rules were applicable, and action was mandatory, it was taken into account by the Project Team.

4.2 Justification Strategy

The SCP Review Team assessed the Justification Strategy that was developed by the Project Team to demonstrate that the detected flaws do not impair the safety function of the Doel 3 RPV.

The SCP Review Team considers that the Project Team strategy is 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 Safety Case.

4.2.1 Scope of the Review

The SCP Review Team closely evaluated to what extent:

- conservativeness
- representativeness
- validity
- safety margins

are taken into account in the Safety Case. The SCP Review Team therefore examined the Safety Case in accordance with the three phases defined by the FANC in its letter (2 August 2012) 2012-07-31-FVW-5-1-3-NL:

- Phase 1: Interpretation of the detected indications and gathering of all available information (historical manufacturing data, results of completed checks, etc.).
- Phase 2: Explanation and root cause of the detected indications.
- Phase 3: Discussion of the potential case file in light of an authorization of the restart of Doel 3.

4.2.2 Conclusions

Sufficiently conservative

The SCP Review Team requested that the Project Team mention the level of confidence in the results of the Safety Case. It also required that a detailed sensitivity analysis be executed when needed. The Project Team prepared a deliverable dealing specifically with an exhaustive review of the conservativeness (see Chapter 4.7).

Representative tests, valid methodologies, and sufficient safety margin

The assessment of a large number of indications is beyond the scope of the existing ASME XI mechanical code. The SCP Review Team insisted on the importance of offering convincing evidence of the representativeness, validity, and reliability of the tests, literature review, expertise, and calculation techniques.

The SCP Review Team observed that the methodologies and tests, which were specifically developed by the Project Team, confirm the arguments of the justification strategy. Results of an additional independent analysis carried out by SNL (see Chapter 5), strengthened the SCP Review Team conclusion that:

- **The Project Team identification of hydrogen flaking resulting from the manufacturing process as a root cause is a plausible explanation.**

- **The margins regarding brittle fracture initiation are safe.** This is based on the results from the global assessment of the structural integrity through 3D analyses involving equally-sized, regularly-spaced, round planar (penny-shaped) flaws within a segment of the RPV, performed by SNL to determine approximate bounds on acceptable flaw size, angle, and density equivalent to those present in the Doel 3 RPV.

However, early in the review process, the SCP Review Team expressed two main concerns. One related to the mechanical properties of flake-affected material and the other to the method applied to calculate the allowable flaw size. Therefore, the SCP Review Team gave the following recommendations, which were then taken into account by the Project Team as follows:

- Carry out tests on material affected by hydrogen flakes (VB395 shell of AREVA) in order to confirm the fracture toughness taken into account in the Safety Case, and to assess the conservativeness of the structural integrity assessment method (see material testing in the Action Plan – Chapter 6).
- Make 3D calculations for all grouped flaws and individual flaws closest to the cladding in the elastic-plastic zone and closest to the maximum allowable size before facing a crack initiation risk (see Chapter 4.4).

4.3 Origin, Interpretation, and Evolution of the Indications

The SCP Review Team agrees with the main conclusions of the Project Team analysis: the indications are most likely hydrogen flakes, which were formed during the manufacturing process, and will not evolve significantly.

The Safety Case gives an overview of the gathered information regarding the manufacturing of the Doel 3 RPV. Although all the required RPV manufacturing documentation is available within Electrabel, the archived documents lack detailed information regarding the RPV casting process. In addition, there is no evidence of a dehydrogenation phase during the first heat treatment after forging. Nevertheless, the Project Team provided ample evidence to link the detected indications to the RPV manufacturing process. This hypothesis is not disputed by the independent external experts of the SCP Review Team.

The research regarding potential flaw growth mechanisms did not identify any possible mechanism other than fatigue crack growth. This mechanism was found to be negligible. Consequently, the SCP Review Team agrees with the Project Team conclusion that the indications will not evolve significantly.

The SCP Review Team advices the Project Team to perform—during the next and some further refuelling outages—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 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.

4.3.1 Scope of the Review

The SCP Review Team closely examined the:

- completeness
- consistency
- reliability

of the documents, literature reviews, and calculation methods that the Project Team has taken into account to substantiate the conclusions of the Safety Case regarding the origin, interpretation, and evolution of the indications.

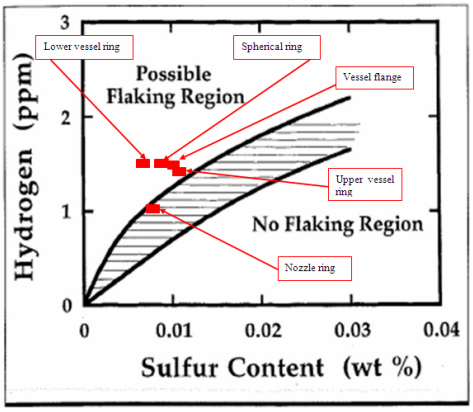
4.3.2 Conclusions

Origin of the indications

The SCP Review Team agrees with the conclusion of the Project Team: the conditions during the fabrication of the Doel 3 RPV allowed for hydrogen flaking to occur.

The Project Team investigation of the indications' origin is largely based on an investigation of the manufacturing files. Regarding these files, the SCP Review Team made the following observations:

- The manufacturing documentation is complete (with the exception of certain minor details), traceable, and in accordance with both specifications and applicable international codes and standards.
- Information regarding the detailed RPV casting process could not be found in the archived documents of Krupp (called today ThyssenKrupp A.G.). This is not unusual because the casting process is considered to be proprietary information.
- The same goes for the dehydrogenation heat treatment for which no evidence was found in the archives and construction manufacturing files of the Rotterdamsche Droogdok Maatschappij/Rotterdam Nuclear (RDM/RN).
- Although the hydrogen concentration of all the forged components of the Doel 3 RPV meets the target value of 1.5 ppm, the development of hydrogen flakes remains possible when the concentration of other chemical elements is very low.
  The following chart illustrates the above statement specifically regarding the influence of the concentration of sulphur—one of the most important chemical parameters for hydrogen flaking—in the forged pieces of the Doel 3 RPV (the actual amount of sulphur measured by Krupp is lower than the specified value of 0.02 wt%). This led AREVA (in the 1980's) to specify a maximum hydrogen concentration of 0.8 ppm to avoid the risk of hydrogen flaking.



Although the chart above (R. J. Fruehan, *Iron & Steelmaker*, 1997)—adapted to the specificities of the Doel 3 RPV—is mainly indicative, both the upper and lower shells of the Doel 3 RPV shell are in the possible flaking region. The lower shell of the Doel 3 RPV, which is most affected by flakes, appears in the deepest part of this region.

- The presence of some indications is reported in UT inspections carried out during manufacturing. However, the manufacturing inspection reports lack detailed information regarding these indications. Nevertheless, Laborelec successfully demonstrated that, using the UT tools and inspection techniques applied at the time of construction, the correct application of the ASME III rejection criteria would not have led to the rejection of a shell affected by flaws as measured in the Doel 3 RPV in the summer of 2012.

Interpretation of indications

The SCP Review Team endorses the Project Team conclusion that flaking is very likely.

Based on a literature review, root cause analysis, and detailed evaluation report from AREVA, the Project Team has identified hydrogen flaking as the most likely origin of the indications. The literature review is comprehensive but restricted to the possible origins of the phenomenon, the physics of hydrogen formation, and how it originates during the manufacturing process. All project deliverables that led to this interpretation were checked for consistency by the SCP Review Team. Comments from the SCP Review Team were clarified by the Project Team, and the project deliverables were adapted where necessary.

Additional actions were taken to confirm the Project Team theory:

- As part of the test campaign (see Chapter 4.6), Laborelec conducted UT inspections on the AREVA VB395 steam generator shell that was rejected due to loss of hydrogen control during the casting process. As a result, a large quantity of hydrogen flakes was generated in the forged shell. Comparisons of the flaw distribution in the depth of the wall, the flaw size, and the amplitude of the indications allow flaw type correlation between the VB395 shell and the Doel 3 RPV shell.
- As part of the additional independent analysis (see Chapter 5), SNL compared the native radio frequency (RF) signals of the UT inspection performed on the Doel 3 RPV and AREVA VB395 shells. This comparison proves a strong signal correlation between the RF signals from the two shells.

Evolution of indications

The research regarding potential flaw growth mechanisms did not identify any possible mechanism other than fatigue crack growth. This mechanism was found to be negligible. The SCP Review Team therefore agrees with the Project Team conclusion that the indications will not evolve significantly.

Once hydrogen flaking was identified as the root cause of the indications, the Project Team thoroughly reviewed the existing literature on this phenomenon in order to identify possible flaw growth mechanisms (e.g. hydrogen-induced cracking, etc.). Based on the residual hydrogen content in the steel and the maximum hydrogen diffusion in the primary circuit, the Project Team concluded that the only relevant flaw growth mechanism to consider is fatigue crack growth. Because of the very low number of transients that occurred in the installation, only low cycle fatigue has to be taken into account. Based on this assumption, the Project Team concluded that the flaws would not grow significantly in the future, as they have not grown considerably during the past years of operation.

The SCP Review Team advises the Project Team to perform—during the next and some further refuelling outages—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 conclusions regarding the absence of the indications' evolution in size, shape, and orientation. As the Action Plan defined by the Project Team includes a formal extension of qualification of the RPV inspection tool, the SCP Review Team recommends to include in this qualification the ability to confirm the absence of such evolution.

Concerning the effect of irradiation, the Project Team did not find information in existing literature on material that was affected by hydrogen flaking. Observations of the data from the UT inspection on the Doel 3 RPV show no relevant correlation between neutron fluence and indication size (see Chapter 4.6.3 in the Safety Case Report). However, the SCP Review Team agrees on the Project Team statement that the most pragmatic way to confirm the absence of an irradiation effect on the evolution of the indications is to perform repeated UT inspections at selected intervals.

4.4 Grouping

The SCP Review Team, with a specific contribution from SNL, has reviewed the methodology that the Project Team has proposed as an alternative to the ASME XI grouping method.

The major concern of the SCP Review Team is related to the degree of conservativeness of this alternative method. In particular, the influence of surrounding flaws on a group of flaws or an isolated flaw needed to be considered in the analysis.

The Project Team has taken this concern into account and has made complementary 3D calculations. Results of these calculations showed a significant retrieval of margins. SNL acknowledged that the concern was correctly addressed.

4.4.1 Scope of the Review

The SCP Review Team closely examined the grouping criteria that the Project Team applied in order to assess the method and results. SNL carried out an alternative evaluation in order to assess the influence of surrounding flaws.

4.4.2 Conclusions

The analyses have shown that the grouping method and grouping criteria used by the Project Team provide a sufficient margin to absorb the influence of surrounding flaws.

Methodology

The SCP Review Team agrees with the Project Team approach to focus detailed multi-flaw analyses on a representative selection of such flaws.

Due to the large number of flaws present in the Doel 3 RPV, grouping of closely-spaced flaws into larger, representative flaws that can be evaluated in isolation was considered appealing due to this approach simplicity.

The Project Team has developed alternative grouping criteria applicable to laminar and nearly laminar flaws. The proposed methodology relies on the assumption that interacting flaws can be replaced by a single equivalent flaw that encompasses the volume of all the flaws in the group of interacting flaws and that this equivalent flaw will result in an equivalent or more conservative estimation of the fracture behaviour of the group of flaws it represents. Flaws are considered to be interacting when an increase in the stress intensity factor for one flaw caused by the presence of a second flaw equals or exceeds 6 %.

For various flaw sizes and orientations, grouping criteria are established. Based on these grouping criteria, each flaw is evaluated to determine whether it should be grouped with neighbouring flaws before being evaluated for flaw fracture initiation.

Once all flaws have been assessed according to the grouping criteria and have been classified either as stand-alone flaws or grouped flaws, they are evaluated in isolation against allowable flaw size envelope curves.

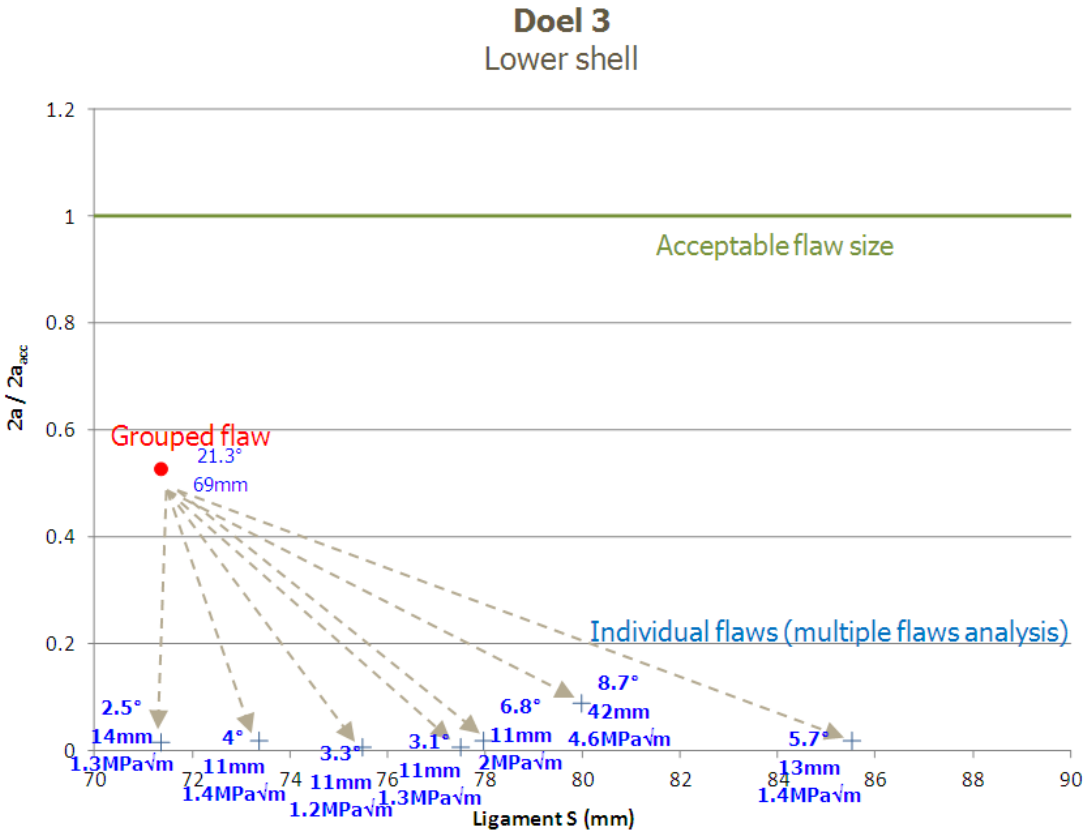
Flaws considered as a group

The SCP Review Team agrees with the Project Team approach to address this concern. Based on the results of this approach, SNL concluded that "*the grouping methodology applied for the Doel 3 RPV is generally conservative*".

Based on the alternative grouping procedure outlined above, any flaw that experiences an increase in its equivalent stress intensity factor of more than 6 % due to the presence of any single neighbouring flaw (each evaluated individually) needs to be grouped with its neighbour(s) and replaced by a single, larger flaw for fracture evaluations. This larger equivalent flaw can then be considered in isolation.

SNL has demonstrated that the grouping procedure can underestimate the equivalent stress intensity factor. Therefore, SNL asked the Project Team to reassess its grouping methodology. SNL recommended that all grouped flaws deemed acceptable using the grouping methodology developed by the Project Team be reassessed. In response, the Project Team has confirmed the global conservativeness of its grouping method through detailed multi-flaw analyses performed for Doel 3 of:

- The three groups closest to the cladding in the elastic-plastic zone and closest to the maximum allowable size before facing a crack initiation risk (see picture in Chapter 4.5.2).
- A group containing a large number of flaws (7) in the linear elastic zone.



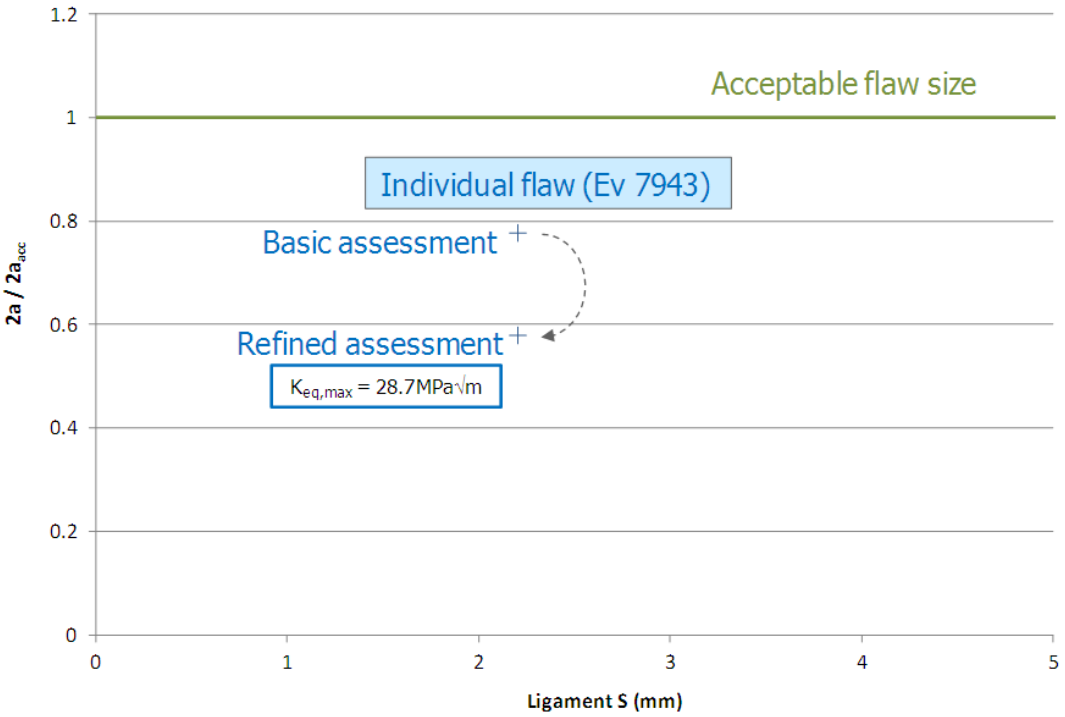
The results of such 3D calculations for the 7 ungrouped flaws show a significant increase of the margin with respect to the maximum allowable size.

Flaws considered in isolation

The SCP Review Team agrees with the Project Team approach to address the concern identified by SNL.

Based on the alternative grouping procedure, any flaw that experiences an increase in its equivalent stress intensity factor of less than 6 % due to the presence of any single neighbouring flaw (each evaluated individually) can be considered in isolation when determining its fracture behaviour.

SNL has shown that considering such flaws in isolation can be non-conservative for some configurations of closely-spaced flaws. SNL recommended that flaws that have been deemed acceptable in isolation by the Project Team be reassessed in light of the effect that neighbouring flaws may have on them. In order to address this concern, the Project Team assessed the influence of the environment on ungrouped flaws through 3D analysis of the two individual flaws closest to the maximum available size. One result is shown in the picture below where the refined assessment shows a significant additional margin:



In light of the results, SNL concludes that the Project Team approach is reasonable and that it will ensure the adequacy of the methodology. The SCP Review Team agrees with this conclusion.

4.5 Structural Integrity

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 structural integrity. As foreseen in the Project Team Action Plan, a medium-term test program on industrial material containing hydrogen flakes is intended to confirm the conservativeness of this approach.

The SCP Review Team was concerned by the limited margin in the initial available results for some grouped indications and remaining non-grouped indications in the Doel 3 lower core shell that were above 75 % of the acceptable flaw size. The 3D calculations performed for the indications close to the acceptable flaw size confirmed that the initial margin for the acceptable flaw size is in fact increased by a factor of two or three.

In the Doel 3 RPV, most of the flaws with the lowest safety margin are located close to the inner surface. Consequently, the SCP Review Team supports the defence-in-depth decision of the Project Team to warm up the safety injection water to 30°C.

4.5.1 Scope of the Review

The SCP Review Team closely examined the:

- methodology
- fatigue crack growth analysis
- deterministic analysis
- probabilistic analysis

applied in the Project Team assessment of the RPV structural integrity.

4.5.2 Conclusions

Methodology

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

The SCP Review Team asked the Project Team to justify the choice of calculation codes used in the Safety Case and to specify whether the conditions (irradiation, material with flaws, etc.) in which they are used are in accordance with the qualification of these codes. The SCP Review Team asked also the Project Team to justify the choice made for the boundary conditions used in the calculations. These justifications were provided and verified. Consequently, the SCP Review Team agrees with the choice of codes.

The SCP Review Team also performed an extensive review of the methodology applied by the Project Team to determine which indication size is acceptable. The following comments were made:

- The methodology only focuses on flaw sizes that would be acceptable to avoid brittle fracture, but makes no reference to consequences of ductile tearing or collapse. The Project Team therefore defined a process that includes additional testing (see Chapter 4.6.2) to address the issue adequately.
- As mentioned by SNL: "*The equation set forth for the calculation of an equivalent mode I stress intensity factor for a crack subjected to mixed-mode loading has been considered in terms of non-self-similar crack growth. While our assessment indicates that the equation used by the Project Team can be non-conservative, the margins carried elsewhere in the analyses can be shown to compensate for this non-conservativeness.*"

Fatigue crack growth analysis

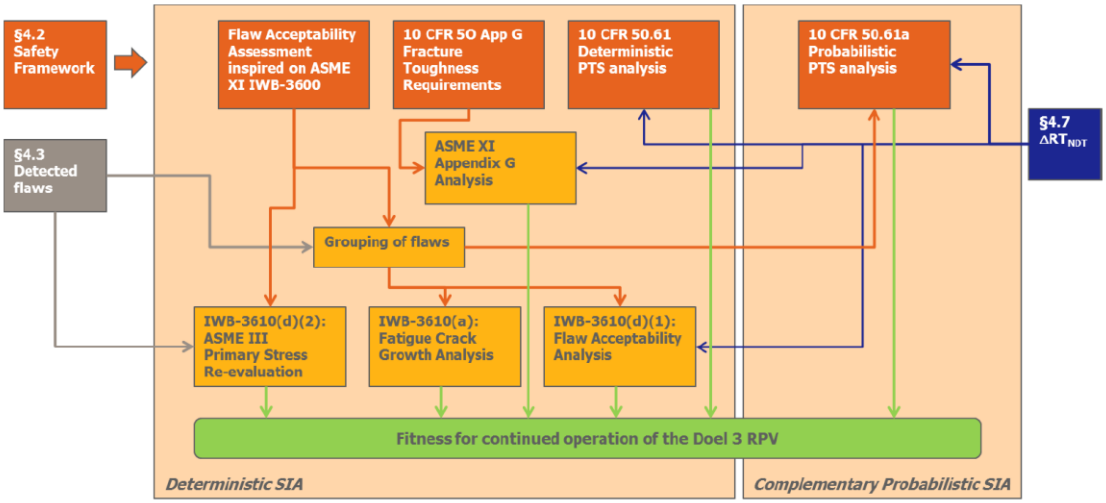
The SCP Review Team endorses the conclusion of the Project Team that the flaw growth is very limited and need not be taken into consideration for further calculations.

The Project Team conclusion is based on:

- The accepted root cause analysis (hydrogen flakes being the identified root cause).
- The mechanisms related to hydrogen flakes (among others, hydrogen-induced cracking).
- The very limited number of transients with respect to the usual number of cycles considered for the fatigue simulations, hence in the low cycle part of the fatigue curve.
- The accepted value of the growth rate for the low cycle fatigue phenomenon.
- The fact that the material between flaws is sound.
- The selection of the envelope flaw to calculate the flaw growth.

Deterministic safety integrity assessment

The SCP Review Team gives a positive advice to the Project Team deterministic Safety Integrity Assessment (SIA).
The global methodology followed by the Project Team is summarized in the left part of the following schematic, taken from the Safety Case Report:

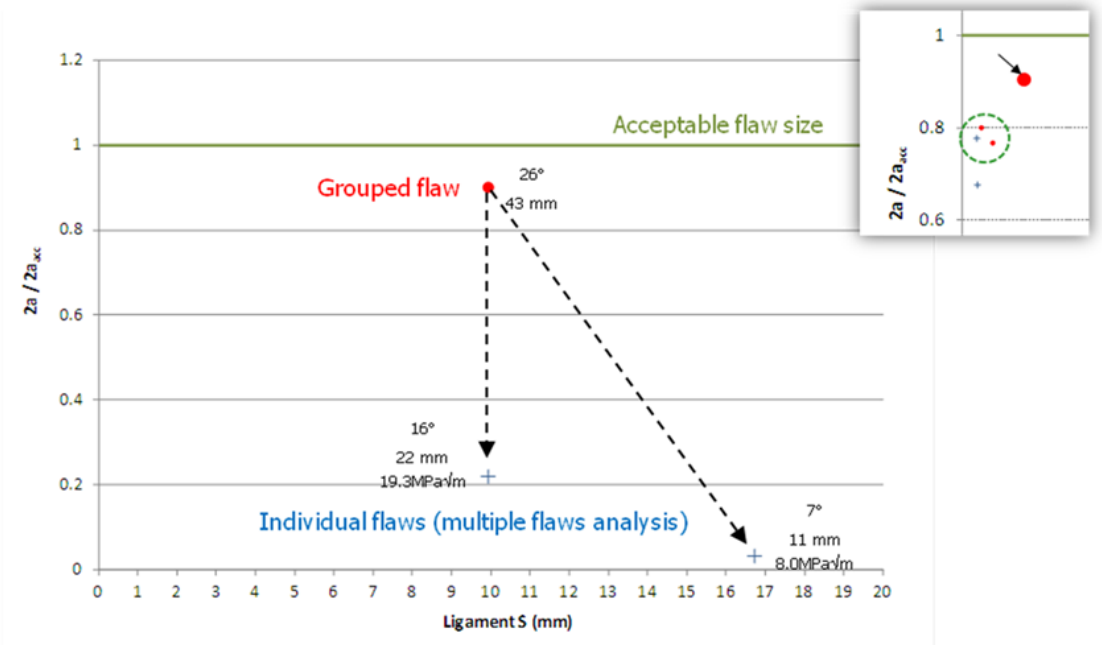


The Project Team proposed to adapt the ASME XI flaw assessment criterion for the large number of quasi-laminar flaws that were found in the Doel 3 RPV.

The flaws have been re-assessed through a primary stress calculation (via ASME III). Next, the potential crack growth of the flaws that could exist at the construction time was determined. This latest assessment was carried out under the rules of the ASME XI. The final judgment regarding the acceptability of those flaws has been deduced according to the ASME XI modified criteria.

SCP Review Team thoroughly challenged the Project Team regarding the modified ASME XI flaw assessment methodology. The most important concerns of the SCP Review Team were about how to conservatively apply the proposed grouping criteria and how to take into account the effect of the surrounding flaws on the isolated flaw.

The Project Team has clearly demonstrated that the only cases for which this question was relevant were acceptable. The relevant cases are the ones in which the flaws (grouped or isolated) are close to the maximum allowable size before facing a crack initiation risk, according to the ASME values. For the flaws close to this limit value, calculations have been made by the Project Team to quantify the impact of the grouping criteria and the surrounding flaws. To perform those calculations, the grouped flaws have been un-grouped. The set of un-grouped flaws has been evaluated through 3D calculations. The results were completely satisfactory, showing that the grouping criteria used were acceptable and offered a large margin versus allowable size, as shown in the graph below.



Similar 3D calculations were performed for the most critical isolated flaw, with similar results. The potential lack of conservativeness due to the neglected influence of the surrounding flaws on the calculated flaw, was largely compensated for by the over-conservativeness of the flaw grouping methodology.

There was another discussion concerning the values for the Pressurized Thermal Shock (PTS) transients. The SCP Review Team obtained clear answers from the Project Team, showing that the values used for the calculations were overly conservative and in accordance with the values used for accident calculations (values presented in the Final Safety Analysis Report).

Regarding the RT_{NDT} calculations, the Project Team was able to prove the existence of large margins, in part thanks to the mechanical test campaign performed by SCK•CEN (see Chapter 4.6).

Probabilistic safety integrity assessment

Based on its review of the probabilistic safety integrity assessment mentioned in the Safety Case, the SCP Review Team concludes that the 10CFR50.61 criteria regarding the Through-Wall Cracking Frequency (TWCF) were respected.

Originally, the SCP Review Team had questioned the original hypothesis for the calculation of the TWCF—taking into account the uncertainties—and the validity of the probabilities used to make such an analysis. The objective of the SCP Review Team was to ensure that sufficient margins were taken into consideration by the Project Team. The response of the Project Team regarding this subject was satisfactory.

4.6 Test Campaign

Tests conducted in two different laboratories revealed an important margin between the fracture toughness taken into account in the ASME code and the Doel 3 RPV material actual fracture toughness. The more than 400 tests have shown the absence of adverse local effects contributing to the fracture toughness, due to either the presence of segregated areas or the orientation effects.

The SCP Review Team agreed with the approach taken by the Project Team regarding the potential influence of irradiation on the material properties. Although no specific effect was shown identified during a past German test program (see Safety Case Report), the Project Team assumed the existence of such an effect of irradiation, linked to the enriched chemical composition of the segregated areas, and estimated its magnitude in terms of temperature shift. The resulting additional shift of 17°C on the RT_{NDT} is sufficiently covered by the conservative overall shift of 50°C taken into account by the Project Team for the Safety Case.

The SCP Review Team agrees that the ultrasonic inspection technique that uses beams perpendicular to the surface gives very good results regarding the detection, localization, and sizing of hydrogen flakes.

4.6.1 Scope of the Review

The Project Team test campaign aimed to provide and confirm input data for the structural integrity of the Doel 3 RPV. The SCP Review Team closely examined the following aspects:

- the test program
- the mechanical properties of representative RPV material in segregated areas
- the accuracy of flaw sizing using ultrasonic inspection
- the metallographic characterization of hydrogen flakes
- the representativeness and extrapolation of the results

To assess the rigour and quality of the test campaign, the SCP Review Team attended test meetings at the Laborelec laboratories, the Creusot Forging Shop, and SCK•CEN.

4.6.2 Conclusions

Test program

Mechanical tests

Based on the additional tests, which were requested by the SCP Review Team, the representativeness of the mechanical properties used in the Safety Case is considered adequate.

The SCP Review Team has reviewed the test program in term of its exhaustiveness and compliance with the objectives.

The test program has been carried out on the following non-irradiated materials :

- Spare surveillance material from the Doel 3 upper core shell
- A cut-out from Doel 3 nozzle shell with an identified segregation area
- AREVA nozzle shell cut-out H2BQ3 with an identified segregation area

During the test program review, the SCP Review Team recommended additional analyses, such as:

- Metallographic analyses on the Doel 3 cut-out, with optical investigations, micro-hardness measurements, carbon mapping, and electron-microscopy. The Project Team has conducted these analyses.
- Additional fracture toughness tests within the segregation areas in the T-L direction to complement the tests performed in the S-L direction. Fifteen additional tests have been performed by the Project Team at the SCK•CEN on the Doel 3 cut-out.
- Complementary tensile tests on samples including ghost lines (where hydrogen flaking is likely to occur). These tests have been conducted by the Project Team.

The SCP Review Team also recommended quality related precautions to be taken on the heat treatments to be performed on the Doel 3 nozzle cut-out to ensure representativeness of testing material.

Mechanical Properties

Flaws are located within segregated areas of the RPV. Segregated areas are formed through cooling and solidification of the molten metal within the cast ingots and have a chemical composition either higher (referred to as positive segregations) or lower (negative segregations) than the average composition in the bulk material.

These areas, typical for any forged piece, are the last ones in the ingot to solidify and contain a number of metallic and non-metallic inclusions.

Because of these differences in chemical composition, some of the steel mechanical properties may be affected locally. Such local mechanical properties include yield strength, ductility, ductile-to-brittle transition temperature (for which a conventional representation temperature is used - RT_{NDT}), and fracture toughness.

Since most hydrogen flakes are located in segregated areas, it was necessary to determine whether local effects needed to be taken into account for the specific assessment of the RPV mechanical properties used in the structural integrity assessment.

Fracture toughness
The SCP Review Team agrees that the fracture toughness evaluation methodology according to the ASME RT_{NDT} formulation is adequate to evaluate fracture toughness within segregated areas. The SCP Review Team agrees that the margin proposed by the Project is sufficiently conservative to cover local effects.

More than 300 fracture toughness tests have been performed through mid-November 2012 on different samples from the materials listed in "Test Program" above, with the objective of detecting any possible local effect within the material that could invalidate the application of the ASME RT_{NDT} approach to the structural integrity justification of the RPV.

The conclusions of these tests are the following:

- No adverse local effect, either of segregation or material orientation, has been detected on fracture toughness
- Fracture toughness estimated by the ASME RT_{NDT} approach is largely conservative, as all results show that the ASME RT_{NDT} approach has a margin of 25°C in terms of brittle-to-ductile transition temperature over the direct Master Curve approach of the tests.

The additional fracture toughness tests requested by the SCP Review Team (see above) confirmed the conclusion of no adverse local effect.

Irradiation effects
After review, the SCP Review Team agrees that no specific irradiation testing is necessary to evaluate the effect of irradiation on segregated areas of the Doel 3 RPV, other than the tests performed through the regular surveillance program and the existing analytical tools (FIS formula).

Steel irradiation induces embrittlement through modification of the metal crystal lattice. The steel becomes more fragile over time, which results in an increased yield strength and lower fracture toughness.

The results of the Doel 3 RPV base metals surveillance program are available and have demonstrated the high accuracy of the FIS formula to predict the RT_{NDT} shift after irradiation. In addition, direct fracture toughness tests (pre-cracked Charpy) have also been performed on the test specimen according to the Master Curve approach and further demonstrated the conservativeness of the ASME RT_{NDT} approach in irradiated conditions.

The SCP Review Team requested that the Project Team explain how cumulative effects of segregations and irradiation on fracture toughness would be taken into account. The Project Team responded that the FIS formula could be used to take into account this cumulative effect. Indeed, each material included in an area subjected to a known fluence has predictable behaviour. As segregations, ghost lines, and other impurities are local, the effect of irradiation on these areas can be predicted by taking into account their specific compositions. Two neighbouring areas can have different behaviour under irradiation, depending on the presence of specific known elements (phosphorus, nickel, copper).

As the chemical composition of the segregated areas has been shown to differ slightly from that of the bulk material, an additional RT_{NDT} shift can be calculated through the FIS formula (taking into account variation in the concentration of phosphorus, nickel and copper elements, as measured in the Doel 3 cut-out).

Yield strength and ductility
Complementary tensile tests in segregated areas and ghost lines in the Doel 3 cut-out requested by the SCP Review Team confirmed safe ductility margins.

Tests have shown a slightly higher yield strength in the segregated zone, which is not significant for the analysis. However, a significant reduction of ductility, consistent with results found in the literature on this matter, has been observed in one of the four tensile tests performed at SCK•CEN on Doel 3 cut-out sample (test performed on one sample at a temperature of -120°C).

In order to confirm the mechanical properties obtained from the 4 tensile tests, the SCP Review Team has required 6 additional tensile tests to be carried out in the segregated areas and ghost lines of the Doel 3 cut-out. These tests have confirmed a safe ductility margin and enable to neglect the significant reduction of ductility observed in one of the initial four tests (described above).

Accuracy of flaw sizing using ultrasonic inspection

The SCP Review Team witnessed several tests and can endorse the accuracy of the UT inspection.

The capability of the UT inspection to localize and size the defects had to be verified in terms of its consistency with the results of observations during the destructive tests on material containing the measured flakes. Destructive tests performed on hydrogen flakes also provided the opportunity to characterize the metallurgical aspect of the hydrogen flake structure and the surrounding base metal and, in particular, to verify the quality of the metal between the hydrogen flakes.

A block from a forged steam generator shell (VB395) rejected by the manufacturer (AREVA) because of hydrogen flaking was used in order to assess the accuracy of the UT L0° beam to detect and correctly size hydrogen flakes in the Doel 3 RPV.

This block was inspected using a qualified ultrasonic technique based on phased array sensors that simulate the L0° sensor and all other angled probes between -20° and 20°, and -45 and 45° as well, in order to accurately map the hydrogen flakes in terms of position and size.

In addition, destructive testing of 18 flakes was performed using a very precise electro erosion wire cutting technique, so that a mapping of the actual flakes could be done and compared to the mapping given by the UT inspection.

The UT inspection L0° sensor was found to be highly accurate in both positioning and sizing the defects. However, flake surfaces are slightly oversized by the UT inspection.

All flakes were detected by the L0° sensor, and while other angled sensors may better detect some nearly laminar flakes, all flakes were correctly detected with the L0° sensor, with high accuracy.

Metallographic examination of hydrogen flakes

The SCP Review Team witnessed several tests and observed that the metallographic examination supports the hypothesis made in the Safety Case.

In terms of metallographic examination of the flakes and the surrounding metal, the status of the metal between some close flakes has been investigated, and it has been confirmed that this material is sound. Inclusions are present on each flake, confirming the hypothesis that these inclusions constitute initiation sites for the flaking phenomenon that occurred during fabrication.

Representativeness and extrapolation of the results

The SCP Review Team estimates that the Doel 3 nozzle cut-out testing material can be considered as representative of the Doel 3 RPV shells' materials.

Regarding the representativeness of the test blocks for mechanical property testing, the Doel 3 surveillance sample blocks, as well as the Doel 3 nozzle cut-out, have been manufactured by RDM according to the same processes and heat treatments as the Doel 3 shells.

In addition, further metallurgical analyses and chemical composition characterizations have been carried out on the Doel 3 nozzle cut-out block. The results have shown that the cut-out structure is very likely to be similar to that of the other Doel 3 RPV shells: observed metallurgical features (very local tempered martensite, ghost lines, inclusions) are consistent with those of segregated areas where hydrogen flaking is likely.

The absence of flaking in the Doel 3 cut-out (confirmed by UT inspection) is most likely due to the difference in its hydrogen content upon fabrication (1.0 ppm measured by Krupp as opposed to 1.4 ppm and above in the affected shells), rather than significant metallurgical differences between the cut-out and the steel in the segregated areas.

The SCP Review Team observed that all tests have been conducted by accredited laboratories using calibrated equipment under strict quality assurance and traceability surveillance, performed independently by the different teams in charge within the Project Team, the SCP Review Team, and AIB Vinçotte as the Authorized Inspection Agency. Fracture toughness tests have been performed in two different laboratories–the SCK•CEN in Mol and AREVA in Erlangen—and have led to equivalent results and the same conclusions. These observations strengthen confidence in the test program results.

4.7 Margin Evaluations

The SCP Review Team noticed that the Project Team did not systematically track the safety margins or conservativeness in the different hypotheses. The Project Team therefore developed a deliverable called "Synthesis of conservative approaches and assumptions considered within the framework of the justification file". This deliverable identifies conservativeness at various levels (ultrasonic examination technique, deterministic structural integrity assessment, probabilistic structural integrity assessment) and categories (conservativeness of input data and of the applied methodology). After clarification given by the Project Team, the SCP Review Team has no additional comment.

4.8 Operational Measures

Although the Project Team safety case assessment revealed that all the criteria for an immediate and safe restart of the Doel 3 RPV have been met, Electrabel has committed itself to taking additional operational measures. The SCP Review Team considers this to be a good manifestation of the Electrabel Safety Culture and the defence-in-depth principle. In this way, the SCP Review Team advices to adapt the Technical Specifications concerning minimum RWST water temperature.

Additional operational measures are currently being implemented to increase the safety margins:

- Electrabel will reduce the authorized heat-up and cool-down rates during start-up and shut-down operations. This will reduce the Doel 3 RPV thermal and pressure load even more during normal operation.
- Guided by its nuclear safety culture, Electrabel has decided to pre-heat the Doel 3 safety injection water to 30°C. The Project Team having demonstrated that this measure is not necessary, given the results of the structural integrity assessment, it will nevertheless add a 20 % margin to the acceptable flaw size close to the vessel inner surface where the PTS is the strongest.
- Modifications to the Technical Specifications will be implemented to take into account the shift of the RT_{NDT} value and the 50°C margin.

The SCP Review Team advices Doel 3 NPP to include in the Technical Specifications the minimum value of the Safety Injection water temperature in the RWST of 30°C.

5 Additional Independent Analysis

Based on the characteristics of the UT signals, SNL concludes that the indications observed in the Doel 3 RPV are not related to open metal-to-air interfaces or voids. Instead, there are a number of observations that support the theory of hydrogen flaking as a plausible explanation for the observed discontinuities within the structure.

Regarding the mechanical evaluation of the RPV, SNL considers the Project Team assumption that the indications are true voids or flaws to be conservative from a mechanical evaluation standpoint.

Concerning the results of SNL Structural Integrity Analyses (SIAs): "*The results of these analyses would tend to indicate that configurations of flaws within the Doel 3 RPV that have similar characteristics to those investigated here, with a flaw size of up to 25 mm, out-of-laminar angle up to 20 degrees, and density up to 35 cracks/litre, will likely have sufficient margin against brittle fracture initiation under A/B transients. In addition, the same statement can be made for the flaws in those configurations that exist within the region of the RPV wall in which LEFM applies, under C/D transients."*
(LEFM: Linear elastic fracture mechanics, transients A/B: heat-up and cool-down, C/D: small/large Loss Of Coolant Accident (LOCA))

The results of SNL analyses, enable the SCP Review Team to assess the effect of a high flaw density, taking into account the limitation of the XFEM method used by SNL. This analysis increases the SCP Review Team confidence in the positive results of the detailed structural analyses performed by the Project Team.

SNL also acknowledged the pertinence of the additional operational measures in Doel 3, consisting in heating up the active safety water injection systems in order to reduce thermal shock.

5.1 Scope of the Independent Assessment

The SCP Review Team asked Sandia National Laboratories (SNL) to provide an additional independent assessment regarding:

- the nature and origin of the indications
- the structural integrity of the RPV with found indiactions

For the first topic, SNL analyzed the raw data from the UT inspections. For the second topic, SNL performed 2D and 3D analyses on their own resources, taking into account RPV design and applicable transients.

5.2 Conclusions

5.2.1 Nature and Origin of the Indications

Based on the characteristics of the UT signals, SNL concludes that "*the observed indications present in the Doel 3 RPV are not related to open metal-to-air interfaces or voids. Instead, there are a number of observations that support the theory of hydrogen flaking as a plausible explanation for the observed discontinuities within the structure*".

Sandia National Laboratories (SNL) compared the native signals (radio frequency signals) of the UT inspection performed on the Doel 3 RPV and on the AREVA VB395 shell containing flakes. This comparison proves a strong signal correlation between the RF signals from the Doel 3 RPV and the AREVA VB395 shell.

SNL considered that the applied UT technique and the data collection and inspection methodology are sound, thorough, and of the highest quality.

SNL recommends monitoring repeated UT inspection of the Doel 3 RPV identical as those carried out by AREVA in 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 conclusions regarding the absence of the indications' evolution in size, shape, and orientation.

5.2.2 Influence of the Flaws on the Structural Integrity of the Doel 3 RPV

Global approach

For the purpose of the mechanical evaluation of the RPV, the assumption was made that the indications are true voids or flaws. **The assumption of voids is conservative from the mechanical evaluation standpoint.** Nevertheless, this conservativeness is justified, given the extremely important role that the RPV plays in the reactor safe operation and in the containment of harmful radio nuclides during a potential accident.

A series of finite element analyses making use of the Extended Finite Element Method (XFEM) capability of the commercially-available general-purpose finite element code ABAQUS were performed by SNL. In these analyses, the indications from the UT inspections were assumed to be flaws. The assessment examined the flaw fracture initiation potential of a number of multi-flaw configurations.

XFEM

XFEM is a recent extension of the finite element method that enables the inclusion of step discontinuities in the displacement shape functions of a traditional finite element. The XFEM methodology also includes enrichment features that account for the $1/\sqrt{r}$ (where r is the radial distance) stress singularity at the flaw tip. Because the enrichment is based on the precepts of Linear Elastic Fracture Mechanics (LEFM) the XFEM method is restricted to situations satisfying LEFM assumptions

Flaw size and spacing characteristics

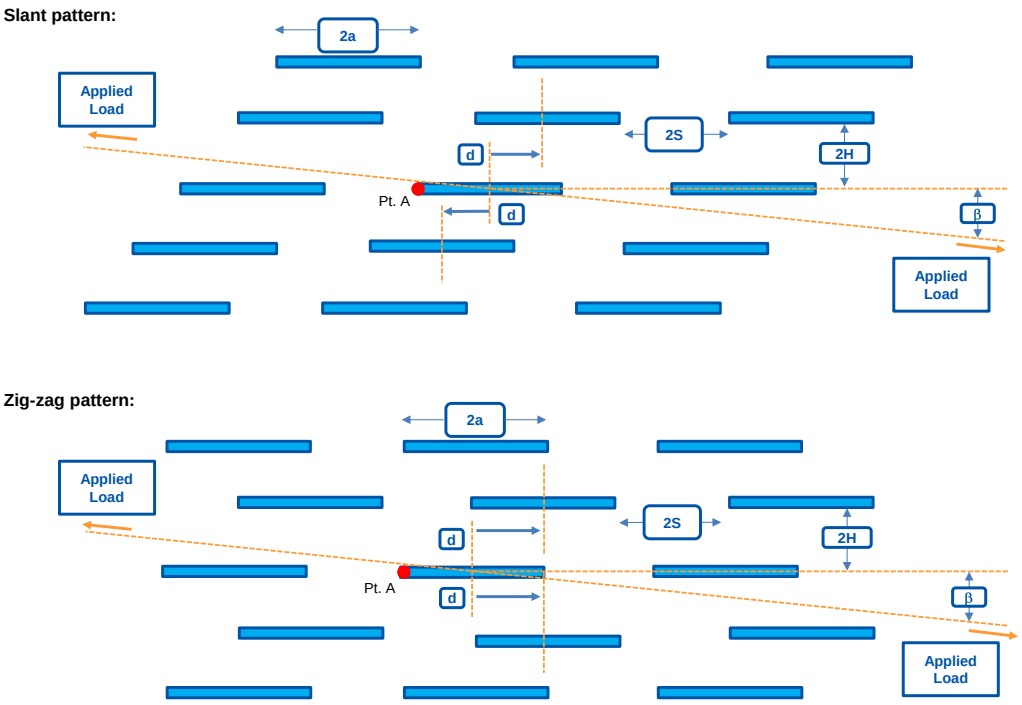
Based on the raw data of the UT inspection of Doel 3 RPV, SNL calculated the average representative dimensions: the median flaw diameter is approximately 11.5 mm, the median out-of-laminar flaw angle is 8 degrees, and the median flaw density is 9 flaws/litre. SNL used these median values as the basis for the standard configuration in their calculation. 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 degrees.

RPV fracture toughness

The RPV fracture toughness was determined using a methodology based on the requirements in ASME XI (1992). The mode I critical flaw fracture initiation and flaw arrest fracture toughness values in MPa$\sqrt{m}$ are computed as functions of the RT_{NDT}, which depends on the material composition (amounts of phosphorus, copper, and nickel) and the neutron fluence the material has received.

2D multi-flaw configuration study

Two-dimensional analyses involving a group of equally-sized, uniformly-spaced planar circular flaws were performed by SNL 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.



A group of 5 by 5 (25 in total) equally-sized flaws in various configurations was assessed. Two flaw patterns were investigated, slant and zig-zag (see Figure above). Four intra-row (within a single row) flaw spacings (S/a) were investigated: 0.5, 1.0, 1.5, and 2.0. For each intra-row spacing several inter-row shifts (d/a) were investigated that span the entire range of possible shifts.

3D multi-flaw assessment study

The results of the analyses performed by SNL enable the SCP Review Team to make a global assessment of the effect of high flaw density on the RPV structural integrity, taking into account the limitations of the XFEM method used by SNL. This analysis increases the SCP Review Team confidence in the positive results of the detailed structural analyses conducted by the Project Team.

Three-dimensional analyses involving Doel 3 equally-sized, uniformly-spaced, planar circular (penny-shaped) flaws in a segment of the Doel 3 RPV were performed by SNL to determine approximate limits on acceptable flaw size, flaw angle, and flaw density for equally-sized, regularly-spaced, round flaw configurations within the Doel 3 RPV. The most penalizing flaw configuration identified in the 2D multi-flaw configurations study was used. Two configurations (median and upper bound) were investigated with their respective flaw size, orientation, and density.

According to SNL, results from this analysis indicated that "*there is likely sufficient margin against brittle fracture initiation under A/B transients. In addition, the same statement can be made for the flaws in those configurations that exist within the region of the RPV wall in which LEFM applies, under C/D transients.*" (LEFM: Linear elastic fracture mechanics, transients A/B: heat-up and cool-down, C/D: small/large Loss Of Coolant Accident (LOCA)).

The SCP Review Team notices that the region where LEFM does not apply, is limited to a few centimetres in the inner part of the RPV wall whether or not the material is affected by flaws. The balance elastic material is able to withstand the residual pressure and weight loads.

6 Action Plan

The Action Plan clearly addresses mandatory operational measures and confirmatory test program on industrial material with flakes. The mandatory operational measures for restart are analyzed by local SCP at the site level and are not addressed in this report.

Concerning the confirmatory test program, the SCP Review Team agrees on the scope and schedule.

Concerning the UT inspections and qualification procedure, the SCP Review Team made some recommendations summarized in its Advice.

Future inspection program

The SCP Review Team agrees with the future re-inspections of the RPV, since this is the most obvious way to confirm the absence of flaw propagation as was shown in the Project Team analyses. Furthermore, flaw sizing is an input to the Structural Integrity Assessment of the RPV and must therefore be verified throughout the RPV lifetime.

The SCP Review Team recommends that the Project Team focus additionally on one-to-one tracking of the most critical flaws in the Doel 3 lower shell and on a few other selected large flaws. It will enable the confirmation of the Safety Case conclusions regarding the absence of the indications' evolution in size, shape, and orientation.

Qualification of ultrasonic testing procedure

The SCP Review Team agrees with the demonstration tests made by the Project Team that the MIS-B is capable and efficient in correctly localizing and sizing laminar or nearly laminar hydrogen flakes.

A formal qualification of the MIS-B equipment to detect hydrogen flakes can be performed in parallel to plant restart. The SCP Review Team also advises the Project Team to make use of this formal process to include the ability to confirm the absence of flakes evolution in size, shape and orientation.

Material testing

Early in the review process, the SCP Review Team recommended that the Project Team carry out a complementary test program on industrial material with hydrogen flakes to confirm the global performance of the methods used in the safety case. The SCP Review Team agrees with the scope of the confirmatory test program defined by the Project Team.

In conclusion, the SCP Review Team will actively monitor the implementation and results of the Action Plan.

7 List of Abbreviations

Abbreviation	Meaning
ASME	American Society of Mechanical Engineers
BEST	Belgian Stress Tests
CARE NS	CARE Nuclear Safety Department of Doel/Tihange site organization
DOE	United States Department Of Energy
ECNSD	Electrabel Corporate Nuclear Safety Department
FANC	(Belgian) Federal Agency on Nuclear Control
FIS	Fragilisation sous Irradiation Supérieure
LEFM	Linear Elastic Fracture Mechanics
LOCA	Loss of Coolant Accident
MIS-B	Machine d'Inspection en Service Belge
NPP	Nuclear Power Plant
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
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
SIA	Safety Integrity Assessment
SNL	Sandia National Laboratories
TWCF	Through-Wall Cracking Frequency
UT	Ultrasonic Testing
XFEM	Extended Finite Element Method