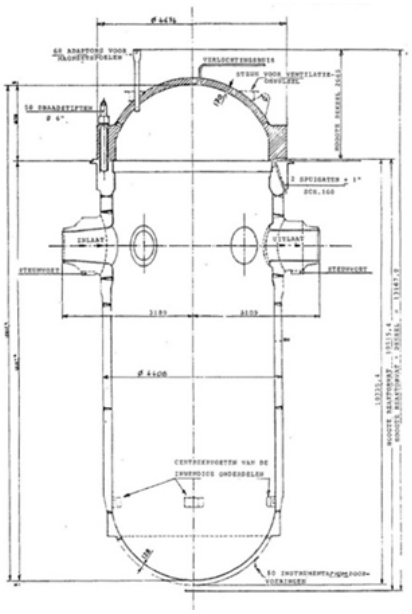

Flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2

Progress report 2014

FANC AFCN
federaal agentschap voor nucleaire controle
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Contents

1. Introduction

2014 saw some new developments on the issue of the flaw indications in the reactor pressure vessels of Doel 3 and Tihange 2. After having been authorized to restart in May 2013, both reactors were shut down again in March 2014 as a precautionary measure following the discovery of unexpected results during complementary tests.

This progress report aims at communicating the main developments and the current situation of the RPV issue at the end of the year 2014, from the point of view of the Belgian Safety Authorities.

2. Historical overview

During the 2012 outage of the Doel 3 nuclear power plant (NPP) operated by Electrabel (a company of the GdF-SUEZ Group) specific ultrasonic (UT) in-service inspections were performed, as a result of lessons learned from Tricastin[1], to check for underclad cracking in the reactor pressure vessel (RPV). No underclad defects were found but a large number of quasi-laminar indications were detected in the lower and upper core shells of the Doel 3 RPV.

A second inspection was performed in July with UT probes able to inspect the whole thickness of the vessel walls. This inspection confirmed the presence of a large number of such indications deeper inside the material. A similar inspection performed in September at the Tihange 2 RPV showed similar indications, albeit to a lesser extent.

Since the inspection results revealed a potential safety concern, the Doel 3 and Tihange 2 NPPs remained in cold shutdown while the licensee performed a safety evaluation to determine if they could safely be returned to service. This safety case was presented to the Belgian Safety Authorities in two separate documents at the end of 2012.

Taking into account the conclusions of Bel V, AIB-Vinçotte, and several national and international expert groups, the FANC issued its Provisional Evaluation Report on the issue in January 2013. In this report, the Safety Authorities required the licensee to carry out a short-term action plan and a mid-term action plan to confirm some assumptions of the safety cases. The short-term actions were needed to complete the assessment of the issue and to allow the restart of both units, while the mid-term actions were due before the next scheduled outage for refuelling.

For the sake of completeness, the 16 requirements of the action plan are repeated here in Table 1: 11 short-term requirements (in white) and 5 mid-term requirements (in red).

[1] Tricastin is a French nuclear power plant.

N°	Description	Status	Deadline
1	The licensee shall re-analyse the EAR acquisition data for Tihange 2 in the depth range of 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 hydrogen flakes.	Short-term	May 2013
2	The licensee shall demonstrate that no critical hydrogen flake type defects are expected in the non-inspectable areas.	Short-term	May 2013
2b	The licensee shall demonstrate that no critical hydrogen flake type defects are expected in the non-inspectable areas.	Follow-up action	September 2014
3	The licensee shall demonstrate that the applied Ultrasonic Testing (UT) 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	May 2013
3b	The licensee shall demonstrate that the applied Ultrasonic Testing (UT) procedure allows the detection of the higher tilt defects in the Doel 3/Tihange 2 data (2012 inspections) with a high level of confidence.	Follow-up action	Ongoing Linked to #7
4	The licensee shall present the detailed report of all macrographical examinations including the sample with the 45°T reflections and shall also analyse and report additional samples with 45°T reflectivity.	Short-term	May 2013
5	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.	Short-term	May 2013
6	The licensee shall re-analyse the tilts of the defects in the block VB395/1 with the same method as applied on-site.	Short-term	May 2013
7	The licensee shall achieve a full qualification program to demonstrate the suitability of the in-service inspection technique for this 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.	Mid-term	Ongoing
8	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.	Mid-term	Ongoing
9	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) and large scale (tensile) specimen tests (see also §9.3.2)	Short-term	May 2013
9b	The licensee shall complete the material testing program	Follow-	April 2014

	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) and large scale (tensile) specimen tests (see also §9.3.2)	up action	
10	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 should demonstrate that the chosen material properties are still valid, even if the upper bound quantity of hydrogen would still be present in critical flaws.	Short-term	May 2013
10b	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 should demonstrate that the chosen material properties are still valid, even if the upper bound quantity of hydrogen would still be present in critical flaws.	Follow-up action	April 2014
11	A further experimental study program on the material properties of irradiated specimens containing hydrogen flakes shall be elaborated by the licensee.	Mid-term	Ongoing
12	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 composition on the local mechanical properties (i.e. fracture toughness) shall be quantified.	Mid-term	Ongoing Linked to #11
13	The licensee shall further evaluate the effect of thermal ageing in the zone of macro-segregation	Mid-term	Ongoing
14	Taking into account the results of the actions related to the previous requirement on the detection of higher tilt defects during in-service-inspections, the licensee shall evaluate the impact of the possible non reporting of flaws with higher tilts on the results of the structural integrity assessment.	Short-term	May 2013
15	The licensee shall complete the ongoing test program by testing larger specimens containing hydrogen flakes.	Short-term	May 2013
15b	The licensee shall complete the ongoing test program by testing larger specimens containing hydrogen flakes.	Follow-up action	Ongoing
16	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 possible 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	Short-term	May 2013

	vessels. The methodology and associated tests (acoustic emission and ultrasonic testing...) will be defined by the licensee and submitted to the nuclear Safety Authorities for approval. The acceptance criterion will be that no crack initiation and no crack propagation are recorded under the pressure loading.		
16b	Additional questions on the load tests.	Follow-up action	April 2014

Table 1: 16 FANC requirements (in blue and red: ongoing actions in the beginning of 2014)

On 15 April and 26 April 2013 the licensee submitted to the FANC two Addenda to the Safety Case Report, which gave a structured answer to each of the FANC's (short-term) requirements for the Tihange 2 and Doel 3 reactor units. After analysis of these documents, the Belgian Safety Authorities confirmed that all safety concerns at the origin of the short-term requirements had been solved in a satisfactory manner and that they authorized Electrabel to restart both reactors in May 2013 (see Final Evaluation Report). More information on this subject can be found on the FANC website.

Nevertheless, the Belgian Safety Authorities imposed additional follow-up actions for the short-term actions #2, #3, #9, #10, #15 and #16 (in blue in Table 1). These additional follow-up actions had to be carried out before the same deadline as the mid-term actions.

Both reactors were allowed to operate during the second half of 2013 while the licensee Electrabel was working on the 5 mid-term requirements and the 6 additional follow-up actions.

3. Progress of the mid-term actions in 2014

Early 2014, the licensee was still working on 11 actions, distributed among the three main topics of the Safety Case:

- ✓ Ultrasonic inspection techniques,
- ✓ material properties and
- ✓ structural integrity assessment.

By the end of 2014, 9 out of 11 actions have been completed by Electrabel and 4 out of 11 actions have been officially closed by the Belgian Safety Authorities, as described in the following sections:

3.1. Ultrasonic inspection techniques

Several actions concerning the ultrasonic inspection techniques were still going on in 2014:

a. Action #7: UT qualification of the MIS-B

In 2014, Electrabel has continued working on the formal UT qualification of the MIS-B tool for the detection and the sizing of the flaws in the reactor pressure vessels. Several improvements, corrections and an upgrading of the data treatment have led Electrabel to develop updated software for the detection and sizing of the flaw indications. In addition, a reanalysis of the UT inspection data of 2012 using a new, more accurate procedure, combined with a lowering of the detection thresholds, resulted in the detection and sizing of more flaw indications than previously detected with the old procedure.

The Belgian Safety Authorities - and in particular AIB-Vinçotte, an officially recognized inspection organization specialized in pressure equipment - are monitoring the development of the UT qualification. During several interactions with the licensee the Belgian Safety Authorities asked a large number of questions and raised their concerns regarding the methodology. By the end of 2014, however, the licensee Electrabel has addressed almost all concerns. The review process for this action is now almost at its end.

b. Action #8: Follow-up inspections

Electrabel had to conduct new UT inspections of the reactor pressure vessels during the planned outages of Doel 3 and Tihange 2 in 2014 to verify if the indications were not evolving any further. Comparison of the 2014 data with the 2012-2013 data, applying the same detection and sizing procedure, has shown that the flaw indications did not evolve during operation from May 2013 to March 2014.

c. Other ongoing actions related to the ultrasonic inspection techniques

Two additional follow-up actions related to the ultrasonic inspection techniques were still going on in 2014: actions #2 and #3. These actions have been completed by the licensee Electrabel in 2014 and have now been reviewed by the Belgian Safety Authorities. The results of action #2 – which demonstrated that no critical hydrogen flake type defects are to be expected in the non-inspectable areas – have been accepted by the Safety Authorities. This action was thus concluded in September 2014. The licensee has also concluded action #3, which is aimed at demonstrating that the UT procedure is suited for the detection of higher tilt defects. The termination of this action is directly linked to the ongoing qualification of the procedure (action #7). Both actions will therefore be concluded at the same time, after the completion of the MIS-B qualification.

In addition to these mid-term actions, the Belgian Safety Authorities requested the licensee to verify the absence of hydrogen flakes in the other forged components of the primary circuits of the Doel 3 and Tihange 2 reactors: elements of the pressurizers, nozzle shells ... UT inspections of these components at the Doel 3 and Tihange 2 NPPs

have been conducted by the licensee Electrabel simultaneously with the follow-up inspections of the reactor pressure vessels in 2014. The results of this inspection showed that there are no flake indications in the other forged components.

3.2. Material Properties

The characterization of the material properties is an important topic of the Safety Case. The Safety Cases submitted in 2013 by Electrabel and the results of the short-term requirements brought insight into the behaviour of flaked material. Nevertheless, the Belgian Safety Authorities required additional testing to be done on the flaked material, which led to actions #9, #10, #11, #12 and #13 of the Electrabel Action plan:

a. Action #11: Irradiation of flaked materials:

On 25 March 2014, the licensee Electrabel informed the Belgian Safety Authorities that the tests related to mid-term action #11 had produced some unexpected results. These tests were meant to assess the mechanical properties of a flaked material under irradiation. The flaked material used for the test came from an AREVA steam generator shell (VB395) that was similar (but not identical) to the Belgian RPV steel. Specimens from the AREVA shell were first irradiated in the Belgian research reactor BR2 at SCK•CEN and then subjected to mechanical tests. The test results showed some unexpected discrepancies between the different material properties: the material's embrittlement appears to be greater than one would expect based on the trend curves reported in the existing literature, whereas the material hardening appeared to be in line with the licensee's predictions. Electrabel decided at that moment to anticipate the planned outages of both reactors and to try and figure out these unexpected results and to evaluate their potential consequences on the safety cases.

The licensee performed a detailed study of the test results from this first irradiation campaign in order to explain the unexpected post-irradiation mechanical properties. Advanced investigations confirmed the unexpected behaviour of the flaked material, so the licensee Electrabel started a second irradiation campaign in April 2014 to answer the various questions raised by this issue and to confirm or discount some potential explanations. This second irradiation campaign again confirmed the unexpected behaviour but did not provide a clear explanation of the non-hardening embrittlement phenomenon observed in the VB395 flaked material. A third irradiation campaign was launched in July 2014, in which the material properties from various pieces were studied at lower fluence, to enhance the understanding of the non-hardening irradiation issue.

The Belgian Safety Authorities set up an exceptional review process to address this major issue. The details of this process are explained in section 3.

b. Other Actions: #9, #10, #12, #13

The other ongoing actions related to material properties are intended to provide additional insight into the effect of macro-segregation (short-term action #9b), the measurement of residual hydrogen (short-term action #10b), the micro-scale properties of flaked materials (#12), and the effect of thermal ageing on materials (#13). The Belgian Safety Authorities expressed no further concern upon receiving the results of actions #9b and #10b. Both actions were concluded in April 2014.

Action #12 is directly linked to the characterization of materials and should be useful in understanding the unexpected behaviour observed after irradiation. The Belgian Safety Authorities therefore consider the formal completion of this action conditional upon the development of action #11. The concerns raised by action #11 have been receiving a lot of attention from the Belgian Safety Authorities.

Action #13 was linked to the effect of thermal-ageing. Since Electrabel did not observe any unexpected behaviour here, this action was concluded. The results will now be reviewed by Bel V.

3.3. Structural Integrity Assessment calculations

a. Action #15: Large-scale tensile tests specimens

Action #15 was a short-term action which required Electrabel to perform tests on larger specimens with hydrogen flakes. This action was completed by May 2013. Some additional studies were requested, however, as a mid-term requirement. Electrabel have submitted the results of these additional studies to the Belgian Safety Authorities. Their review is still going on.

b. Action #16: Load tests

The additional follow-up action requested by the Belgian Safety Authorities for this action was completed by Electrabel in 2014. Since the results raised no concerns, the Belgian Safety Authorities officially terminated action #16 in April 2014.

4. Review process by the Safety Authorities

The unexpected behaviour of the material properties of hydrogen-flaked steel under irradiation is a very specific and complicated problem. The Belgian Safety Authorities are addressing this issue with due care. They have decided to establish a special process for the review and the analysis of the test results. This process comprises two steps: a first review of the Electrabel

methodology and a second review of the application of this methodology for demonstrating the structural integrity of the Doel 3 and Tihange RPVs.

Now, at the end of 2014, the Belgian Safety Authorities are still engaged in the first step of the review process.

An International Review Board, composed of scientists who are world-renowned experts in radiation damage mechanisms and mechanical testing, has been convened to assist the Belgian Safety Authorities in the review process.

In September 2014, Electrabel finished its first analysis of the unexpected results and adapted its previous safety case methodology to take into account this unexpected behaviour.

In order to assess this methodology and to review the unexpected irradiation results, the FANC convened a meeting of the International Review Board. The experts met in Brussels between 3 November and 7 November 2014. Their main preliminary conclusion was that the licensee's methodology is not yet mature enough. The International Review Board proposed several suggestions for additional work to help them better understand and evaluate the Electrabel methodology.

More information on the review process can be found on the FANC website.

5. Conclusions

At the moment, Electrabel has completed 9 out of 11 mid-term actions and the Belgian Safety Authorities have officially concluded 4 out of 11 mid-term actions. Actions #3, #7, #8, #11, #12, #13 and #15 are still at different levels of completion.

The current position of the Belgian Safety Authorities is that the methodology proposed by Electrabel for the safety case on the structural integrity of both reactors is not yet mature enough, and that further work is needed to clarify the implications of the unexpected irradiation results on the material properties of the RPVs.

Electrabel is still providing the Belgian Safety Authorities with new test results, new data analyses and new interpretations of archived documents. The Belgian Safety Authorities will need time to review all this new information.

In December 2014, the Belgian Safety Authorities already issued several additional requirements to Electrabel, based on the documents reviewed so far and on the results of the first International Review Board workshop: e.g. providing the raw data of the different tests, identifying and evaluating the conservatisms and margins in every step of the safety demonstration. Furthermore, some suggestions were made for additional actions and material tests. These requirements and suggestions are needed to complement the Electrabel methodology and to validate the underlying hypotheses of the Electrabel safety demonstration.

The Belgian Safety Authorities will continue their review of this dossier in 2015.