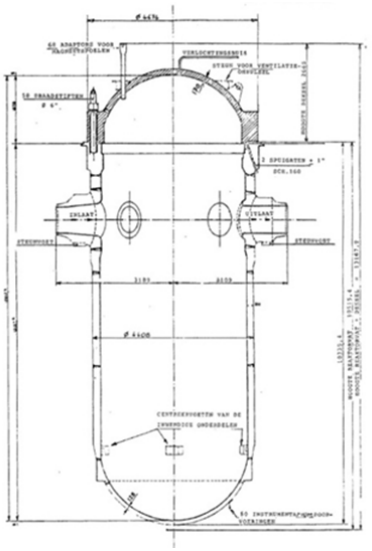

2013

Doel 3 – Tihange 2 RPV issue
International Expert Review Board
Final Report

Executive Summary

During the outage of the Doel 3 nuclear power plant in June 2012, an in-service inspection revealed the existence of numerous quasi-laminar indications in the reactor pressure vessel. Comparable, yet fewer, indications were found three months later in the Tihange 2 nuclear power plant after a similar inspection.

The International Expert Review Board was asked by The Federal Agency for Nuclear Control to conduct an independent assessment of the licensee's safety case in view of the future safe operation of the two power plants.
The Board has organized its assessment and recommendations to the FANC on three main topics: the origin and characteristics of the indications, the evolution in time of these indications, and the adequacy and appropriateness of the structural integrity assessment.

The Board has evaluated the licensee's safety case in-depth, keeping these three main issues in mind. Particular attention was focused on assessing the conservatisms of the claims made by the licensee on the various technical aspects of their evaluation. In general the Board agrees with the evaluation of the licensee that:

- The indications found in the RPVs of Doel 3 and Tihange 2 were identified as being, most likely, hydrogen flakes that were created during manufacture and can be attributed to macro-segregations in the reactor vessel steels.
- The indications have not grown significantly in the 30 years the plants were in operation and will not grow significantly in the future under normal operating conditions.

With respect to the issue of the adequacy and appropriateness of the structural integrity assessment, the Board finds the licensee’s safety case to be methodologically sound and consistent with current technological understanding. This assessment demonstrates that the vast majority of flaws are inconsequential to safety. For the limited number of indications and groups of indications identified as being the most structurally significant, the licensee demonstrated the continued operating integrity of both Doel 3 and Tihange 2, which are supported by the conservatisms inherent to the licensee’s calculations. In addition, the Board endorses the operational measures that were proposed by the licensee.

The Board, however, expresses some reservations concerning details of the safety case. The Board recommends to the FANC that the following issues should be addressed to strengthen the confidence in the licensee's safety case:

- A detailed assessment on the local (micro-scale) material properties is needed. The impact on the structural integrity assessment of the chemical composition in the ghost lines of the vessels' steel, the segregation along the grain boundaries of phosphorus, copper, carbon, etc. should be investigated in more detail. This issue is recommended to be covered by an appropriate sensitivity analysis before any decision on restart, and further reinforced later by additional material properties' measurements.
- In the short-term, a verification of the cladding integrity near the most structurally significant flaws should be performed. Additionally, it should be demonstrated that there are no surface connected flaws in the vicinity of non-inspected areas;
- The effect of thermal ageing should be taken into account in the structural integrity assessment;
- The effect of any residual hydrogen on the fracture toughness of the reactor pressures vessel steel has not been fully investigated. The Board suggests that this issue be addressed in the calculations for the structural integrity assessment as well as via dedicated experiments;
- A verification of the conservatism used in the treatment of the heat affected zone and the residual stresses of the cladding model in the structural integrity assessment is recommended.

The impact of these issues raised by the Board on the structural integrity assessment are more critical for Doel 3 than for Tihange 2 because the amount, the location, the size, and the inclination of the indications are all less significant for Tihange 2 than they are for Doel 3.

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Preface

During the 2012 outage at the Doel 3 nuclear power plant (NPP), specific ultrasonic (UT) in-service inspections were performed to check for underclad cracking in the reactor pressure vessel (RPV). No underclad defects were found but a large number of quasi-laminar indications were detected mainly in the lower and upper core shells.

A second inspection was performed in July with UT probes able to inspect the whole thickness of the vessel. This inspection identified a large number of such indications deeper in the material. An inspection performed in September at the Tihange 2 NPP showed similar indications but to a lesser extent.

As a consequence, the Doel 3 and Tihange 2 NPPs remained in cold shutdown while the licensee has performed an engineering evaluation to determine if either NPP can be safely returned to service.

In view of the unusually large number of indications found in Doel 3 and Tihange 2, the Federal Agency of Nuclear Control (FANC) has assembled a group of international experts in the fields of reactor vessel technology, non-destructive testing, fracture mechanics, ASME XI code evaluation, deterministic safety assessment, and probabilistic safety assessment.

The mission of this International Expert Review Board, hereafter named the Board, is to perform an independent review regarding the safe operability of the Doel 3 and Tihange 2 plants based on the information provided to the Board by the licensee. This document summarizes the recommendations of the Board, which are submitted to the FANC for its consideration.

Scope of this document

The scope of this review is restricted to the assessment of the quasi-laminar indications found in the forged rings of the two reactor vessels and focuses on the potential safety-related effects of these indications on the structural integrity of these RPV's. This review does not aim to consider other potential challenges to the reactor primary circuit integrity or to the safety of these NPPs in general.

The recommendations of the Board are based on the documentation provided by the licensee. The Board presumes that all information provided in these reports is correct, that the codes used to support the safety case are sufficiently qualified (verified and validated) and that the results of the computations in the reports are accurate.

The Board has had the opportunity to examine documents of the safety cases developed by the licensee, and to interrogate in depth the licensee's experts on issues likely to influence those RPVs' integrity as these may affect the final recommendation of the Board to the FANC. The Board unanimously wishes to express its appreciation for the tremendous efforts of the licensee to construct a consistent safety case for this first-of-a-kind safety issue, and to provide answers to the comments, questions and requests for clarifications that arose during the review of the licensee documents and the internal discussions held by the Board.

The recommendations summarized in this report have been formulated based on the information that was available on January 7th 2013. The Board was not able to take into consideration all information provided by the licensee after this date.

Structure of the report

The section of this document concerning *Analysis of the Safety Case by the Board* describes all the aspects that were considered to be important to the Board for the formulation of its recommendation regarding the operability of the units.

The Board has organized its assessment and recommendation to the FANC into three main topics:

Topic 1: Origin and characteristics of the indications

What is the origin of the indications observed in the Doel 3 and Tihange 2 RPVs? Is their characterization by non-destructive evaluation of acceptable accuracy?

Topic 2: Evolution of the indications

Have these indications grown during the 30 years of plant operation? Is future growth of the indications expected?

Topic 3: Adequacy and appropriateness of the Structural Integrity Assessment

Given the large number of quasi-laminar indications, can these plants be restarted and operated in a safe manner? Are the safety margins with respect to the structural integrity assessment during normal operation and postulated accident scenarios acceptable? Has the evaluation been performed in a manner consistent with current technological understanding and internationally acceptable practices?

The analysis of the safety case by the Board is structured in such a way that for each topic the claims of the licensee are first summarized, after which the analysis of the Board on that specific topic is given.

Analysis of the Safety Case by the Board

Topic 1: Origin and characteristics of the indications

Synopsis of the claims by the licensee

Following the unexpected observation of these indications, the licensee has conducted an in-depth investigation on all reports documenting the manufacture of the forged rings from which the RPV core shells are constructed, from the pouring of the ingots to the final acceptance of the different rings and parts of the vessel by the licensee. These documents demonstrate that all parts were poured, forged and inspected according to the codes and standards that were applicable at the date of their manufacture (i.e. the mid 1970s). During manufacture, several indications were found in different parts of the RPV but were determined to be within acceptable limits.

The inspection program carried out in 2012 was intended to determine if underclad cracks existed in the Doel 3 and Tihange 2 RPV's. While no underclad cracks were detected, numerous quasi-laminar indications were observed, these being concentrated in the upper and lower core shells of the vessels with a total of about 8500 and 2000 for the Doel 3 and Tihange 2 RPVs, respectively. The UT inspection reports conclude that the indications are quasi-laminar, are located within the first 120 mm of the vessel starting from the interface of the RPV with the austinitic cladding and having an increasing concentration between 10 and 50 mm depth; their typical dimension is 10 mm. A root cause analysis has been carried out by the licensee and its partners, complemented with a literature survey, to identify the origin and nature of these indications. According to these investigations, the observed indications are hydrogen flakes that were created during manufacturing. The literature survey ruled out almost all other types of known defects because their characteristics do not match those found in the two subject RPV's. For those defect types that were not completely ruled out, it is argued that hydrogen flaking represents the worst case with respect to the impact on potential crack propagation, and is therefore conservative.

Several arguments are provided to explain why the indications can be characterized as being hydrogen flakes. The shape of the indications and the fact that these are

quasi-laminar are characteristics of hydrogen flakes that have been seen in heavy section steel forgings used in other industries. The location of the indications can be attributed to the existence of macro-segregations, which are typical of forgings made from large ingots. The case for hydrogen flaking being the root-cause of the quasi-laminar indications is further strengthened since the manufacturing archives show no evidence of a dedicated dehydrogenation process and the concentration of hydrogen in the base material before forging was shown to be sufficient to cause flaking.

The licensee has conducted a set of tests and measurements on a block extracted from a steam generator shell owned by AREVA known to contain numerous hydrogen flakes (block designation: VB395/1). One of the objectives of these tests was to confirm the capability and performance of the UT inspection techniques used in Doel 3 and Tihange 2 to correctly detect and size hydrogen flakes. This step was viewed as necessary because the NDE (Non-Destructive Evaluation) inspection technique used on Doel 3 and Tihange 2, while representing best- and sound-inspection practices, are not yet formally qualified for quasi-laminar indications. Destructive tests validated the licensee's claim that the defects can be detected and sized accurately. The destructive evaluation of block VB395/1 showed that the size of the defects is over-estimated by NDE in most cases, while the size of the corresponding ligaments between the defects is consequently under-estimated by NDE. Both of these factors constitute conservatisms when they are included in the structural integrity analysis, which is discussed in a later section of this report.

Assessment by the Board and recommendations to the FANC

The discrepancy between the indications reported in the acceptance reports of the rings from the 1970s and in the 2012 inspection in the core shells of the two plants remains unresolved, since the UT technology available at that time should have had the capacity to detect the indications found. Furthermore, it is documented that some other parts, like the transition rings, were rejected exactly because of these hydrogen flakes.

Despite these questions, the Board is convinced that the indications found are most likely related to hydrogen flakes that were created during manufacturing of the vessel.

The Board had some concerns regarding the transferability of the data received from the UT inspections on the VB395/1 steam generator shell block to the results retrieved from the Doel 3 and Tihange 2 vessels. The UT equipment used to characterize the indications in the steam generator shell is not the same as for the inspection of the vessels and the boundary conditions are different (absence of cladding, no immersion in water).

However, despite these differences, the Board believes that the destructive evaluation performed on Block VB395/1 provides reasonable and appropriate assurance that the quasi-laminar indications in Doel 3 and Tihange 2 have been appropriately located and sized. Additionally, the Board notes that the licensee has committed to qualify the inspection technique in Doel 3 and Tihange 2 to the ENIQ (European Network for Inspection and Qualification) procedure, and use this qualified technique to re-inspect both vessel shells at the end of the first fuel cycle following re-start. The Board views these commitments as being both prudent and appropriate contributors to the operating safety of these NPPs.

In closing, the Board notes that there are some areas of the vessels (e.g., under the brackets) that have not to date been inspected. These should be accounted for in the safety analysis.

Topic 2: Evolution of the indications

Synopsis of the claims by the licensee

Based on an extensive literature survey on crack propagation mechanisms it is concluded that future propagation of the observed indications can only be caused by low-cycle fatigue. The licensee ruled out most crack propagation mechanisms (creep, swelling, corrosion...) because the combination of applied stresses, operating temperatures and irradiation doses were deemed to be insufficient to cause crack propagation. Additionally, the observed orientation of the indications is not consistent with that exhibited by any of the proposed crack growth mechanisms. Hydrogen-related crack propagation mechanisms are ruled out as it was demonstrated that the originally trapped hydrogen, that is suspected to have caused the observed indications, has diffused out of the base material as a result of pre-service heat

treatments and in-service conditions. The possibility for in-service hydrogen was assessed: it was shown that hydrogen concentrations would not be sufficient to cause hydrogen related crack propagation and it is furthermore not in agreement with the observed distribution of the flaws in terms of size and location.

The premise that low-cycle fatigue is the only credible mechanism for crack growth has been studied in detail. The conclusion of this assessment, according to the rules of ASME XI, is that the growth of the laminar defects (a) was not significant in the past 30 year operating period, and (b) will not be significant in the remaining time of plant operation.

Assessment by the Board and recommendations to the FANC

These arguments are acceptable and the Board agrees that the non-evolution in time of these indications is very likely justified.

Nevertheless the Board advises a dedicated follow-up program to monitor the size of at least the most adverse indications, namely the largest ones closest to the inner side of the vessel wall and the areas with pronounced concentrations of flaws.
The Board notes that the licensee has agreed to perform such follow-up inspections beginning at the first refuelling outage following restart.

In the Board's view, one of the most convincing arguments supporting the licensee's contention of the non-evolution of the defects during the lifetime of the vessels is that after 30 years of operation these defects are still characteristic of hydrogen flakes (i.e., generally round in shape and oriented along lines of known metallurgical segregations in the forging). These characteristics are consistent with observations made in steels that have not been subjected to the in-service conditions of the affected reactor vessels and that are known, based on destructive evaluations, to contain hydrogen flakes.

Topic 3: Adequacy and appropriateness of the Structural Integrity Assessment

Synopsis of the claims by the licensee

An extensive experimental program has been performed by the licensee in collaboration with specialized laboratories to estimate the mechanical properties of

the RPV steel in the region of the hydrogen flakes, in particular to take into account the effects of segregation, irradiation and the orientation of the flakes. Based on this program, the licensee concluded the following:

- Effect of segregation: From data available from external sources and results from dedicated experiments, the licensee concluded that there was no effect of macro-segregation on RT_{NDT} (Reference Temperature for Nil Ductility Transition); the toughness of the region of bulk macro-segregation in which the hydrogen flakes were located were found to be essentially the same as that in regions of nominal composition. There was thus no need to add an allowance to the RT_{NDT} values to account for segregation in the Doel 3 and Tihange 2 RPVs because these values had been measured before service in the regions of nominal composition.
- Effect of crack orientation: The dedicated experiments also demonstrated that crack orientation produces no effect on toughness that can be distinguished from the scatter inherent to the data. It should be noted that the tests used to make this determination were replicated at a number two-times or greater than that required by the applicable ASTM (American Society for Testing and Materials) standard.
- Effect of irradiation: The effect of irradiation is quantified by tests conducted as part of the licensee's surveillance program. These tests show a relatively modest effect of irradiation due to the low copper content of the forgings and the welds in both Doel 3 and Tihange 2. The licensee has demonstrated that the irradiation effects are conservatively bounded by the FIS (Formule d'Irradiation Supérieure) formula, which is used in the licensee's assessment. However, the surveillance program was carried out on material from the region of nominal composition. The estimated shift (using the FIS formula) for the estimated composition in the regions of macro-segregation showed that the effect of segregation on irradiation shift is no larger than 17 °C.

The licensee has adopted an additional RT_{NDT} shift of 50 °C in the structural integrity calculation to account for the combined effect of the above factors. This is claimed to be a conservative approach, adding 33 °C more than is necessary, since only the effect of segregation on irradiation sensitivity (17 °C) need be taken into account.

Using this information on the mechanical properties of the vessel steel the licensee performed the following calculations to assess the structural integrity of Doel 3 and Tihange 2:

- A primary stress assessment using ASME Section III Subsection NB-3000 rules
- A critical flaw size assessment using rules based on ASME Section XI. This assessment was validated using three dimensional finite element calculations.
- Assessment of pressurized thermal shock (PTS) using rules from the USA (10 CFR 50.61 and 10 CFR 50.61a).
- An assessment of the adequacy of the cold overpressure protection system

The licensee performed a primary stress assessment according to ASME III Subsection NB-3000, taking into account the reduction of the load-bearing cross-section of the RPV by the detected hydrogen flakes. These calculations demonstrate that both RPV's meet the requirements of this Subsection, although this calculation assumes that the specified material properties are met in all ligaments between indications.

The licensee also performed an assessment of critical flaw size in Doel 3 and Tihange 2 in a manner consistent with the principles of fracture mechanics and the provisions of Section XI of the ASME Code. In order to perform this assessment the licensee needed to develop a procedure taking explicit account of the angle of the indications, their embrittlement level, and their proximity to one another. With regards to proximity the licensee developed a grouping criterion based on extensive 2D finite element analysis of two flaws. The significant conservatism inherent to this procedure (over-estimating the applied stress intensity ($K_{applied}$) factor by at least 1.7-times) was demonstrated by 3D finite element analysis of a number of the most critical indication groupings. These analyses considered both normal operation (heat up – cool down) conditions as well as postulated accident (small break loss of coolant accident (SBLOCA) and large break loss of coolant accident (LBLOCA)) conditions. These analyses demonstrate that no indication, or indication grouping, in either Doel 3 or Tihange 2, reaches the critical flaw size. In Doel 3 only six indications, or indications groupings, exceed 60% of the critical size, and the overwhelming majority of the

indications, or indications groupings, are below 20% of the critical size. In Tihange 2 the flaws are smaller, all being less than 40% of the critical size.

The licensee has demonstrated conformance to the requirements of 10 CFR 50.61 (the PTS rule) by calculating a sufficient margin of the RT_{NDT} with respect to the embrittlement limits for PTS in 10 CFR 50.61.

As a further demonstration of the structural integrity of the pressure vessel and, although not legally obliged to do so, the licensee has also performed a probabilistic PTS analysis, based on the methods used in the development of 10 CFR 50.61a. The analysis was performed by integrating the conditional probability for crack initiation with the probability of each PTS transient. This analysis includes several conservatisms:

1. The number of indications assumed in this analysis exceeds the number of indications found in Doel 3 and Tihange 2 by a considerable margin. The margin is highest (≈30x) for the largest, and therefore the most structurally significant, indications.
2. The fracture driving force on the flaws is estimated based on axial and circumferential projections of the flaws rather than based on their actual orientation in the RPV. The licensee has demonstrated the considerable conservatism of this approach (typically a factor of 2x to 4x on critical flaw size)
3. The acceptance metric adopted (crack initiation with no credit for warm pre-stress) is significantly conservative relative to the acceptance metric adopted by the United States Nuclear Regulatory Commission in the development of 10 CFR 50.61a (i.e. the through wall cracking frequency).

Even including these significant conservatisms, these calculations showed that the estimated frequency of crack initiation is two orders of magnitude lower than the acceptance criterion defined in 10 CFR 50.61a.

The fracture toughness requirements for protection against cold over-pressurization of the vessels were also analysed. A modification of the technical specifications is

proposed by the licensee to address, with conservatism, the effect of segregations by adding an additional RT_{NDT} shift of 50 °C.

Assessment by the Board and recommendations to the FANC

On request of the Board, the licensee has submitted a dedicated assessment of the conservatisms used in all documents. Based on this and its own discussions the Board notes that the licensee's assessment is conservative in most respects, and wishes to note the following factors that it considers to be most significant:

- Some questions will be later raised regarding the appropriateness of the RT_{NDT} values used by the licensee. It should be noted that these questions are relevant only when the driving force to fracture exceeds the lower bound value of crack-initiation fracture toughness, which is well established as being no lower than 20 MPa√m in RPV structural steels regardless of the degree of embrittlement (i.e., RT_{NDT} shift) that has occurred by any mechanism. Calculations performed by the licensee demonstrated that values of driving force above 20 MPa√m exist for only two indication groupings and two individual indications, all in Doel 3. Thus, the Board views the vast majority of the quasi-laminar indications found in Doel 3 and Tihange 2 as inconsequential to RPV fracture.
- The licensee's assessment uses RT_{NDT} (a correlative parameter) as a transition index temperature rather than RT_{To} which provides a direct and accurate measurement of fracture toughness. Reference measurements made by the licensee confirmed general experience that use of RT_{NDT} instead of RT_{To} most usually produces a margin, which is un-credited in the safety case. This margin is explicitly demonstrated for the Doel 3 upper core shell, but is negligible for the Tihange 2 upper core shell. For the lower core shells of both reactors there are no direct data.
- One of the pillars of this safety case is the accuracy of the UT results for the identification of the size and location of the flaws. As some of the most critical flaws are very close to the inner surface of the vessel, hence with a small ligament, the Board believes it is important to demonstrate that uncertainties associated with the positioning of these flaws relative to the inner surface of the vessel do not compromise the robustness of the safety case. By performing a sensitivity study, the licensee has demonstrated that the

conclusions of the structural integrity assessment are still valid even if the most critical flaws found in Doel 3 were assumed to exist at the interface between the cladding and the base metal (i.e., have no ligament). This increases the Board's confidence in the fact that, even if underclad cracks had been missed by the UT tests or if they happened to exist at the non inspectable zones beneath or around the welds or to develop and connect to nearby flaws during the potential future operation of the plant, these situations are still covered by the present safety case.

These factors notwithstanding, the Board expressed reservations regarding the safety case in the following respects:

- *Phosphorus, Ghost Lines, and Ageing*: The local chemical composition of the so-called 'ghost lines', which can be attributed to segregations, might be higher than assumed (for example a 35% enhancement of the bulk phosphorus content). This would increase the irradiation shift calculated using the FIS formula (which depends on both phosphorus and copper) and might also increase the unirradiated value of RT_{NDT} in these regions by phosphorus segregation to grain boundaries during heat treatment or aging in service. The overall effect of the enhanced segregation in the ghost lines may be substantially greater than the 17 °C allowance used by the licensee.
- *Hydrogen*: There is currently a lack of experimental data quantifying the effects of the hydrogen related defects on the mechanical properties.
- *Completeness of Inspection*: The Board notes that the area under the brackets has not been inspected. These brackets are welded with inconel, which is known to be prone to cracking and therefore might represent a location that requires additional consideration.
- *Cladding Model*: The safety case did not consider the effects of residual stresses or the heat affected zone produced by the cladding.
- Transferability of these data to the Doel 3 and Tihange 2 vessels relies on an additive combination of various separate effects (i.e. segregation, orientation, irradiation). While such an approach is commonly used in various industries (including the nuclear industry), it is noted that no single test combining all

potential influencing effects that could be detrimental to RPV structural integrity has yet been performed. Moreover, the investigations could not be carried out on material that can be proven to be fully representative for the materials in the region of the indications, and the effect of thermal ageing has not been accounted for.

Recommendations and conditions to address these concerns are made in the following section.

Conclusions and recommendations of the Board regarding the operability of the Doel 3 and Tihange 2 NPP's

Subject to conditions listed below, the Board finds the licensee's safety case to be sound and consistent with current technological understanding, demonstrating the continued operating integrity of both Doel 3 and Tihange 2. Of these conditions, the Board's view is that only the second under the heading *"Phosphorus, Ghost Lines, and Aging"* need be accomplished before restart. In view of the many conservatisms inherent to the safety case and the low magnitude of fracture driving force for most flaws it is, in the Board's view, acceptable for all other conditions to be fulfilled within a short time after restart.

- *Phosphorus, Ghost Lines, and Ageing*
    1. Considering unresolved issues regarding the representativeness of the materials used in the mechanical tests, the Board has requested more detailed information on the local (micro-scale) material properties. To be specific, the chemical composition (i.e. phosphorus, copper, nickel, and other key elements) in the ghost lines, and the segregation or desegregation of these elements at grain boundaries within these and reference regions of the base material should be investigated experimentally in more detail. Depending on these results the effect of composition on the local mechanical properties (i.e. fracture toughness) should also be quantified.
    2. In view of the potentially large increase in RT_{NDT} that may be revealed by the tests just described, the Board recommends that before restart, a sensitivity study be performed using a RT_{NDT} shift up to 100 °C (instead of 50 °C used in the current calculations) to take into account the uncertain effect of the segregation of chemical impurities and other uncertain effects. It is the Board's view the successful outcome of such a sensitivity analysis provides assurance of the continued operating safety of these reactors while the necessary experiments are being conducted.
    3. The Board requests that the effect of aging is taken into account in the structural analysis. The licensee has provided some information to the

Board, although it was estimated by the Board to be insufficient. The Board suggests that the effect of aging could be estimated by performing step cooling experiments on representative material, to be followed with the standard mechanical properties tests.

- *Hydrogen*
    1. The licensee has estimated an upper bound on the amount of residual hydrogen that might still be present in the flaws. The Board would like the licensee to demonstrate that the conclusions of the structural integrity assessment are still valid, even if the upper bound quantity of hydrogen would still be present in critical flaws. The Board also requests a longer-term study by cracking flaws of a sample from the AREVA shell in a vacuum chamber, using a spectrometer allowing to detect any trace of residual hydrogen.
    2. The effect of the hydrogen flakes on the local fracture toughness should also be investigated in more detail. A suggestion by the Board is to conduct an appropriate bending test on a sample with a slightly inclined flaw. This should be representative of a mixed K_I and K_{II} mode of loading, which is similar to the actual loading in the Doel 3 and Tihange 2 RPV's.
- *Completeness of Inspection*: The licensee should ensure that the cladding in the vicinity of the most significant flaws is intact. Further, the licensee should demonstrate that there are no quasi-laminar or surface connected flaws in the vicinity of the non-inspected areas, e.g. under the brackets.
- *Cladding Model*: The licensee should verify that the effects of the heat affected zone and potential residual stresses are conservatively treated in the structural integrity assessment

The Board would like to stress that the impact of these issues on the structural integrity assessment are more critical to a restart decision for Doel 3 than for Tihange 2 because of the amount, the location, the size and the inclination of the quasi-laminar indications is less severe in Tihange 2.

In addition to the future successful resolution of these conditions, the Board would like to note that various measures that have been proposed by the licensee will

enhance the operating safety of the NPPs. The Board endorses these measures, which include the following:

- Reduction of the maximum allowed normal cooldown rate
- Heating of the water in the Doel 3 refueling water storage tank to a year-round temperature of 30 °C.
- Formal qualification of NDE techniques applying the ENIQ procedure to detect quasi-laminar flaws.
- Use of these qualified NDE techniques during future refuelling outages to determine if the quasi-laminar indications are increasing in size.
- Continuing respectively introducing a neutron fluence reduction program to minimize further material embrittlement until clarification is achieved on the other issues.

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Acronyms

ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CFR	Code of Federal Regulations
ENIQ	European Network for Inspection and Qualification
FANC	Federal Agency for Nuclear Control
FEM	Finite Element Modelling
FIS	Formule d'Irradiation Supérieure
LBLOCA	Large Break Loss Of Coolant Accident
NDE	Non-Destructive Evaluation
NPP	Nuclear Power Plant
PTS	Pressurized Thermal Shock
RPV	Reactor Pressure Vessel
RT_{NDT}	Reference Temperature for Nil Ductility Transition
SBLOCA	Small Break Loss Of Coolant Accident