Flaw indications in reactor pressure vessels: The Doel/Tihange RPV Issue

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Background
Background of the Doel/Tihange issue

• In June 2012, a UT examination was conducted at Doel Unit 3, to identify the presence of under-clad cracks.

• No underclad cracks were found but thousands of quasi-laminar indications forming clusters were noted. A similar examination was performed on the Tihange Unit 2 reactor vessel in September 2012, which was procured from the same fabricator (Rotterdam Dockyard).

• After extensive causal analysis work by Electrabel was completed, the basis for the indications was declared to be, most likely, hydrogen flaking during the vessel forging process that can be attributed to macro-segregations in the vessel steels.
Background of the Doel/Tihange issue

• Characteristics of the flaw indications:
  – **Affected shells**: Concentrated in the **upper and lower core shells**,  
  – **Number**: About **8150 indications for the Doel 3** and **2000 for the Tihange 2** RPVs,  
  – **Orientation**: **Quasi-laminar**, maximum tilt about 10-15°  
  – **Location**: **within the first 120 mm** of the vessel wall, starting from cladding to base metal interface, with **increasing concentration between 10 and 50 mm** in the vessel wall.  
  – **Typical dimension**: circular / round, about 10 mm in diameter, very thin (1 to 4 μm).
Background of the Doel/Tihange issue

• Sample result from Doel 3

Indications appear to be nearly laminar and form a cluster sinking with increasing altitude, from the inner surface up to a depth of about 120 mm.
EBL / TE Safety Case
a huge and comprehensive effort!
High level summary of the Safety Case developed by Electrabel/Tractebel

- Capability and performance of the UT technique (UT validation & qualification)
- Review of fabrication records of the vessel shells from pouring to final acceptance
- Root Cause Analysis (literature survey)
- Material Testing
- Evolution of the indications / Structural Integrity Assessment (Flaw Evaluations – Probabilistic Facture Mechanics / PTS)
- Load Test
High level summary of the Safety Case developed by Electrabel/Tractebel

• **Conclusions relative to the UT technique:**
  – Applied straight beam ultrasound technique is valid and has been qualified for both detecting and sizing quasi-laminar indications. Size is over-estimated in most cases.
  – Correct characterization of ligaments between flakes (rather undersized), partially hidden or indication with tilt also correctly detected and sized.
  – Formal qualification of UT system has been conducted. This qualification has been based on destructive testing of material samples containing flakes (VB395/1 steam generator shell block.)
Conclusions relative to the review of Fabrication Records & Root Cause Analysis:

- Hydrogen flaking has been identified as the root cause. The most susceptible locations are segregation zones.
- RCA is based on:
  - Literature review,
  - Analysis of the influencing parameters: microstructure, chemical composition (carbon, alloying elements, impurity content), hydrogen content, heat-treatment, out-gasing, stresses.
- The UT technology available at that time had the capacity to detect these indications. The indications were reportable but have not been recorded! It is documented that some other parts (e.g. T2 transition ring) were rejected exactly because of these hydrogen flakes. This remains unexplained!
High level summary of the Safety Case developed by Electrabel/Tractebel

• Conclusions relative to material testing and structural integrity:
  – The justification of the structural integrity is based on the fracture toughness curves of the ASME Code indexed on the RT_{NDT},
  – The irradiation effect is evaluated by the FIS formula (irradiation embrittlement correlation / trend curve),
  – Factors related to flaking having a potential effect on RT_{NDT} have been identified and each potential effect has been addressed through material tests,
  – The goal was to quantify each effect and determine an additional shift for each relevant parameter
High level summary of the Safety Case developed by Electrabel/Tractebel

• Conclusions relative to material testing and structural integrity:
  – To take the effect of the composition of the macro-segregation into account, the contents in copper, nickel and phosphorus is increased (by 25% for Cu, 35% for P and 8% for Ni). This lead to an additional shift of at most 17°C for 40 years.
  – The presence of flakes (as pre-cracking) and ligaments between flakes has been found to have a detrimental effect and bring another additional shift of 25 °C.
  – Other factors identified do not have any effect. The total additional shift is thus 42°C that was rounded up to 50°C.
High level summary of the Safety Case developed by Electrabel/Tractebel

• Conclusions relative to material testing and structural integrity:
  – Flaw evaluation showing acceptance based on:
    • proximity rules developed by K. Hasegawa et al. (ASME Section XI rules, i.e. IWA-3300 are not appropriate for clusters)
    • Acceptance criteria per Section XI IWB-3612
    • $K_{IC}$, $K_{Ia}$ curves per Appendix A indexed on $RT_{NDT}$
  – FCG negligible (Section XI Appendix A FCG curves)
  – ASME III NB-3228.3 Plastic Analysis has shown that primary stress criteria are met with reduced net section – validated by test (4-point bending test on specimen containing flakes)
High level summary of the Safety Case developed by Electrabel/Tractebel

- **Conclusions relative to material testing and structural integrity:**
  - Recalculation of **PT limits** with new ARTs (10 CFR 50 App. G), LTOP => Tech Spec updated.
  - **PTS rule**: screening criteria still met (10 CFR 50.61).
  - Additional evaluations per alternate PTS rule shows also TWCF well below $1.10^{-6}$ event / year (10 CFR 50.61a).
  - **Load test successful:**
    - (T between 125°C and 145°C), target pressure 175 bar abs.
    - Acoustic emission
    - Re-inspection (UT)
This is not the end...
• Some 500 tests, commissioned by Electrabel, were conducted. The safety case was developed.
• After being shut down for 10 months, the Federal Agency for Nuclear Control (FANC) gave green light to restart both reactors on May 17th 2013. Both plants restarted on June 3rd.
• However, FANC requested additional tests to obtain more insight into the behavior of the reactor vessel steel in the long term. Electrabel developed a testing plan. Tests were conducted after plants restart.
• Among all the realized additional tests, one of them did not deliver results in line with experts expectations.
• March 25, as a safety measure, Electrabel itself has decided to shutdown the reactors, while waiting for additional results.
• Due to its importance, its complexity, this program of mechanical tests and metallurgical assessments will run until autumn 2014.
Significance of the issue: 

*US - Europe*
Significance for the operating fleet: US Response

• This issue has raised questions regarding the possibility that U.S. forged-ring vessels may also have such indications. There are 21 PWR vessels with forged shells currently operating in the U.S.

• The PWR Materials Management Program recommended that action be taken to address this issue for the U.S. fleet.

• The purpose of the program is to assess the implications of the discovery at Doel-3 for U.S. vessels with beltline ring forgings.

• The program is based on:
  – Fabrication Non Destructive Examination Records Review
  – Generic Structural Evaluation consisting of a Generic Probabilistic Fracture Mechanics
Significance for the operating fleet: US Response

• **Task 1 – Evaluation of Original Equipment Manufacturers (OEM) Records and Fabricator Records**
  – For W and AREVA OEM plants with ring-forged reactor vessel beltline shells, the readily available records (which include the relevant Engineering Specifications that document the ultrasonic inspection requirements and pertinent ASME and ASTM code requirements) was evaluated.

• **Task 2: Ultrasonic Modeling Simulation of Inspection Sensitivity**
  – Ultrasonic model simulations were performed for the laminar flaw detection capability in the vessel wall using the typical inspection practices required by US NSSS vendors to satisfy the ASTM, as well as ASME requirements at the time of fabrication.
  – Ultrasonic modeling of the Doel 3 ISI methods was performed to assess the reported results
Significance for the operating fleet: US Response

• For Task 1, a search of the individual plant records identified the criteria for reporting of indications, for each unit.

• For each plant the following information was documented:
  • The Equipment specification and E-spec add. referenced the relevant ASME III Code Edition. ASME III referenced ASTM A388 “Inspection and Testing of Heavy Steel Forgings”.
  • The E-Spec could include additional UT reporting requirements:
    – ASTM A388 1959 Edition stated that the reporting criteria was agreed upon by buyer and seller. PVRC3 or ASME III Code Case N-1359-1 were invoked for reporting criteria in these cases,
    – ASTM A388 1967 and later contained reporting criteria.

• The reporting criteria were linked to the sensitivity for each inspection type, as determined by the modeling of Task 2 of the program.
Significance for the operating fleet: US Response

- The goal of task 2 was to demonstrate the UT sensitivity of the forging inspections carried out for each of the affected units.
- Each of the inspection techniques was modeled, using CIVA, a complex software code developed originally by CEA in France, to demonstrate the ability of various inspection techniques to detect indications.
- This ultrasonic simulation code is used as part of the requirements of the European Network on Inspection Qualification (ENIQ).
- The inspection methods were categorized as Method A through Method H; individual plants were not identified in the report.
- The individual plants did not need to be linked to their specific UT inspection procedure, just the indication reporting criteria normalized to an equivalent flat bottom hole (FBH) sensitivity.
- The goal was to determine if the techniques employed at all affected plants were capable of detecting the condition that was found at Doel.
Significance for the operating fleet: US Response

• There were four basic reporting criteria
  – ¼” diameter FBH DAC reference
    • No equivalent FBH simulation required (Technique A)
  – Indication exceeding remaining backwall
    • Equivalent to ½” diameter FBH in depth of interest (Tech. D)
  – 10% of backwall
    • Equivalent to ¼” FBH (Technique C)
  – -2 dB change in backwall
    • Equivalent to 0.4” FBH (Technique G)

• Shop Techniques
  – 1” diameter, 2.25 MHz, 0° transducer, minimum 15% scan overlap
  – 1 1/8” diameter, 2.25 MHz, 0° transducer, minimum 15% scan overlap
    (following images)
  – 25 mm diameter, 2 MHz, 0° transducer, minimum 15% scan overlap
  – OD manual contact inspection
Significance for the operating fleet: US Response

Figure B-1  Flaw histogram as reported by Electrabel, with report categories for reportable inspection criteria from Table 4-1.
Significance for the operating fleet: US Response

- As seen in this figure, even the least sensitive technique would have reported over 1000 indications at Doel.
- Also, additional inspections were required after the vessels were welded into sub-assemblies; these would have been likely to find even more indications, but these inspections only covered a portion of the total forging area (2T on each side of the weld), so they were not credited in the PWROG project.
- The report concludes that the inspection techniques used during fabrication of U.S. vessels were capable of detecting a condition such as Doel-3.
- Each plant had to review the inspection records showing no reportable indications.
Significance for the operating fleet: EU Response

• In Europe, several regulatory authorities have required some plants to conduct base metal inspections of the forgings in order to address the issue (e.g. Sweden, Switzerland, …)

• WENRA (the Western European Nuclear Regulators Association that includes Switzerland) has now proposed that all RPVs at European reactors be checked for flaws. Its recommendation includes guidance for the performance of the review.

• However, it is up to national nuclear safety authorities to define the necessity, testing scope, volume and non-destructive method.

• The process proposed by WENRA is a two-stage review process.
  – The first step would be a comprehensive review of the manufacturing and review records.
  – The second would involve examination of the RPVs with non-destructive test methods, but only in cases where the national nuclear safety authority considers it necessary, depending on the available information on the vessels.
New Fabrications
ASME Code - Section III & Section II requirements

Would Doel-like indications still be acceptable per recent ASME Code editions?

ASME Boiler and Pressure Vessel Code, Section III, Paragraph NB-2542.2 Acceptance Standards (US examination of forgings)

... 

(b) *Straight Beam Special Rule for Vessel Shell Sections*

(1) A ring forging made to fine grain melting practice and used for vessel shell sections shall be unacceptable if the results of the straight beam radial examination show one or more reflectors producing a continuous complete loss of back reflection accompanied by continuous indications on the same plane that cannot be encompassed with a circle whose diameter is 3 in. (75 mm) or one-half of the wall thickness, whichever is greater.

(2) In addition, two or more reflectors smaller than described in (1) above shall be unacceptable unless separated by a minimum distance equal to the greatest diameter of the larger reflector or unless they may be collectively encompassed by the circle described in (1) above.

Doel like indications may thus still be acceptable today...
ASME Code - Section III & Section II requirements

BUT... the Code is not as prescriptive as other country’s codes and rely on the owner / designer who can select appropriate rules, as:

1. Alternative method to the back wall reflection per NB-2542 Ultrasonic Examination:

NB-2542.1 Examination Procedure. All forgings in the rough-forged or finished condition, and bars, shall be examined in accordance with Article 5 of Section V and the following supplemental requirements. The techniques of (a) through (d) below are required, as applicable.

(a) Forgings may be examined by the use of alternative ultrasonic methods which utilize distance amplitude corrections, provided the acceptance standards are shown to be equivalent to those listed in NB-2542.2.
ASME Code - Section III & Section II requirements

2. Supplementary requirements given in the material specification (Section II-A, SA-508/SA-508M):

S2. Ultrasonic Testing-Reference Block Calibration

S2.2 For test sections up to 12 in. [305 mm] thick, the reference blocks shall contain a 1/4 in. [6.4 mm] diameter flat-bottom hole; for over….

S2.3 A distance-amplitude correction curve shall be established for the proper grade of steel and specified hole size.

S2.4 A forging containing one or more indications equal in amplitude to that of the applicable reference hole, when properly corrected for distance, is subject to rejection.

Doel like indications are unacceptable if the designer requires the use of NB-2542.1 Examination Procedure (a) and imposes the forging to be purchased per the material spec with supplementary requirements.
3. Supplementary requirements through the Design or Equipment Specification as e.g.:

The recording criteria and acceptance standards for the ultrasonic examinations shall be in accordance with the ASME Boiler and Pressure Vessel Code, Section III, Paragraph NB-2542.2 except that ... all indications that display crack-like characteristics shall be reported to the Purchaser for evaluation and acceptance.

This is the responsibility of the owner or its designee!
Reactor Pressure Vessel Construction Bases within the U.S. Regulatory Framework

A few highlights:

Construction is defined in the glossary of ASME B&PV Code Section III, Subsection NCA, Article NCA-9000 as:

“An all-inclusive term comprising materials, design, fabrication, examination, testing, inspection, and certification required in the manufacture and installation of an item.”

Thus substantially more than the requirements included in Section III, Subsection NB for the construction of Class 1 nuclear components…:

- Nuclear Regulatory Commission (NRC) regulations associated with obtaining a license (10 CFR 50)
- ASME Code + reference Codes & Standards
A few highlights:

• The Design Specification identifies all of the applicable reference documents. Numerous documents and drawings are identified, in addition to the applicable Codes, regulations, Regulatory Guides, and other industry standards. It also integrates experience and knowledge of RPV design, fabrication and examination.

• Design Specification addresses the selection of ASME Code materials and associated requirements.

• NB-2160 DETERIORATION OF MATERIAL IN SERVICE: “…It is the responsibility of the Owner to select material suitable for the conditions stated in the Design Specifications (NCA-3250), with specific attention being given to the effects of service conditions upon the properties of the material…”

It is up to the designer to select appropriate materials and specify additional requirements for materials to address any adverse effects due to the operating environment related to corrosion, irradiation, thermal exposure or other potential degradation mechanisms.
Reactor Pressure Vessel Construction Bases within the U.S. Regulatory Framework

A few highlights:

• **Preservice** and inservice **inspection:**
  The techniques, procedures and personnel qualification requirements used to perform the PSI are required to be the same as those that will be used to perform the ISI of the RPV during its operation. The current Section XI performance based requirements for RPV PSI/ISI utilize sophisticated automated systems with computerized data acquisition systems.

• **Quality Assurance Requirements**
  The Authorized Nuclear Inspector verifies compliance with the requirements of the Design Specification, including codes and standards invoked therein, documents used for construction, and the Quality Assurance program applicable to activities being performed. The inspector does not have the authority to impose additional requirements. However, if the inspector has reason to question the sufficiency of required examinations, he has the duty to communicate his concern to the Owner.
Dossier Pressure Vessel Doel 3 & Tihange 2

English press release

- 26/03/2014 - Doel 3 and Tihange 2 reactors in outage earlier than planned
- 17/05/2013 - FANC experts give positive opinion on restart Doel 3 & Tihange 2 reactor units

Rapports

- 17/05/2013 (FANC) | Doel 3 and Tihange 2 reactor pressure vessels: Final evaluation report
- 15/05/2013 (ABWR/Sequoia) | Tihange 2 - ISI 2012 - Justification of the Reactor Pressure Vessel (RPV) shell
- 15/05/2013 (ABWR/Sequoia) | Doel 3 - ISI 2012 - Justification of the Reactor Pressure Vessel (RPV) shell
- 15/05/2012 (Doel V1) | Safety Evaluation Report - Flaw indications in the RPV's of Doel 3 and Tihange 2
- 07/05/2013 | Report of the National Scientific Expert Group on the RPV Doel 3
- 29/04/2013 (Electrabel) | Report on independent analysis and advice regarding the safety case addendum - Tihange 2 Reactor Pressure Vessel Assessment
- 29/04/2013 (Electrabel) | Report on independent analysis and advice regarding the safety case addendum - Doel 3 Reactor Pressure Vessel Assessment
- 22/04/2013 | Report of the National Scientific Expert Group on the RPV Tihange 2
- 25/04/2012 (Electrabel) | Safety case report - Addendum: Doel 3 - Reactor Pressure Vessel Assessment
- 15/04/2012 (Electrabel) | Safety case report - Addendum: Tihange 2 - Reactor Pressure Vessel Assessment
- 30/01/2012 (FANC) | Doel 3 and Tihange 2 reactor pressure vessels: Provisional evaluation report
- 11/01/2013 | Report of the National Scientific Expert Group on the RPV Doel 3
- 19/12/2012 (Electrabel) | Report on independent analysis and advice regarding the safety case - Doel 3 Reactor Pressure Vessel Assessment
- 19/12/2012 (Electrabel) | Report on independent analysis and advice regarding the safety case - Tihange 2 Reactor Pressure Vessel Assessment
References


http://pbadupws.nrc.gov/docs/ML1334/ML13340A072.pdf

https://www.sckcen.be/en/News/20140326_tests_doel_tihange


WENRA Recommendation in connection with flaw indications found in Belgian reactors, 15.08.2013

WCAP-17786-NP Rev. 0, A Review of the Shop Inspections Performed on US Reactor Vessels, and the Potential for Indications such as those found in the Recent Doel 3/Tihange 2 Inspections (PWROG PA-MSC-1172, Task 2), July 2013.