

Flawed Reactor Pressure Vessels in Belgian Nuclear Plants Doel-3 and Tihange-2

Some Comments

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Executive Summary

In August 2012 the Belgian Federal Agency for Nuclear Control (FANC) informed the public about the finding of thousands of flaws in the reactor pressure vessel of the nuclear power plant Doel 3. Similar flaws in the reactor pressure vessel of the nuclear power plant Tihange 2 were revealed in September 2012.

In December 2012, Electrabel - the owner/operator of the nuclear power plants - announced the planned restart of the two plants in January 2013. No detailed information on the background of this decision had been provided.

Also in December 2012, Rebecca Harms, Co-President of the Greens/EFA Group in the European Parliament asked the author to evaluate the available facts on the issue.

Both pressurized water reactor-type nuclear power plants are operated by Electrabel, part of the GDF-Suez Group, since the early 1980ies.

The information given by FANC has revealed that the documentation of the reactor pressure vessel manufacture for both nuclear power plants is not complete.

It was also revealed that the vessel manufacturer RDM—a Dutch company that went bankrupt in the meantime—has obviously not performed any dehydrogenation treatment and this had not been known by the Regulatory Authorities.

Ultrasonic testing of the reactor pressure vessel's base metal outside the weld region has been performed for the first time in 2012 at Doel-3, that is after 30 years of operation.

The Safety Authorities obviously were never asking for documentation, fabrication methodology (incl. hydrogen control) and ultrasonic testing results.

Electrabel's statement that the flaws originate from manufacture cannot be followed, since no defects were found during the final tests after manufacture while the flaws found 30 years later have extensions up to 24 mm wide and up to 100 mm deep and exist in remarkable density (ca. 8,000 in the case of Doel-3 and ca. 2,000 at Tihange-2).

The real nature of the flaws is still unknown and can hardly be determined with a high confidence level, since sampling cannot be performed without destruction of the vessel.

The assumed hydrogen flaking process has a considerable incubation time and is continued during operation, hydrogen flakes are considered as very dangerous defects causing unexpected failures.

The influence of radiation effects and low-cycle fatigue on possibly manufacture-induced defects during operation resulting in growth of defects has obviously not been considered by Electrabel.

Electrabel's argument that each defect was individually justified to be not dangerous for the vessel's structural integrity is not sufficient since interactions and growth of thousands of defects with sizes up to 24 mm under operational conditions (temperature, pressure, radiation) cannot be excluded.

The absence of similar flaws should be proven in all reactor pressure vessels that have not yet undergone full body inspection or where their documentation leaves doubts about appropriate hydrogen control in the fabrication process. While this aims primarily at vessels of the same manufacturer/steel provider as in the Doel/Tihange cases, similar flaws cannot be excluded in vessels from other manufacturers/providers.

In summary the restart of the two power plants has to be considered as hazardous. A possible failure of the reactor pressure vessels due to sudden crack growth in case of local thermal stresses cannot be excluded and would have catastrophic consequences, especially in the vicinity of densely populated and high-economic activity areas (Antwerp, Liège). The corium (melted reactor core) relocation to the lower plenum entailing steam explosions would sooner or later cause containment failure with the consequence of large scale radioactive releases to the environment.

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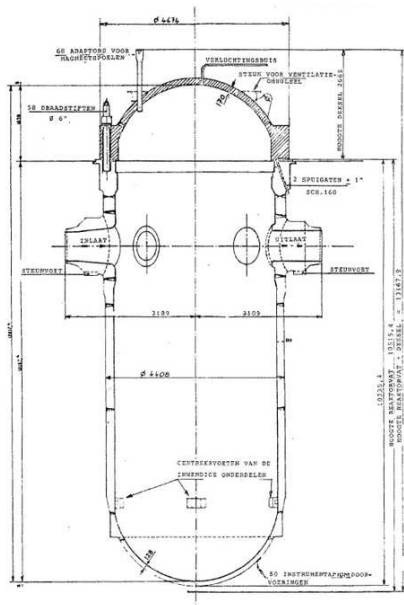
Note: At the time of writing the author had no access to operator Electrabel's justification reports nor to their assessment by the Belgian Federal Agency for Nuclear Control (FANC) and/or its self-appointed scientific review teams.

1. Facts

The NPP¹ Doel 3 started operation in 1982, Tihange 2 started operation in 1983. Both PWR (pressurized water reactor)-type NPPs are operated by Electrabel, part of the GDF-Suez Group.

The reactor pressure vessel (RPV) is the main component of the primary circuit enclosing the reactor core. The radionuclides produced by the nuclear reactions in the core are retained by the cladding of the fuel elements (first barrier), in case these claddings fail, the reactor pressure vessel is the main barrier (second barrier) towards the environment. The reactor containment is the last barrier for radioactive material release into the environment, but in case of an RPV failure the containment can only delay the radioactive releases, as the Fukushima accidents have revealed. The reactor pressure vessel cannot be replaced (at least it is not economically justifiable).

Figure 1: Reactor Pressure Vessel Doel 3



In the cases of Doel 3 and Tihange 2, the reactor pressure vessel consists of welded forged rings in the cylindrical part and a lower and upper head, the RPV has a height of about 13 m (incl. head), a diameter of about 4.4 m and a wall thickness of 20 mm (see figure 1)².

The reactor pressure vessels of the NPPs Doel 3 and Tihange 2 were manufactured by Rotterdamsche Droogdok Maatschappij (RDM), a Dutch company having the ASME N-stamp, from raw material supplied by Krupp. In the meantime RDM has gone bankrupt. Cladding and assembling have then been performed by Cockerill for the lower part (two core shells, transition ring and bottom plate) and by Framatome—now AREVA NP—for the upper part (RPV head, nozzle shell), and the final assembly.³

¹ NPP: nuclear power plant

² FANC (Federal Agency for Nuclear Control) Incident at Doel nuclear power station
<http://www.fanc.fgov.be/GED/00000000/3200/3271.pdf>

³FANC, Flaw indications in the reactor pressure vessel of Doel 3 and Tihange 2, September 3,2012,
<http://www.fanc.fgov.be/GED/00000000/3200/3288.pdf>

1.1 Flaw detection

Regular inspections of the reactor pressure vessel (RPV) in the NPPs Doel 3 and Tihange 2 performed according to ASME XI, IWB-2500-1 are restricted to the welds and surrounding material (HAZ⁴ and $\frac{1}{2}$ t⁵ base material on both sides of the weld). These regular inspections in June 2012 did not show significant changes compared to former inspections.

In the frame of complementary inspections performed in June 2012 at Doel 3 to detect and characterize underclad defects in the whole cylindrical part of the RPV in the region of the reactor core in the forged rings (SA-508-cl.3) unexpected flaws were detected⁶. (According to the Owner, no underclad cracks were found.) The flaws were found in the base metal in areas further away from the weld.

“The core lower shell is the most affected with a total of 7,776 indications. The core upper shell contains 931 indications. The other parts of the reactor vessel contain some indications, but to a lower extent and these are of a different nature in the transition ring.”⁷

According to FANC the flaws are “quasi-laminar” (parallel to the surface) “almost circular in shape” with extensions up to 24 mm. The recorded depth (from the inside of the RPV) was up to 100 mm.

“Inside the core shells, which are the most affected, flaws have been observed up to a depth of 100 mm from the inside surface. However, most of the flaws are located between 20 mm and 70 mm. As to the flaw dimensions, flaws up to 24 mm large have been observed (depending on the transducer). However, most flaws are smaller than 10 mm.”

Additional reactor pressure vessel inspections performed in September 2012 in the NPP Tihange 2 revealed similar flaws:

“A total of 2,011 indications have been identified in the shells. More particularly: In the vessel flange shell (zones 1 to 3): no indications; in the upper core shell (zones 4 to 6): 1,931 indications; in the lower core shell (zones 7 to 9): 80 indications. In the transition ring, no indications have been reported. In the flange, 19 indications have been identified.”

REMARKS:

- A significant disparity in the flaw densities between the upper and the lower shell rings is obvious.

⁴ HAZ: heat affected zone

⁵ t is the thickness of the RPV wall

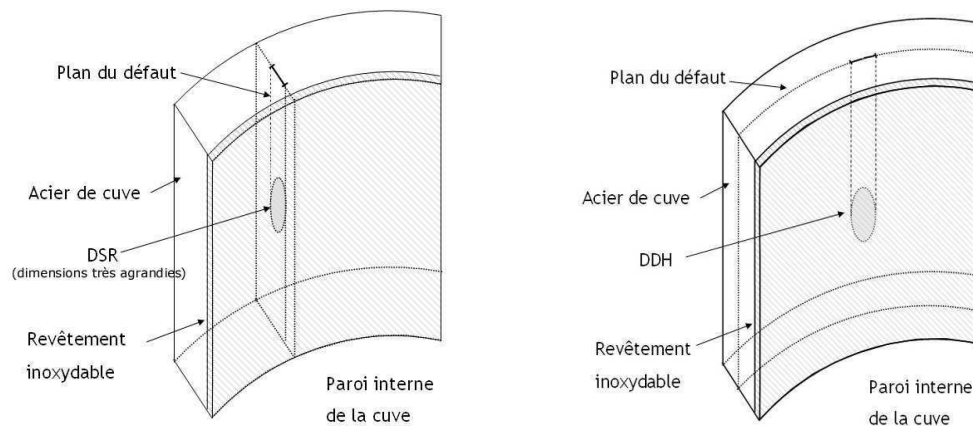
⁶FANC: Flaw indications in the reactor pressure vessel of Doel 3 and Tihange 2 , 12th October 2012
<http://www.fanc.fgov.be/GED/00000000/3300/3323.pdf>

⁷ FANC, Flaw indications in the reactor pressure vessel of Doel 3 and Tihange 2, September 3,2012,
<http://www.fanc.fgov.be/GED/00000000/3200/3288.pdf>

- The existence of underclad flaws is expected by the Standards, but the type of flaws observed is not described. Therefore no appropriate UT⁸ techniques have been developed, and regular testing of the base metal in the cylindrical RPV part is not foreseen.

While underclad cracks are directly under the stainless steel cladding oriented normal to the inside surface of the RPV wall, the observed flaws are parallel to the wall surface (see the following figures⁹; DSR¹⁰ are underclad cracks, DDH¹¹ the hydrogen-induced flaws).

Figures 2a and 2b: Underclad cracks (a) and hydrogen-induced flaws (b)



1.2 Origin of the observed flaws according to operator/authority

With respect to the possible origin of the observed flaws FANC stated in September 2012 that during the steel ingot casting impurity segregation zones may develop were trapping of diffusing hydrogen can occur during heat treatment and forging. This hydrogen accumulation might induce the flaw formation.

“The flaws would have appeared during fabrication. During the casting of the ingots, some segregation zones develop inevitably. These correspond to a modification in the content of some constituents, which locally implies a change of the physical properties. In this way, during the thermal treatments applied on the shells, hydrogen present in the material behaves differently according to the region it crosses. More specifically, during the cooling steps, hydrogen diffuses

⁸ UT: ultrasonic testing

⁹ IRSN (Institut de Radioprotection et de Sûreté Nucléaire): Note d’information—Intégrité des cuves des réacteurs électronucléaires à eau sous pression. Cas des cuves des réacteurs français
http://www.irsn.fr/FR/Actualites_presse/Actualites/Pages/20120924-Integrite_cuves_reacteurs_francais_eau_sous_pression.aspx

¹⁰ Défaut sous revêtement

¹¹ Défaut du à l’hydrogène

more into the segregation region, and accumulates there. If the initial hydrogen content is sufficient, the hydrogen accumulation may imply the formation of flaws.”¹²

In December 2012 Electrabel declared:

“The initial hypothesis of hydrogen flaking that are stable and that were formed during the forging process, was confirmed.”¹³

REMARKS:

- This statement does not explain which techniques have been used to identify the real nature of the observed flaws.
- There is also no information why the defects should be stable and how an effect of further operation of the plant on growth or propagation on the defects can be excluded.

1.3 Reactor vessel fabrication

According to FANC¹⁴ the documentation of the RPV production is not complete:

“Most of the fabrication steps have been documented, and most of this documentation has been retrieved by has been recovered by Electrabel and Tractebel Engineering (engineering studies). In this way, some data about the fabrication process of Krupp are known, such as chemical composition (and hydrogen in particular) of the blooms. However, some documents are lacking. Notably, detailed documentation about the first thermal treatment performed by RDM (which according to the LOFC has been done), an intermediate UT inspection and some RDM specifications are lacking.”

Dehydrogenation procedures during component manufacture to prevent possible hydrogen-induced defects were either not performed or are not documented:

“Experience gained since several decades shows that it is possible to avoid the formation of these flaws if the hydrogen content is kept below a certain level, if long annealing is applied, and if a dehydrogenation step is carried out. During the fabrication of the shells of the Doel 3 and Tihange 2 reactor vessels, no trace of a dehydrogenation treatment at RDM can be found.”

The documented ultrasonic testing during manufacture did show flaw indications in an acceptable range (according FANC):

“For the core upper shell, the first inspections carried out during the fabrication indicated the presence of a large zone containing acceptable indications. During the intermediate inspection, this affected zone has however not been observed anymore. During the final inspection, 12 flaws

¹² FANC, Flaw indications in the reactor pressure vessel of Doel 3 and Tihange 2, September 3,2012, <http://www.fanc.fgov.be/GED/00000000/3200/3288.pdf>

¹³ Electrabel, Group GDF SUEZ, submit conclusions for restart Doel 3 and Tihange 2, 6 December 2012, <http://www.gdfsuez.com/en/journalists/press-releases/electrabel-group-gdf-suez-submit-conclusions-restart-doel-3-tihange-2/>

¹⁴ FANC, Flaw indications in the reactor pressure vessel of Doel 3 and Tihange2, 12th October 2012 <http://www.fanc.fgov.be/GED/00000000/3200/3323.pdf>

were observed, but it has been concluded that these flaws were acceptable according to the applicable criteria. - For the core lower shell, only the documentation regarding the final inspections has been retrieved. During this final inspection, no flaws have been noticed."

REMARKS:

- It is not understandable why the Owner does not have a complete documentation on the manufacture of the main components, esp. for crucial components as the reactor pressure vessel.
- It is also surprising that the Regulatory Authorities (FANC, Bel V) did not control the completeness of the documentation.

Note: FANC was established by a Belgian law April 15, 1994. Bel V, is a subsidiary of the FANC (Federal Agency for Nuclear Control) and has since April 14, 2008, taken over the regulatory controls in nuclear installations formerly carried out by the Authorized Inspection Organization AVN. The FANC is the competent authority in the field of nuclear applications. It relies on the technical expertise of its subsidiary Bel V for carrying out inspections in nuclear power plants and other nuclear installations in Belgium (hospitals, universities, radiological installations,...)¹⁵.

1.4 Overview on other RPVs from the same manufacturer

In addition to the RPVs from the NPP Doel 3 and NPP Tihange 2 another 19 reactor pressure vessels were manufactured by the Rotterdam Drydock Company (Rotterdamsche Droogdok Maatschappij, RDM) for other countries:

"FANC organized a meeting of nuclear safety authorities in Brussels on 16 August to discuss the issue. The meeting was attended by experts from the USA, France, Switzerland, the Netherlands, Germany, Spain, Sweden and the UK. Most of these countries have nuclear power plants whose vessels have been manufactured by RDM"¹⁶.

Sweden: NPP Ringhals 2

Spain: NPP Cofrentes , NPP Garoña

Switzerland: NPP Mühleberg, NPP Leibstadt

Germany: NPP Brunsbüttel, NPP Philippsburg-1

Netherlands: NPP Borssele, NPP Dodewaard

USA: NPP Catawba-1, NPP McGuire-2, NPP North Anna-1 and -2, NPP Quad Cities-2, NPP Sequoyah-1, and-2, NPP Surry-1 and -2, NPP Watts Bar-1.¹⁷

¹⁵ <http://www.fanc.fgov.be/fr/page/le-statut-de-l-agence/15.aspx>

¹⁶ http://www.world-nuclear-news.org/RS-Safety_checks_on_reactor_vessels-2808124.html

¹⁷ According to <http://www.i-nuclear.com/2012/09/04/new-inspections-confirm-cracking-in-belgiums-doel-3-reactor-pressure-vessel/>

Several of these reactors have already been shut down permanently: Brunsbüttel, Garoña, Philippsburg-1, Dodewaard.

International response:

Sweden:

*"The Swedish Radiation Safety Authority has decided that Ringhals AB must increase the number of its planned inspections of Ringhals 2's reactor pressure vessel as of the reactor's annual refuelling and maintenance outage on 15 September. The background is the manufacturing defects reported from inspections of the Belgian nuclear reactor Doel 3. Doel 3 and Ringhals 2's reactor pressure vessels are from the same manufacturer. Ringhals AB already conducts regular inspections of the underclad cracks present in Ringhals 2. The Swedish Radiation Safety Authority now requires Ringhals to increase the number of inspections and consider their improvement in the future. To this aim, Ringhals is to present an action plan to the Authority by 1 June 2013."*¹⁸

Spain:

The Spanish Nuclear Safety Council (Consejo de Seguridad Nuclear, CSN) has analyzed the documentation and the fabrication process of reactor pressure vessels of the Cofrentes and Garoña plants.

*"CSN noted significant differences between the Garoña and Doel 3 vessels - including the size, thickness, number of forged pieces and the type of reactor. "Therefore the defects from Doel 3 cannot be extrapolated to Garoña," according to CSN."*¹⁹

"CSN will carry out the necessary inspections to verify:

- *The acceptance tests and trials in the manufacturing process.- The characteristics of the steel used in the manufacturing process of the vessels.*
- *The results of the tests carried out in the inspection programs conducted under ASME Code. This Code sets the inspection criteria for U.S. designed plants, such as Santa María de Garoña and Cofrentes. Once this process is finished, CSN will report on the results obtained."*²⁰

Switzerland:

"The Swiss federal nuclear safety inspectorate ENSI said that no indications of manufacturing defects have been detected in the reactor pressure vessel of the Mühleberg nuclear power plant.

¹⁸ Swedish Radiation Safety Authority: Additional inspections of reactor pressure vessel of Ringhals 2, 24-08-2012

<http://www.stralsakerhetsmyndigheten.se/In-English/About-the-Swedish-Radiation-Safety-Authority1/News1/Additional-inspections-of-reactor-pressure-vessel-of-Ringhals-2/>

¹⁹ world nuclear news, Safety checks on reactor vessels, 28 august 2012, http://www.world-nuclear-news.org/RS-Safety_checks_on_reactor_vessels-2808124.html

²⁰ CSN (Consejo de Seguridad Nuclear), CSN analyzes the incident in Doel 3 NPP (Belgium) and its relationship with the Spanish plants, 27 August 2012

http://www.csn.es/index.php?option=com_content&view=article&id=22209%3Acsn-analyzes-the-incident-in-doel-3-npp-belgium-and-its-relationship-with-the-spanish-plants&catid=204%3Anews&Itemid=612&lang=en

However, further ultrasound examinations will be conducted to confirm this. The vessel of the Leibstadt plant, while featuring piping supplied by RDM, was made using rolled steel, not forged steel, from Japanese and French suppliers."²¹

"BKW Inc. has completed its ultrasonic tests on the reactor pressure vessel at Mühleberg nuclear power plant (KKM). No anomalies were detected. The safety of the plant is assured.

Towards the middle of August, suspected manufacturing faults in the base material of the pressure vessel of Reactor 3 at Belgium's Doel nuclear power plant were reported. This prompted the Federal Nuclear Safety Inspectorate (ENSI) to ask BKW to provide the manufacturing and test documentation. On 14 August 2012, BKW submitted this documentation to ENSI within the set deadline, showing that the KKM's pressure vessel had been in zero-defect order since going into operation. Nevertheless, to exclude any error in the manufacturing and inspection processes carried out before the facility went into operation, BKW inspected a representative area of the pressure vessel base material over the entire height of the cylinder. ENSI was immediately informed of these planned inspections, whereupon the supervisory authority defined the test conditions. The inspection was carried out in accordance with these criteria. Evaluation of the ultrasonic data provided proof that the pressure vessel is intact and is not affected by manufacturing faults of the type suspected at Doel 3."²²

Germany:

"Ingo Strube, a spokesman for Germany's environment ministry in Berlin, said Friday that none of the country's nine operating reactors are affected by the "anomalies" found at Doel-3. Strube said the ministry is checking on whether any of the eight reactors shut permanently in 2011 after the Fukushima I accident have the Rotterdam-supplied vessels."²³

Netherlands:

"Germany's Siemens supplied the reactor vessel for the Netherlands' 485MW Borssele, but RDM was responsible for welding on the vessel in the 1970s. The Dutch nuclear watchdog does not plan to conduct additional tests on Borssele."²⁴

"Dutch utility EPZ said Thursday that Rotterdam manufactured part of the reactor vessel for its Borssele-1, but the use of different steel and components at that unit meant the situation at Doel-3 was "not the same" as at Borssele-1."²⁵

USA:

²¹ http://www.world-nuclear-news.org/RS-Safety_checks_on_reactor_vessels-2808124.html

²² <http://www.bkw->

[fmb.ch/bkwfmb/en/home/ueber_uns/Medien/medienmitteilungen/2012/August/RDB_abgeschlossen.html](http://www.bkw-fmb.ch/bkwfmb/en/home/ueber_uns/Medien/medienmitteilungen/2012/August/RDB_abgeschlossen.html)

²³ Platts (Washington), 10 August 2012, Dominion reactor parts from company that supplied shut Belgian unit <http://www.platts.com/RSSFeedDetailedNews/RSSFeed/ElectricPower/6550521>

²⁴ Argus, 10 August 2012, Belgian nuclear regulator plans Doel safety meeting <http://www.argusmedia.com/pages/NewsBody.aspx?id=809624&menu=yes>

²⁵ Platts (Washington), 10 August 2012, Dominion reactor parts from company that supplied shut Belgian unit <http://www.platts.com/RSSFeedDetailedNews/RSSFeed/ElectricPower/6550521>

*"The NRC is sending a materials expert to a meeting in Belgium on the matter next week, agency spokesman Scott Burnell said Friday. It is too early to say whether NRC will impose additional requirements based on the Belgian incident."*²⁶

*"The US Nuclear Regulatory Commission told NEI on 6 September that it sees no reason for US reactors to take action at this stage."*²⁷

NEA²⁸ (OECD):

According to the trade press, the NEA said in a statement: *"Inspections of the reactor pressure vessel (RPV) are usually carried out about every ten years, but it would be prudent to use this type of operating experience to ensure that future inspections check the reactors for these kinds of micro-fissures."*²⁹

REMARKS:

- All the international responses found by the author seem to show that such number of cracks were not found elsewhere than in Doel 3 / Tihange 2. It is nevertheless crucial to clarify whether the inspections (techniques, sizing, etc.) carried out elsewhere actually do allow to conclude on the absence of cracks.
- The Swiss BKM statement that " *a representative area*" was inspected indicates that not the whole cylindrical part of the RPV was inspected. Therefore the following statement that "*ultrasonic data provided proof that the pressure vessel is intact and is not affected by manufacturing faults of the type suspected at Doel 3*" is not convincing.
- The German statement that "*that none of the country's nine operating reactors are affected by the "anomalies" found at Doel-3*" does not include whether the complete base metal zones of all reactor pressure vessels were inspected as a consequence of the information on the flaws found at Doel 3.
- It is puzzling to see that both Belgian reactors are affected, and none of the foreign ones manufactured by RDM. One reason might be that material with highly segregated zones were used for the Belgian RPVs.
- It could also be that dehydrogenation procedures have been performed during the manufacture of the other RPVs.

²⁶ Platts (Washington), 10 August 2012, Dominion reactor parts from company that supplied shut Belgian unit <http://www.platts.com/RSSFeedDetailedNews/RSSFeed/ElectricPower/6550521>

²⁷ Nuclear Engineering International, 01 November 2012, Cracks found at Doel 3, <http://www.neimagazine.com/story.asp?storyCode=2063255>

²⁸ NEA: Nuclear Energy Agency

²⁹ Nuclear Engineering International, 01 November 2012, Cracks found at Doel 3, <http://www.neimagazine.com/story.asp?storyCode=2063255>

1.4 Studies performed by the operator

On December 06, 2012 Electrabel, GDF SUEZ Group, submitted conclusions to restart Doel 3 and Tihange 2³⁰:

“The technical report and the engineering and calculations demonstrate that the vessels’ structural integrity meets, within significant margins, all safety criteria for each of the detected indications. The investigations and calculations carried out were subjected to a stringent control procedure that was validated by outside experts. In conclusion, the results confirm the structural integrity of the reactors in question, justifying the immediate restart and safe operation of Doel 3 and Tihange 2.”

“Tests on more than 400 samples, performed by different laboratories, show that the metal of the reactor vessels is sound, with properties that meet the required standards.”

“The technical report and the engineering and calculations demonstrate that the vessels’ structural integrity meets, within significant margins, all safety criteria for each of the detected indications. The investigations and calculations carried out were subjected to a stringent control procedure that was validated by outside experts.”

REMARKS:

- Electrabel's press release does not inform on the type of samples, on the kind of tests performed and on the calculations performed.
- The samples investigated are very likely archive materials, which have neither experienced the neutron and gamma irradiation during reactor operation, nor the thermo-mechanical history (due to operation) of the real reactor pressure vessels.
- The information that "safety criteria" are met for each detected indication does not imply that the safety of the combination of the large amount of indications has been evaluated (it has to be kept in mind that the exact nature of the observed flaws is still unknown).
- The behavior of the large number of defects in case of pressurized thermal shock events (locally large thermal stresses due to emergency cooling in case of a LOCA³¹ accident and re-pressurization) cannot be predicted by simple procedures, catastrophic pressure vessel ruptures cannot be excluded by justification of individual flaws.³²
- Since it can be assumed that sample material representative for the real status of the RPV is not available there is no evidence that the structural integrity of the RPV can be assured for further operation. It can be assumed that no experimental tests on the behavior of such a

³⁰ Electrabel press release, 6 December 2012: <http://www.gdfsuez.com/en/journalists/press-releases/electrabel-group-gdf-suez-submit-conclusions-restart-doel-3-tihange-2/>

³¹ LOCA: loss-of-coolant accident

³² Compare: “De Roovere (FANC) said as these (i.e. the observed flaws, I.T) were parallel there was little risk compared to perpendicular cracks, but that he felt "a malaise given the large number" of defects. (<http://www.google.com/hostednews/afp/article/ALeqM5jTmQ9SdhUoXg-fkdu1iiwy2NL5gg?docId=CNG.ff07ae66976d8bdbe3c71c64ad1a1a01.4a1>)

combination of defects under operational conditions have been performed (component-size test would be necessary³³).

2. Material degradation

2.1 Manufacture-induced defects

2.1.1 Impurity segregation

During the manufacturing process of reactor pressure vessels inclusions (oxides) and precipitates (sulfides, carbides) can develop, due to forging and heat treatment unfavorable sizes and distributions of these defects may occur.

2.1.2 Hydrogen effects: embrittlement, cracking, flaking

Hydrogen atoms in the steel can accumulate by diffusion, recombine to hydrogen molecules, interact with lattice defects (vacancies, interstitials, impurities, dislocations, grain boundaries), form small cavities or larger defects that impede dislocation slip (reducing the toughness of the material: hydrogen embrittlement), the cavities can also open under pressure forming cracks (hydrogen-induced cracking) or attach to precipitates or inclusions (hydrogen flaking).

Hydrogen flaking is described in the scientific literature as a very dangerous defect:

"Flakes are special discontinuities in steel parts that have the form of silver-colored spots on fracture surfaces or thin hair-like cracks on a ground and etched template. They appear and grow after a considerable incubation period, often in the operation of the part, which makes them a dangerous defect. Depending on the dimensions, number and position in the metal, flakes can decrease the toughness and ductility of the steel to zero and reduce markedly the service life of steel parts and structures, causing unexpected serious failures."³⁴

Japanese experts' discussion relating their experiences on hydrogen induced cracking phenomena to the observed flaws in the RPVs of Doel 3 and Tihange 2 comes to the following statement:

The defect morphology resembles to hydrogen induced cracking (HIC) observed in heavy plate steel for line-pipes in sour gas service and for offshore structure. ... Non-metallic inclusions may have collected hydrogen to form high pressure and as a result they formed flaws. Hydrogen content and sharp edged inclusions, such as one dimensionally deformed MnS particles are important.... The growth of the flaws is dependent on the environment. If hydrogen invades into the materials, there is a possibility for flaws to evolve.³⁵

³³ realistic conditions comparable to the operational history of the RPV cannot be simulated with small samples in laboratory equipment

³⁴ B.I.Voronenko, Hydrogen and flakes in steel, Metal science and heat treatment, November 1997, Volume 39, Issue 11, pp 462-470

³⁵ Atsuki Okamoto, Letter to Hiromitsu Ino, 8 December 2012

The material degrading hydrogen effects can be prevented by degassing processes during the steel production.³⁶

2.2 Operation-induced degradation (Aging)

2.2.1 Radiation effects

During the operation of a nuclear power plant neutrons are emitted from the reactor core and reach the reactor pressure wall. Neutrons (with energies above about 0.5 MeV) cause atomic displacements in the RPV materials, creating interstitials and vacancies (so-called Frenkel defects) that can diffuse through the lattice, recombine or agglomerate forming larger defects. These defects impede dislocation movement causing embrittlement of the material. This radiation embrittlement results in an increase of the ductile-brittle transition temperature (DBTT) to higher temperatures and a reduction of toughness/ductility. The DBTT has to be far below the operational temperatures of the RPV otherwise there is a risk of brittle fracture of the component.

Radiation reaching the RPV wall without displacing atoms in the materials lattice structure, can enhance diffusion of impurities by the deposited energy, the so-called radiation-enhanced diffusion (RED). Hydrogen diffusion in the material can also be supported by radiation.

“The effects of neutron irradiation will lead, in the core area, to an embrittlement of the material and the generation of heat sources by γ -radiation. Heat sources caused by the absorption of γ -radiation are a special type of thermal loading.”³⁷

Another effect originating from radiation impact on materials is the radiation-induced segregation (RIS), defined as a radiation-induced redistribution of alloy constituents and impurities at point defect sinks.³⁸

Radiation effects are complicated processes due to the simultaneous influence of temperature causing thermal diffusion of the produced defects. This diffusion can cause recombination of interstitials and vacancies, but can also induce the formation of vacancy or interstitial clusters. A consequence is for instance a reduced radiation embrittlement at higher irradiation temperatures³⁹.

Another effect of simultaneous radiation and temperature influence is the so called dose-rate effect: embrittlement may be higher at lower irradiation flux compared with the embrittlement at higher

³⁶ A.Barnoush, Hydrogen embrittlement, 2011;

http://www.uni-saarland.de/fak8/wwm/research/phd_barnoush/hydrogen.pdf

³⁷ KTA 3201.2 (06/96) Components of the Reactor Coolant Pressure Boundary of Light Water Reactors. Part 2: Design and Analysis, page 8

http://www.kta-gs.de/e/standards/3200/3201_2e.pdf

³⁸ Todd Allen, Gary Was; Radiation-enhanced Diffusion (RED) and Radiation-induced Segregation (RIS), Summer School on Radiation Effects July 2004

http://www.lanl.gov/mst/radefects/docs/Allen_Waas_RIS_and_RED.pdf

³⁹ Due to the diffusion-initiated recombination of vacancies and interstitials - which is higher at higher temperatures - the radiation embrittlement is lower. This is why the temperature of the surveillance samples has to be monitored because a temperature in the capsules higher than at the wall could yield less embrittled samples, therefore the real embrittlement of the wall would be underestimated on the basis of these samples.

flux for the same total radiation dose. Due to the possible dose rate effect the prediction of the radiation embrittlement by irradiation of RPV-representative samples in test reactors (that have significantly higher neutron flux compared to the neutron flux at the RPV wall) might not be appropriate. The dose rate effect has been observed in Western RPV steels⁴⁰ and Russian RPV steels^{41,42}. Up to now the consideration of the dose rate effect for the embrittlement prediction has not been included in the national standards.

In the last years another radiation effect in case of high-dose irradiation has been discussed: the so-called late phase blooming, i.e. a sudden significant increase of embrittlement at very high neutron fluences. This effect is of interest in case of plant life extension to 60 years.

MOX fuelling

In both Doel 3 and Tihange 2 NPPs MOX⁴³ fuel elements were used instead of pure UOX⁴⁴-fueling during the 1990ies⁴⁵.

The consequence of MOX-fuelled reactor cores is a shift of the neutron spectra and the neutron flux for the impinging neutrons at the RPV wall depending on the core configuration⁴⁶. There is not much known on the effect of these changes with respect to radiation embrittlement of the RPV wall materials.

"Surveillance specimen results from the High Flux Isotope Reactor (HFIR) indicated a more pronounced degradation of fracture toughness than expected. An early theory for this discrepancy is that the thermal neutrons were responsible. A more recent explanation is that intense gamma rays enhanced the damage. It is likely that the spectral shift compared to other radiation experiments is a contributing factor. Thus, detailed studies are warranted to evaluate the possibility of an appreciably greater rate of embrittlement when MOX fuels are used."⁴⁷

REMARKS:

⁴⁰ A-S. Bogaert, R. Gérard, R. Chaouadi; Belgian RPV embrittlement studies for LTO issues; IAEA Technical Meeting on Irradiation Embrittlement and Life Management of Reactor Pressure Vessels in Nuclear Power Plants, Znojmo, 18-22 October 2010

<http://www.iaea.org/NuclearPower/Downloads/Engineering/meetings/2010-10-TM-Czech/48.pdf>

⁴¹ Ya. Strombach, RRCKI, *Examination of WWER-440 RPV steel re-irradiation behaviour using materials from operating units*, Journal of Pressure Vessels and Piping 77 (2000)

⁴² A.A. Chernobaeva, Radiation embrittlement of RPV materials, Joint scientific program: Joint Helmholtz – ROSATOM school and ITEP winter school of physics «extreme state of matter», Feb. 19th – Feb. 26th 2012

⁴³ MOX: mixed-oxide

⁴⁴ UOX: uranium oxide

⁴⁵ Belgonucleaire 2002:

<http://www.belgonucleaire.be/uk/reperesct.htm>

⁴⁶ Ali R. Massih, January 2006, Models for MOX fuel behavior. A selective review

<http://dSPACE.mah.se/bitstream/handle/2043/4896/SKIRapport2006-10.pdf?sequence=2>

⁴⁷ G.T.Yahr, Impact of Conversion to Mixed-Oxide Fuels on Reactor Structural Components

<http://www.ornl.gov/~webworks/cpr/rpt/96889.pdf>

- Changes of the neutron spectra, the neutron flux and the gamma flux at the RPV wall due to the use of MOX fuel elements should be considered in the frame of radiation embrittlement prediction (PTS analysis).
- Explicit investigations on the influence of the MOX fuel on radiation damage of the RPV materials would have to be performed.
- Possible effects on radiation-enhanced diffusion by an increased gamma flux should be investigated with respect to hydrogen-related defects.

2.2.2 Hydrogen loading

In the coolant medium of the primary cooling circuit radiolysis continuously produces hydrogen atoms. The austenitic steel cladding at the inside of the RPV is supposed to avoid hydrogen invasion into the ferritic RPV wall but it is known that hydrogen cannot be completely prevented to penetrate into the steel. The additional hydrogen could trigger the growth of hydrogen-related defects (see the Japanese experience described in 2.1.2: "*The growth of the flaws is dependent on the environment. If hydrogen invades into the materials, there is a possibility for flaws to evolve.*"⁴⁸).

German investigations have shown that hydrogen loading causes a strong toughness reduction of RPV steels and the radiation embrittlement is enhanced by hydrogen loading.⁴⁹

As described in 2.1.2 hydrogen flakes "*grow after a considerable incubation period, often in the operation of the part, which makes them a dangerous defect*"⁵⁰, thus the process of hydrogen flaking based on manufacture induced impurities and hydrogen has to be expected to continue during operation.

REMARKS:

- It is not proven that radiolytic hydrogen is completely retained by the cladding from penetration into the RPV wall.
- The effect of possibly invading hydrogen during operation has to be considered discussing the integrity of the reactor pressure vessel.

2.2.3 Fatigue

LCF (low-cycle fatigue) of RPV materials is caused by the thermo-mechanical cycling during the startup and shutdown procedures; an influence of the LCF on the microstructure (for instance hydrogen-related defects) and radiation-induced material degradation has to be expected.

⁴⁸ Atsuki Okamoto, Letter to Hiromitsu Ino, 8 December 2012

⁴⁹ – Stellungnahme: Einfluss von Wasserstoff auf das Zähigkeitsverhalten von bestrahlten RDB-Stählen. Beratungsauftrag zum Abschlussbericht des Vorhabens 1501267 der Leibnitz-Institute IFW und FZR, Dresden vom Dezember 2004

<http://www.rskonline.de/downloads/zaehigkeitwasserstoff.pdf>

⁵⁰ B.I.Voronenko, Hydrogen and flakes in steel, Metal science and heat treatment, November 1997, Volume 39, Issue 11, pp 462-470

REMARK:

- Specific experiments concerning the effect of LCF on hydrogen-related defect containing materials and on interactions with radiation embrittlement have - to the author's knowledge - not been performed anywhere. The surveillance programs are performed without mechanical loading of the samples.

3. Safety measures

3.1 Non-destructive testing

3.1.1 Non-destructive testing during fabrication

During the manufacturing process destructive testing (strength, toughness, hardness) and non-destructive testing (ultrasonic testing UT, radiography) of the RPV materials has to be performed for quality control and assessment. The used samples are supposed to have experienced the same thermo-mechanical treatments (forging, heat treatments, welding etc.) as the component. A detailed documentation of the testing results is required.

In France the EDF specifications since the 1970^{ies} require volumetric US inspections during manufacture. An expertise from 2012 confirms that these inspections were able to detect and characterize unacceptable hydrogen-defects "DDH" as found in Doel 3. Hydrogen-induced defects have been detected in the early 1980^{ies} at Creusot Loire, the respective components have been discarded⁵¹; more detailed studies on this issue were performed during 1985/1986 by ASN (Autorité de Sûreté Nucléaire, France). ASN demanded a re-analysis of the manufacture-accompanying inspection protocols.⁵²

*"ASN also said that the manufacturing defects detected in France are periodically checked and do not evolve while operating."*⁵³

German Standards KTA 3201.3, Components of the Reactor Coolant Pressure Boundary of Light Water Reactors. Part 3: Manufacture:

"(3) The requirements specified under KTA 3201.3 address, in particular,
a) the organisations that are involved in manufacture,
b) the weld design, welding, heat treatment, and forming of the components in consideration of the materials and the type of welded joints,
c) the certification and supervision procedures for attaining and meeting the required quality of the components such as welding procedure qualifications, production control and non-destructive

⁵¹ EDF, contrôles de la cuve, 16/10/2012,

http://www.hctisn.fr/IMG/pdf/EDF_Contrôles_de_la_cuve_cle8dd38d.pdf

⁵² ASN, Détection de défauts sur la cuve de Doel 3 (Belgique). Contrôles exercés en fabrication, HCTISN, octobre 4, 2012,

http://www.hctisn.fr/IMG/pdf/Cuve_Doel_3_-_HCTISN_-_contrôle_fabrication_cle891bd6.pdf

⁵³ Nuclear Engineering International, Cracks found at Doel 3, 01 November 2012,

<http://www.neimagazine.com/story.asp?storyCode=2063255>

tests as well as fabrication supervision and final inspection,
d) the preparation of documents concerning manufacture and the documentation of the test results obtained during manufacture.”⁵⁴

According to FANC the non-destructive testing during manufacture of the RPVs in Doel 3 and Tihange 2 was performed following the ASME Code regulations:

“Inspections at the fabrication stages have been carried out following the rules of the ASME Code Section III, edition 1974. These inspections involved UT controls and volumetric examinations. These examinations were performed manually and from the external surface of the vessel. In addition to the ASME Code, the CCA imposed some complementary controls (for the welds in particular), but these didn’t lead to the observation of indications.”

“For the core upper shell, the first inspections carried out during the fabrication indicated the presence of a large zone containing acceptable indications. During the intermediate inspection, this affected zone has however not been observed anymore. During the final inspection, 12 flaws were observed, but it has been concluded that these flaws were acceptable according to the applicable criteria.

For the core lower shell, only the documentation regarding the final inspections has been retrieved. During this final inspection, no flaws have been noticed.”⁵⁵

REMARKS:

- According to ASN the hydrogen-induced flaws during manufacture should have been detected during fabrication surveillance testing, the UT testing methods applied at the time of manufacture had the required ability.
- Some of the flaws detected in 2012 in the RPVs of Doel 3 and Tihange 2 have extensions up to 24 mm (the mean size is 10 mm), it is not imaginable that the large number of defects – assumed they were present at the time of manufacture - would not have been detected by manual UT testing.

3.1.2 In-service inspections (ISI)

The UT equipment used for in-service inspection in Doel 3/Tihange 2 is appropriate for detection of axially-oriented flaws.

“The complementary inspection was performed using a UT technique qualified for detecting under clad defects, i.e. axially-oriented defects. The supplementary inspection was performed using the UT technique qualified to detect and size defects in the weld area.

No formal demonstration according ASME XI appendix VIII has been done. Actually both inspection techniques have been qualified applying the ENIQ principles. For under clad defects, use was made of the qualification file for France, completed with specificities for Belgium reactors.”⁵⁶

⁵⁴KTA 3201.3 (11/07) Components of the Reactor Coolant Pressure Boundary of Light Water Reactors. Part 3: Manufacture, http://www.kta-gs.de/e/standards/3200/3201_3e.pdf

⁵⁵FANC, Flaw indications in the reactor pressure vessel of Doel 3 and Tihange 2, September 3, 2012, <http://www.fanc.fgov.be/GED/00000000/3200/3288.pdf>

“A new ultrasound measuring technique was used for the first time in June 2012 over the whole surface of the Doel 3 reactor vessel. This inspection was conducted by a specialist French firm on behalf of Electrabel. This is the first time in Belgium that the basic material of the reactor vessel was tested (elsewhere than in the weld zones). The whole wall of the reactor vessel was also inspected, although the ASME XI standards only recommend inspection on sensitive components.”⁵⁷

According to the Standards (ASME XI, KTA 3201.4) in-service inspection is only required for the weld region (weld + HAZ + a small part of the base metal on both sides of the weld).

ASME XI:

“The regulatory inspection according to ASME XI, IWB-2500-1, which is restricted to the welds and surrounding material (HAZ, base material). This inspection was performed from the inside of the vessel, with the usual qualified procedure for in-service inspection. Those inspections encompass the full circumference and 100% of the wall thickness (in this case 205 mm), over a length of $\frac{1}{2}t$ on both sides of the weld (see ASME XI fig. IWB-2500-1).”⁵⁸

KTA 3201.4 (2010-11), Components of the Reactor Coolant Pressure Boundary of Light Water Reactors. Part 4: In-service Inspections and Operational Monitoring⁵⁹:

“5.2 Extent of testing

5.2.1 Non-destructive examinations

5.2.1.1 General

(1) When testing weld seams, the examination shall include the weld metal (including buttering in the case of weld connections between ferritic and austenitic steels) and the base metal zone on both sides of the weld seam. The base metal zone to be included shall normally have a width of not less than 10 mm for a wall thickness ≤ 30 mm and a width of at least 20 mm on both sides for a wall thickness exceeding 30 mm.”

REMARKS:

- The Standards (ASME Code, KTA) do not require in-service inspection of the base metal outside the weld region. This is one of the reasons, why flaws as found in the RPVs of Doel 3 and Tihange 2 have not been found earlier.
- Since “quasi-laminar” flaws were not expected it has to be assumed that no adequate test blocks exist for UT technique qualification.

⁵⁶ FANC: Flaw indications in the reactor pressure vessel of Doel 3 and Tihange 2 , 12th October 2012, <http://www.fanc.fgov.be/GED/00000000/3200/3323.pdf>

⁵⁷FANC, Incident at Doel nuclear power station, <http://www.fanc.fgov.be/GED/00000000/3200/3271.pdf>

⁵⁸ FANC: Flaw indications in the reactor pressure vessel of Doel 3 and Tihange 2 , 12th October 2012, <http://www.fanc.fgov.be/GED/00000000/3200/3323.pdf>

⁵⁹ KTA 3201.4 (2010-11), Components of the Reactor Coolant Pressure Boundary of Light Water Reactors. Part 4: In-service Inspections and Operational Monitoring, http://www.kta-gs.de/e/standards/3200/3201_4_engl_2010_11.pdf

- It is surprising that the National Regulatory Authorities do not request inspections of the base metal in the frame of the 20-year ISI inspection (as performed in France)⁶⁰.

3.1.3 PTS (pressurized thermal shock) analysis

A fracture mechanical analysis of the RPV's structural integrity during normal and accidental operation, the so-called pressurized thermal shock (PTS) analysis, is required in the frame of the safety analysis according to the Standards (ASME code, KTA, etc.). Under severe transients (thermal shock under pressure) an existing critical-size flaw could propagate rapidly through the vessel wall and cause vessel rupture with catastrophic consequences. Using thermal-hydraulic codes and fracture mechanical methods the thermal stresses on a hypothetical crack are calculated for assumed transients and the stress intensity curves are then compared with the experimental fracture toughness characteristics. The Standards (PTS Rule in Title 10, Section 50.61, of the Code of Federal Regulations 10 CFR 50.61; KTA 3201.2) define the shape and size of the cracks to be considered.

KTA 3201.2 Components of the Reactor Coolant Pressure Boundary of Light Water Reactors. Part 2: Design and Analysis⁶¹

“7.9.3.2 Levels A and B⁶²

(1) For the cylindrical section of the reactor pressure vessel the respective stress intensities shall be determined from the sum of the determined primary and secondary stresses by assuming a surface defect the plane of which is vertical to the highest stress (depth: 0.25 x wall thickness; length: 1.5 x wall thickness; the assumption of smaller defects is acceptable if justified). In this case the stress intensities derived from the primary stresses shall be multiplied with a safety factor of 2. This sum must be less than the reference fracture toughness (KIR) of the material.

(2) For the other areas of the reactor pressure vessel the stress intensities derived from the primary stresses need not be multiplied with a factor of 2, the assumption of smaller defects with a depth of less than 0.25 x the wall thickness and a length of less than 1.5 the wall thickness is acceptable if this can be justified.

7.9.3.3 Levels C and D⁶³

For Levels C and D the brittle fracture resistance for the cylindrical section in the core area of the reactor pressure vessel shall be verified by means of fracture mechanics. The stress intensity factor $K_I(t, T)$ is the sum of stress intensity factors caused by internal pressure, temperature gradient etc. It shall be proved that a defect with half the magnitude on which the calculation is based can be detected positively.”

⁶⁰ J.P.Launay, Near-surface non-destructive examination of reactor steels, CSNI Report No. 111, OECD/NEA, 1985, "The Belgian authorities have opted for identical stance as that taken by France with regard to underclad defects: backed up by research program results, it is considered that no risks will arise for 20 years period."

⁶¹ KTA 3201.2 (06/96) Components of the Reactor Coolant Pressure Boundary of Light Water Reactors. Part 2: Design and Analysis, http://www.kta-gs.de/e/standards/3200/3201_2e.pdf

⁶² Anomalous operational load cases

⁶³ „service limits“

REMARKS:

- The type of flaws (and the remarkable density) observed in the RPVs of Doel 3/Tihange 2 is not included in the Standards as flaws to be considered in the frame of PTS analyses.
- It has to be assumed that no validated procedures exist for the fracture mechanical calculation procedures in the frame of the PTS analysis considering a very large density of quasi-laminar defects as have been detected in the RPVs of Doel 3 and Tihange 2.

3.1.4 Surveillance program

For prediction of neutron-induced materials degradation (strength, toughness) RPV-specific samples are irradiated in the RPV with a lead factor (ratio of the dose rate at the sample position and the dose rate at the RPV wall) of around 2. The destructive testing (Charpy tests, COD-tests) of samples withdrawn after defined irradiation times allow to determine the materials characteristics for an irradiation dose higher than the actual RPV wall irradiation. These data can be compared with the predicted embrittlement evolution with irradiation time. The experimentally determined radiation caused shift of the DBTT (ductile-brittle transition temperature) derived from the measurements is an input value for the PTS analysis.

KTA 3203 (6/01), Surveillance of the Irradiation Behaviour of Reactor Pressure Vessel Materials of LWR Facilities:

“3.1 Purpose of the irradiation surveillance program

Specimens of the original ferritic materials shall be subject to accelerated irradiation in capsules inside the reactor pressure vessel to experimentally verify the tensile and fracture toughness properties of the RPV material at assessment fluence.”⁶⁴

REMARKS:

- These tests in the frame of surveillance programs are performed with small samples, radiation-enhanced diffusion or segregation effects cannot be studied within this program.
- It has also to be mentioned that the samples in the irradiation capsules are not under load, which is a difference to the real condition in the RPV wall. A possible strain influence on radiation-enhanced diffusion processes cannot be detected.

⁶⁴ KTA 3203 (6/01), Surveillance of the Irradiation Behaviour of Reactor Pressure Vessel Materials of LWR Facilities, http://www.kta-gs.de/e/standards/3200/3203_e.pdf

4. Summarizing Case Study: Flaws in the RPVs Doel 3 and Tihange 2

4.1 Origin of the flaws

Electrabel claims that

“The initial hypothesis of hydrogen flaking that are stable and that were formed during the forging process, was confirmed.”⁶⁵

UT inspections in connection with the manufacture have shown acceptable indications, these defects were in other parts of the reactor pressure vessel:

“Karina De Beule, a spokeswoman for Belgium's nuclear regulatory agency, told The Associated Press on Thursday that the cracks discovered in 1979 were in a different part of the reactor vessels than the possible cracks discovered this summer, and were entirely unrelated.”⁶⁶

REMARKS:

- There is no information how this hypothesis was confirmed.
- Without destructive testing the real nature of the flaws cannot be known.
- The assumed hydrogen-induced defects as origin for the indications might have been evolved or grown in inhomogeneous (segregated) regions of the forged rings due to combined effects of thermal diffusion, radiation-enhanced diffusion, radiation-induced segregation and low-cycle fatigue (start-up and cool-down procedures).
- The fact that these flaws have not been detected during UT inspection in the course of fabrication and during the final inspection is supporting an alternative hypothesis of defect formation or growth during operation.
- It is not credible that the larger number of flaws with sizes up to 24 mm (mean size 10 mm) should not have been detected during manufacture by manual UT testing or volumetric radiography.
- The fact that only in the RPVs Doel 3 and Tihange 2 flaws have been detected might indicate that RDM has used several highly segregated⁶⁷ rings for these two RPVs. A high hydrogen

⁶⁵ 2012_12_06 Electrabel, Group GDF SUEZ, submit conclusions for restart Doel 3 and Tihange 2
<http://www.gdfsuez.com/en/journalists/press-releases/electrabel-group-gdf-suez-submit-conclusions-restart-doel-3-tihange-2/>

⁶⁶ Associated Press, Aug 23, 2012: Belgian newspaper reports cracks in nuclear reactor vessels were first found in 1979, <http://finance.yahoo.com/news/belgian-paper-flaw-nuke-plants-115932086.html>

⁶⁷ segregations = small precipitations of impurities, sulfides, carbides etc. due to manufacture, were diffusing hydrogen might attach

loading during manufacture can be assumed since no documentation on degassing/dehydrogenation procedures has been retrieved.⁶⁸

- According to experiences described in the scientific literature hydrogen flaking is a process with long incubation time, often continuing during operation. Hydrogen flakes are considered as very dangerous defects that can cause unexpected serious failures⁶⁹.

4.2 Detection of the flaws

Inspections during manufacture have not revealed defects in the base metal of the rings of concern. However, the documentation is obviously not complete:

“Notably, detailed documentation about the first thermal treatment performed by RDM (which according to the LOFC has been done), an intermediate UT inspection and some RDM specifications are lacking.”⁷⁰

FANC⁷¹ admits that the base metal examination was not required for ISI until today, not even adequate test blocks exist:

“For under clad defects, the qualification was performed using relevant test block with relevant defect simulations to demonstrate the measurement accuracy of the sizing capability and reliability. For the base material examination, no additional test blocks made from base material only were used. Everything is based on experience with weld examination procedure. The qualification includes procedure, personnel/operators and equipment.”

“The height of the inspected zone is 4080 mm (starting from 3320 mm under the vessel flange up to 7400 mm, thus covering the full height of the core). This means that clad base material is inspected where no volumetric in-service inspection has been performed up to now.”

The type of flaws detected in the RPVs Doel 3 and Tihange 2 has worldwide not been observed in other RPVs. In France underclad-cracks were observed and tracked thereafter by regular in-service inspections:

“The undercladding defects in cladding identified in France are isolated and well-defined. They do not affect the quality of metal over a large area and the reasons for their occurrence are known.”

⁶⁸ FANC: „ During the fabrication of the shells of the Doel 3 and Tihange 2 reactor vessels, no trace of a dehydrogenation treatment at RDM can be found.“

FANC 03-09-2012: Flaw indications in the reactor pressure vessel of Doel 3 and Tihange 2, <http://www.fanc.fgov.be/GED/00000000/3200/3288.pdf>

⁶⁹ B.I.Voronenko, Hydrogen and flakes in steel, Metal science and heat treatment, November 1997, Volume 39, Issue 11, pp 462-470

⁷⁰ FANC 03-09-2012: Flaw indications in the reactor pressure vessel of Doel 3 and Tihange 2, <http://www.fanc.fgov.be/GED/00000000/3200/3288.pdf>

⁷¹ FANC 03-09-2012: Flaw indications in the reactor pressure vessel of Doel 3 and Tihange 2, <http://www.fanc.fgov.be/GED/00000000/3200/3288.pdf>

*As such, they are not comparable to the defects detected on Doel 3's vessel, where several thousands of clustered defects have been observed.*⁷²

REMARKS:

- The Owner has obviously no complete documentation on the manufacture and testing of the reactor pressure vessel which has to be considered as the most crucial component of a nuclear power plant.
- The Regulatory Authorities did obviously not control the completeness and the safeguarding of the documentation on manufacturing and testing during manufacture.
- The possible evolvement of hydrogen-related defects in forged steel was known at the time of manufacture, nevertheless the behavior of defects detected during the manufacturing process was not traced during the operation of the nuclear power plants and the base metal outside the weld regions had never been inspected.
- Inspections of the reactor pressure vessel wall aimed to identify possible underclad cracks in the base metal remote from the circumferential welds have obviously been performed for the first time in 2012, i.e. after 30 years of operation. This implies that the Belgian Authorities did not until then request inspections concerning underclad cracks in the base metal.

4.3 Performed tests

Electrabel claims in the December press release:

"Tests on more than 400 samples, performed by different laboratories, show that the metal of the reactor vessels is sound, with properties that meet the required standards.

*The technical report and the engineering and calculations demonstrate that the vessels' structural integrity meets, within significant margins, all safety criteria for each of the detected indications. The investigations and calculations carried out were subjected to a stringent control procedure that was validated by outside experts.*⁷³

With respect to justification of defects French Nuclear Safety Authorities declare:

"Cracks" defects, in particular, must be repaired if they are not appropriately justified. The justification must demonstrate the absence of any evolution of the defect in any situation, including in case of an accident, taking into account the margins imposed by regulation and

⁷² ASN press release 20 August 2012, ASN reports on controls imposed on nuclear reactors' vessels in France, <http://www.french-nuclear-safety.fr/index.php/English-version/News-releases/2012/ASN-reports-on-controls-imposed-on-nuclear-reactors-vessels>

⁷³ Electrabel press release, 6 December 2012: <http://www.gdfsuez.com/en/journalists/press-releases/electrabel-group-gdf-suez-submit-conclusions-restart-doel-3-tihange-2/>

ensuring that each step of calculations is based on penalizing hypothesis.

ASN enforces the compliance with these rules before any reactor involved can be restarted.”⁷⁴

REMARKS:

- It is not clarified in Electrabel's press release what kind of samples was used for the investigations. It can be assumed that archive material has been used.
- Even in case of sufficient archive material the thermo-mechanical and irradiation history of the RPVs cannot be simulated. It is also doubtful that archive material with the possibly fabrication-induced defects is available, since segregated areas in the produced ingots are randomly distributed. Faulty samples very probably would have been discarded in the course of sample archiving.
- It can therefore be assumed that the available archive material is not as inhomogeneous as the base material of the affected rings presumably was after manufacture.
- The type of flaws found in the RPVs of Doel/Tihange is not covered by the regulations in the Standards, therefore the calculation procedure used for justification has to be validated by experiments.
- Electrabel states in the press release on justification that the safety criteria are met by “each detected indication”. This of course does not imply that the huge amount of such defects (more than 8,000 for Doel 3 and 2,000 for Tihange 2) will not be dangerous for the RPV's structural integrity in case of further operation.
- Several of the observed flaws are as large as 24 mm, the possibility of interactions of these defects under operational (normal and accidental) conditions, including the thermo-mechanical low-cycle fatigue (start-up and cooling down) should have been considered in the justifying procedure - the press release does not indicate such investigations.
- Since no inspections of the base metal outside the weld regions have been performed since manufacture of the RPVs it is astonishing that Electrabel claims that the manufacture-caused defects have not evolved during operation.
- Electrabel's press release on justification does not explain what “safety margin” explicitly means.
- The real nature of the defects behind the observed indications is obviously still unknown (sampling from the affected RPV rings can hardly be realized as it would irreversibly damage the RPV).

⁷⁴ <http://www.french-nuclear-safety.fr/index.php/English-version/News-releases/2012/ASN-reports-on-controls-imposed-on-nuclear-reactors-vessels>

4.4 Surveillance program

The surveillance program of the Belgian NPPs is performed according to the 10.CFR50.61, based on Charpy toughness tests⁷⁵ to determine the ductile-brittle transition temperature RT_{PTS} shift due to neutron irradiation. The permitted values (PTS screening criteria) are⁷⁶

$$RT_{PTS}(\text{circumferential weld}) = 149^{\circ}\text{C}$$

$$RT_{PTS}(\text{base material}) = 132^{\circ}\text{C}$$

The application of US NRC Regulatory Guide 1.99 rev.2 embrittlement correlations to Belgian data shows that especially the predicted embrittlement of the base metal is underestimated. Experimental data also imply that a dose rate effect (higher embrittlement for lower neutron flux compared to the embrittlement at higher flux for equal irradiation doses) should be taken into account. Up to now no late phase blooming (embrittlement acceleration at high doses) has been observed.

REMARKS:

- The embrittlement of the base material of the Belgian RPVs is obviously higher than expected by the US NRC regulatory guide 1.99 rev.2 correlations.
- In the above cited study⁷⁷ a significant scatter of the determined reference temperature shift data (embrittlement) has been observed that could not be explained.
- It is surprising that these facts (underestimated embrittlement of the base metal and possible dose rate effect) have not triggered an in-service inspection of the base metal outside the weld areas.
- Both observations could be in relation to the inhomogeneous base metal of the forged rings. In combination with the observed defects (flaws) the “safety margins” stated by Electrabel should be explained in detail.
- Explicit investigations on the influence of the MOX fuel on radiation damage of the RPV materials would have to be performed.
- Possible effects on radiation-enhanced diffusion by an increased gamma flux should be investigated with respect to hydrogen-related defects.

⁷⁵ Charpy test: a specific toughness test procedure that is used for all RPVs in the world

⁷⁶ A-S. Bogaert, R. Gérard, R. Chaouadi; Belgian RPV embrittlement studies for LTO issues; IAEA Technical Meeting on Irradiation Embrittlement and Life Management of Reactor Pressure Vessels in Nuclear Power Plants, Znojmo, 18-22 October 2010

<http://www.iaea.org/NuclearPower/Downloads/Engineering/meetings/2010-10-TM-Czech/48.pdf>

⁷⁷ A-S. Bogaert, R. Gérard, R. Chaouadi; Belgian RPV embrittlement studies for LTO issues; IAEA Technical Meeting on Irradiation Embrittlement and Life Management of Reactor Pressure Vessels in Nuclear Power Plants, Znojmo, 18-22 October 2010

<http://www.iaea.org/NuclearPower/Downloads/Engineering/meetings/2010-10-TM-Czech/48.pdf>

4.5 PTS analysis

FANC stated in the “information available on the 12th of October 2012” that

“A PTS study based on 10CFR50.61a is planned.”⁷⁸

REMARKS:

- It has to be mentioned that 10CFR50.61a is “*voluntary alternative PTS rule*” differing from the PTS rule 10CFR50.61 using the less restrictive limits⁷⁹.
- The use of rules differing from the licensed methodology needs approval by the Regulatory Authority. It is unclear whether/how FANC has officially granted such an approval.
- It is surprising that in case of unknown defects observed in remarkable abundance the use of a PTS rule with less restrictive limits compared to the normal procedure is announced by FANC without any comment.

⁷⁸ FANC 12-10-2012: Flaw indications in the reactor pressure vessel of Doel 3 and Tihange 2, <http://www.fanc.fgov.be/GED/00000000/3200/3323.pdf>

⁷⁹ M.E.Kirk, US NRC, Risk informed revision of the NRC’s rules regulating pressurized thermal shock (PTS), ANS Meeting 2009
http://mit.edu/ans/www/documents/seminar/S09/kirk_slides.pdf

5. Conclusions

5.1 Open questions

5.1.1 Manufacture

- Why did the regulating authority not control whether dehydrogenation procedures were performed during manufacture of the reactor pressure vessels?
- What is the cause for the incomplete manufacture documentation? Why did the regulating authority never control that the Owner indeed was in possession of such complete documentation?

5.1.2 UT (ultrasonic testing) inspection

- Why did the Regulating Authority refrain from requesting ultrasonic testing (UT) inspection of the complete RPV base metal to detect underclad cracks earlier than 30 years after start-up? The occurrence of underclad cracks has been known for decades⁸⁰.
- What is the explanation for the fact that thousands of defects with sizes up to 24 mm large that are supposed to originate from manufacture have not been detected during final testing following manufacturing?
- Which sizes had the “acceptable” indications detected during manufacture?

5.1.3 Origin/nature of the flaws

- Which techniques have been used to identify the real nature of the observed flaws?
- Why should the defects be stable during operation and how can an effect of further operation of the plant on growth or propagation of the defects be excluded?

5.1.4 Tests performed by Electrabel

- What kind of samples has been used?
- Which experiments have been performed (Charpy toughness tests, strength, fracture toughness, electron microscopy, SANS⁸¹, SIMS⁸²)?

⁸⁰ J.P.Launay, Near-surface non-destructive examination of reactor steels, CSNI Report No. 111, OECD/NEA, 1985, *"The Belgian authorities have opted for identical stance as that taken by France with regard to underclad defects: backed up by research program results, it is considered that no risks will arise for 20 years period"*

⁸¹ Small angle neutron scattering

⁸² Secondary ion mass spectroscopy

- In case that archive materials have been used, has this archive material comparable defects as the RPV forged rings?
- What does it mean *“that the vessels’ structural integrity meets, within significant margins, all safety criteria for each of the detected indications”*? Has there been any study on the simultaneous effects of thousands of defects that can interfere with each other under operational conditions (temperature, pressure, radiation)?

5.1.5 Materials aging (radiation, fatigue)

- Why did Electrabel apparently not consider radiation effects and fatigue interfering with existing probably hydrogen-related defects in the material?
- How can the evolvement of defects during operation be excluded while no indications have been found following manufacturing and thirty years later thousands of flaws with extensions up to 24 mm and up to 100 mm depth were found?
- How can a further growth of the defects or interactions with other defects by operational conditions (temperature, pressure, radiation) be excluded?
- Have neutron spectra and neutron flux at the reactor pressure vessel wall changed for MOX⁸³ fueling compared to UOX⁸⁴ fueling?
- Has the gamma flux on the reactor pressure vessel wall been changed by the MOX fuelling?

5.1.5 PTS analysis

- Why did FANC not comment the announced application of the voluntary alternative PTS (pressurized thermal shock) rule 10CFR50.61a that is less restrictive and differs in a non-conservative way from the approved methodology?
- Has the use of the “voluntary alternative PTS rule” been officially approved by FANC or Bel V?
- Are there approved procedures for the fracture mechanical consideration of “quasi-laminar defects” in varying depth of the vessel wall?
- What is the critical crack size (for assumed axially oriented cracks) determined so far from PTS analyses?

5.2 Recommended requests

- Destructive/nondestructive tests to prove the hydrogen flaking hypothesis.
- Implementation of an enlarged test program into the National standards: periodic ultrasonic testing of the complete RPV base metal, not only in the weld/HAZ⁸⁵ area.

⁸³ MOX fuel: mixed oxide fuel

⁸⁴ UOX: uranium oxide fuel

- Experimental tests in order to reproduce the assumed flaw origin.
- Research concerning radiation effects on segregation, hydrogen embrittlement etc.
- Research on possible effects of MOX fueling compared to pure UOX fueling on radiation effects (radiation embrittlement, radiation-enhanced diffusion).
- PTS analysis considering the observed flaws (size, shape and orientation) according 10CFR50.61 (as opposed to the less restrictive 10CFR50.61a proposed by the Owner).
- Research using component-size tests on the influence of LCF (low-cycle fatigue) on high density hydrogen-related defects.
- Development and validation of adequate UT equipment/test blocks for characterization and sizing of quasi-laminar flaws.
- Investigations on the possible effects of MOX fuel elements on radiation embrittlement and radiation-enhanced diffusion, i.e. influence of the shifted neutron spectra, an increased neutron flux and an increased gamma flux at the reactor pressure vessel wall.

5.3 Consequences for other RPVs (not only those manufactured by RDM)

The fact that not all reactor pressure vessels from a specific manufacturer are affected by the same type base metal defects indicates that the quality of forged materials can vary in a wide range.

Therefore the manufacturing documentation for each reactor pressure vessel in Europe and worldwide should be re-analyzed with respect to performed dehydrogenation treatments and adequate documentation.

The periodic non-destructive testing of the base metal in the whole reactor pressure vessel seems to be necessary since unexpected defect evolvments are obviously possible.

5.4 Final conclusion

The information related to the unexpected flaw detection in the reactor pressure vessels of the nuclear power plants Doel 3 and Tihange 2 has revealed that the documentation of the vessel manufacture is not complete.

It was also revealed that the vessel manufacturer RDM - a Dutch company that went bankrupt in the meantime - has obviously not performed any dehydrogenation treatment and this has not been known by the Regulatory Authorities.

⁸⁵ HAZ: heat affected zone

Ultrasonic testing (UT) of the base metal outside the weld region has been performed for the first time in 2012, i.e. after 30 years of operation.

The Safety Authorities obviously were never asking for documentation, fabrication methodology (incl. hydrogen control) and ultrasonic testing results.

Electrabel's statement that the flaws originate from manufacture cannot be followed, since no defects were found during the final tests after manufacture while the flaws found 30 years later have extensions up to 24 mm wide and up to 100 mm deep and exist in remarkable density.

The real nature of the flaws is still unknown and can hardly be determined, since sampling cannot be performed without destruction of the reactor pressure vessel.

The assumed hydrogen flaking process has a considerable incubation time and is continued during operation, hydrogen flakes are considered as very dangerous defects causing unexpected failures.

The influence of radiation effects and low-cycle fatigue on possibly manufacture-induced defects has not been considered by Electrabel although it is known the radiation embrittlement of the base metal is underestimated by the predictive curves.

The eventual influence of MOX fuelling on radiation effects in the RPV wall has not been considered.

Electrabel's argument that each defect was individually justified to be not dangerous for the reactor pressure vessel's structural integrity is not sufficient since interactions and growth of thousands of defects with sizes up to 24 mm under operational conditions (temperature, pressure, radiation) cannot be excluded.

In summary the restart of the two power plants has to be considered as hazardous. A possible failure of the reactor pressure vessels due to sudden crack growth in case of local thermal stresses cannot be excluded and would have catastrophic consequences, especially in the vicinity of densely populated and high-economic activity areas (Antwerp, Liège). The corium (melted reactor core) relocation to the lower plenum entraining steam explosions would sooner or later cause containment failure with the consequence of severe radioactive releases to the environment.