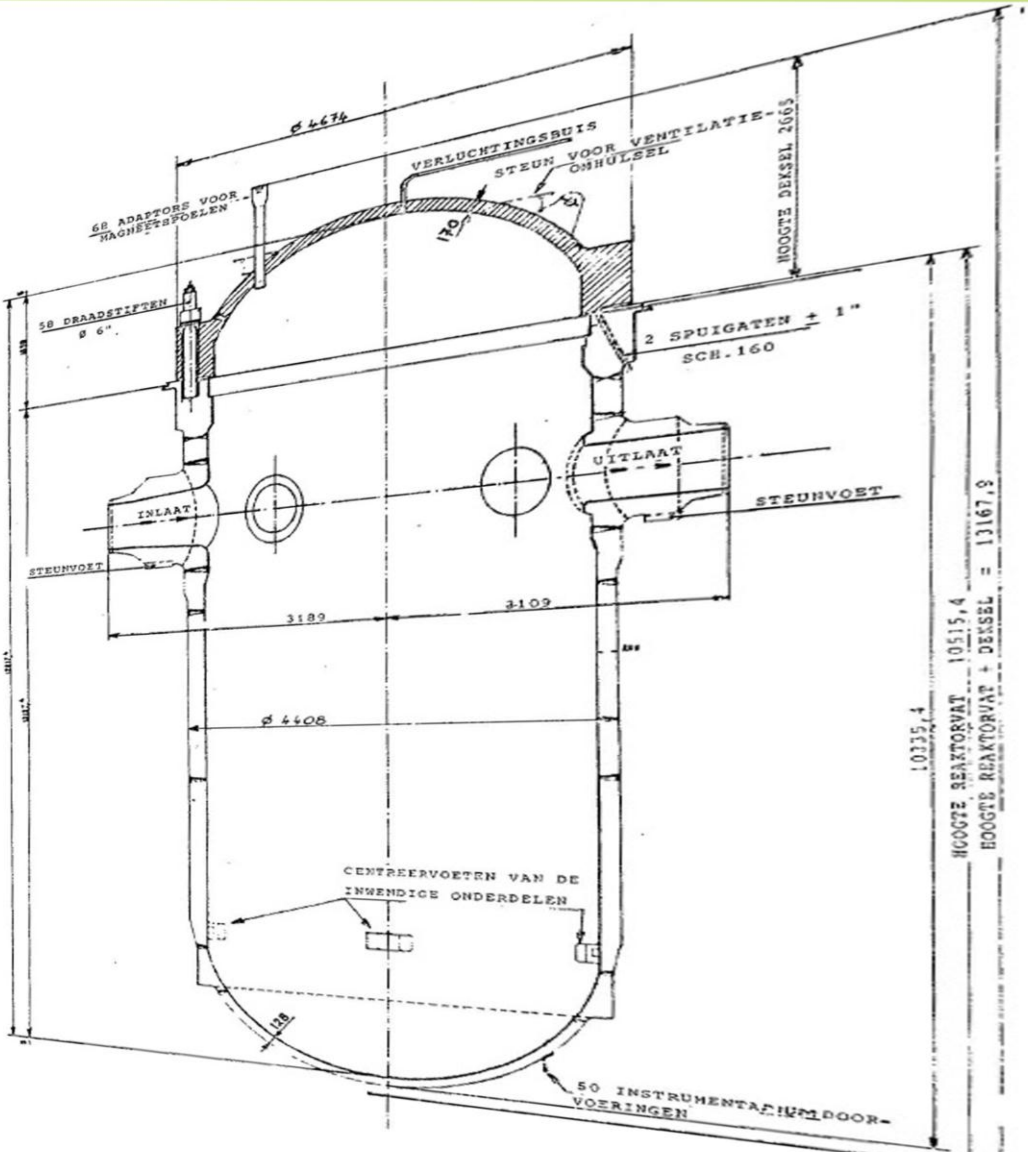
Doel 3 and Tihange 2 reactor pressure vessels

Provisional evaluation report



FANC
federal agency for nuclear control

30 January 2013

Contents

1. Summary

Doel 3 and Tihange 2 are two of the seven Belgian nuclear reactors operated by Electrabel, a GDF-SUEZ Group company.

In June 2012, during a new type of in-service inspection conducted for the first time in Belgium, several thousands of flaw indications were detected in the base metal of the Doel 3 reactor pressure vessel, located mainly in the upper and lower core shells. As a precaution, similar inspections were conducted in September 2012 on the Tihange 2 unit, whose reactor pressure vessel is of identical design and construction. Flaw indications were detected as well, but to a lesser extent.

The pressure vessel is a key-component in a reactor unit, and its failure is not covered by safety studies. As a result, the licensee decided to keep both units in cold shutdown state, core unloaded, until in-depth analyses have been achieved and submitted to the Federal Agency for Nuclear Control (FANC) in view of a possible restart of the operation.

With the support of internal and external experts, the licensee started an investigation of the precise nature and origin of these indications, and built its own analysis to determine whether or not the reactor units in question could safely resume operation in spite of the detected flaws. The demonstration of the licensee was recorded in two safety case reports and backed by a number of technical documents, leading the licensee to conclude that both Doel 3 and Tihange 2 reactor units were eligible for immediate restart. In parallel, the licensee also proposed several additional measures designed to further increase the safe operation of the units, to monitor the pressure vessels state along time or to extend its initial material testing program.

Meanwhile, the FANC built up a dedicated organisation and commissioned several national and international expert groups to seek scientific and technical advice in order to elaborate an independent, founded and balanced judgement about the issue.

Along the assessment process, the expert groups raised a number of questions that were discussed with the licensee and its technical supports. From those discussions, a number of open issues were raised about the manufacturing of the reactor pressure vessels, the suitability of the in-service inspection technique, the possible evolution of the flaws during future operation, the characterization of the material properties, and the structural integrity of the reactor pressure vessels under penalizing loadings. The conclusions of each expert group on the open issues in question were discussed in a plenary assembly on 8 and 9 January 2013.

In the current state of knowledge and given the available data, these open issues do not represent conditions that require a definitive shutdown of the Doel 3 and Tihange 2 reactor units.

However, these open issues lead to some uncertainties that might reduce the conservatism of the licensee's safety demonstration and hence impair the level of confidence in the safe operability of the reactor units in question. As a consequence, the Federal Agency for Nuclear Control considers that, in the current state, the Doel 3 and Tihange 2 reactor units may only restart after the requirements listed in the present evaluation report are fulfilled by the licensee.

The licensee shall elaborate an action plan to meet those requirements, including a methodology and associated acceptance criteria where applicable. This action plan shall be approved by the Belgian nuclear safety authority.

Once the licensee has implemented its action plan, the FANC, together with Bel V and AIB-Vinçotte, will evaluate whether all the safety concerns at the origin of the requirements are solved and whether the related reservations can be lifted. On this basis, the FANC will motivate its decision about the possible restart of the Doel 3 and Tihange 2 reactor units in a subsequent final evaluation report.

This position applies only to the Doel 3 and Tihange 2 reactor units and does not extend to other nuclear reactors potentially concerned elsewhere in the world. The evaluation of their safety remains within the jurisdiction of the competent national authorities.

2. References

[1] Safety case report
Doel 3 Reactor Pressure Vessel Assessment
Electrabel
5 December 2012

[2] Safety case report
Tihange 2 Reactor Pressure Vessel Assessment
Electrabel
5 December 2012

[3] Report on independent analysis and advice regarding the safety case
Doel 3 Reactor Pressure Vessel Assessment
Electrabel
19 December 2012

[4] Report on independent analysis and advice regarding the safety case
Tihange 2 Reactor Pressure Vessel Assessment
Electrabel
19 December 2012

[5] Report of the National Scientific Expert Group on the RPVD3T2
National Scientific Expert Group
11 January 2013

[6] Scientific Council of 21 December 2012
Doel 3 and Tihange 2 Reactor Pressure Vessel Indications issue
Scientific Council of ionizing radiation established with the Federal Agency for Nuclear Control
21 December 2012

[7] Doel 3 - Tihange 2 RPV issue
International Expert Review Board report
International Expert Review Board
15 January 2013

3. Safety concern

3.1 Context

Doel 3 and Tihange 2 are two of the seven Belgian nuclear reactors operated by Electrabel, a GDF-SUEZ Group company. Table 1 gives the dates of the main phases of the lifecycle of the two units:

Phases of the reactor units lifecycle	Doel 3	Tihange 2
Start of construction	1975	1975
First connection to the national grid	1982	1983
Replacement of steam generators and power increase	1993	2001
Scheduled date for end of operation	2022	2023

Table 1 – Dates of the main phases of the lifecycle of Doel 3 and Tihange 2

In June 2012, during a new type of in-service inspection conducted for the first time in Belgium, as part of the planned outage of the Doel 3 reactor unit, flaw indications[1] were detected in the reactor pressure vessel. The location, number, density and size of these indications caused the licensee and the Belgian nuclear safety authority to extend the outage period for this unit until further notice in order to assess whether the safe operation of the reactor could still be guaranteed.

Similar inspections were conducted in September 2012 on the Tihange 2 unit, whose reactor pressure vessel is of identical design and construction. Flaw indications were detected here too. Therefore, the unit was also maintained in cold shutdown state (core unloaded).

The licensee Electrabel started an investigation of the precise nature and origin of these indications. Their potential impact on the structural integrity of the reactor vessels was discussed in two safety case reports [1][2] and two independent review reports [3][4], which were presented respectively on 5 December 2012 and 19 December 2012 to the Belgian nuclear safety authority for evaluation.

The present evaluation report aims to set out the details of the problem, present the results of the analyses and support the conclusions of the Belgian nuclear safety authority regarding the possible restart of the two affected Belgian reactor units. In order to provide a self-standing evaluation report, the relevant information supplied by the licensee in its safety case reports is recalled where needed.

[1] The ASME code uses the following definitions:

- Indication: The response or evidence from the application of a non-destructive examination. An indication is an elementary record or set of records indicating the possible presence of a flaw. The definition of an indication is directly linked to the type of flaw (nature and size) which is aimed at in a given examination.
- Flaw: An imperfection or unintentional discontinuity which is detectable by a non-destructive examination.
- Defect: A flaw (imperfection or unintentional discontinuity) of such size, shape, orientation, location, or properties as to be rejectable. A defect is a flaw that is defined as rejectable by a code or specification. While all defects are flaws, not all flaws are defects.

3.2 Importance of the reactor pressure vessel

The Doel 3 and Tihange 2 units are pressurized water reactors. Each unit has a primary circuit (also called reactor coolant system), one of the main elements of which is the reactor pressure vessel. The pressure vessel contains the reactor core, where heat is generated by nuclear fission reactions. The water of the primary circuit circulates through the reactor core where it is heated. It then transfers its heat to the secondary circuit in the steam generators before returning to the reactor. In operation, the pressure of the primary circuit is maintained at approximately 155 bar and the temperature of the primary water at approximately 300°C.

3.2.1 Description of the reactor pressure vessel

The pressure vessel of a nuclear reactor consists of a vessel body and a vessel head.

At Doel 3 and Tihange 2, the pressure vessel (including the vessel head) is approximately 13 metres in height with an outer diameter of 4.4 metres for a total weight of 330 tonnes. The pressure vessel is made of thick low-alloy steel (up to 20 cm thick for the cylindrical portion of the vessel). The main components (core shells, flanges and nozzle shells – see Figure 1) are the result of operations of metal forging and machining. These parts are welded together and protected from corrosion by means of a thin coating of stainless steel (a few millimetres thick, called ”cladding“), fixed by welding on the inside of the vessel.

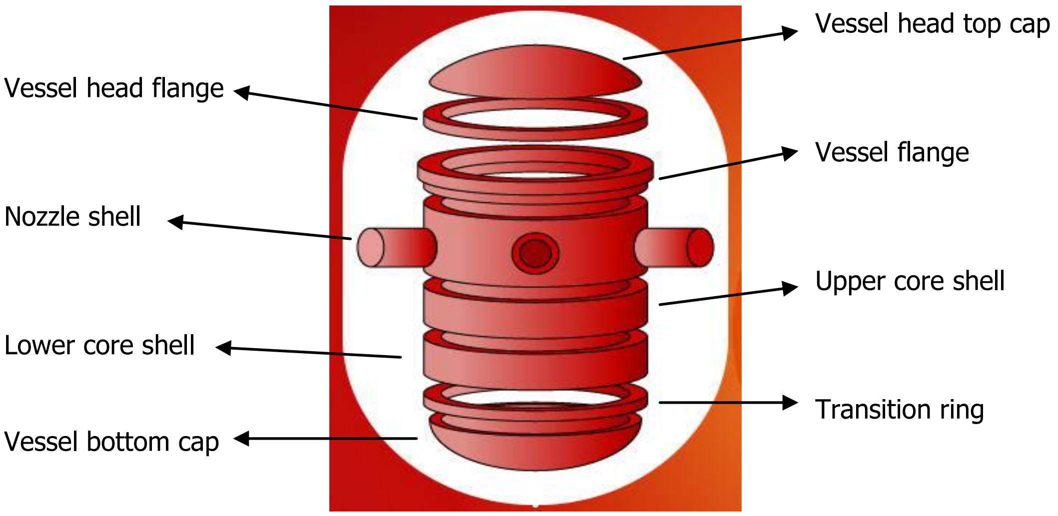


Figure 1 – Reactor pressure vessel structure and components

3.2.2 The reactor pressure vessel, an essential and irreplaceable component

Unlike the other large components of a reactor unit, there is no provision in the design for the replacement of a reactor pressure vessel. The reactor pressure vessel is an essential component that determines the service life of the unit. Its ageing is closely monitored, the steel becoming more brittle over time due to irradiation by the reactor core. Therefore, care is taken to ensure a considerable safety margin for the mechanical properties of this component so as to avoid cracking due, for example, to heat-induced stresses and strains.

3.2.3 Failure of the reactor pressure vessel

The failure of the reactor pressure vessel is not envisaged: the margins incorporated in the design and construction of this component, according to stringent codes, ensure that cracking or failure of the reactor vessel is virtually impossible.

Moreover, this scenario is not covered by safety studies, and the existing safety systems are not designed to handle such an occurrence.

A major crack or fracture in the reactor pressure vessel would lead to a loss of water inventory and, in case of absence of cooling, to a possible core meltdown (referred to as a "severe accident").

For these reasons, it must be demonstrated with certainty that (taking into account the indications found at Doel 3 and Tihange 2), the structural integrity of the reactor pressure vessel is maintained at all times and in all circumstances, in order to withstand the pressure and temperature ranges and guarantee the cooling of the nuclear fuel under any circumstances.

4. Safety assessment process for the Doel 3 and Tihange 2 reactor pressure vessels issue

4.1 Actors involved in the safety assessment

4.1.1 Licensee and associated technical support

The safety case was complex enough so that the licensee took the decision to set up a multidisciplinary project team. This team is composed of experts from:

- Electrabel (GDF-SUEZ): license holder of Doel 3 and Tihange 2, with expertise in nuclear operation and safety,
- Laborelec (GDF-SUEZ): technical competence centre in electrical power and energy technology, with extensive know-how in non-destructive testing techniques and material properties,
- Tractebel Engineering (GDF-SUEZ): engineering company, with specialized knowledge of nuclear design as well as structural integrity, materials, and safety.

The project team was supported by external expert entities such as AREVA, the SCK●CEN, and the Oak Ridge National Laboratory. In addition, the work of the project team was reviewed by a team of external experts, in order to ensure the completeness and soundness of the safety case.

As required by the Belgian nuclear safety regulations, an independent analysis and review of the safety case reports [1][2] was also performed by the Electrabel physical control service [3][4].

Electrabel developed a safety case roadmap to carry out a comprehensive safety assessment of the Doel 3 and Tihange 2 reactor pressure vessels. The roadmap had to achieve the following objectives:

- Confirm the origin and stability of the indications. The first diagnosis had to be evaluated against other possible causes during a thorough root-cause analysis.
- Validate the inspection technique.
- Obtain the necessary material properties needed for the structural integrity assessment. A material testing program had to be put in place. This program should make use of the appropriate archive materials.
- Develop a methodology for the assessment of the pressure vessels structural integrity that was robust and conservative.

This licensee's roadmap is summarized in Figure 2.

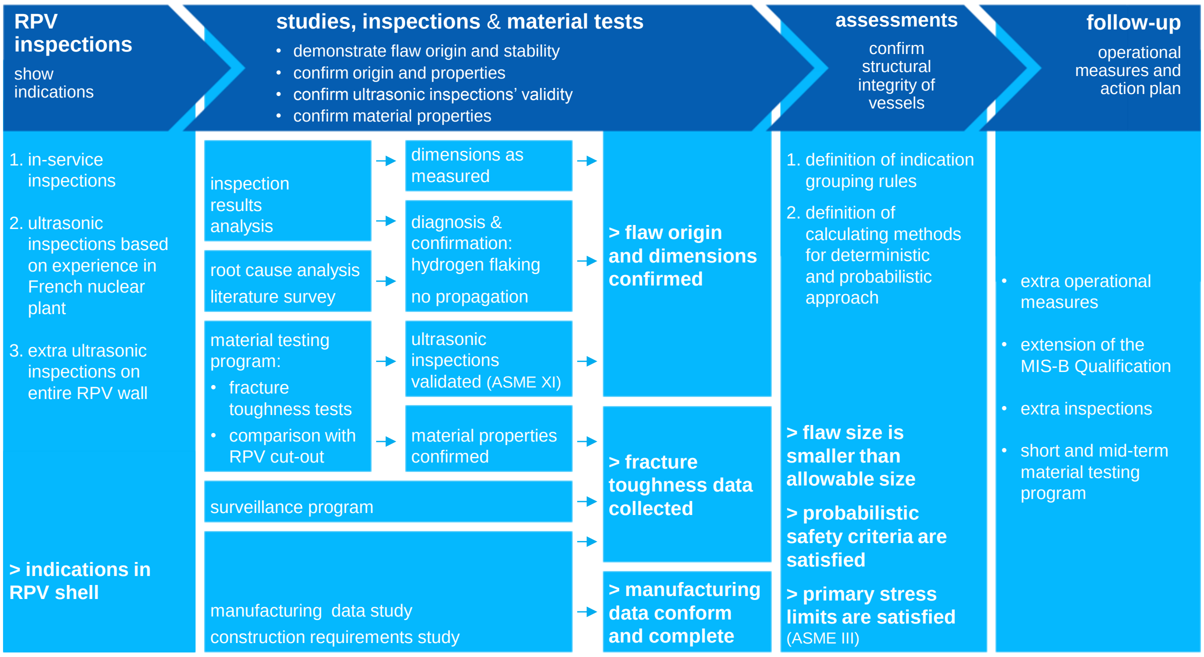


Figure 2 – Licensee's roadmap

4.1.2 Belgian nuclear safety authority and associated expert groups

4.1.2.1 Belgian nuclear safety authority

The Federal Agency for Nuclear Control (FANC) ensures close monitoring of the Doel 3 / Tihange 2 reactor pressure vessels issue in cooperation with Bel V, its technical subsidiary, and the company AIB-Vinçotte, an organization commissioned in Belgium for monitoring the "in-service inspections" referred to in the ASME XI code.

The FANC is a public interest agency acting as an independent watchdog in charge of nuclear safety, protection against ionising radiation, physical protection and nuclear non-proliferation. Its activities include regulations, licencing, inspections and monitoring of the radioactivity throughout the country.

Bel V is the technical subsidiary of the FANC. Bel V is tasked with conducting continual and periodic inspections in the major Belgian nuclear facilities. Bel V is also involved in the safety assessment of nuclear projects, periodic safety reviews or installation modifications.

AIB-Vinçotte is the authorized inspection agency (AIA) appointed for reviewing the tests required in application of sections III and XI of the ASME code adapted to the Belgian context. AIB-Vinçotte is responsible for the follow-up of in-service inspections and the review of the results. AIB-Vinçotte is also in charge of the verification of the non-destructive examination procedures and the review and follow-up of their qualification programs.

Considering the extent of the indications detected and the necessity of conducting an independent evaluation on the basis of all available information, the Belgian nuclear safety authority (FANC, Bel V and AIB-Vinçotte) defined early after detection of the flaws a three-step approach for the safety assessment of this issue:

- interpretation of the identified indications and collection of available information (historical vessel fabrication data, inspection results…);
- explanation of the origin of the indications and evaluation of their possible evolution during operation;
- demonstration of the reactor pressure vessels' structural integrity.

On the basis of the assessments provided by Bel V and AIB-Vinçotte, the FANC is responsible for the formulation of an independent judgement on all the elements of this case. In parallel, the FANC has made provision to seek third-party advice from foreign nuclear safety authorities and Belgian or foreign experts (see below).

4.1.2.2 Foreign nuclear safety authorities expert working groups

As soon as detailed and confirmed results were made available about the indications found at Doel 3, the Belgian nuclear safety authority informed its counterparts in other countries endowed with reactor pressure vessels built by the same manufacturer through the normal information exchange channels (IAEA incident database). In addition, a broad international information meeting was organized in Brussels on 16 August 2012 to discuss this issue.

To increase transparency and cooperation between potentially interested countries and to benefit from external insights on the case, the FANC decided in August 2012 to set up three international working groups to explore three distinct themes:

- non-destructive testing techniques;
- metallurgical origin of flaw indications;
- structural mechanics and fracture mechanics.

The participants were expert members proposed by foreign nuclear safety authorities or related organizations (IAEA, OECD/NEA, EC) willing to participate in the review of this issue. The chairman and technical secretary of each working group were provided by the Belgian nuclear safety authority.

Their mission was to:

- share information and experience between nuclear safety authorities about regulatory approaches and actions in relation to this issue;
- take account of the lessons learned from this issue, discuss actions to be considered in other countries;
- provide technical advice to the Belgian nuclear safety authority (FANC, Bel V, AIB-Vinçotte) on specific topics/questions related to the Doel 3 and Tihange 2 reactor pressure vessels issue. However, the final evaluation about continuing or not the operation of both Doel 3 and Tihange 2 reactor units remains the responsibility of the Belgian nuclear safety authority.

During the meetings of the three expert working groups, expert members were asked to express their opinion on the basis of their knowledge and experience but no consensus was expected nor required on each topic. All observations expressed during the meetings were collected but no assessment report was formally written as a conclusion of these discussions.

These three nuclear safety authorities expert working groups met for the first time on 16 October 2012 at the headquarters of the FANC. Besides the Belgian representatives of the FANC, Bel V and AIB-Vinçotte, these technical meetings were attended by experts from Finland, France, Germany, Japan, the Netherlands, South Korea, Spain, Sweden, Switzerland, the United Kingdom and the United States, and by experts from IAEA, OECD/NEA and EC. The findings of these three working groups were discussed during a two-day plenary assembly that was held in Brussels on 8 and 9 January 2013. The observations made during this meeting by the experts of other nuclear safety authorities were considered in the final evaluation by the Belgian nuclear safety authority.

4.1.2.3 Scientific Council and national scientific expert group

The Scientific Council of ionizing radiation established by the Belgian regulation to advise the Federal Agency for Nuclear Control was also mobilized to perform a safety assessment.

The Council is composed of 16 members appointed for 6 years by the Ministry of Internal Affairs on account of their scientific and technical expertise in the competency areas of the FANC. The various tasks of the Scientific Council include in particular advising on the attribution of licenses to major new nuclear installations, or on the extension or modification of the licences of those installations. During its meeting held on 14 September 2012, the members of the Scientific Council were informed about the indications found at Doel 3.

Exceptionally for this occasion, Belgian personalities from universities (KU Leuven, UCL, UGent, ULg), eminent figures in their disciplines, were specially invited to join the Council and provide an expert opinion in the field of fracture mechanics. Several working meetings involving this national scientific expert group were held on 13 October, 8 and 23 November and 7 December 2012. The contribution of this national scientific expert group resulted in the issuance of a preliminary assessment report to the Scientific Council, which was formally endorsed by the Scientific Council during the meeting held on 21 December 2012 [6].

A final version of the national scientific expert group was released on 11 January 2013 [5].

4.1.2.4 International review board

Finally, with a view to ensuring an evaluation as objective as possible, the FANC decided to promote the creation of an independent group of international experts dedicated to achieve a comprehensive technical review of the Doel 3 and Tihange 2 reactor pressure vessels issue.

The candidates were selected by the Federal Agency for Nuclear Control on the grounds of their expertise in reactor vessel technology, fracture mechanics, ASME XI code evaluation and probabilistic approach. These members were active in, or retired from, the following foreign or international organizations:

- Institute of Metallography Science, Bulgaria;
- Technical Research Centre of Finland (VTT), Finland;
- Ecole des Mines de Paris, France;
- Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Germany;
- Rolls Royce, United Kingdom;
- Nuclear Regulatory Commission (NRC), United States of America;
- International Atomic Energy Agency (IAEA);
- Nuclear Energy Agency (NEA).

This independent expert group was chaired by a member of the ULB Belgian university, while the scientific secretary was provided by the SCK●CEN Belgian Nuclear Research Centre.

These experts were involved in several working meetings held on 27 and 28 November and 17 December 2012. The contribution of this group resulted in a final review report [7] released on 11 January 2013, including a recommendation about the operability of the Doel 3 and Tihange 2 reactor units.

4.2 Process leading up to the final evaluation

As previously mentioned, the Federal Agency for Nuclear Control asked for external advice from foreign nuclear safety authorities and Belgian or foreign experts. However, the final evaluation about the safe operability of both Doel 3 and Tihange 2 reactor units remains the responsibility of the Belgian nuclear safety authority.

The evaluation released by the FANC takes account of all available inputs, evaluations and recommendations issued by the interested parties involved in the process. The key steps of the methodology are as follows:

1. The licensee's safety case reports and related technical documents are examined in detail by the experts from Bel V and AIB-Vinçotte. Where appropriate, the judgement of the working groups of foreign nuclear safety authorities experts is taken into account.

2. This first evaluation is then complemented by the advice issued by:
   - the Scientific Council of the FANC, based in turn on the works of the national scientific expert group;
   - the international review board.

3. A joint meeting is held on 8 and 9 January 2013 between the Belgian safety authority (FANC, Bel V and AIB-Vinçotte), the three regulatory expert working groups, the Scientific Council and the international review board. All reviewers can present their conclusions and judgement for discussion with the other actors.

4. At the conclusion of these different steps, the FANC communicates its position to the Belgian political authorities and the licensee.

This approach is illustrated in the Figure 3 below:

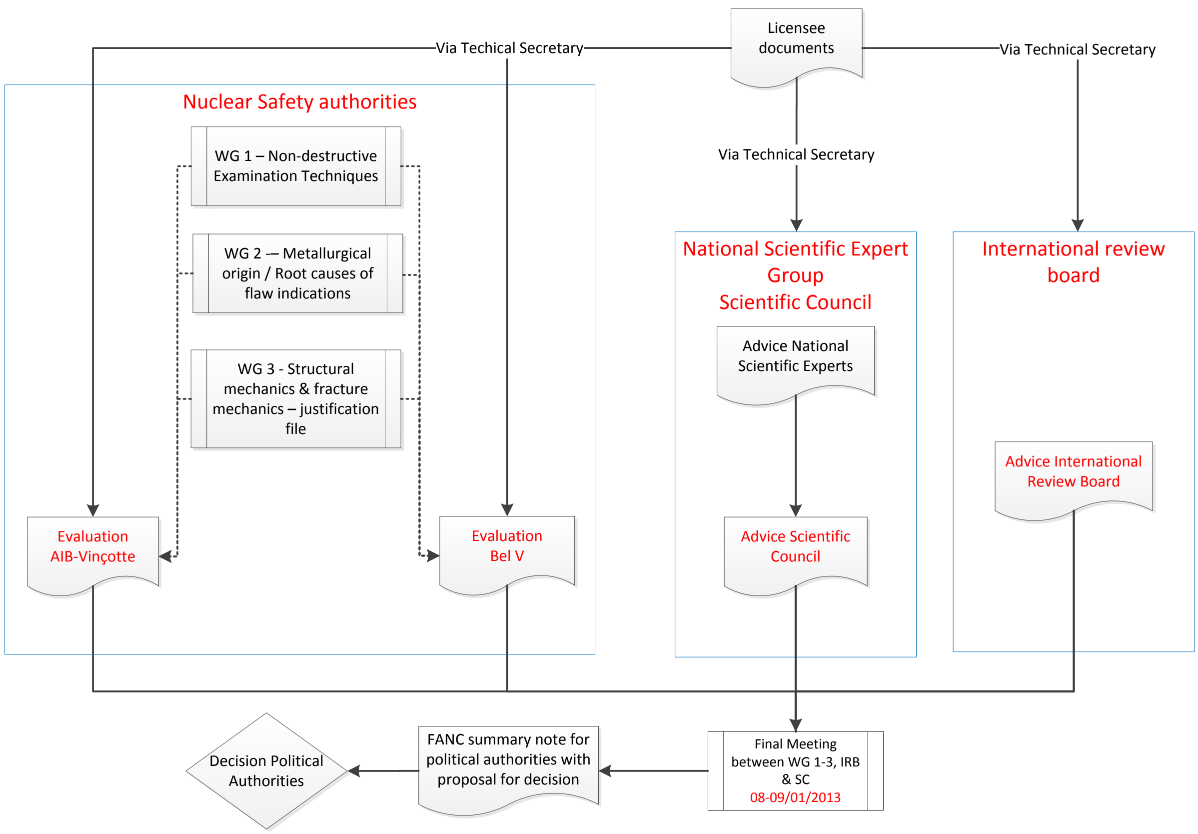


Figure 3 – General overview of different experts groups and interactions

4.3 Timeline

The main milestones in the safety assessment process for the Doel 3 and Tihange 2 reactor pressure vessels are the following:

- June 2012: start of the planned outage of the Doel 3 reactor unit; a first in-service inspection of the reactor pressure vessel reveals flaw indications;
- mid-July 2012: second round of inspections of the Doel 3 reactor pressure vessel through its entire thickness; the flaw indications are confirmed;
- late July 2012: the Belgian nuclear safety authority informs its foreign counterparts of the incident;
- early August 2012: the Belgian nuclear safety authority provides Electrabel with a list of information and documents required for the evaluation; the FANC arranges cooperation at international level with a first working meeting between safety authorities;
- September 2012: start of the planned outage of the Tihange 2 reactor unit; the in-service inspections of the reactor pressure vessel reveal flaw indications of the same kind as those found at Doel 3;
- October-November 2012: the Belgian safety authority, the foreign safety authorities expert working groups, the national scientific expert group of the Scientific Council and the independent international review board examine the technical documents submitted by the licensee;
- early December 2012: Electrabel provides the Belgian safety authority with its safety case reports for Doel 3 and Tihange 2;
- late December 2012: Bel V, AIB-Vinçotte, the Scientific Council and the independent international review board present the conclusions of their works;
- early January 2013: the Belgian safety authority (FANC, Bel V and AIB-Vinçotte), the three foreign safety authorities expert working groups, the Scientific Council and the international review board discuss their positions in a joint meeting.
- late January 2013: the FANC releases its provisional evaluation report.

4.4 Structure of the safety assessment report

The following main topics are discussed in this safety assessment report:

- Chapter 5: Manufacturing of the reactor pressure vessels,
- Chapter 6: In-service inspections,
- Chapter 7: Metallurgical origin and evolution of the indications,
- Chapter 8: Material properties,
- Chapter 9: Structural integrity of the reactor pressure vessels,
- Chapter 10: Action plan.

In order to provide a self-standing safety assessment report, the relevant data supplied by the licensee in its safety case reports are recalled in each of the following chapters. The safety case reports provided by the licensee are released in full in appendix for further reference.

At the end of each chapter, a section provides the evaluations supplied by Bel V, AIB-Vinçotte, the national scientific expert group / Scientific Council, and the independent international review board. The observations from the meetings of the foreign nuclear safety authorities expert working groups are also provided for information purpose.

As a general summary, the global conclusions of Bel V, AIB-Vinçotte, the national scientific expert group / Scientific Council, and the independent international review board are quoted in a dedicated chapter at the end of the report.

The suggestions, observations and conclusions of these different organisations and working groups were evaluated by the Federal Agency for Nuclear Control. Wherever appropriate and relevant, the FANC decided to use this input in the formulation of the FANC conclusions and specific requirements for the licensee. These conclusions and requirements (where applicable) are presented in a distinct section at the end of each chapter.

Lastly, the global position of the FANC is detailed in a final chapter which also gives an overview of all the specific requirements the licensee must fulfil prior to a final decision about a possible restart of the operation of the Doel 3 and Tihange 2 reactor units.

5. Manufacturing of the reactor pressure vessels

5.1 Data provided by the licensee

5.1.1 Actors involved in the manufacturing

Several actors were involved in the manufacturing and assembling of the components of the Doel 3 and Tihange 2 reactor pressure vessels. These components were made of steel provided by the German company KRUPP, and forged by the former Dutch company RDM (Rotterdamsche Droogdok Maatschappij) also known as RN (Rotterdam Nuclear). The assembling of the forged components and the stainless steel lining of the pressure vessels was then performed by the Belgian company COCKERILL for the lower parts of the pressure vessels, and by the French company FRAMATOME for the upper parts and the final assembling.

The manufacturing of these two reactor pressure vessels took place between 1974 and 1978 (installation of the vessel in the reactor building).

Information has been gathered regarding the manufacturing of the components of the Doel 3 and Tihange 2 reactor pressure vessels and vessel heads (see also Figure 1), namely:

- the vessel head flange;
- the vessel flange;
- the nozzle shell;
- the upper core shell;
- the lower core shell;
- the transition ring.

The information sources that were consulted are the COCKERILL construction files of the forged components, the archives of Friedrich KRUPP Hüttenwerke and Rotterdamsche Droogdok Maatschappij/Rotterdam Nuclear (RMD/RN), and the communications between the engineering company of the licensee and the different manufacturers.

5.1.2 Production process of ingots and blooms

The Doel 3 and Tihange 2 reactor pressure vessels components are made of low-alloy steel (SA-508 class 3).

The ingots were poured by Friedrich KRUPP Hüttenwerke in Bochum (Germany) using a vacuum casting technique aiming at a maximum hydrogen content of 1.5 ppm (part per million). The maximum allowable hydrogen content according to the specification is 1.7 ppm.

The ingot of the transition ring was delivered directly to RDM/RN in the Netherlands where it was cropped (i.e. top and foot parts of the ingots were removed) by flame cutting. The ingots for the remaining components were pre-forged by KRUPP and they were also cropped. The resulting blooms were delivered to RDM/RN.

For all components, the main forging operations as well as heat treatment and different types of examinations were performed by RDM/RN.

All components were finally delivered with their required dimensions either to COCKERILL in Belgium or to FRAMATOME in France. COCKERILL and FRAMATOME were in charge of the stainless steel cladding and the assembling of the components.

Regarding the forging operations, there is no detailed information included in the specifications or construction file. The only information included in the RDM/RN forging procedure are approximate values for the amount of material removed from the ingot and approximate values for the forging ratios.

Regarding the heat treatments applied to the ingots and blooms, the following conclusions can be drawn:

- Because the ingots were poured by KRUPP and the main forging operations were done by RDM/RN, the ingots/blooms were cooled down to ambient temperature before transportation to RDM/RN (with one exception, namely the transition ring of Tihange 2 which was transferred in hot condition). In general, there is no cooling when forging is performed by the same company as the one that pours the ingot: in that case, the ingot arrives in hot condition from the steel work. The KRUPP procedure related to the manufacturing of blooms states that the cooling is done in a controlled manner, but no details are given.
- The RDM/RN documents, which list the subsequent steps of manufacturing and inspection, mention a first heat treatment referred to as "Austenitizing and tempering", and a second heat treatment referred to as "Hardening-Quenching-Tempering".

5.1.3 Construction code and material

The examination of the construction files showed that the Doel 3 and Tihange 2 reactor pressure vessels were constructed in accordance with the ASME B&PV code, section III for class 1 components, edition 1974 up to and including the summer 1974 addenda, and in accordance with the additional owner requirements included in the *Conditions Complémentaires d'Application* regarding ASME Code Sections III, V, IX and XI. The base material of the forgings complies with ASME material specification SA-508 class 3.

5.1.4 Manufacturing inspections and reports

The status "Accepted" was granted to all Doel 3 and Tihange 2 reactor pressure vessel components in the final inspection reports.

The manufacturing inspection reports make clear that the forged components were subjected to various types of inspections at the RDM/RN workshop, including dimensional controls, ultrasonic testing (UT), and magnetic testing (MT). In addition, micrographic, mechanical and chemical tests were performed on samples taken from the forged components.

There is an associated procedure and there are component-specific reports for each inspection and test. All reports are included in the construction file, with the exception of:

- the final ultrasonic testing inspection report of the nozzle shell. Instead, the construction file contains a number of telex messages between RDM/RN and COCKERILL on the ultrasonic testing inspections. These messages confirm the acceptance of the component.
- the first ultrasonic testing inspection report of the lower core shell. However, this inspection was not required according to the ultrasonic testing inspection specification. Nevertheless, the final mandatory ultrasonic testing inspection report is available.

5.1.5 Acceptance criteria

According to the component-specific reports, the ultrasonic examinations did not reveal any indications in the lower core shells of Doel 3 and Tihange 2 and the nozzle shell of Doel 3. However, some indications were found in the upper core shell of Doel 3, the transition rings, and the nozzle shell of Tihange 2, but all of them were within the acceptance criteria.

For the upper core shell of Doel 3, indications were found during final ultrasonic testing inspections. All of the indications were within the acceptance criteria and therefore the component was accepted. It should be noted that a first non-mandatory inspection report of the upper core shell of Doel 3 mentioned a large area of indications. There are elements in favour of the hypothesis that this report, currently filed with the upper core shell, would be in fact related to the lower core shell, where a large number of indications were found in 2012.

Initially, the intention was to manufacture the transition ring for Doel 3 and Tihange 2 from a single ingot. Ultrasonic testing examination on the Doel 3 transition ring revealed minor indications. The component was accepted. Inspection of the transition ring of Tihange 2 revealed unacceptable indications that were due to hydrogen flaking, according to RDM/RN. The component was rejected and a new transition ring was manufactured for Tihange 2.

The nozzle shell initially made for Doel 3, was rejected because of an excessive reference temperature for nil ductility transition value (RT_{NDT} – the reference temperature value for the transition from brittle to ductile behaviour). It was decided to install the Tihange 2 nozzle shell (with a RT_{NDT} value that had been accepted) on the Doel 3 vessel instead. A new nozzle shell was subsequently constructed for Tihange 2.

5.1.6 Conclusion of the licensee about the manufacturing of the reactor pressure vessels

As a conclusion about the manufacturing of the reactor pressure vessels, the licensee states in its safety case reports [1][2] that:

> *"The construction [is] in accordance with international codes and standards. A close review of all of the original manufacturing data and documentation revealed that the Doel 3 / Tihange 2 reactor pressure vessel was manufactured in accordance with the prevailing international codes and standards, in particular the ASME Boiler & Pressure Vessel Code. All manufacturing inspections required by the construction code were performed and witnessed by the customer and regulatory body and concluded in the acceptance of all parts of the reactor pressure vessels.*
>
> *The manufacturing data and documentation proved to be complete, traceable, and in accordance with international codes and standards".*

5.2 Evaluation by Bel V, AIB-Vinçotte and expert groups

5.2.1 Bel V

Bel V did not specifically assess the manufacturing process of the pressure vessels and the associated documentation, which were outside of its initial scope.

However, Bel V considers that the root cause analysis provided by the licensee was not fully conclusive and the reasons why the phenomenon has not been identified and/or reported during the fabrication process have not been clearly provided.

In addition, Bel V considers that even if those flaws were found to be acceptable according to the applicable acceptance standards of Section III of the ASME B&PV code, the presence of such flaws does not comply with the quality level expected for a reactor pressure vessel.

5.2.2 AIB-Vinçotte

AIB-Vinçotte reviewed the ultrasonic testing procedure applied during fabrication of the forgings. The procedure complies with the code requirements. However, review of the ultrasonic testing inspection reports raises some questions.

AIB-Vinçotte points out that the final reports during fabrication do not mention the presence of indications. Only one report for the intermediate non-mandatory examinations mentions a zone with indications in the upper core shell of Doel 3, but these findings were no longer present in the final reporting.

Although AIB-Vinçotte recognizes that the indications observed in 2012 might have been acceptable according to the ultrasonic testing acceptance criteria at the time of fabrication, it is likely that many of the indications should have been reported.

As the flaw indications are not reported in the final ultrasonic testing reports of the forgings, AIB-Vinçotte concludes that uncertainty remains about the level of quality of the performed ultrasonic testing inspections during fabrication.

Considering the (quasi-) laminar character of the hydrogen flakes, it is not unlikely that surface examinations like penetrant testing or magnetic testing, performed prior to the deposition of the cladding, have not detected the defects. The non-reporting of hydrogen flake-type indications during these surface examinations can be considered as normal.

5.2.3 Nuclear safety authorities expert working groups

During their meetings held on 16 October 2012 and 8 January 2013, the nuclear safety authorities experts of working group 1 (non-destructive examination techniques) and working group 2 (metallurgy and material properties) discussed the licensee's documents available and issued the following observations:

- At the time when the Doel 3 and Tihange 2 reactor pressure vessels were constructed, specific manufacturing steps (such as heat treatment) were not routinely documented in detail in the manufacturing files, this information being considered as proprietary.
- Whether the Doel 3 and Tihange 2 reactor pressure vessel pieces should have been accepted at that time (in the case the indications were detected and duly reported during manufacturing) remains an open question. Indeed, although ASME section III does not address directly such problems, the presence of such flaws does not comply with the quality level expected for a reactor pressure vessel.
- Based on an assessment of the RDM ultrasonic inspection procedures used at the time of manufacturing, it is clear that the flaws which were found in 2012 were detectable and should have been reported during manufacturing.

5.2.4 National scientific expert group - Scientific Council

The national scientific expert group points out that the recently detected flaw indications in the Doel 3 and Tihange 2 reactor pressure vessels were not reported in the manufacturing reports. Thus, the indications were not detected by the inspection equipment/procedure used and/or were not reported, possibly due to human factors.

The national scientific expert group also notes that the manufacturer RDM had rejected similar components for hydrogen flaking reasons.

5.2.5 International review board

According to the international review board, the discrepancy between the indications reported in the acceptance reports of the pressure vessel rings and in the 2012 inspection in the core shells of the two reactor units remains unresolved, since the ultrasonic testing technology available at that time must have had the capacity to detect the indications found.

Furthermore, it is documented that some other parts, like the transition rings, were rejected especially because of these hydrogen flakes.

5.3 FANC conclusions and requirements

The suggestions, observations and conclusions of the different organisations and working groups were evaluated by the Federal Agency for Nuclear Control. Wherever appropriate and relevant, the FANC decided to use this input in the formulation of the final FANC conclusions and specific requirements for the licensee.

5.3.1 Conclusions

Based on the data provided by the licensee and the conclusions released by Bel V, AIB-Vinçotte and the expert groups about the manufacturing of the reactor pressure vessels, the FANC draws a number of conclusions as follows.

The original manufacturing files of the reactor pressure vessels were retrieved and examined. The content of these files seems to be in line with the standards at the time of manufacturing. However, some key-information was not recorded (manual ultrasonic inspection results) or was not sufficiently detailed (heat treatment steps during forging).

Hydrogen flaking was a known issue during the manufacturing of the reactor pressure vessels in question, as similar other pieces were rejected at that time at the manufacturer's workshop. Furthermore, all common manufacturing inspections (ultrasonic testing, surface examinations) seem to have been performed as required. However, no mention of hydrogen flakes indications was reported in the manufacturing files of the affected parts. All the more, the pressure vessels parts were accepted and given compliance certificates with respect to the ASME III acceptance criteria.

These findings leave open issues regarding the actual presence of flaw indications since the manufacturing stage. If present, the indications should have been identified with the available ultrasonic testing technology used at the time, and should then have been reported in accordance with the RDM inspection procedures, for which the reporting criteria were even more stringent than required by the ASME section III code. Only one report for the intermediate non-mandatory examinations mentions the presence of indications, but these findings were no longer present in the final reporting. Moreover, it is unlikely that a reactor pressure vessel part with thousands of reported indications would have been accepted by the manufacturer or the licensee at that time (as well as today). Finally, the conjecture assuming that the lack in the reporting of indications at the manufacturing stage is due to "human factor" cannot be definitely demonstrated.

Hence, based on the sole manufacturing files, the presence of flaw indications since the manufacturing stage cannot be confirmed as, for a number of forged components, the indications which were detectable at this stage were not reported in the inspection reports. (See however § 7.3 for additional conclusions on the metallurgical origin of these indications).

5.3.2 Requirements

Given that the whole documentation currently available was exploited and no additional finding can be derived from that material, **the FANC issues no further requirement on this topic.**

6. In-service inspections

6.1 Data provided by the licensee

6.1.1 Context

The results of the in-service inspections that were undertaken in both reactor pressure vessels are presented hereafter.

At first, the inspections performed in June 2012 at Doel 3 were designed to detect potential underclad defects, such as the ones reported earlier in France. As foreseen in the qualified procedure, these inspections covered only the first 30 mm in depth (from the inner side of the pressure vessel) of the core shells.

A second series of inspections using another method was performed in July 2012 to examine the whole thickness of the pressure vessel material at Doel 3 and then at Tihange 2 in September 2012. They encompassed the vessel flange, the welds, the nozzle shell, the upper and lower core shells, and the transition ring. However, this method, which is formally qualified for weld inspections in the pressure vessels, was not formally qualified for the pressure vessel base material according to the usual procedures in force in the nuclear sector.

The inspections were conducted by the specialized company Intercontrole (part of the French Group AREVA). Intercontrole inspects a large number of reactor pressure vessels each year according to the mandatory and complementary requirements of the relevant construction code (ASME or equivalent French code) and has a lot of experience in this field. These inspections were carried out using the automated MIS-B ("Machine d'inspection en service belge") equipment.

These inspections were monitored in first instance by an authorized inspection agency (namely AIB-Vinçotte) in charge of the surveillance of the inspections findings.

6.1.2 Indications in the Doel 3 reactor pressure vessel

The first round of in-service inspections of the Doel 3 reactor pressure vessel conducted in late June 2012 found no underclad defects. However, it resulted in the detection of a high number of indications in the base steel of the reactor pressure vessel, more precisely in the lower core shell of the vessel.

The second round of inspections, which started mid-July 2012 to examine the base steel of the reactor pressure vessel in depth, confirmed the presence of a high number of indications. The inspection found:

- 857 indications in the upper core shell;
- 7,205 indications in the lower core shell.

In both core shells, the laminar flaws form a cluster in the central strip of the shell, which ranges in depth from the stainless steel clad interface up to 120 mm. The indications measure on average 10-14 mm in diameter (with some even exceeding 20-25 mm).

71 indications were also detected in the transition ring. They are laminar as well but do not form a cluster.

The initial analyses confirmed that these indications were not due to measurement errors, but genuine signs of deterioration in the inspected areas.

Figure 4 below displays a typical example of data recorded in the lower core shell. Left: an axial section, with indications appearing as colour spots. Right: the indications, all detected in a 20° sector of the shell, are cumulated on the figure plane (333 sections).

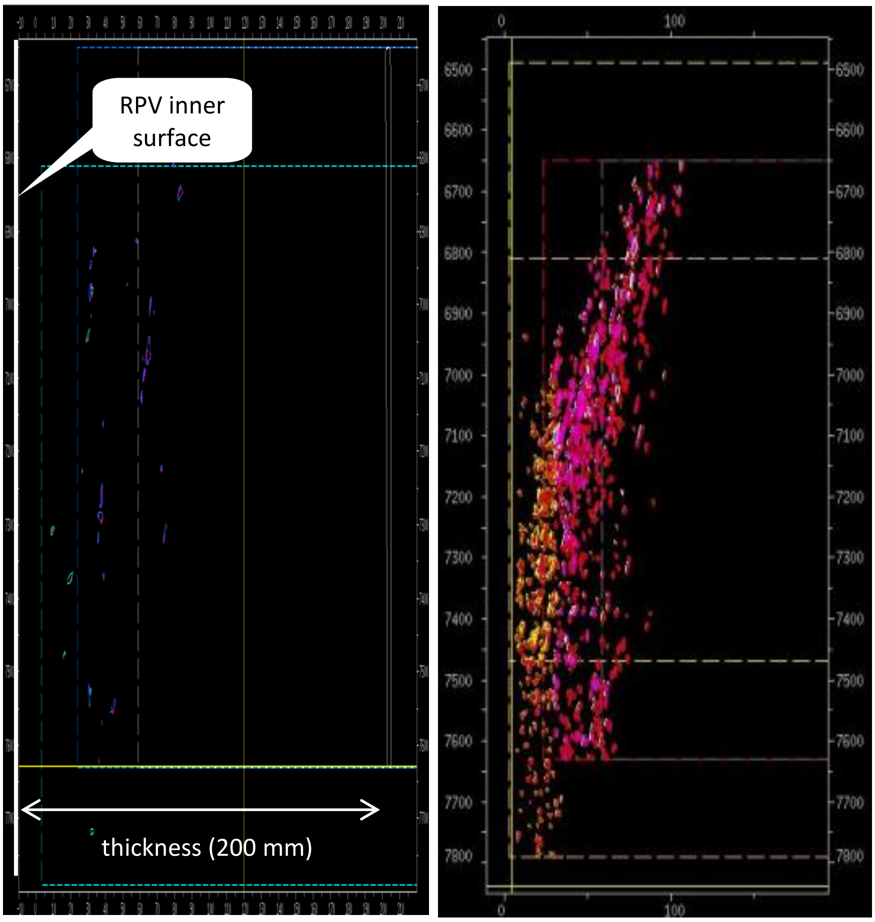


Figure 4 – Indications recorded in the lower core shell of the Doel 3 reactor pressure vessel

6.1.3 Indications in the Tihange 2 reactor pressure vessel

Similar inspections were performed in September 2012 to detect potential underclad defects and investigate the possible presence of flaws in the Tihange 2 reactor pressure vessel.

No underclad crack was detected. However, flaws similar to those detected at Doel 3 were identified through the thickness of the shells, though to a much lesser extent.

A total of 2,011 indications were identified in the upper and lower core shells, distributed as follows:

- 1,931 indications in the upper core shell;
- 80 indications in the lower core shell.

In the transition ring and the nozzle shell, no indications were reported.

The flaw indication distribution in the upper and lower core shells of the Tihange 2 reactor pressure vessel is similar to the distribution at Doel 3.

Inside the core shells, which are the most affected, flaws have been observed up to a depth of 100 mm from the inner surface. However, most of the flaws are located between 20 mm and 70 mm. Regarding the flaw dimensions, flaws up to 24 mm large have been observed. However, most flaws are smaller than 10 mm.

6.1.4 Overview of the characteristics of the indications detected at Doel 3 and Tihange 2

The confirmed number of flaw indications in both pressure vessels and their location are presented in Table 2:

Reactor pressure vessel components	Number of flaw indications in the reactor pressure vessels	
	Doel 3	Tihange 2
Vessel head flange	3	5
Vessel flange	2	19
Nozzle shell	11	0
Upper core shell	857	1,931
Lower core shell	7,205	80
Transition ring	71	0

Table 2 – Number of flaw indications in the reactor pressure vessels

To sum up, the flaw indications detected show the following characteristics:

- the indications are situated mainly in the upper and lower core shells;
- the indications are situated more in the lower core shell of Doel 3 and the upper core shell of Tihange 2;
- the indications are located roughly in the first half of the shells thickness (inner part);
- the indications are spread over the whole circumference of the shells;
- the indications represent laminar flaws, almost parallel to the wall of the pressure vessels;
- the flaws are rounded in shape and have a typical size of about 10 mm.

6.1.5 Conclusions of the licensee about the in-service inspections

As a conclusion about the in-service inspections, the licensee states in its safety case reports [1][2] that:

> *"UT inspection technique is valid. The ultrasonic inspection was performed with the automated MIS-B (Machine d'Inspection en Service Belge) equipment, which has been used for over thirty years to inspect the reactor vessels of all Belgian units. The ultrasonic inspection technique that was used to characterize the indications at Doel 3 / Tihange 2 is state-of-the-art and is used in many nuclear power plants worldwide. It has been qualified for all mandatory inspections and underclad crack detection and sizing against international standards, prior to its use and under the control of the AIA.*
>
> *For this specific safety case, the chosen inspection technique was evaluated through cross-checking and extensive destructive tests on a reference block. This block was known to have hydrogen flakes and was taken from an available archive forged shell of equivalent material and size to the reactor vessel shell.*

The testing program demonstrated that the applied inspection technique is valid and appropriate for characterizing the types of indications found in the Doel 3 / Tihange 2 reactor pressure vessel. Moreover, it was shown that the applied inspection technique tends to oversize the dimensions of the indications, making it more conservative."

6.2 Evaluation by Bel V, AIB-Vinçotte and expert groups

6.2.1 Bel V

Bel V recalls that the ultrasonic testing inspections performed on the Doel 3 and Tihange 2 reactor pressure vessels were closely monitored by AIB-Vinçotte, which is the authorized inspection agency. Hence Bel V relies on the expertise of AIB-Vinçotte for the pure technical ultrasonic testing issues related to the in-service inspections.

The main concerns are essentially related to the qualification of the methods and procedures used to detect and characterize the indications in the core shells of the Doel 3 and Tihange 2 reactor pressure vessels. The methods and procedures used are those usually used to inspect the (circumferential) welds of the pressure vessels, as required by section XI of the ASME B&PV code. They are qualified to detect and characterize the flaws expected to occur in the welds, i.e. circumferential and axial planar flaws. In order to demonstrate that these methods and procedures are well-suited for the present issue, i.e. to ensure that they are able to detect, correctly size, and characterize hydrogen-induced flaws, the licensee set up an experimental program on a material known for containing such defects. This material is a block (VB-395/1 block) taken from an AREVA steam generator lower shell (VB-395) that was rejected in 2012.

So far, all experiments have been carried out on the VB-395/1 block that is not exactly representative of the Doel 3 and Tihange 2 reactor pressure vessels, as it contains no cladding. A second phase for the qualification is thus foreseen by the licensee, consisting in performing the same examinations on another block (VB-395/2) of the AREVA steam generator lower shell, but on which a cladding has been added. Thus, the qualification of the methods and procedures used by the licensee to detect and characterize the indications in the core shells of the Doel 3 and Tihange 2 reactor pressure vessels is not complete yet.

6.2.2 AIB-Vinçotte

<u>Ultrasonic testing examinations in-service at Doel 3 and Tihange 2</u>

AIB-Vinçotte remarks that the qualification scope of the extended in-service inspection examinations of the reactor pressure vessels (2012) is limited to service-related flaws and does not cover actually the detection and characterization of hydrogen flake type defects. The procedures used for the extended in-service inspection examinations shall be formally qualified for the detection and characterization of hydrogen flake-type defects. The results obtained on the VB-395/1 block shall be confirmed on the VB-395/2 block (mid-term requirement).

AIB-Vinçotte observed that in the interpretation of the UT results, a clear distinction cannot always be made between technological cladding defects (DTR = Défaut Technologique de Revêtement) and hydrogen flake type defects. In the structural integrity assessment of the Doel 3 RPV, the licensee made an analysis considering conservatively all the DTR's as hydrogen flake type defects.

AIB-Vinçotte asks the licensee to re-analyze the EAR acquisition data for Tihange 2 in the depth range from 0 to 15 mm in the zones with hydrogen flakes to confirm whether or not some of these technological cladding defects have to be considered as hydrogen flakes (short-term requirement).

AIB-Vinçotte notes that there are some non-inspectable areas (i.e. under the radial keys) in the reactor shells of Doel 3 and Tihange 2. AIB-Vinçotte asks the licensee to demonstrate that no critical hydrogen flake type defects are expected in the non-inspectable areas (short-term requirement).

Ultrasonic testing examinations on VB-395/1 block (first quick validation effort)

The licensee performed a first quick validation effort of the effectiveness of the in-service ultrasonic testing examinations used at Doel 3 and Tihange 2 through ultrasonic testing examinations on the VB-395/1 block (which is known to contain hydrogen flakes) and through simulations.

AIB-Vinçotte observed that in the submitted documentation, a minor part of the hydrogen flakes in block VB-395/1, especially the ones with important tilt, were situated below the on-site reporting criterion although being detected with 0°L. Lowering the reporting criterion is not a straightforward solution, because other material imperfections start generating false calls below that level.. AIB-Vinçotte asks the licensee to demonstrate that the applied ultrasonic testing procedure allows the detection of the higher tilt defects in the Doel 3/Tihange 2 data (2012 inspections) with a high level of confidence (short-term requirement).

Furthermore, AIB-Vinçotte observed during the ultrasonic testing examinations on the VB-395/1 block that the selection of flaws to be macrographically examined was mainly based on their direct 0°L characteristics. AIB-Vinçotte is in particular interested also in the macrographical examination of defects based on their 45°T reflectivity, to understand why some defects present such reflections and others don’t. An action is ongoing on one sample with both 0°L and 45°T reflections and the detailed report shall be submitted. AIB-Vinçotte asks the licensee to present the detailed report of all macrographical examinations including the sample with the 45°T reflections and asks also for additional samples with 45°T reflectivity (short-term requirement).

AIB-Vinçotte also asks to include a set of defects partially hidden by other defects for macrographic examination, to confirm whether the sizing method continues to function well (short-term requirement).

AIB-Vincotte observes that different methods were used for the measurement of the tilts on-site and on the VB-395/1 block. AIB-Vinçotte asks to re-analyze the tilts of the defects in the VB-395/1 block with the same method as applied on-site (short-term requirement).

Ultrasonic testing examinations on VB-395/2 block (fully representative qualification campaign)

In parallel to block VB-395/1, a sample block VB-395/2 is under preparation for use in a fully representative qualification campaign at mid-long term. Sample VB-395/2 was selected in such a way that it contains also an important number of hydrogen flakes, but differs from VB-395/1 for the following aspects:

- a cladding with representative surface conditions will be present,
- the final heat treatment will be performed,
- the block will be examined with ultrasonic testing immersion techniques while being positioned in a testing pool.

The effectiveness of the actually applied in-service inspection ultrasonic testing immersion techniques will be evaluated and modifications or enhancements will be applied wherever required. AIB-Vinçotte points out that the fully representative qualification on VB-395/2 is pending and will not be finished at short term.

AIB-Vinçotte observes that there are no hydrogen flakes near the inner surface of the VB-395/2 block. So measures shall be taken to assure the VB-395/2 block to be representative for qualification of the ultrasonic testing procedures for detection and characterization of defects near the cladding/base metal interface. AIB-Vinçotte asks the licensee to present the qualification program for detection and characterization of the flaws nearby the interface cladding/base metal (as part of the formal qualification program at mid-term).

AIB-Vinçotte asks the licensee to include in the formal qualification program the following examinations (mid-term requirement):

- macrographic examination on ultrasonically sound material, complemented by penetrant testing (between flakes and on large macro's elsewhere),
- ultrasonic testing examination from the lateral side on a significant test piece.

As part of the formal qualification program at mid-term, AIB-Vinçotte also asks the licensee to perform macrographic examination of flaws that were sized smaller than the beam diameter, in order to verify if small size indications correspond to flakes or to another type of material imperfections.

6.2.3 Nuclear safety authorities expert working groups

During their meetings held on 16 October 2012 and 8 January 2013, the nuclear safety authorities experts of working group 1 (non-destructive examination techniques) discussed the available licensee's documents and made the following observations:

- To ensure a high degree of confidence in the ultrasonic testing inspection results of 2012, the remaining open issues on the capability of the in-service inspection technique to detect all flaws should be addressed (e.g. the capability to detect hidden flaws or highly tilted flaws). It should be confirmed that flaws with higher tilts (above 10°) were adequately reported during the in-service inspections of the reactor pressure vessels. It was suggested to firstly perform a sensitivity analysis in the fracture mechanics calculation to evaluate the impact of flaws with higher tilts. This does not exclude the use of small angle techniques during an additional reactor pressure vessel inspection.
- A full qualification of the ultrasonic testing inspection technique is required (using the VB-395/2 block). The aim is to lift all the limits derived from the validation exercise on the VB-395/1 block, by using a specimen with hydrogen flakes which needs to be cladded and inspected with the actual in-service inspection probes. During this qualification, an issue for consideration is the possibility to adequately detect bridges between flakes.
- An additional cladding inspection to ensure that the cladding of the Doel 3 and Tihange 2 reactor pressure vessels does not contain any cracks, could be envisaged, especially in the areas where the most critical flaws are located. However, there was no clear consensus on the need for this additional inspection.

6.2.4 National scientific expert group - Scientific Council

The national scientific expert group notes that the licensee performed the on-site inspection with an inspection technique that was not fully calibrated for the detection and sizing of large amounts of laminar flaws occurring in different planes in the forged shells of the Doel 2 and Tihange 3 reactor pressure vessels. However, the capabilities of the on-site ultrasonic testing technique to detect and size laminar and nearly laminar flaws as well as the integrity of the ligament between the flaws were validated by the licensee on a similar material – without the stainless steel clad layer – and containing similar, though larger flaws (VB-395/1 block).

Yet, the national scientific expert group considers that there is still a possibility that potentially critical flaws were not captured during on-site inspection. Indeed, the flaws occur in different planes in very large numbers, the inclination of the individual flaws varies, and it cannot be excluded that potentially critical flaws, damaged or embrittled ligaments, were not captured by the onsite non-destructive procedure used. However, the national scientific expert group does not have the expertise nor the means to provide a definitive judgment on the accuracy and the degree of conservatism with respect to reported indications/flaws.

6.2.5 International review board

Regarding the inspection method and its capability to detect and characterize the indications, based on a comparison exercise with the AREVA VB-395/1 block, the international review board had some concerns regarding the transferability of the data received from the ultrasonic testing inspections on the test block to the results retrieved from the Doel 3 and Tihange 2 reactor pressure vessels. The ultrasonic testing equipment used to characterize the indications in the steam generator shell is indeed 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 international review board considers that the work done provides reasonable and appropriate assurance that the quasi-laminar indications in Doel 3 and Tihange 2 have been appropriately located and sized.

6.3 FANC conclusions and requirements

The suggestions, observations and conclusions of the different organisations and working groups were evaluated by the Federal Agency for Nuclear Control. Wherever appropriate and relevant, the FANC decided to use this input in the formulation of the final FANC conclusions and specific requirements for the licensee.

6.3.1 Conclusions

Based on the data provided by the licensee and the conclusions released by Bel V, AIB-Vinçotte and the expert groups about the in-service inspections, the FANC draws the following conclusions.

The in-service inspection techniques used to examine the Doel 3 and Tihange 2 reactor pressure vessels provide a high level of confidence in the reality of the indications detected. In other words, the actual presence of great numbers of flaw indications in both pressure vessels is confirmed.

Some uncertainty still exists regarding the capability to properly detect and characterize all present flaws in the reactor pressure vessels. In particular, tilted flaws, hidden flaws, flaws nearby the interface cladding/base metal and smaller flaws may not be completely identified or fully described, implying a possible underestimation of the number and significance for safety of the flaw indications reported to date. Additional studies and/or examinations may be needed to resolve these questions.

Besides, the opportunities to experimentally qualify the ultrasonic inspection techniques used so far are limited: only one component (belonging to AREVA) containing hydrogen flakes is available and this component is not fully representative of the reactor pressure vessel shells in question (no internal cladding, no heat treatment). The experimental qualification of the ultrasonic inspection technique using more representative specimens is pending.

6.3.2 Requirements

The FANC would like to stress that the requirements related to the verification of the non-destructive examination procedure and the review and follow-up of their qualification program is the responsibility of AIB-Vinçotte, which is the authorized inspection agency in Belgium.

The FANC issues the following requirements about the in-service inspections.

As a prerequisite to the restart of both reactor units, the short-term requirements on inspections mentioned in the AIB-Vinçotte assessment shall be fulfilled by the licensee:

- **The licensee shall re-analyze the EAR acquisition data for Tihange 2 in the depth range from 0 to 15 mm in the zones with hydrogen flakes to confirm whether or not some of these technological cladding defects have to be considered as hydrogen flakes.**
- **The licensee shall demonstrate that no critical hydrogen flake type defects are expected in the non-inspectable areas.**
- **The licensee shall demonstrate that the applied ultrasonic testing procedure allows the detection of the higher tilt defects in the Doel 3/Tihange 2 data (2012 inspections) with a high level of confidence.**
- **The licensee shall present the detailed report of all macrographical examinations including the sample with the 45°T reflections and shall also analyze and report additional samples with 45°T reflectivity.**
- **The licensee shall include a set of defects partially hidden by other defects for macrographic examination, to confirm whether the sizing method continues to function well.**
- **The licensee shall re-analyze the tilts of the defects in the VB-395/1 block with the same method as applied on-site.**

As soon as possible after the restart of both reactor units, the licensee shall achieve a full qualification program to demonstrate the suitability of the in-service inspection technique for the present case. The qualification shall give sufficient confidence in the accuracy of the results with respect to the number and features (location, size, orientation…) of the flaw indications. Where appropriate, the process shall be substantiated by appropriate experimental data using representative specimens. The specific remarks and mid-term requirements of AIB-Vinçotte related to this full qualification program shall be satisfied before the next planned outage for refuelling.

7. Metallurgical origin and evolution of the indications

7.1 Data provided by the licensee

7.1.1 Origin of the indications

According to the licensee, the origin of the indications found during the 2012 in-service inspections of the Doel 3 and Tihange 2 reactor pressure vessels can be attributed to hydrogen flaking during fabrication. The licensee indicates that this conclusion is based on:

- a profound evaluation by AREVA (a company which manufactured numerous reactor pressure vessels in France),
- a root cause analysis evaluating all possible flaw formation mechanisms,
- a detailed comparison with a reference block with known hydrogen flakes.

According to the licensee, the full screening of all potential forming mechanisms confirms the hydrogen flaking as the most likely origin of the indications.

7.1.2 Evolution of the indications

The potential evolution of the indications during operation was also addressed. To this end, the following actions were undertaken:

- A literature review on propagation mechanisms. Several mechanisms were considered, such as fatigue crack growth, hydrogen-induced growth, irradiation-induced growth and the combination of several of these mechanisms. In relation with hydrogen-induced growth, the possible sources of hydrogen were investigated.
- A comparison of the sizes of the ultrasonic testing indications found at Doel 3 and Tihange 2 with the typical sizes of hydrogen flakes found during manufacturing.
- A mapping of the distribution of the indications versus the neutron fluence at the location of the indications (correlation check).
- An analysis of the fatigue crack growth according to appendix A of the ASME XI code.

The licensee carried out an assessment of the flakes potential growth over time, showing that the only possible propagation mechanism is fatigue crack growth, the evolution of which is calculated to be less than 2.2 % over 40 years. Based on this study, the licensee concludes that there is no risk of ligament cracking between the flakes.

7.1.3 Conclusions of the licensee about the metallurgical origin and evolution of the indications

As a conclusion about the metallurgical origin and evolution of the indications, the licensee states in its safety case reports [1][2] that:

> *"Hydrogen flaking [is] confirmed and stable. The first diagnosis of hydrogen flaking was evaluated based on:*
>
> - *An extensive literature study*
> - *A root cause analysis of all potential causes*
> - *An evaluation of the possible flaw formation mechanisms*

- *A detailed evaluation report of the AREVA metallurgy experts based on the construction files and the shape and size of the indications*

This report was challenged and completed by external experts. As a result, the first diagnosis was confirmed. It was also concluded that the identified indications were stable."

7.2 Evaluation by Bel V, AIB-Vinçotte and expert groups

7.2.1 Bel V

According to the licensee, the mechanism at the origin of the flaws, namely hydrogen-induced cracking, is no longer to be considered as a possible mechanism for crack growth under service conditions, as the hydrogen is no longer present or only at very low levels at the flake sites. The only possible crack propagation mechanism is fatigue. Bel V did not find any element that could invalidate those findings.

Bel V notes however that no comprehensive root cause analysis could explain why the hydrogen-induced degradation did not evenly affect all the forged components of the Doel 3 and Tihange 2 reactor pressure vessels, though their hydrogen content is comparable.

7.2.2 AIB-Vinçotte

Regarding the origin of the indications, AIB-Vinçotte considers that it is likely that the detected flaws are hydrogen flakes appeared after the cooling following the forging operations in the RDM workshop. The number and location of the indications revealed in service, in relation to the residual metallurgical features from the original ingot (mainly positive macro-segregation), support this assumption. Furthermore, hydrogen flakes are commonly parallel to the direction of the material flow, and the pattern of the observed indications seems to be in line with that consideration. Hydrogen flaking is considered the worst case scenario for the possible propagation of those flake-like flaws, due to the crack morphology (thin, sharp tips) and the presence of hydrogen.

AIB-Vinçotte also agrees that irradiation is probably not the cause as the distribution of the flakes in the reactor pressure vessels is not correlated with the irradiation level in the material. Moreover, irradiation cannot account for the in-depth indications where the irradiation level is lower.

Regarding the propagation during operation, AIB-Vinçotte notes that it is unlikely that the detected flaws have propagated in service as their dimensions are considered acceptable with respect to the criteria for manufacturing flaws. The presented root cause analysis concludes that low cycle fatigue resulting from transients is the only theoretically possible propagation mechanism.

The presence of a high density of flakes inducing the possibility to link flakes by ligament cracking due to fatigue is the remaining concern, as the flakes would grow jumpwise, after a limited propagation phase between two flakes in close proximity. The grouping of nearby flaws in the calculations deals with this concern.

AIB-Vinçotte observes further that (almost) no literature or experience is available regarding the influence, if any, of the irradiation on flaw propagation in segregation zones and zones with hydrogen flakes.

In the eventuality of a restart of the reactor units, AIB Vinçotte asks that the absence of service-related propagation shall be verified by regular in-service inspections (mid-term requirement).

7.2.3 Nuclear safety authorities expert working groups

During their meetings held on 16 October 2012 and 8 January 2013, the nuclear safety authorities experts of working group 1 (non-destructive examination techniques) and working group 2 (metallurgy and material properties) discussed the available licensee's documents and made the following suggestions and observations:

- The literature review performed by the licensee to determine the origin of the flaws is considered as satisfactory.
- The indications found seem very likely to be hydrogen-flakes. The manufacturing conditions and chemical composition of the reactor pressure vessel parts do not exclude this phenomenon. However, there is no clear reason for the apparition of the flakes specifically in these components, given that other components forged by RDM for Doel 3 and Tihange 2 following a similar process have no hydrogen flakes. The nuclear safety authorities experts consider that, even with more detailed data, it would be very difficult to determine the precise root cause. Potential root cause factors among others are a cooling of the ingot to room-temperature before forging (as a result of the transport of the ingot from Krupp to RDM) or an inadequate heat treatment.
- Regarding the morphology of the flakes, ultrasonic testing results from the Doel 3 and Tihange 2 reactor pressure vessels are one of the inputs, but additional data could perhaps be extracted from the AREVA VB-395 specimen.
- Regarding the possible growth of the flaws, the nuclear safety authorities experts consider that it is important to have more information about the hydrogen content of the flakes. Hydrogen-induced cracking could occur shortly after forging, affecting the crack tip. But normally, hydrogen diffuses quickly after forging and is not liable to induce further evolution during operation. Additional measurement of the hydrogen content in the flakes from the AREVA VB-395 block and a sensitivity study to assess the impact of intergranular hydrogen were also discussed, but it is not clear how to perform such an assessment.
- Regarding the follow-up ultrasonic in-service inspection during the next planned outage after a possible restart, a fully qualified baseline examination is needed in order to evaluate the results.

7.2.4 National scientific expert group - Scientific Council

Regarding the origin of the indications, the national scientific expert group requested the licensee to demonstrate that flaw growth, for example due to the presence of H or H_2 in the flaws, did not occur prior to the 2012 inspections. This concern was also addressed by AREVA. The licensee argues that the possible causes for the formation of the flaws (during manufacturing and in service) have been analysed in detail and that other origins can be ruled out. Since the orientation of the flaws is not perpendicular to the major principal stress during loading, the licensee concludes that hydrogen flaking at the manufacturing stage is the most likely cause.

Regarding the possible in-service flaw growth, only low cycle flaw propagation during transient loading could be a possibility. However, this effect is shown to be negligible, while the effect of H can be considered as negligible on propagation. Furthermore, ligament cracking can be excluded given the low H/H_2 levels measured in AREVA flakes.

The national scientific expert group considers that the recently detected flaw indications in the Doel 3 and Tihange 2 reactor pressure vessels are very likely manufacturing related (hydrogen flakes) and that the flaws/indications were, for unknown reasons, not mentioned in the manufacturing reports after the manual inspection procedure that was conducted before commissioning the reactor pressure vessel.

In addition, the fatigue calculations covering the past 30 years of operation illustrate that the undiscovered flaws/indications should not have grown significantly during the operation.

7.2.5 International review board

Regarding the origin of the flaws, the international review board is convinced that the indications identified can be related to hydrogen flakes that were created during manufacturing of the vessel, though the non-detection of these quasi-laminar indications at the manufacturing stage remains an open question.

Regarding the possible evolution of the indications, the international review board considers that the licensee's arguments are acceptable and that the non-evolution in time of the flaws induced by hydrogen flaking is very likely justified. One of the most convincing arguments of the non-evolution of the defects during the lifetime of the pressure vessels is that after 30 years of operation, these flaws are still characteristic of hydrogen flakes. Nevertheless, the international review board advises a dedicated follow-up program to monitor the size of at least the most adverse flaws, namely the largest ones closest to the inner side of the vessel wall and the areas with pronounced concentrations of flaws.

7.3 FANC conclusions and requirements

The suggestions, observations and conclusions of the different organisations and working groups were evaluated by the Federal Agency for Nuclear Control. Wherever appropriate and relevant, the FANC decided to use this input in the formulation of the final FANC conclusions and specific requirements for the licensee.

7.3.1 Conclusions

Based on the data provided by the licensee and the conclusions released by Bel V, AIB-Vinçotte and the expert groups about the metallurgical origin and evolution of the indications, the FANC draws the following conclusions.

The most likely origin of the indications identified in the Doel 3 and Tihange 2 reactor pressure vessels is hydrogen flaking due to the manufacturing process. This assumption is supported by the number of flaws, their shape, orientation, and location in zones of suspected macro-segregation. No other plausible origin was identified. However, it is not possible to guarantee this assumption with absolute certainty without performing destructive testing on the reactor pressure vessels, which is not an option.

Meanwhile, the exact root cause of the hydrogen flaking could not be precisely defined so far. The formation of hydrogen flakes is probably due to different contributing factors, such as the hydrogen concentration in ingots, the absence of or inadequate heat treatment, or the ingot size. The fact that only these vessel shells were affected (and not other similar parts manufactured by RDM) also remains an open issue to date.

Besides, significant evolution over time of hydrogen flakes due to the operation of the reactor units is unlikely. Indeed, the indications identified are still characteristic of hydrogen flakes even after 30 years of operation. Furthermore, the only theoretical propagation mechanism is low cycle fatigue, which is considered to have a limited effect. However, there is little literature or experience about the influence of irradiation on flaw propagation in zones with hydrogen flakes. Hence, the potential evolution of the flaws under irradiation cannot be completely ruled out at this stage.

7.3.2 Requirements

The FANC issues the following requirement about the metallurgical origin and evolution of the indications.

After the restart of both reactor units, the licensee shall perform follow-up in-service inspections during the next planned outage for refuelling to ensure that no evolution of the flaw indications has occurred during operation.

8. Material properties

8.1 Data provided by the licensee

8.1.1 Determination of the material properties

In order to determine the actual material properties, the licensee carried out a material testing program during which more than 400 specimens were tested in different laboratories (AREVA, Laborelec, SCK●CEN). According to the licensee, the tests were carried out on highly representative material, using samples with the same or similar chemical composition, mechanical characteristics and origin, compared to the reactor pressure vessels in question. The samples also contained similar segregation zones.

After the performance of the tests, no effect of orientation nor segregation was found on the samples. To the licensee, this means that no additional margin needs to be considered to cover the orientation and segregation effects on fracture toughness during the structural integrity assessment of the Doel 3 and Tihange 2 reactor pressure vessels. There is a slightly higher sensitivity to irradiation embrittlement of the segregated zone that is taken into account by applying an additional shift of 50°C in the reference temperature of nil-ductility transition (RT_{NDT}) on top of the irradiation effect. This 50°C shift also covers a number of uncertainties on segregation and orientation effects, local properties of ghost lines, etc. The licensee considers that this approach is very conservative.

8.1.2 Conclusions of the licensee about the material properties

As a conclusion about the material properties, the licensee states in its safety case reports [1][2] that:

> *"Affected material is sound and with good properties. In addition to a material-related literature survey, a comprehensive testing program was launched. Many mechanical and metallurgical tests (on more than 400 test samples) were performed in different laboratories (AREVA, Laborelec, SCK●CEN) on archive materials, including a piece of 1.2 m diameter originating from the Doel 3 vessel itself. These tests showed that there is no significant effect of orientation or macro-segregation on fracture toughness. All results confirmed that the curves that the ASME code requires to be used in the assessment are conservative. The destructive tests performed on steel samples with hydrogen flaking also showed that the material between and around the flaws is sound and of a normal metallurgical structure."*

8.2 Evaluation by Bel V, AIB-Vinçotte and expert groups

8.2.1 Bel V

Regarding the structural assessment procedure, Bel V considers that some of the effects affecting potentially the material properties due to the hydrogen-induced flaws have been investigated and quantified by the licensee with respect to reference temperature for nil-ductility transition (RT_{NDT}). However, Bel V considers that the results of mechanical testing in material samples with hydrogen-induced flaws are needed to confirm the conservatism of the tensile and fracture toughness properties adopted in fracture mechanics evaluations. All the effects (segregation, orientation, microstructure, hydrogen content, irradiation…) affecting the local material properties need to be considered but also their potential interactions. There is so far no demonstration that the 50°C shift in RT_{NDT} proposed by the licensee to take account of the hydrogen-induced flaws is appropriate to cover the potential deterioration of the local fracture toughness properties in the vicinity of the flaws.

Bel V considers that experimental verification of the conservatism of the calculation procedure for flaw evaluation is a necessary condition for having the required high confidence in the demonstration of the serviceability of the reactor pressure vessels.

High confidence in the safety demonstration also requires that the presence of hydrogen-induced flaws does not decrease the ductility to an unacceptable level. Tensile testing on large specimen with flakes parallel to the specimen axis is planned as part of the complementary testing program. The results of those tests will provide useful information on the ductility. AIB-Vinçotte has also required performing additional tensile testing on large-scale specimen with flakes having a tilt angle of about 20° relative to the specimen axis. The objective of those tests is to demonstrate that the material has sufficient ductility and load bearing capacity, and that there is no premature brittle fracture. Those AIB-Vinçotte requests are endorsed by Bel V.

8.2.2 AIB-Vinçotte

With regard to the test program carried out by the licensee, AIB-Vinçotte verified the traceability of the test samples and specimens and was intensively involved in the witnessing of the tests. AIB-Vinçotte notes that no test samples or specimens with hydrogen flakes are available from the Doel 3 and Tihange 2 reactor pressure vessels shells. Therefore, some uncertainty about the representativeness of the test program for the actual reactor pressure vessel shells cannot be excluded.

AIB-Vinçotte notes the following conclusions from the test program related to the toughness properties of macro-segregation zones:

- Fracture toughness in zones of macro-segregation is not significantly different from the one measured outside these zones, for the tests performed in the transition domain. Some small differences are seen in the ductile domain but they are not relevant in the analysis of the risk of brittle fracture.
- Similarly, no effect of orientation in zones of macro-segregation is identified in the transition domain (differences are within the normal scatter of this type of tests), although some effect is visible in the ductile domain.
- In all cases, the measured fracture toughness value remains enveloped by the fracture toughness curve of the code indexed on the RT_{NDT}.

AIB-Vinçotte also notes that mechanical tests are ongoing on samples with ghost lines. To date, no test results are available from samples taken from the zones with hydrogen flakes in the VB-395/1-block.

Little literature is available about the mechanical properties of materials containing hydrogen flakes.

AIB-Vinçotte asks the licensee to demonstrate that it can be expected that the Doel 3 and Tihange 2 reactor pressure vessel materials have sufficient elongation and toughness in the zones containing hydrogen flakes. At least the following tests shall be performed on specimens taken from zones with hydrogen flakes (short-term requirement):

- local toughness tests at hydrogen flake crack tip,
- local tensile tests on ligament material near the flakes,
- large-scale tests with the plane of the hydrogen flakes inclined with respect to the loading direction.

In this context, the flaw density in the VB-395 shell where the test samples are taken shall be compared to the maximum flaw density in the reactor pressure vessel shells to get information about the representativeness of the test samples.

Besides, little literature is available about the effects of irradiation on toughness and elongation of zones with macro-segregations. No data at all are available regarding the effect of irradiation in zones with hydrogen flakes. Therefore, AIB-Vinçotte asks the licensee to validate the assumptions, made in the structural integrity assessment, for the determination of the mechanical properties in irradiated conditions in zones with macro-segregations and hydrogen flakes (mid-term requirement).

AIB-Vinçotte also notes that the final residual hydrogen content in the base material could not be evaluated through the literature survey. To date, the licensee only performed a limited number of tests to evaluate the residual hydrogen content in the base material from fabrication. According to AIB-Vinçotte, additional hydrogen measurements are needed to confirm the results obtained so far.

8.2.3 Nuclear safety authorities expert working groups

During their meetings held on 16 October 2012 and 8 and 9 January 2013, the nuclear safety authorities experts of working group 2 (metallurgy and material properties) and working group 3 (structural mechanics and fracture mechanics) discussed the available licensee’s documents and made the following observations:

- Regarding the mechanical properties, two material specimens are available for testing (namely the AREVA VB-395 steam generator shell and the nozzle cut from the Doel 3 reactor pressure vessel). They can be considered as representative to a certain extent rather than fully representative, since there are differences in the fabrication process for the AREVA shell and no hydrogen flakes are present in the Doel 3 nozzle cut. The nuclear safety authorities experts consider that more tests results are needed to determine (for calculation purposes) the mechanical properties of the materials affected by hydrogen flakes, and especially to confirm the conservatism of the RT_{NDT} shift proposed by the licensee. The nuclear safety authorities experts also consider that this RT_{NDT} shift is most relevant for the limited number of critical flaw indications. Mechanical tests should therefore be continued on the AREVA piece affected by hydrogen flakes.
- In order to experimentally validate the analytical demonstrations developed by the licensee, some large-scale tests on the available specimens containing hydrogen flakes would be desirable.
- A sensitivity analysis on material properties used in the calculations would be useful to show the conservativeness of the calculation results.
- The impact of irradiation on the in-service evolution of hydrogen flakes is difficult to evaluate, since it is not possible to compare the flakes with their initial characteristics (this information is not available). No experiment exists on this topic.

8.2.4 National scientific expert group - Scientific Council

The national scientific expert group has asked for clarification about the following items:

- combined effects of micro-structure, embrittlement, orientation and metallurgical composition on toughness;
- toughness of the material surrounding the flaws.

Based on the answers provided by the licensee, the national scientific expert group considers that the fracture toughness estimates used in the calculations are conservative, given that:

- the flaws/hydrogen flakes were formed during manufacturing;
- the shift of 50° in RT_{NDT} is higher than the FIS ("Formule d'irradiation supérieure") predicted shift in irradiated macro-segregated zone; however, to remove any discussion, the licensee should document the phosphor content effects on RT_{NDT};
- the fluence map up to 40 years was used;
- neither segregation nor anisotropy effects have been found in the new test campaigns;
- the ligaments between hydrogen flakes in the VB-395 block look sound;
- literature does not report any ligament embrittlement effect;
- the grouping methodology used also circumvents the problem of ligament embrittlement.

8.2.5 International review board

In its assessment of the adequacy and appropriateness of the structural integrity assessment, the international review board identified some issues regarding materials properties and associated test programs:

- 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 un-irradiated value of RT_{NDT} in these regions by phosphorus segregation to grain boundaries during heat treatment or ageing 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.
- There is currently a lack of experimental data quantifying the effects of the hydrogen related flaws on the mechanical properties.
- Transferability of these data to the Doel 3 and Tihange 2 reactor pressure 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 the reactor pressure vessel 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.

The international review board notes that the issues regarding the appropriateness of the RT_{NDT} values used by the licensee are relevant only when the driving force to fracture exceeds the lower bound value of crack-initiation fracture toughness. This exists for only two indication groupings and two individual indications, all located in the Doel 3 reactor pressure vessel. Thus the international review board views the vast majority of the quasi-laminar indications found in Doel 3 and Tihange 2 as inconsequential to the reactor pressure vessels failure.

The international review board notes also an additional conservatism related to the use of RT_{NDT} (a correlative parameter) as a transition index temperature rather than RT_{To} (margin demonstrated for the Doel 3 upper core shell and impact negligible for the Tihange 2 upper core shell, no evaluation of the impact for both lower core shells).

To address these concerns, the international review board presented in its final conclusions some recommendations and conditions for additional measures and testing of samples and sensitivity studies.

8.3 FANC conclusions and requirements

The suggestions, observations and conclusions of the different organisations and working groups were evaluated by the Federal Agency for Nuclear Control. Wherever appropriate and relevant, the FANC decided to use this input in the formulation of the final FANC conclusions and specific requirements for the licensee.

8.3.1 Conclusions

Based on the data provided by the licensee and the conclusions released by Bel V, AIB-Vinçotte and the expert groups about the material properties, the FANC draws the following conclusions.

Within a limited timeframe, a material testing program was performed by the licensee on the available specimens. However, no test sample or specimen containing hydrogen flakes is available from the Doel 3 and Tihange 2 reactor pressure vessel shells. Therefore, some uncertainty about the representativeness of the test program exists.

Furthermore, there is at present little experimental data available about the (local) mechanical properties of materials in zones with macro-segregations containing hydrogen flakes. This applies even more to irradiated materials containing hydrogen flakes. Hence more experimental data on tensile and toughness properties of the materials are needed to validate the approach followed in the structural integrity assessment for both reactor pressure vessels and especially to confirm that the additional 50° shift in RT_{NDT} proposed by the licensee is conservative.

8.3.2 Requirements

The FANC issues the following requirements about the material properties.

As a prerequisite to the restart of both reactor units:

- **The licensee shall complete the material testing program using samples with macro-segregations containing hydrogen flakes. This experimental program shall include:**
  - **small-scale specimen tests:**
    - **local toughness tests at hydrogen flake crack tip,**
    - **local tensile tests on ligament material near the flakes;**
  - **large-scale (tensile) specimen tests (see also § 9.3.2).**
- **The licensee shall perform additional measurements of the current residual hydrogen content in specimens with hydrogen flakes, in order to confirm the results of the limited number of tests achieved so far. For example, the licensee has estimated an upper bound on the amount of residual hydrogen that might still be present in the flaws. The licensee shall demonstrate that the chosen material properties are still valid, even if the upper bound quantity of hydrogen would still be present in critical flaws.**

As soon as possible after the restart of both reactor units,

- **A further experimental program to study the material properties of irradiated specimens containing hydrogen flakes shall be elaborated by the licensee.**

- **The licensee shall further investigate experimentally the local (micro-scale) material properties of specimens with macro-segregations, ghost lines and hydrogen flakes (for example local chemical composition). Depending on these results, the effect of the composition on the local mechanical properties (i.e. fracture toughness) shall be quantified.**
- **The licensee shall further evaluate the effect of thermal ageing of the zone with macro-segregation.**

9. Structural integrity of the reactor pressure vessels

9.1 Data provided by the licensee

9.1.1 Results from the structural integrity assessment

The licensee performed deterministic structural integrity assessments (SIA) and an additional probabilistic SIA for both Doel 3 and Tihange 2 reactor pressure vessels. According to the licensee, all acceptance criteria are fulfilled and the reactor units can hence continue safe operation.

The structural integrity assessment consists of a deterministic SIA and a complementary probabilistic SIA, covering 40 years of operation of Doel 3 and Tihange 2. The licensee presents the following main results from both SIAs (deterministic and probabilistic) for each pressure vessel:

- The criteria regarding the primary stresses are met at all reactor pressure vessel locations considering a reduced wall thickness that accounts for the presence of flaws.
- Mechanical interactions between geometrically close flaws are taken into account before assessing their acceptability using fracture mechanics.
- A conservative assessment shows that fatigue crack growth over the service lifetime of the reactor pressure vessels is very small. The detected flaws could not have grown significantly due to fatigue during Doel 3 and Tihange 2 operation (1982-2012) and will not do so in the future. Therefore, fatigue crack growth is not a concern.
- Each flaw or group of flaws in the Doel 3 and Tihange 2 reactor pressure vessels has a size that fully meets the applicable ASME XI acceptance criteria:
    - lower core shell: the margin to acceptable size is at least 22 % (Doel 3) and 79 % (Tihange 2) for individual flaws, and 10 % (Doel 3) and 79 % (Tihange 2) for grouped flaws.
    - upper core shell: the margin to acceptable size is at least 50 % (Doel 3) and 73 % (Tihange 2) for individual flaws, and 48 % (Doel 3) and 64 % (Tihange 2) for grouped flaws.
    - vessel flange, transition ring and nozzle shell: a very conservative assessment shows that the few flaws detected in these components are acceptable.
- Protection against low temperature overpressure is guaranteed.
- The plants technical specifications have to be adapted to take account of updated pressure-temperature limits and protection against cold overpressure.
- The protection of the reactor pressure vessels against pressurized thermal shock events is confirmed for all pressure vessel components.

The complementary probabilistic SIA concludes that the frequency of crack initiation of the Doel 3 reactor pressure vessel amounts to 2.3×10^{-8} per reactor-year, which is two orders of magnitude below the acceptance criterion of 10^{-6} defined in 10CFR50.61a. The same applies to the Tihange 2 reactor pressure vessel with a frequency of 1.4×10^{-8} per reactor-year.

9.1.2 Conclusions of the licensee about the structural integrity of the reactor pressure vessels

As a conclusion about the structural integrity of the reactor pressure vessels, the licensee states in its safety case reports [1][2] that:

"Structural integrity is confirmed. After studies and testing, the multidisciplinary team developed detailed methodologies for assessing the structural behaviour of each flaw detected in the vessels shell, in all possible operational modes and transients. These methodologies have been validated after research and were challenged by external experts specialized in fracture mechanics and structural analysis, who confirmed the conservativeness of the methods.

Based on these methodologies, detailed calculations were made using state-of-the-art modelling and computing techniques, in order to verify the applicable structural integrity requirements. Calculations were performed using conservative data: in particular, very conservative fracture toughness data were used compared to actual material test results. These calculations included the following:

- *Deterministic calculations according to ASME Section III, to assess general stresses in the vessel*
- *Deterministic calculations according to ASME Section XI, to demonstrate that the dimensions of every flaw and group of flaws are well below the allowable dimensions, in all operating conditions*
- *Probabilistic safety analyses based on the US regulation*

All studies and calculation results have been thoroughly reviewed internally and by external experts and academics. The calculations confirm that the acceptance criteria of the deterministic studies are met with a significant safety margin. The criterion of the probabilistic safety analysis is widely satisfied as well, even under the conservative assumptions."

9.2 Evaluation by Bel V, AIB-Vinçotte and expert groups

9.2.1 Bel V

Regarding the structural assessment procedure, Bel V notes that Electrabel has performed a deterministic flaw evaluation of each detected flaw in accordance with the basic principles of Section XI of the ASME B&PV Code and a complementary probabilistic assessment using the FAVOR software code. Bel V remarks that the analytical evaluation procedure as provided in the current section XI of the ASME B&PV code fails to address the fitness-for-service of a component affected by clustered flaws. Hence, Bel V considers that the structural assessment should be founded on the safety objective of ensuring the safe performance of the reactor pressure vessels rather than on the compliance with Section XI of the ASME B&PV code. Bel V considers that the objective of the safety demonstration is to show that the hydrogen-induced degradation does not affect significantly the safety level of the RPV that was expected after the fabrication. With regard to that, the safe operation of the reactor pressure vessels cannot be demonstrated only by showing that each detected flaw is individually acceptable. Bel V proposed Electrabel to use a deterministic "screening criterion approach" to assess the effects of the high number of detected flaws. That approach aims at ensuring the non-significant impact of a widespread degradation on the safety level of the RPVs. It also aims at determining which flaws require a more in-depth analytical evaluation. Analyzing the results of the evaluation of the individual flaws based on this approach demonstrated that the severity of the hydrogen-induced degradation affecting the Doel 3 and Tihange 2 RPV shells has been eventually evaluated through a graduated approach, which identifies only a limited amount of flaws requiring an in-depth analytical evaluation. This conclusion also permits to confirm the complementary character of the probabilistic assessment.

Regarding the flaw modelling, Bel V notes that the detected hydrogen-induced flaws are referred to by the licensee as nearly-laminar flaws because, although being planar indications, some of them are oriented within more than 10 degrees (max 15 degrees) of the plane parallel to the surface of the component. Bel V recognizes that the metallographic examination of a limited number of hydrogen flakes taken from AREVA steam generator shell VB-395 shows that the geometry of the examined flake deviates from a plane geometry by no more than 500 µm. However, Bel V remarks that the effect of flaws having a geometry deviating from the in-plane geometry could be more detrimental than that of the planar flaws. Since no analysis of the UT signals has been performed to assess whether some flaws could have a geometry deviating from the in-plane geometry, Bel V asked Electrabel to evaluate the detrimental effect of non-purely in-plane flaws. The results show that, for a deviation from in-plane geometry not exceeding 10 degrees, the variation of the stress intensification factor is lower than 5%, which is considered acceptable for the present case.

Regarding the flaw interactions, the description of the hydrogen-induced degradation shows that, at some locations in the Doel 3 and Tihange 2 reactor pressure vessel shells, a relatively high density of closely-separated flaws exists. The licensee has proposed a methodology for analysing the interaction between two neighbouring nearly-laminar flaws in a vessel under pressure. An important issue is related to the application of the proximity rules to a case where the number of flaws is much greater than 2. The justification of the application of proximity rules – defined for a model with two interacting flaws – to multiple interacting flaws is not straightforward. Furthermore, the proximity rules are defined considering pressure as the only acting loading, although the pressure vessel shells also experience thermal loading. Bel V considers that the definition of the proximity rules when applied to a vessel containing multiple flaws and subjected to both pressure and thermal loadings is a key step in the analytical evaluation of the hydrogen-induced flaws. Electrabel did not provide a validation of the proximity rules within their specified limits of application. However the results of detailed 3D calculations of multiple flaw configurations present in the Doel 3 RPV shells provide confidence that the application of those proximity rules to the present case is conservative and, even if some non-conservatism could potentially occur for specific configurations, the effect on the calculated stress intensification factor would not be significant.

Regarding large-scale testing, Bel V considers that experimental confirmation of the conservatism of the 3D finite element analysis for flaw evaluation is a necessary condition for having the required high confidence in the demonstration of the serviceability of the reactor pressure vessels. The experimental verification that the presence of hydrogen-induced flaws does not lower ductility of the material to an unacceptable level is also necessary for validating the calculations. To Bel V opinion, the performance of such large-scale testing has high safety significance and is therefore required. The licensee confirmed his intent to perform the required large-scale tests out of the AREVA steam generator lower shell VB-395.

Regarding the transients, Bel V reminds that a conservative fracture mechanics flaw assessment requires that the most penalizing transients under all the specified plant operating conditions (levels A/B and levels C/D) be considered and that, for each of those transients, the most penalizing applied loadings for the considered application be defined. Applying that statement to the transients involving injection of cold water, the potential detrimental effect of non-axisymmetric distribution of the thermal loads around the RPV shell ("plume effect") needs to be investigated. Electrabel provided Bel V with information allowing concluding that the "plume effect" may be neglected.

Regarding the fatigue crack growth, Electrabel provided calculations of the fatigue crack growth of the hydrogen flakes. The calculated fatigue crack growth in depth was found to be less than 2% for a 40 year lifetime. Bel V considers that, even if the calculated fatigue growth could possibly be qualified as low in the absolute, it may not be considered as non-significant in the context of the reactor pressure vessels issue. In fact, Bel V considers that the hydrogen-induced flaws are required to experience no fatigue growth. Reducing the conservatism of the calculations by using the actual stress intensification factor of nearly-laminar flaws and by using the fatigue crack growth threshold provided in more recent editions of Section XI of the ASME B&PV Code allowed reducing significantly the calculated fatigue crack growth.

Regarding the primary stress limits, the objective is to demonstrate that the presence of flaws does not reduce the wall thickness to the extent that its load-carrying capacity is lost, i.e., the specified design margin against collapse is not satisfied. As required by Bel V, the licensee performed a limit load analysis of a 2D analysis model of a reactor pressure vessel to demonstrate that the primary stress limits of Section III of the ASME B&PV code were satisfied.

Regarding the analytical flaw evaluation, Bel V stresses that a precise description of the degradation affecting the Doel 3 and Tihange 2 reactor pressure vessels is needed to get a good understanding of the severity of the degradation that is related in particular to the presence of clustered flaws with small spacing between one another and to the potential location of the flaws in highly irradiated zones in the pressure vessel shells. A technical report providing a more detailed description of the degradation, in particular for the lower shell of the Doel 3 reactor pressure vessel, was transmitted to Bel V. Bel V considers that the additional information given in the document is valuable for the review.

Regarding the probabilistic assessment, Bel V considers that the use of a probabilistic assessment in the demonstration of the fitness-for-service of the Doel 3 and Tihange 2 reactor pressure vessels raises issues, in particular because the acceptability of probabilistic analyses in structural assessments has not been evaluated so far and, as a result, acceptance criteria have not been defined yet. Bel V emphasizes that the use of a screening criterion as described above allows demonstrating on its own the required global level of safety of the reactor pressure vessels. In that case, the probabilistic assessment can be considered as complementary.

9.2.2 AIB-Vinçotte

AIB-Vinçotte considers the probabilistic risk analysis only for information and limits its evaluation to the review of the deterministic flaw acceptability assessment, based on ASME XI procedures but tailored to the nature and number of flaws encountered in the base metal of the Doel 3 and Tihange 2 reactor pressure vessels. For this assessment, the licensee developed a methodology for grouping of flaws.

To AIB-Vinçotte, it might be questioned whether the ASME XI code is suitable or not for the justification of a large number of manufacturing flaws. The use of the analytical assessment approach of the ASME XI code may be envisaged provided the vast majority of the flaws show very large safety margins indicating that their influence on the structural integrity is negligible, and that conservative values for the input parameters (defect sizes and locations, material properties, loadings) are considered in the analysis.

From the submitted safety case, AIB-Vinçotte notes that for the majority of the flaws, a large safety margin is calculated with respect to the allowable flaw size.

However, AIB-Vinçotte identified several issues related to the calculations.

The review of the ultrasonic testing results on the VB-395/1 block showed that some hydrogen flakes with important inclination (> 10°), were situated below the on-site ultrasonic reporting criteria. In function of the results of the action related to the detectability and characterization of the higher tilt flaws, AIB-Vinçotte asks the licensee to evaluate the impact of the possible non-reporting of flaws with higher tilts on the results of the structural integrity assessment (short-term requirement).

In addition, the approach described in ASME XI code is in principle applicable for the justification of indications originating from in-service degradation mechanisms and not for the justification of large numbers of fabrication flaws in base materials, the exact origin of these defects being uncertain. Hence the suitability and conservativeness of the approach shall be validated on the large-scale tests (short-term requirement). This test on a sample with multiple hydrogen flake defects, shall in particular demonstrate that there's no risk for brittle fracture and that the material has sufficient ductility.

9.2.3 Nuclear safety authorities expert working groups

During their meetings held on 16 October 2012 and 9 January 2013, the nuclear safety authorities experts of working group 3 (structural mechanics and fracture mechanics) discussed the available licensee's documents and made the following observations:

- The Doel 3 and Tihange 2 reactor pressure vessels issue is an unprecedented case in the world. The ASME section XI code is not really formulated to be applied to this case with multiple clustered flaws, but the conceptual model and principles of this code can be used.
- A criterion to distinguish critical flaws from other non-relevant flaws (so-called "screening rule") was discussed but no clear consensus on this topic was reached. From a regulatory body point of view, such a criterion could be useful to clearly identify critical flaws (close to vessel wall, area with highest density…) to be looked at in detail and to assess their impact on safety, and on the other hand to show that the large majority of indications has no safety impact. The licensee has already identified some critical flaws for which a 3D analysis was performed on a very limited number of critical flaws.
- The information that was recently provided by the licensee on the characteristics of the indications (3D visualization, distance distribution between indications, slope vs. depth…) is considered as useful from a regulatory body point of view, to clearly understand where the most significant flaws are located.
- Regarding the modelling of flaws, it should be evaluated whether deviations from pure planar geometry of hydrogen flakes are an issue.
- Regarding the flaw proximity rules (grouping criteria), the nuclear safety authorities experts consider that these rules need to be validated but refer in this case to the 3D analysis of some critical flaws which has been performed by the licensee. If additional validation efforts are required, the additional cases to be studied should be clearly defined by the licensee. Mention was made of some rare cases where ultrasonic testing could not detect continuous flaws (flaws with physical links between them), therefore the grouping criteria should cover flaws that are physically linked.
- The arguments provided by the licensee are sufficient to show that the fatigue crack growth results are conservative, but the claims by the licensee stating that fatigue crack growth is insignificant can be demonstrated further, for example by comparing the calculated stress intensity range ΔK values to the fatigue crack growth threshold ΔK_{th}.
- Regarding the loadings used in the deterministic analysis, the nuclear safety authorities experts remark that only a limited number of C/D transients were used, whereas in the probabilistic pressurized thermal shock (PTS) analysis, a larger selection of transients was used.

9.2.4 National scientific expert group - Scientific Council

At the request of the national scientific expert group, the licensee has provided clarification about the following items:

- hypothesis related to licensee's grouping criteria,

- application of the new grouping criteria,
- verification of the ASME III code requirements,
- fatigue analysis,
- use of linear elastic fracture mechanics (LEFM) far away from the cladding.

The national scientific expert group considers that the estimate of the K (stress intensity factor) value is conservative, given that*:*

- the grouping criteria have shown to be conservative because 3D numerical calculations account for the interactions, plasticity when needed, and mechanical and thermal stresses;
- the inclinations of the grouped indications are higher than for the individual flaw(s). In addition, the use of the projected area in the circumferential and axial directions of the grouped indications is also a conservative approach;
- the pressure closing effect of the laminar and nearly-laminar flaws is neglected;
- the analysis is focused on crack initiation and not on crack arrest, which is a conservative approach;
- the multiple service and accidental transients used to calculate the flaw size limits is conservative;
- warm-pre-stress effect has not been considered, which is conservative.

9.2.5 International review board

For all calculations provided by the licensee, the international review board assumes 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 correct.

The international review board recalls the different calculations and assessments performed by the licensee:

- primary stress reassessment according to ASME III subsection NB-3000,
- assessment of critical flaw size at Doel 3 and Tihange 2 in line with the principles of fracture mechanics and the provisions of section XI of the ASME code,
- 3D finite element modelling (FEM) analysis covering all individual flaws belonging to the most penalizing group of flaws,
- demonstration of conformance to the requirements of 10CFR50.61 (the pressurized thermal shock rule),
- probabilistic pressurized thermal shock analysis, based on the methods used in the development of 10CFR50.61a,
- additional sensitivity study of the structural integrity assuming that the most critical flaws found at Doel 3 exist at the interface between the cladding and the base metal.

The international review board notes that the licensee's assessment is conservative in most respects. An additional point of attention concerns the cladding, as the safety case did not consider the effects of residual stresses or the heat affected zone produced by the cladding. This should be assessed in the short term after restart of the reactor units.

9.3 FANC conclusions and requirements

The suggestions, observations and conclusions of the different organisations and working groups were evaluated by the Federal Agency for Nuclear Control. Wherever appropriate and relevant, the FANC decided to use this input in the formulation of the final FANC conclusions and specific requirements for the licensee.

9.3.1 Conclusions

Based on the data provided by the licensee and the conclusions released by Bel V, AIB-Vinçotte and the expert groups about the structural integrity of the reactor pressure vessels, the FANC draws the following conclusions.

The fracture mechanics evaluation procedures need an appropriate level of conservatism backed by experimental validations where appropriate. Indeed, a high level of confidence is required in fracture mechanics evaluations as the failure of the reactor pressure vessels is to be excluded.

A deterministic flaw evaluation of each detected indication in accordance with the basic principles of Section XI of the ASME Code was performed by the licensee. However, the approach described in this ASME code is in principle applicable for the justification of indications originating from in-service degradation mechanisms and not for the justification of large numbers of interacting flaws in base materials. Therefore, though the philosophy and background of the ASME code can be used for reference, the suitability of the approach adopted by the licensee to justify the structural integrity of the reactor pressure vessels needed to be validated on some topics. Several issues in the fracture mechanics evaluation were therefore studied more in detail to ensure that sufficient conservatism was included in the analytical flaw calculations: modelling of flaws, grouping criteria used for flaw interactions, use of most penalizing transients,…

The development of a ”screening criterion” for the analytical flaw evaluation was in this way also useful to clearly identify the flaws that are most detrimental for the safety of the reactor pressure vessels and focus attention on these flaws. The licensee’s calculations show that a very large majority of indications has no safety impact.

Deterministic calculations also demonstrated that the primary stress limits of Section III of the ASME B&PV code are satisfied and that fatigue crack growth over the remaining service lifetime of the reactor pressure vessels is very small.

The probabilistic assessment approach provided by the licensee can be considered as complementary, and does not represent a determining input for the final evaluation of the safe operability of both reactor pressure vessels.

9.3.2 Requirements

The FANC issues the following requirements about the structural integrity of the reactor pressure vessels.

As a prerequisite to the restart of both reactor units, the licensee shall resolve a remaining issue identified in the fracture mechanics evaluation and shall perform an additional experimental validation. In this respect:

- **The licensee shall evaluate the impact of the possible non-reporting of flaws with higher tilts on the results of the structural integrity assessment (taking into account the results of the actions related to the previous requirement on the detection of the higher tilt defects during in-service-inspections).**
- **The licensee shall complete the on-going material testing program by testing larger specimens containing hydrogen flakes, with the following 2 objectives:**
    - **Objective 1: Tensile tests on samples with (inclined) multiple hydrogen flake defects, which shall in particular demonstrate that the material has sufficient ductility and load bearing capacity, and that there is no premature brittle fracture.**
    - **Objective 2: An experimental confirmation of the suitability and conservatism of the 3D finite elements analysis.**

10. Action plan

10.1 Action plan proposed by the licensee

Based on the results of its safety assessment, the licensee concluded that both Doel 3 and Tihange 2 reactor units could continue safe operation with no restrictions, and could thus be restarted without delay.

However, the licensee proposed a basic action plan destined to improve the safety margins, extend the subsequent follow-up and develop the knowledge and experience feedback on this issue.

10.1.1 Additional operational measures

The licensee proposed to implement the following actions before the restart of the Doel 3 and Tihange 2 reactor units, on top of the existing operational measures:

- For Doel 3 and Tihange 2, the licensee will reduce the authorized heat-up and cool-down gradients during start-up and shut-down operations. According to the licensee, this will further reduce the thermal and pressure loadings on the reactor pressure vessels during normal operation.
- For Doel 3, the licensee will implement a permanent preheating of the safety injection water reservoirs to 30°C. According to the licensee, this measure is not necessary given the results of the structural integrity assessment; nevertheless, it will add a 20% margin to the acceptable flaw size close to the vessels' inner surface.
- All operators of the Doel 3 and Tihange 2 reactor units had a refresher training session on the full scope simulator in the last quarter of 2012. An extended briefing will be given to all shift personnel about the start-up and changes in the operational parameters and specifications.

10.1.2 Short-term and mid-term actions

10.1.2.1 Future inspection program

The licensee will perform the same inspection of the entire reactor pressure vessels wall thickness at the end of the first cycle of both units. Therefore, a program for extending the qualification of the MIS-B equipment will be launched under the supervision of the licensee's qualification body and the authorized inspection agency. The basic objective of the qualification extension is to document the flaw detection and characterization capability on a block of an AREVA shell known to contain hydrogen flakes.

10.1.2.2 Material testing

The licensee will launch a confirmatory testing program on materials from the block of the AREVA shell that contains hydrogen flakes. This program, still to be finalized with the safety authorities, will encompass two phases:

- In the short term (about 4 months), the licensee, together with SCK●CEN, will perform a test program on a series of small-scale tensile and fracture toughness specimens located in two zones: one in material outside of the segregated zone, and the other in material located between flakes (ligaments) in the segregated zone. The objective is to assess the conservativeness of the ligament's mechanical properties that were used in the structural assessment.

- In the medium term (about one year), the licensee will conduct a test of large tensile specimens containing hydrogen flakes in an orientation comparable to the orientation of the indications present in the Doel 3 and Tihange 2 reactor pressure vessels. The objectives are:
    - to confirm that the flakes in a nearly laminar orientation do not significantly affect the load-bearing capacity of the specimens,
    - to assess the conservativeness of the structural integrity assessment method.

  In order to be representative, the specimens need to be of large dimensions, which requires more time for preparation and execution.

10.2 Evaluation by Bel V, AIB-Vinçotte and expert groups

10.2.1 Bel V

Bel V considers that experimental verification of the conservatism of the calculation procedure for flaw evaluation is a necessary condition for having the required high confidence in the demonstration of the serviceability of the reactor pressure vessels.

High confidence in the safety demonstration also requires that the presence of hydrogen-induced flaws does not decrease the ductility to an unacceptable level. Tensile testing on large specimen with flakes parallel to the specimen axis is planned as part of the complementary testing program. The results of those tests will provide useful information on the ductility. AIB-Vinçotte has also required performing additional tensile testing on large-scale specimen with flakes having a tilt angle of about 20° relative to the specimen axis. The objective of those tests is to demonstrate that the material has sufficient ductility and load bearing capacity, and that there is no premature brittle fracture. Those AIB-Vinçotte requests are endorsed by Bel V.

In order to account for the actual condition of the Doel 3 and Tihange 2 reactor pressure vessels and therefore to complete the demonstration of the serviceability of the reactor pressure vessels, a non-destructive test on the reactor pressure vessels needs to be performed. Theoretically, the non-destructive test should be representative of the most severe loadings applied to the reactor pressure vessel. Practically, the only test that can be performed is a pressure test.
The objective of the pressure test is not to validate the analytical demonstration on the reactor pressure vessel itself but to demonstrate that no unexpected condition is present in the reactor pressure vessels. With regard to that objective, the pressure test needs to be complemented by acoustic emission testing. The acceptance criterion will be that no initiation of crack propagation is recorded. It may indeed be expected that, in the condition of the reactor pressure vessels as considered in the fitness-for-service evaluation, no initiation of crack propagation is expected under the pressure loading.

10.2.2 AIB-Vinçotte

AIB Vinçotte considers that, in the eventuality of a restart of the Doel 3 and Tihange 2 reactor units, the absence of any service-related flaw propagation shall be verified by regular in-service inspections, as already announced by the licensee.

With regard to the material testing program, AIB-Vinçotte requires the licensee to demonstrate that it can be expected that the Doel 3 / Tihange 2 reactor pressure vessel materials have sufficient elongation and toughness in the zones containing the hydrogen flakes. At least the following tests shall be performed on specimens taken from zones with hydrogen flakes:

- local toughness tests at hydrogen flake crack tip,

- local tensile tests on ligament material near the flakes,
- large-scale tests with the plane of the hydrogen flakes inclined with respect to the loading direction.

As uncertainties exist at all levels in the structural integrity assessment, AIB-Vinçotte reiterates its demand to verify the possibility of performing a loading on both reactor pressure vessels accompanied with appropriate non-destructive testing (i.e. pressure loading accompanied with acoustic emission and ultrasonic testing examination thereafter), in order to minimize the uncertainties about the structural strength conditions of the reactor pressure vessels.

10.2.3 Nuclear safety authorities expert working groups

During their meetings held on 16 October 2012 and 8 and 9 January 2013, the nuclear safety authorities experts of working group 1 (non-destructive examination techniques) and working group 3 (structural mechanics and fracture mechanics) discussed the available licensee's documents and made the following observations:

- Different views were expressed on the usefulness of a load-test on the reactor pressure vessels combined with acoustic monitoring and follow-up ultrasonic inspections. However, the fact that this kind of test is the only one that can be performed on the reactor pressure vessels is not questioned.
- In some countries, this kind of test is performed every 10 years, or it would be required when a piece of equipment shows degradations potentially jeopardizing its fitness for service. However, such a test is not to be considered as a validation of the calculations, but as a complementary test to exclude unexpected conditions which are not considered in the calculations.
- The results of the acoustic emission monitoring must be correctly interpreted.
- A balance should also be sought between the advantages of this test and the expected difficulties (e.g. exposure of personnel to ionizing radiation and associated collective dose).

10.2.4 National scientific expert group - Scientific Council

The Scientific Council recommends that similar in-service inspections be performed after one cycle on the Doel 3 and Tihange 2 reactor pressure vessels (as announced by the licensee).

10.2.5 International review board

In its assessment of the possible evolution of the indications, the international review board advises a dedicated follow-up program to monitor the size of at least the most adverse flaws, namely the largest ones closest to the inner side of the vessel wall and the areas with pronounced concentrations of flaws. The international review board notes that the licensee has agreed to perform such follow-up inspections during the first refuelling outage following restart.

The international review board also notes that various measures that have been proposed by the licensee will enhance the operating safety of the nuclear power plants. The international review board endorses these measures, which include the following:

- reduction of the maximum allowed normal cooldown rate;
- heating of the water in the Doel 3 refuelling water storage tank to a year-round temperature of 30 °C;

- formal qualification of non-destructive examination (NDE) techniques applying the European network for inspection and qualification (ENIQ) procedure to detect nearly-laminar flaws;
- use of these qualified non-destructive examination techniques during future refuelling outages to determine if the quasi-laminar indications are increasing in size;
- continuing a neutron fluence reduction program to minimize further material embrittlement until clarification is achieved on the other issues.

10.3 FANC conclusions and requirements

The suggestions, observations and conclusions of the different organisations and working groups were evaluated by the Federal Agency for Nuclear Control. Wherever appropriate and relevant, the FANC decided to use this input in the formulation of the final FANC conclusions and specific requirements for the licensee.

10.3.1 Conclusions

Based on the data provided by the licensee and the conclusions released by Bel V, AIB-Vinçotte and the expert groups about the action plan, the FANC draws the following conclusions.

The additional operational measures proposed by the licensee are relevant and will contribute to increase the confidence in the safe operation of the Doel 3 and Tihange 2 reactor pressure vessels.

The in-service inspection program proposed by the licensee to follow up the potential evolution of the flaws during operation should focus particular attention on the most adverse flaws, e.g. the largest flaws that are closest to the inner side of the vessel wall or located inside the areas with the highest flaw distributions.

The experimental testing program proposed by the licensee is essential to confirm the properties of the affected material and validate the calculations. However, some uncertainties still remain at all levels in the structural integrity assessment and need to be dealt with through additional experimental verification.

10.3.2 Requirements

The FANC issues the following requirement about the action plan proposed by the licensee.

In addition to the actions proposed by the licensee and the additional requirements specified by the FANC in the previous sections, the licensee shall, as a prerequisite to the restart of both reactor units, perform a load test of both reactor pressure vessels. The objective of the load test is not to validate the analytical demonstration on the reactor pressure vessel itself but to demonstrate that no unexpected condition is present in the reactor pressure vessels. The methodology and associated tests (acoustic emission and ultrasonic testing...) will be defined by the licensee and submitted to the nuclear safety authority for approval. The acceptance criterion will be that no crack initiation and no crack propagation are recorded under the pressure loading.

11. Global conclusions by Bel V, AIB-Vinçotte and expert groups

11.1 Bel V

Bel V has reviewed the justification file documenting the assessment by the licensee of the fitness-for-service of the Doel 3 and Tihange 2 reactor pressure vessels. Additional information made available to Bel V in December 2012 and January 2013 have also been reviewed. The objective of that review was to assess whether the justification provided by the licensee was comprehensive, complete and technically sound and included the necessary conservatism to ensure the required high confidence in the safe performance of the reactor pressure vessels, also taking into account that reactor pressure vessel failure is not assumed in the safety analysis of the plant (break preclusion assumption).

Considering that objective but also given the time constraints, the review has been focused on the evaluation of (i) the approach used by the licensee to demonstrate analytically the fitness-for-service of the reactor pressure vessels, (ii) the conservatism included in each step of the demonstration and the associated confidence, (iii) the conservative determination of the material mechanical properties and the associated confidence, and (iv) the validation of the models and/or assumptions.

The review by Bel V of the justification file raised major concerns. Those were addressed through technical exchanges with the licensee during December 2012 and January 2013. These allowed to satisfactorily resolve some of them.

The mechanism at the origin of the detected flaws has been identified by the licensee as hydrogen-induced degradation. However the root cause analysis provided by the licensee is not fully conclusive since it does not allow to explain why the hydrogen-induced degradation has not affected evenly the core shells of the Doel 3 and Tihange 2 reactor pressure vessels nor the other forged components of the reactor pressure vessels (e.g. transition rings) although the hydrogen content is not significantly different in the four shells. Moreover, the reasons why this phenomenon has not been identified and/or reported during the fabrication process have not been clearly provided.

The procedure of deterministic analytical flaw evaluation used by the licensee to demonstrate the fitness-for-service of the reactor pressure vessels is based on the analytical flaw evaluation procedure provided in Section XI of the ASME B&PV Code. That procedure for analytical flaw evaluation is considered by Bel V as technically sound for evaluating individual defects. However, to Bel V opinion, the use of such a procedure is not sufficient to demonstrate that the global level of safety of the reactor pressure vessels is not significantly affected by the presence of thousands of flaws. The use of a “screening criterion” as proposed by Bel V allowed to achieve that objective by showing that almost all detected flaws belong to the category that contains the flaws having non-significant impact on the safe performance of the reactor pressure vessel, even if they are in large numbers, and the (few) remaining flaws belong to the other category containing the flaws requiring a specific detailed analysis to demonstrate their low significant impact on the safety level of the reactor pressure vessels. A targeted review by the licensee of the available results of the various flaw evaluations has shown that a screening criterion procedure could be satisfactorily implemented for both the Doel 3 and Tihange 2 reactor pressure vessels. Following the determination of an appropriate screening criterion, the “screening criterion approach” was shown to be a valuable tool to evaluate the non-significant impact of the hydrogen-induced degradation of the level of safety of the Doel 3 and Tihange 2 reactor pressure vessels. The licensee agreed to integrate that approach in his safety case.

The fracture mechanics evaluation of the flaws may be seen as a sequence of steps, each requiring the appropriate level of conservatism and, when necessary, validation or verification. In this regard, the review of the technical file had identified lacks or uncertainties that could jeopardize the required high confidence of the demonstration. The technical exchanges with the licensee during January 2013 and the additional technical information made available to Bel V during the same period have allowed Bel V to conclude that some of its concerns were satisfactorily solved. The remaining concerns are:

(1) The lack of experimental values of the tensile and fracture material properties that are representative of the local condition of the steel in the vicinity of the hydrogen-induced defects. That lack of data precludes a conservative definition of the local material properties with a high confidence. The licensee committed to finalise the ongoing test program at SCK•CEN on material tensile and fracture toughness properties on test specimens taken from material with hydrogen flakes. An objective of that test program is to demonstrate that the 50°C shift of RT_{NDT} is appropriate to cover the potential deterioration of the local fracture toughness properties in the vicinity of the hydrogen-induced flaws.

(2) Experimental verification of the conservatism of the calculation procedure for flaw evaluation is a necessary condition for having the required high confidence in the analytical demonstration of the serviceability of the reactor pressure vessel. To this end, appropriate large-scale mechanical testing of representative samples with hydrogen-induced flaws is required. The licensee committed to perform a monitored large-scale test (four-point bending test) on a specimen of about 60 x 60 mm with flakes having a significant tilt angle relative to the specimen axis. A concurrent 3D finite element analysis of the specimen under the applied testing conditions and applying the analytical procedure used for detailed 3D calculations of the safety cases will allow demonstrating the conservatism of the applied analytical evaluation.

(3) High confidence in the safety demonstration requires that the presence of hydrogen-induced flaws does not decrease the ductility to an unacceptable level. The licensee committed to perform tensile testing on large specimen with flakes having a tilt angle of 20 degrees relative to the specimen axis. The objective of those tests is to demonstrate that the material has sufficient ductility and load bearing capacity, and that there is no premature brittle fracture.

Obtaining satisfactory results from those additional mechanical tests is a prerequisite for the satisfactory demonstration of the serviceability of the Doel 3 and Tihange 2 reactor pressure vessels.

In order to account for the actual condition of the Doel 3 and Tihange 2 reactor pressure vessels and so, to complete the demonstration of the serviceability of the reactor pressure vessels, a non-destructive test on the reactor pressure vessels needs to be performed. The objective of the test is to demonstrate that no unexpected condition is present in the reactor pressure vessels.

Practically, the only test that can be performed is a pressure test. With regard to the pursued objective, the pressure test needs to be complemented by acoustic emission testing.

11.2 AIB-Vinçotte

The review of revised documents and recently received replies and clarifications from the licensee is still ongoing. Also all material test results are not available yet. However, the main considerations and requirements of AIB-Vinçotte are included in their report.

AIB-Vinçotte expects an answer to the requirements mentioned in the different chapters of their report: inspection, documentation, metallurgy, calculations. The short-term requirements shall be satisfied before start-up. The mid-term requirements shall be fulfilled before or at the next planned outage.

AIB-Vinçotte notes that uncertainties exist at different levels: manufacturing, ultrasonic testing, material properties, structural integrity assessment. Therefore AIB-Vinçotte raises the question to verify whether it is not possible to perform a loading on the reactor vessel, accompanied with appropriate non-destructive testing, to minimize the uncertainties about the structural strength conditions of the reactor pressure vessel (i.e. pressure loading accompanied with acoustic emission and an ultrasonic testing examination thereafter).

11.3 National scientific expert group - Scientific Council

The global conclusions issued by the national scientific expert group of the Scientific Council as part of the assessment of the Doel 3 and Tihange 2 reactor pressure vessels issue are quoted hereafter [5]:

> *"The analysis of the technical documents and the complementary clarifications provided by licensee, allow the NSEG to conclude:*
>
> 1) *that the recently detected flaws in Doel 3 and Tihange 2 RPVs are very likely manufacturing related and that the flaws/indications were, for unknown reasons, not mentioned in the manufacturing reports after the manual inspection procedure that is conducted before commissioning the RPV. In addition, the fatigue calculations covering the past 30 years of operation illustrate that the undiscovered indications/flaws should not have grown significantly during the operations;*
> 2) *that the methodology and fracture mechanics calculations, performed and/or subcontracted by the licensee, are sound and reflect the current state-of-the art;*
> 3) *that all assumptions and the numerical values of input parameters used in the calculation - other than those related to the size, orientation and position of the flaws as they are detected by the inspection tool - are conservative. However, a study of the detrimental effect of the potentially high phosphor contents in ghost-lines on fracture toughness merits consideration;*
> 4) *that, as a result of observations 2 (methodology) and 3 (geometrical and load input data), the predictions on the structural resistance of the RPVs of Doel 3 and Tihange 2 may be considered to represent a worst case scenario once the effect of the phosphor content on fracture toughness has been investigated (4, material property input data);*
> 5) *that, as a result of observation 4 (results of the analysis), the restart of operations on the nuclear reactors Doel 3 and Tihange 2 would have to be taken into consideration;*
> 6) *that, however, the available information on the validation of the inspection procedure does not give conclusive evidence that the inspection tool and inspection procedure used ensure that all potential critical flaws have been detected with certainty. In addition, the top and bottom parts adjacent to the circumferential welds of the vessel shells were not inspected. Also information on potential flaws with inclinations higher than 30° is lacking;*
> 7) *that, because of observations 5 (conservatism) and 6 (uncertainties with respect to NDE inspection), the restart of the nuclear reactors Doel 3 and Tihange 2 can only be justified when an expert opinion on the available and additional (observation 6) NDE inspection results confirms that the real number, size, position and orientation of the flaws are no worse than the reported and detected flaws."*

During its session held on 21 December 2012, the Scientific Council discussed the report of the national scientific expert group. The global conclusions of the Scientific Council are quoted hereafter [6]:

> *"The Scientific Council accepts and endorses the conclusions of the NSEG on the restart of operations of the nuclear reactors Doel 3 and Tihange 2, and in addition recommends that similar in-service inspections be performed after one cycle on the reactor pressure vessels in both units."*

Regarding the point under 7) above, the Federal Agency for Nuclear Control stated during the Scientific Council held on 21 December 2012, that it considers that the appropriate independent expert for non-destructive testing inspection is the authorized inspection agency in Belgium, namely AIB-Vinçotte.

11.4 International review board

The global conclusions issued by the international review board as part of the assessment of the Doel 3 and Tihange 2 reactor pressure vessels issue are quoted hereafter [7]:

> *"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 Ageing" 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*
    - *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.*
    - *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.*
    - *The Board requests that the effect of ageing 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 ageing could be estimated by performing step cooling experiments on representative material, to be followed with the standard mechanical properties tests.*
- *Hydrogen*
    - *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.*
    - *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."

Regarding the international review board's statements *"that only the second under the heading 'Phosphorus, Ghost Lines, and Ageing' need be accomplished before restart"*, and "*that 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*", the Federal Agency for Nuclear Control considers that these conditions are no longer relevant as their achievement is already required under § 8.3.2 and represents a prerequisite for a possible restart of the Doel 3 and Tihange 2 reactor units.

12. FANC global conclusions and requirements

12.1 Global conclusions

Based on the data provided by the licensee and the conclusions released by Bel V, AIB-Vinçotte and the national and international experts groups about the flaws of the Doel 3 and Tihange 2 reactor pressure vessels, the Federal Agency for Nuclear Control draws the following **global conclusions** for each topic assessed in the previous sections.

Regarding the manufacturing of the reactor pressure vessels:

Based on the sole manufacturing files, the presence of flaw indications since the manufacturing stage cannot be confirmed as the indications which were detectable at this stage were not reported in the final inspection reports.

Regarding the in-service inspections:

Some uncertainty still exists regarding the capability of the in-service inspection techniques to properly detect and characterize all present flaws in the reactor pressure vessels.

Regarding the metallurgical origin and evolution of the indications:

The most likely origin of the indications identified in the Doel 3 and Tihange 2 reactor pressure vessels is hydrogen flaking due to the manufacturing process. Significant evolution over time of hydrogen flakes due to the operation of the reactor units is unlikely.

Regarding the material properties:

More experimental data on tensile and toughness properties of the materials are needed to validate the approach followed in the structural integrity assessment.

Regarding the structural integrity of the reactor pressure vessels:

The approach adopted by the licensee to justify the structural integrity of the reactor pressure vessels still needs to be completed or validated for some topics. The probabilistic assessment approach provided by the licensee is used only for information.

Regarding the action plan proposed by the licensee:

The additional operational measures proposed by the licensee are relevant.

The in-service inspection program proposed by the licensee should focus particular attention on the most adverse flaws.

Some uncertainties still remain in the structural integrity assessment and call for additional experimental verification.

The failure of the reactor pressure vessel is not envisaged. A major crack or fracture in the reactor pressure vessel would lead to a loss of water inventory and, in case of absence of cooling, to a core meltdown. This scenario is not covered by safety studies, and the existing safety systems are not designed to handle such an occurrence. For these reasons, it must be demonstrated with certainty that the structural integrity of the Doel 3 and Tihange 2 reactor pressure vessels is not challenged by the reported flaw indications.

In the current state of knowledge and given the available data, the open issues identified along the assessment process and described in the current evaluation report do not represent conditions that require a definitive shutdown of the Doel 3 and Tihange 2 reactor units.

However, these open issues lead to some uncertainties that might reduce the conservatism of the licensee's safety demonstration and hence impair the level of confidence in the safe operability of the reactor units in question.

As a consequence, the Federal Agency for Nuclear Control considers that, in the current state, the Doel 3 and Tihange 2 reactor units may only restart after the requirements listed under §12.2 hereafter are fulfilled by the licensee.

The licensee shall elaborate an action plan to meet those requirements, including a methodology and associated acceptance criteria where applicable. This action plan shall be approved by the Belgian nuclear safety authority.

Once the licensee has implemented its action plan, the FANC, together with Bel V and AIB-Vinçotte, will evaluate whether all the safety concerns at the origin of the requirements are solved and whether the related reservations can be lifted. On this basis, the FANC will motivate its decision about the possible restart of the Doel 3 and Tihange 2 reactor units in a subsequent final evaluation report.

This position applies only to the Doel 3 and Tihange 2 reactor units and does not extend to other nuclear reactors potentially concerned elsewhere in the world. The evaluation of their safety remains within the jurisdiction of the competent national authorities.

12.2 Requirements

The suggestions, observations and conclusions of these different organisations and working groups were evaluated by the Federal Agency for Nuclear Control. Wherever appropriate and relevant, the FANC decided to use this input in the formulation of the specific requirements for the licensee.

The FANC issues the following requirements for each topic assessed in the previous sections.

Regarding the manufacturing of the reactor pressure vessels:

Given that the whole documentation currently available was exploited and no additional finding can be derived from that material, the FANC issues no further requirement on this topic.

Regarding the in-service inspections[2]:

As a prerequisite to the restart of both reactor units, the short-term requirements on inspections mentioned in the AIB-Vinçotte assessment shall be fulfilled by the licensee:

- The licensee shall re-analyze the EAR acquisition data for Tihange 2 in the depth range from 0 to 15 mm in the zones with hydrogen flakes to confirm whether or not some of these technological cladding defects have to be considered as hydrogen flakes.
- The licensee shall demonstrate that no critical hydrogen flake type defects are expected in the non-inspectable areas.
- The licensee shall demonstrate that the applied ultrasonic testing procedure allows the detection of the higher tilt defects in the Doel 3/Tihange 2 data (2012 inspections) with a high level of confidence.
- The licensee shall present the detailed report of all macrographical examinations including the sample with the 45°T reflections and shall also analyze and report additional samples with 45°T reflectivity.

[2] The FANC would like to stress that the requirements related to the verification of the non-destructive examination procedure and the review and follow-up of their qualification program is the responsibility of AIB-Vinçotte, which is the authorized inspection agency in Belgium..

- The licensee shall include a set of defects partially hidden by other defects for macrographic examination, to confirm whether the sizing method continues to function well.
- The licensee shall re-analyze the tilts of the defects in the VB-395/1 block with the same method as applied on-site.

As soon as possible after the restart of both reactor units:

- The licensee shall achieve a full qualification program to demonstrate the suitability of the in-service inspection technique for the present case. The qualification shall give sufficient confidence in the accuracy of the results with respect to the number and features (location, size, orientation…) of the flaw indications. Where appropriate, the process shall be substantiated by appropriate experimental data using representative specimens. The full qualification program shall be achieved before the next planned outage for refuelling.

Regarding the metallurgical origin and evolution of the indications:

After the restart of both reactor units:

- The licensee shall perform follow-up in-service inspections during the next planned outage for refuelling to ensure that no evolution of the flaw indications has occurred during operation.

Regarding the material properties:

As a prerequisite to the restart of both reactor units:

- The licensee shall complete the material testing program using samples with macro-segregations containing hydrogen flakes. This experimental program shall include:
    - small-scale specimen tests:
        - local toughness tests at hydrogen flake crack tip,
        - local tensile tests on ligament material near the flakes;
    - large-scale (tensile) specimen tests.
- The licensee shall perform additional measurements of the current residual hydrogen content in specimens with hydrogen flakes, in order to confirm the results of the limited number of tests achieved so far. For example, the licensee has estimated an upper bound on the amount of residual hydrogen that might still be present in the flaws. The licensee shall demonstrate that the chosen material properties are still valid, even if the upper bound quantity of hydrogen would still be present in critical flaws.

As soon as possible after the restart of both reactor units:

- A further experimental program to study the material properties of irradiated specimens containing hydrogen flakes shall be elaborated by the licensee.
- The licensee shall further investigate experimentally the local (micro-scale) material properties of specimens with macro-segregations, ghost lines and hydrogen flakes (for example local chemical composition). Depending on these results, the effect of the composition on the local mechanical properties (i.e. fracture toughness) shall be quantified.
- The licensee shall further evaluate the effect of thermal ageing of the zone with macro-segregation.

Regarding the structural integrity of the reactor pressure vessels:

As a prerequisite to the restart of both reactor units:

- Taking into account the results of the actions related to the previous requirement on the detection of the higher tilt defects during in-service-inspections, the licensee shall evaluate the impact of the possible non-reporting of flaws with higher tilts on the results of the structural integrity assessment.
- The licensee shall complete the on-going material testing program by testing larger specimens containing hydrogen flakes, with the following 2 objectives:
    - Objective 1 : Tensile tests on samples with (inclined) multiple hydrogen flake defects, which shall in particular demonstrate that the material has sufficient ductility and load bearing capacity, and that there is no premature brittle fracture.
    - Objective 2 : An experimental confirmation of the suitability and conservatism of the 3D finite elements analysis.

Regarding the action plan proposed by the licensee:

As a prerequisite to the restart of both reactor units:

- In addition to the actions proposed by the licensee and the additional requirements specified by the FANC in the previous sections, the licensee shall perform a load test of both reactor pressure vessels. The objective of the test is not to validate the analytical demonstration on the reactor pressure vessel itself but to demonstrate that no unexpected condition is present in the reactor pressure vessels. The methodology and associated tests (acoustic emission and ultrasonic testing...) will be defined by the licensee and submitted to the nuclear safety authority for approval. The acceptance criterion will be that no crack initiation and no crack propagation are recorded under the pressure loading.

13. Acronyms

AIA	Authorized inspection agency
ASME	American Society of Mechanical Engineers
DTR	Défaut technologique de revêtement (technological cladding defect)
EAR	Examen d’Accrochage du revêtement (specific straight beam transducer)
EC	European Community
ENIQ	European network for inspection and qualification
FANC	Federal Agency for Nuclear Control
FEM	Finite element modelling
FIS	Formule d’irradiation supérieure
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit
IAEA	International Atomic Energy Agency
KU Leuven	Katholieke Universiteit Leuven
LEFM	Linear elastic fracture mechanics
MIS-B	Machine d’inspection en service belge
MT	Magnetic testing
NDE	Non-destructive examination
NEA	Nuclear Energy Agency
NRC	Nuclear Regulatory Commission
OECD	Organisation for Economic Co-operation and Development
ppm	Parts per million
PTS	Pressurized thermal shock
RDM	Rotterdamsche Droogdok Maatschappij
RN	Rotterdam Nuclear
RPV	Reactor pressure vessel
RT_{NDT}	Reference temperature for nil ductility transition
SIA	Structural integrity assessment
SCK●CEN	Belgian Nuclear Research Centre
UCL	Université Catholique de Louvain
UGent	Universiteit Gent
ULB	Université Libre de Bruxelles
ULg	Université de Liège
UT	Ultrasonic testing
VTT	Technical Research Centre of Finland

14. List of appendices

Appendix [1] Safety case report – Doel 3 Reactor Pressure Vessel Assessment
Electrabel

Appendix [2] Safety case report – Tihange 2 Reactor Pressure Vessel Assessment
Electrabel

Appendix [3] Report on independent analysis and advice regarding the safety case - Doel 3 Reactor Pressure Vessel Assessment
Electrabel

Appendix [4] Report on independent analysis and advice regarding the safety case - Tihange 2 Reactor Pressure Vessel Assessment
Electrabel

Appendix [5] Report of the National Scientific Expert Group on the RPVD3T2
National Scientific Expert Group

Appendix [6] Scientific Council of 21 December 2012 - Doel 3 and Tihange 2 Reactor Pressure Vessel Indications issue
Scientific Council of ionizing radiation established with the Federal Agency for Nuclear Control

Appendix [7] Doel 3 - Tihange 2 RPV issue - International Expert Review Board report
International Expert Review Board