KU LEUVEN

"INRAG Meeting"
Aachen, April 13-14, 2018

Tihange 2 RPV Material Integrity : *New Inspections & "New" Cracks ?*

– Mechanisms for Instability and Potential Growth of 'Hydrogen Flakes' during reactor operation

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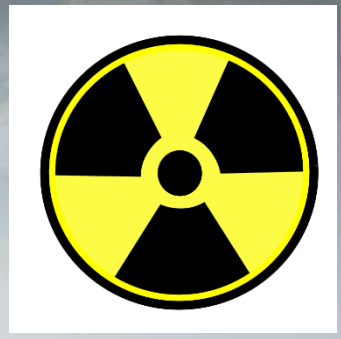

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2. **Can the Cracks Grow?**
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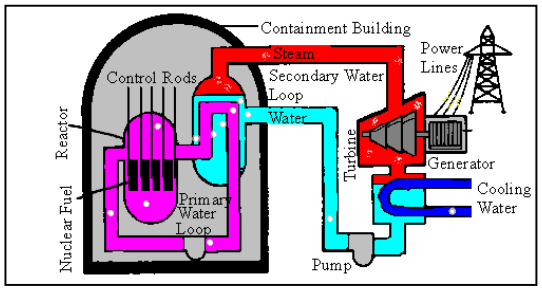
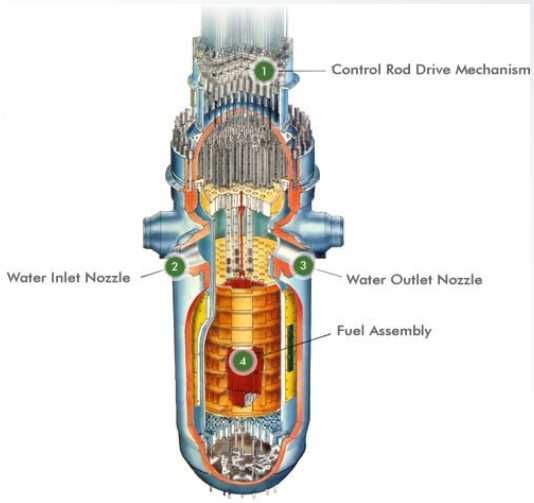


1. The Story…

- **Inspection NPP Doel 3**
  - Mid 2012 : UT inspections of RPV
  - New instrumentation
  - Check for underclad cracking (cf. Tricastin, F)
  - No underclad cracking found, but unexpected atypical “indications”
  - “Thousands” …
- Inspection NPP Tihange 2
  - +/- *idem*, but to somewhat lesser extent …

Doel & Tihange RPV



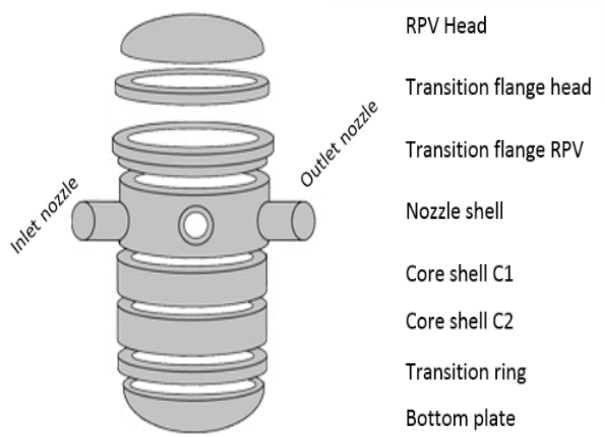


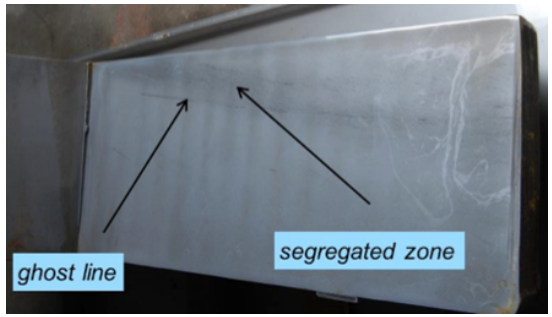
Illustration translated from FANC, showing the original forged steel ring sections of the RPV separated for clarity.
These rings are welded together and cladded internally with a stainless steel lining to form the reactor pressure vessel.

- H = approx. 13 m; Φ = 4.4 m
- Vessel wall: Mn-Mo-Ni low-alloy steel ASME SA 508 – Class 3; 205 mm
  (Mn = 1.2-1.5%, Mo = 0.45-0.60%, Ni = 0.40-1.0%, C_{max} = 0.25 wt%, Si = 0.15-0.40%, Cr_{max} = 0.25%, P_{max} and S_{max} = 0.015%)
- Primary water side: stainless steel AISI 308/309 cladding; 7 mm
- Material supplier: Krupp (D)
- Manufacturing: RDM – Rotterdamsche Droogdok Maatschappij (Nl)

Major findings

- Unexpected atypical “indications”
- Various measuring methods
- Up to 40 per dm^3 (!); total 7776 (& much more, according to new measurements (2014) : total: **13,047** !?)
- Down to a depth of (30) to 120 mm (measured from primary water side)
- Concentration in bottommost and upper core shell
- Located in base metal, outside of weld regions
- Can be correlated to steel microstructure & thermo-mechanical history (theoretical modeling SCK-CEN)
- …

- Technique ?? Instrumentation ?? Interpretation ?? Real problem ??...

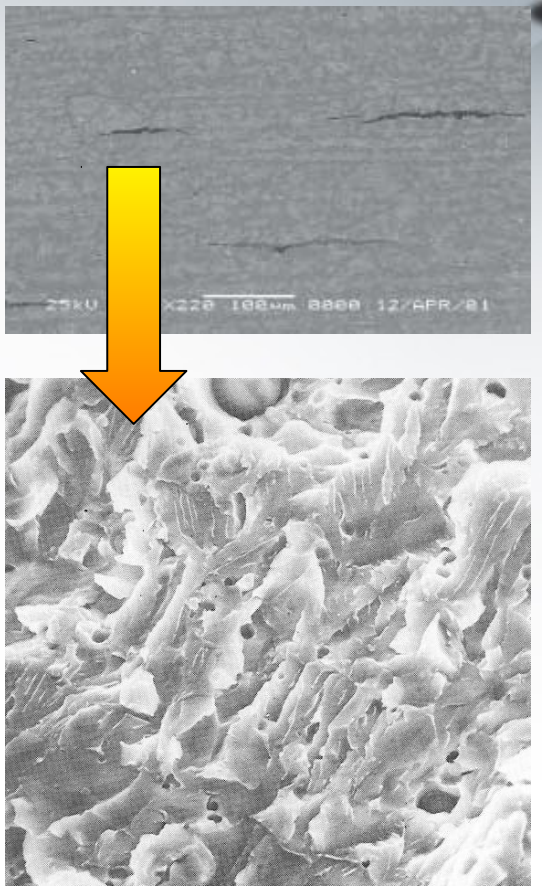


VB 395 component

Investigations – Root cause

- "***Hydrogen flakes***"…!
- OR: *"**Hydrogen Flaws**"* **("vlokken")**
  - *euphemism…??*
    (cf. 'shatter **cracks**')

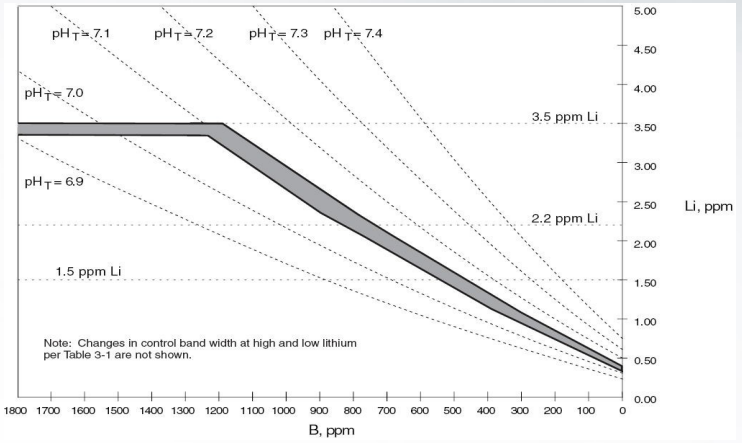
- Origin:
  - H solubility: 30 ppm in steel melt
  - H solubility: 0.1 ppm at RT
- H collected at internal voids, such as non-metallic inclusions (sulfides, oxides), shrinkage pores, etc…
- BUT: quasi spherical cracks;
  i.e. = hydrogen-induced **brittle fracture** !
- Mostly 'laminar' or 'quasi-laminar'
- High density of flaws in some zones



Typical flake cracking in carbon or low-alloy steel. Typical features of hydrogen-induced brittle fracture are: micro-quasi-cleavage fracture, pores and fine hair-lines (indicating ductile fracture on a micro-scale)

2. Initial Situation *(2012-2014)*

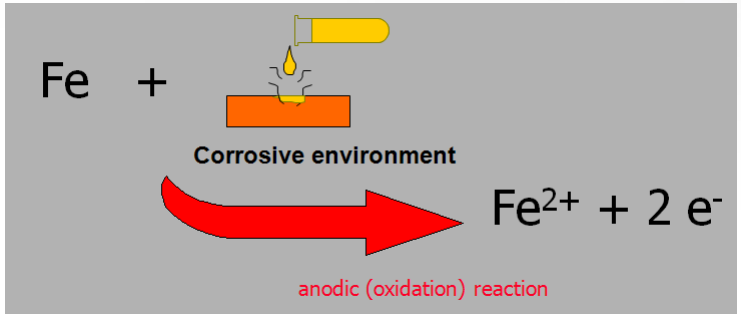
- Reporting: *"Currently no source of hydrogen anymore…"* (sic)
- But :
  - Cathodic corrosion reaction
    - $H_2O + e^- \rightleftharpoons H + OH^-$
  - Radiolysis
    - Radiolysis of water
    - Reaction of H_2 with radiolysis products: $OH^* + H_2 \rightarrow H^* + H_2O$
- And :
  - ~~Typical sizes: 4 to 15 mm~~
  - ~~Current findings: up to 20, 25 or 30 mm (!?)~~



pH control in PWR primary coolant by adjusting the lithium concentration as the boron is consumed during fuel burn-up. The trajectory commonly employed over a typical fuel cycle is marked by the dark path (EPRI PWR Primary Water Chemistry Guidelines TR-105714-V1R4).

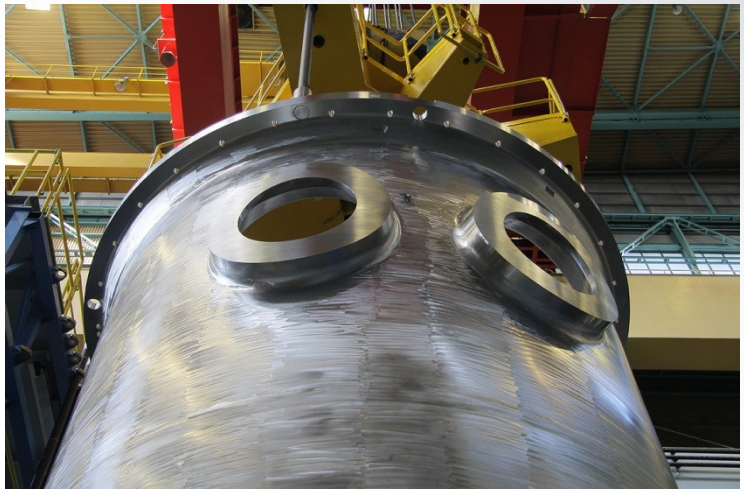
Reality …

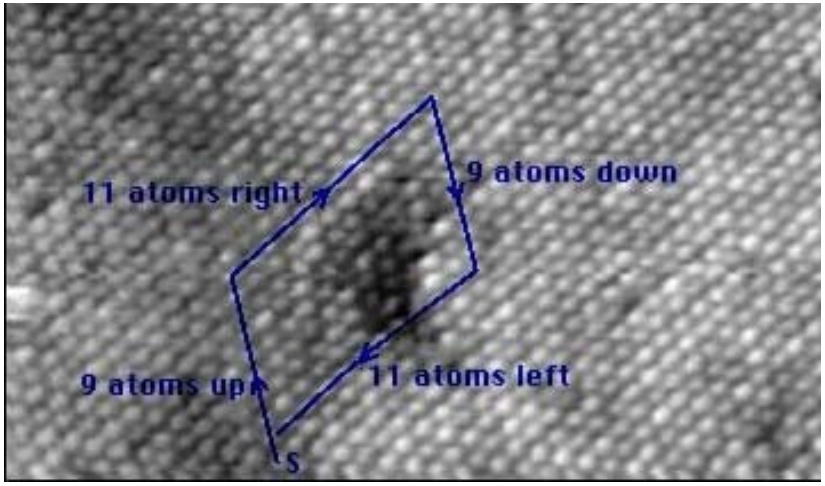
- Reporting: *"Currently no source of hydrogen anymore…"* (sic)
- But :
  - Cathodic corrosion reaction
    - $H_2O + e^- \rightleftharpoons H + OH^-$
    - Possibly: $H + H \rightleftharpoons H_2$
  - Radiolysis
    - Radiolysis of water
    - Reaction of H_2 with radiolysis products: $OH^* + H_2 \rightarrow H^* + H_2O$
- And :
  - Typical sizes H-flakes: 4 to 15 mm
  - Current findings: up to 20, 25 or 30 mm (!?)

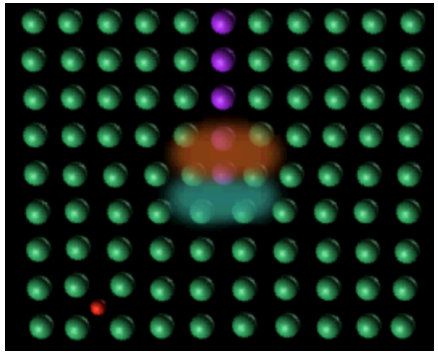


Steel …

20 cm thick steel & individual atoms







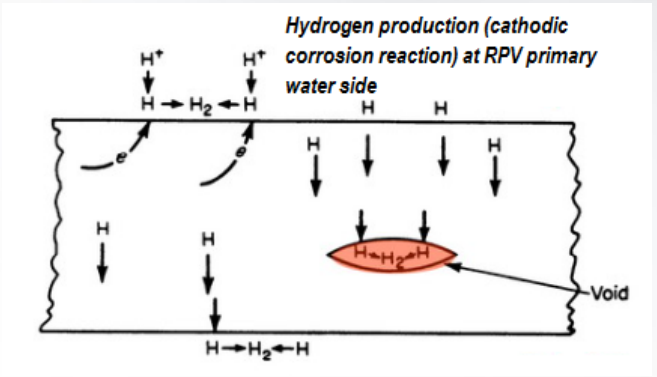
What can this “new” hydrogen do ?...

Illustration: hydrogen blistering …

Hydrogen diffusion, hydrogen induced cracking (HIC) and severe blister formation

> … 2.10^{24} – 10^{25}… atoms **H** / yr

= >> 1 million x 1,000,000,000 x 1,000,000,000



Schematic diagram of hydrogen diffusion and blister formation.

Hydrogen-induced Damage in PWR Reactor Pressure Vessels

W.F. Bogaerts [1], J.H. Zheng [2], A.S. Jovanovic[3] & D.D. Macdonald [4]

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[2] Technologica Group – INS, Intelligent Nuclear Solutions Div. (Belgium)
[3] Eu-VRi – European Virtual Institute for Integrated Risk Assessment (Germany)
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CORROSION 2015 –
Research in Progress Symposium
Session: "Corrosion in Energy Systems"
Dallas, March 15-19, 2015

Abstract

Recently, the potential problem of (hydrogen-related) cracks in RPV-steels has become imminent in the Belgian nuclear power reactors Doel 3 and Tihange 2. This paper briefly elaborates on some reported findings and identifies possible mechanisms for the detected flaws in the reactor pressure vessel walls.

The hydrogen risk (1)

Hydrogen diffusion and blister formation

- **Cathodic half-cell reaction :**

  0.1 – 1 µm/yr ▭ ≈ 28 mol H // 60 mol H_2

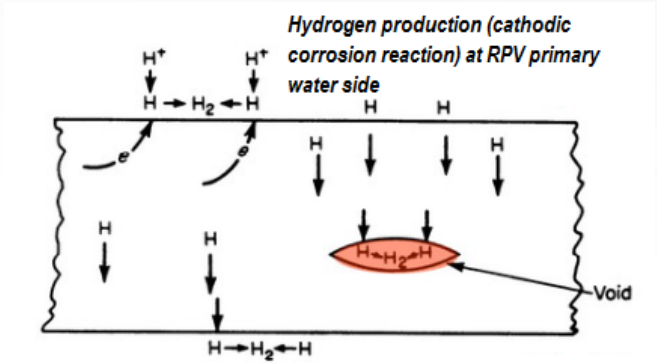
  > … 2.10^{24} – 10^{25}… atoms H / yr
  at RPV wall (≤ 200m^2) in contact with Reactor Coolant System

  = >> 1 million x 1,000,000,000 x 1,000,000,000

  = (as hydrogen gas) 1.3 m^3 STP

- ≤ 90% absorbed into base steel? *(e.g. Tomlinson study),* enhanced by irradiation (?); Stainless steel = only 'retarding barrier'; no effect at equilibrium?

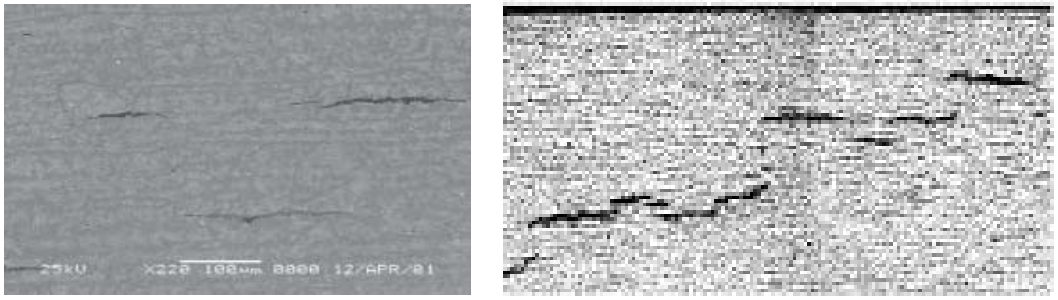
- **Radiolytic Hydrogen :**
  - Unaccounted for …
    (Modeling: D.D. Macdonald)

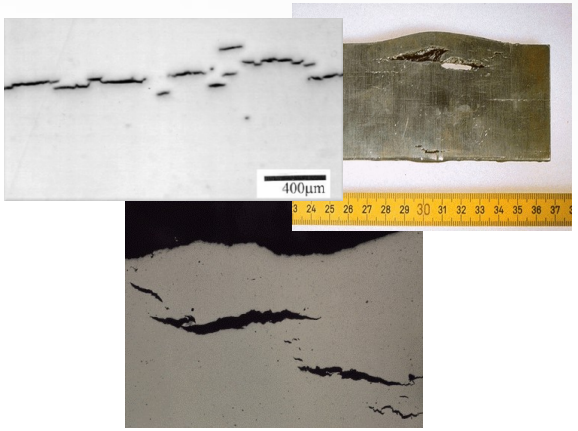


Schematic diagram of hydrogen diffusion and blister formation.

The hydrogen risk (2)

- A most significant concern is the possibility of having through-thickness flaw linkage, due to the high density of flaws in some zones
- Such types of morphology appear to occur in pressure equipment where the hydrogen damage is associated with hydrogen charging from the process environment (see **API** 579-1/ASME FFS-1 2007 Fitness-For-Service).



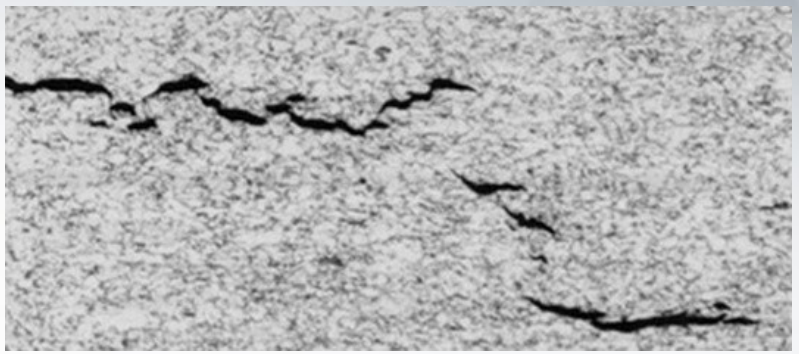


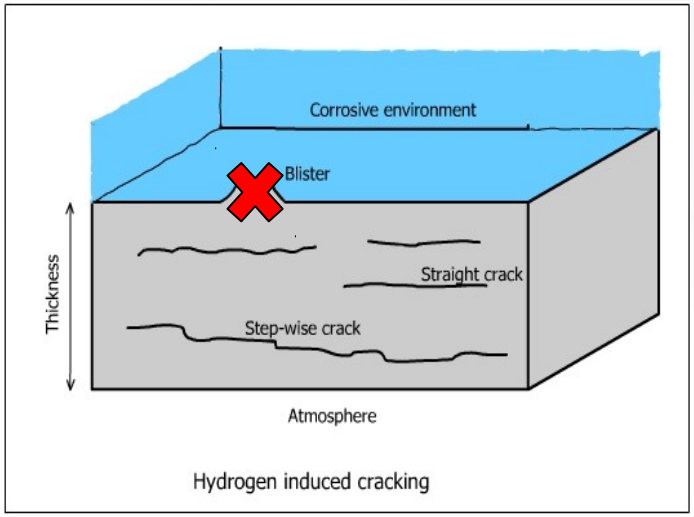
Typical hydrogen induced cracks

(source: MTI Atlas of Corrosion and Related Materials Failures – electronic ed.)

Situation – Revisited… *(2015)*

- Reporting: ~~*"Currently no source of hydrogen anymore…"*~~ (sic)
- But :
  - Cathodic corrosion reaction
    - $H_2O + e^- \rightleftharpoons H + OH^-$
  - Radiolysis
    - Radiolysis of water
    - Reaction of H_2 with radiolysis products: $OH^* + H_2 \rightarrow H^* + H_2O$
- And :
  - Typical sizes: 4 to 15 mm
  - "Current findings": up to ~~20, 25 or 30 mm~~ (!?)
    - Doel (*13.047*) : **68** [**179***] mm (vertical) x **38** [**72**] mm (horizontal)
    - Tihange (*3.149*) : **38** [**155**] mm (vertical) x **25** [**71**] mm (horizontal)

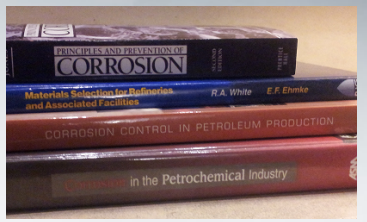




* *Figures released – February 2015 (data dd. May-June 2014 & adapted detection parameters)*

Discussion - Dispute

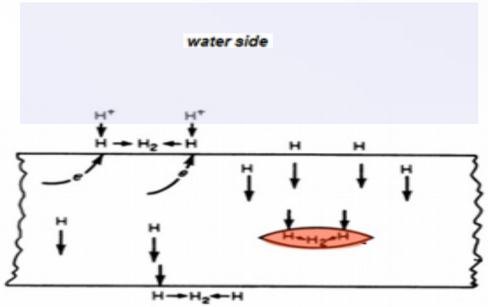
General Corrosion Science & Engineering knowhow…

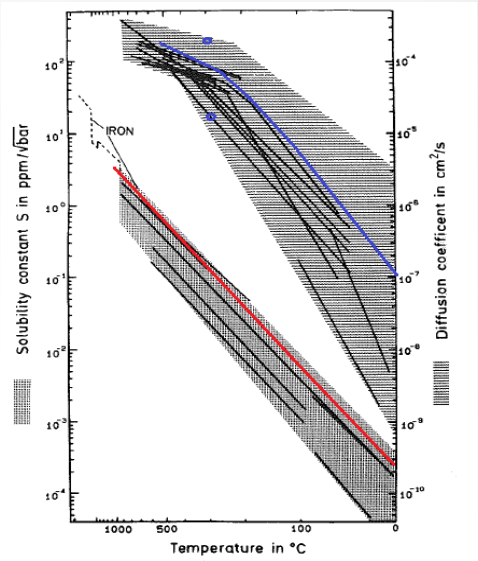


Can H_2 escape again from (micro)-void ?

- What could then be the mechanism ???
- What could be the maximum pressure in the voids ?

- General corrosion engineering (textbook) theory…





- Physicists: diffusion Fick's law, Sieverts' law, equilibrium pressures, etc…

❖ What happens during
Outage / (Emergency) Shutdown ?
i.e. PTS (Pressurized Thermal Shock)

Doel 3 en Tihange 2 voor Gevorderden:

'The Inconvenient Truth' omtrent Inspectieresultaten en Nucleaire Wetenschap

L.S.,

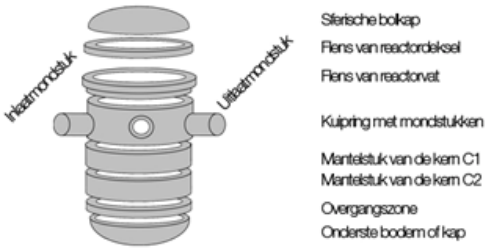
U bent gewaarschuwd; dit wordt een zorgvuldig nagez
echter eens verteld worden aan het brede publiek
wereld te helpen (dus misschien ook nuttig voor het

Bovendien mag een ingenieur soms ook eens trach
discussie die eigenlijk technologisch van aard is. Een p

Wat volgt zijn grotendeels feiten, niets anders dan feit
bare, speculaties. Waar dat wel het geval is, wordt dit

Wat voorafging

De problematiek rond de 'scheurtjescentrales' Doel
genoegzaam bekend. Na desastreuse inpectieresulta
Vessel) in de zomer van **2012** werden beide kernr
exploitant Electrabel, noch het Federaal Agentschap v
moeite of middelen bespaard om de oorzaak van de g
in te schatten. Na eerste onderzoekingen worden d
voorjaar van **2014** ijlings opnieuw te worden stilgel
Studiecentrum voor Kernenergie (SCK) te Mol.



Een serie van merkwaardige, letterlijke citaten uit het 49-pagina's tellende 'Safety Evaluation Report" van Bel-V omtrent Doel 3 en Tihange 2, met datum van 5-11-2015:

"Bel V concludes that the updated condition of the Doel 3 and Tihange 2 RPV core shells as revealed by the examination performed in 2014 using the qualified UT inspection procedure is to be considered as having a substantially increased structural significance when compared to the condition determined in 2012." (pagina 9);

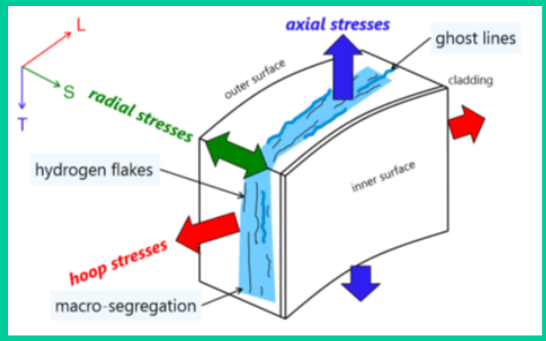
- *"Compared to the 2012 inspection, the results of the 2014 UT inspection showed a significantly increased number of detected flaw indications, much higher than was expected by Bel V"* (pagina 14);
- *"Another important feature of the 2014 UT inspection is the identification of some flaw indications having a size significantly larger than those identified in 2012. In the Doel 3 lower core shell, the maximal axial dimension for a flaw indication was reported to be 179 mm in 2014 and 68 mm in 2012. Those flaw indications with large size were identified at locations deeper than 50 mm."* (pagina 15);
- *"The identification of indications with large size (> 25 to 30 mm) raises an important issue because "elementary" flakes of such size are practically excluded due to metallurgical considerations." (pagina 15) – sic.*
- *"To Bel V opinion, considering that the time elapsed between the restart in 2013 and the shutdown in 2014 is less than one year, the results of the comparison **do not allow to claim that there is an experimental evidence of no in-service growth**." (pagina 17).*

Bijna ongelooflijk echter, 12 dagen later op 17-11-2015, geven de verantwoordelijken van het Fanc desondanks, en ondanks alles, formeel toestemming tot de heropstart van de reactoren!... Ondertussen had o.a. het kabinet van Minister Marghem wel moeten onderhandelen over het bedrag van de door de Frans-Belgische exploitant Engie-Electrabel te betalen 'nucleaire rente'.

‘D3/T2’ : Results & Restart …

- Despite all: Official Go-Ahead for Restart End 2015
- WENRA & Beznau 1 (Zwitserland) + Beznau 2 (77)
- FANC – ‘International Review Board’ & ORNL (USA)
  - **Minority Opinion** (‘equipment ageing’ specialist – Appendix B van ***Final Report***)
    crack growth: 2012 ⊔ 2014 !?
  - **Inspection after 1 year of operation**
  - **The public version …**

13.047 “indications” in Doel,
3.149 (?) in Tihange



"Are these Cracks" "Het zijn geen Scheur(tjes)" …?

25 year ago: **'Hydrogen Flakes' …**

Journal Nuclear Engineering and Design (1991) :
H. Pircher, "Hydrogen corrosion of pressure-vessel steels"

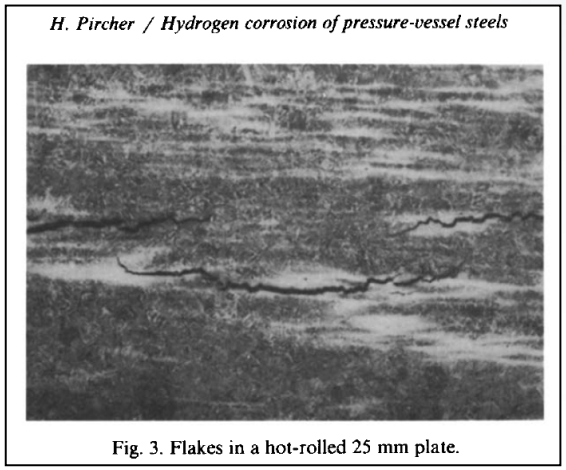
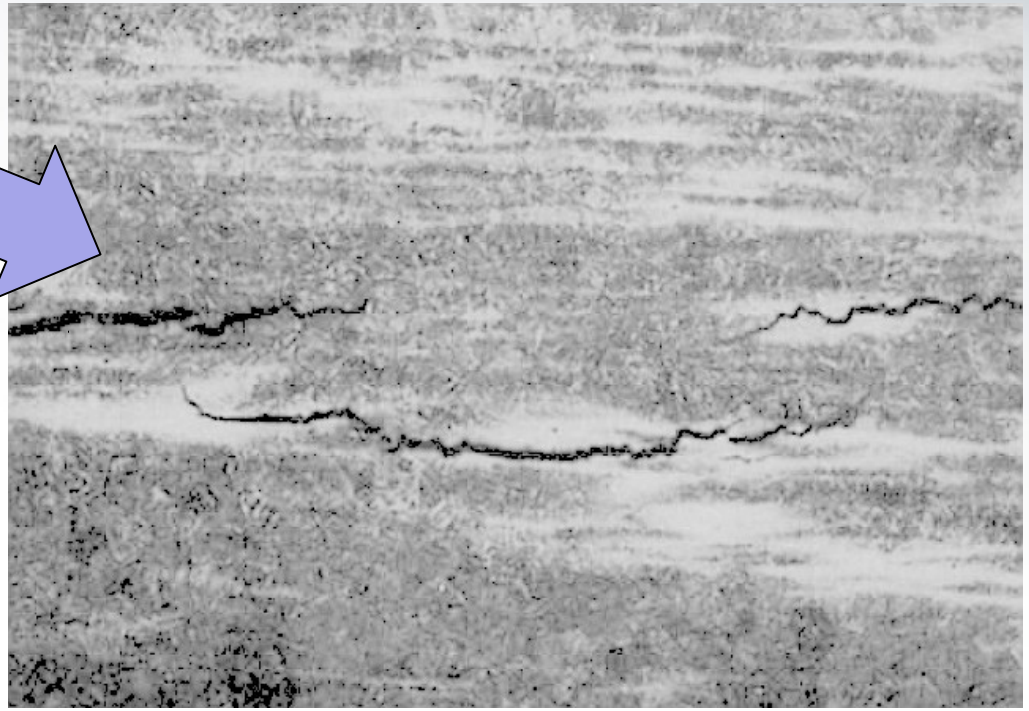


Fig. 3. Flakes in a hot-rolled 25 mm plate.

FANC: Het zijn géén scheurtjes, het zijn …

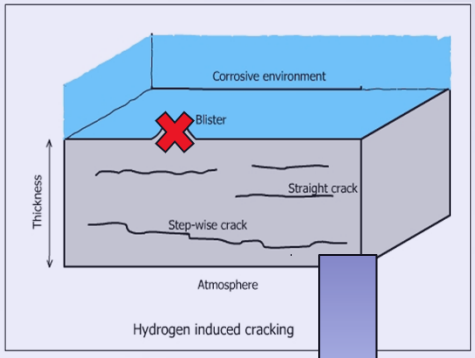


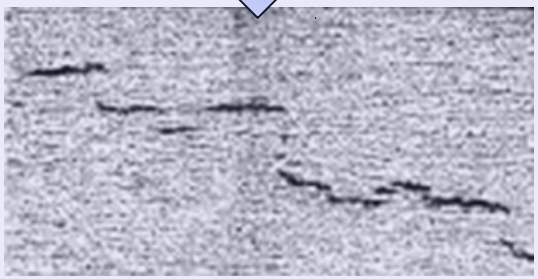
H. Pircher / Hydrogen corrosion of pressure-vessel steels

Fig. 3. Flakes in a hot-rolled 25 mm plate.

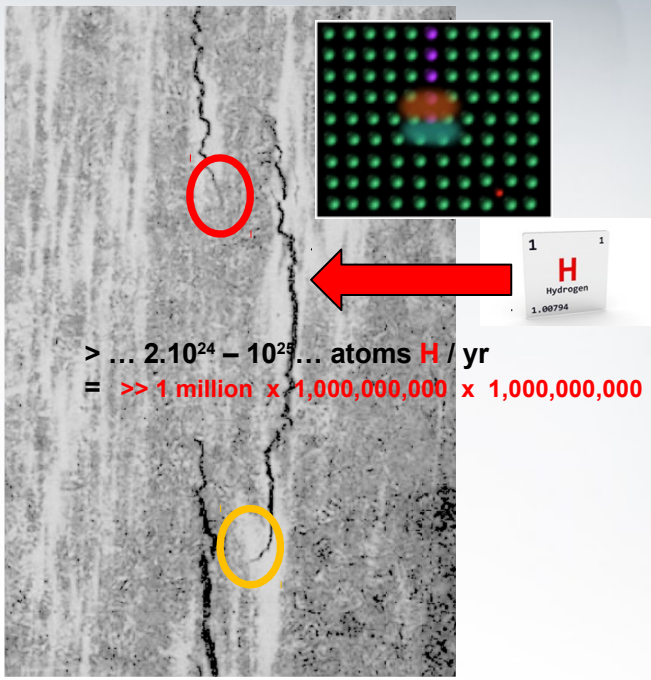
The Real Risk:

e.g.: "hydrogen-induced stepwise cracking"





FANC: …zij gaan dus nooit tot aan de wand geraken; dus dat probleem stelt zich niet…



Flakes in a hot-rolled 25 mm plate.

Total: 13.047 (!)…

Meanwhile up to 7 à 12 cm deap into wall … ca. 8 cm reserve…

D: "Bröckel-Reaktor"

Regulator (end 2015)

IEEE SPECTRUM

Follow on:

Belgian Regulators Approve Restart of Flawed Reactors

By Peter Fairley

Posted 24 Nov 2015 | 18:00 GMT

Belgian nuclear authorities have authorized the restart of two reactors whose steel reactor pressure vessels (RPVs)—which contain the reactors' fissioning cores and primary coolant—are riddled with flaws. The flaws were discovered during routine maintenance in 2012. After followup ultrasonic imaging of the RPVs, experimental testing of steel samples, and extensive computational analyses, the regulators accepted the operator's argument that the RPV flaws are decades old and do not compromise the vessels' structural integrity.

Photo: Oliver Berg/dpa/AP Photo

Steam will rise again from Reactor 2 at Belgium's Tihange nuclear power station

Belgian nuclear authorities have authorized the restart of two reactors whose steel reactor pressure vessels (RPVs)—which contain the reactors' fissioning cores and primary coolant—are riddled with flaws. The flaws were discovered during routine maintenance in 2012. After followup ultrasonic imaging of the RPVs, experimental testing of steel samples, and extensive computational analyses, the regulators accepted the operator's argument that the RPV flaws are decades old and do not compromise the vessels' structural integrity.

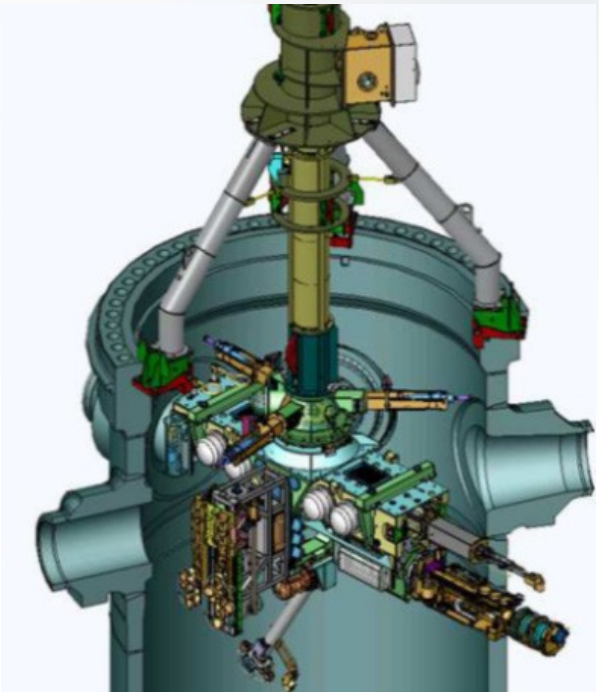
Doel 3 & Tihange 2 : An Update

***'The Inconvenient Truth'* about Inspection Results & Nuclear Science**

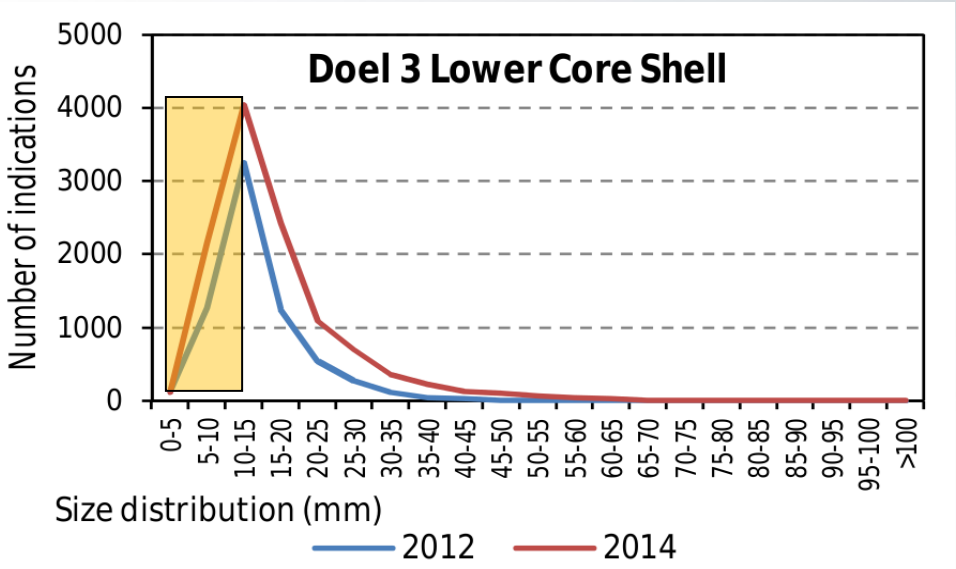
3. ‘D3/T2’ : The Sequel *(1)* …

Do they Grow ?

Inspection Results …

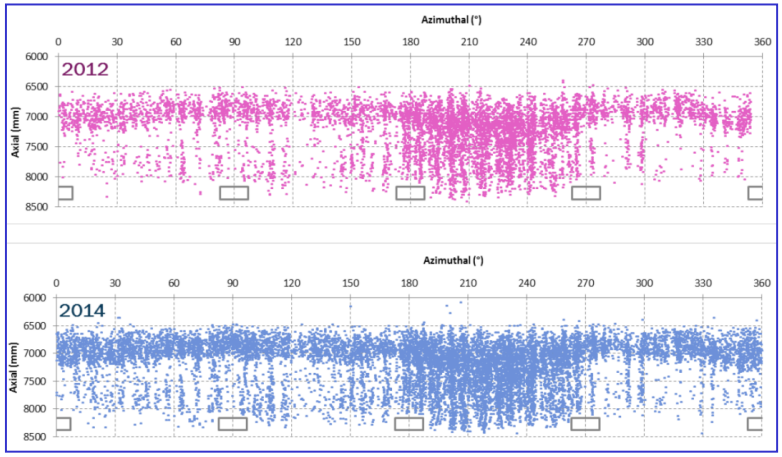


Old UT-Inspections 2012 & 2014

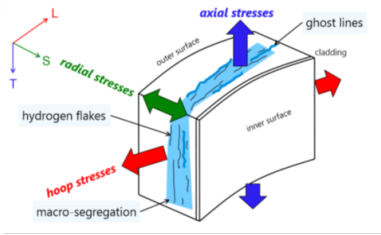


Statistical Distribution of Crack Sizes in 2012 compared to 2014 *(Source: Fanc/Electrabel)*

Yellow border shows typical range of real Hydrogen Flakes

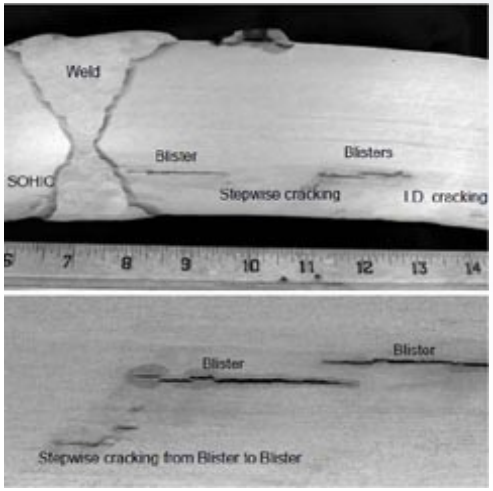


***Distribution** of the flaws over the Doel 3 lower shell circumference, measured in 2012 (upper part) and in 2014 (lower part).*



13.047 "indications" in Doel 3.149 (?) in Tihange

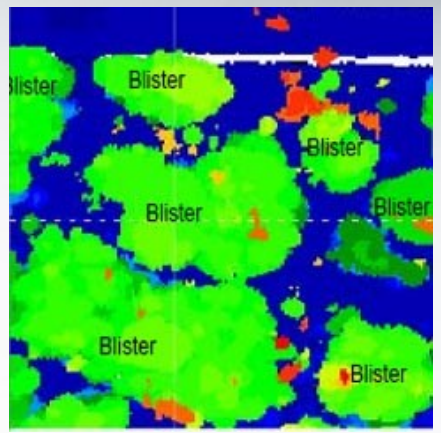
Illustration: data interpretation …



Ultrasonic Interpretation…

Blisters: A planar cavity formed as a result of hydrogen charging. Typically the indication will show some variation in through-wall depth and does not display a smooth profile. There is normally a noticeable through-thickness extent- which may be confirmed by Time of Flight Diffraction (TOFD). Loss of back-wall signal is greater than that found with laminations. Length and/or breadth would typically exceed 25mm.

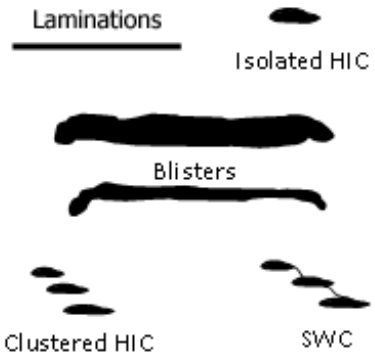
Blisters are normally discovered near to process or outer surface of the plate and under some circumstances may be seen visually as a bulging of the plate surface.

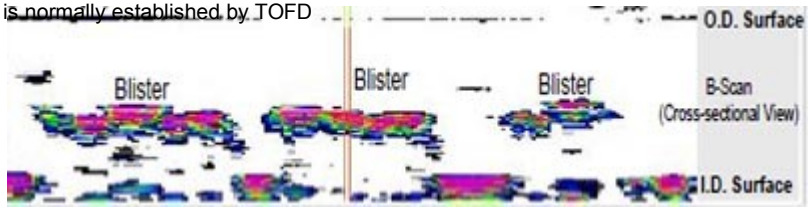


Ultrasonic Interpretation…

HIC: Planar cavity formed as a result of hydrogen charging. Individual cracks are generally quite small in area (length and/or breadth less than 25mm) and have no measurable through-thickness extent. HIC may be isolated (i.e. one by itself) or form clusters of cracks. Clustered HIC involves areas of individual HIC in close proximity to one another, both in terms of area and through-thickness extent, normally within 1 to 3mm. Note, although the cluster might show some through-thickness extent, the individual cracks in the cluster do not.

SWC: The CGI image of SWC is similar to that obtained for Clustered HIC (above), however SWC also exhibits through-thickness cracking, resulting in the linking of individual HIC cracks on multiple planes. These features are normally detected by the use of Time of Flight Diffraction (TOFD) and 45° shear wave ultrasonic. The extent of the through-thickness cracking is normally established by TOFD





Inspections 2016 / 2017

AFCN

agence fédérale de contrôle nucléaire

Notre mission

' L'AFCN promeut la protection efficace de la population, des travailleurs et de l'environnement contre les dangers des rayonnements ionisants'.

Radon

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Accueil > Messages publiés

Pas d'évolution des flocons d'hydrogène à Doel 3

December 8, 2016

L'analyse des inspections par ultrasons réalisées lors de la révision planifiée de ces dernières semaines révèle que la taille des flocons d'hydrogène constatés dans les parois de la cuve du réacteur de Doel 3 n'a pas évolué et qu'aucune nouvelle indication n'a été constatée. A l'instar de Tihange 2, l'unité de Doel 3 a été mise à l'arrêt pendant une période prolongée dans le cadre de l'examen des flocons d'hydrogène observés sur les cuves de ces réacteurs.

Le 17 novembre 2015, l'Agence fédérale
l'exploitant Electrabel à redémarrer le ré
décision sur base de l'évaluation des **dos**
Electrabel. Ces dossiers démontraient qu
les parois des cuves des réacteurs n'ava
sûreté des réacteurs. L'AFCN avait toute
flocons d'hydrogènes lors de la révision
forme d'inspections par ultrasons réalisé
forgés de Doel 3.

Ces inspections par ultrasons ont été co
dernières semaines. Les résultats de ces
analysés en utilisant une méthode appro
L'analyse a révélé l'absence d'évolution
indication n'a été observée, tandis que la
augmenté.

Sur base de ces résultats, l'AFCN n'a formulé aucune objection au sujet du redémarrage de Doel 3, le réacteur a redémarré hier. L'AFCN et Electrabel continuent de vérifier l'état de la cuve, comme le prévoient les règles internationales. Une inspection par ultrasons similaire est également programmée pour Tihange 2 lors de la révision planifiée d'avril 2017.

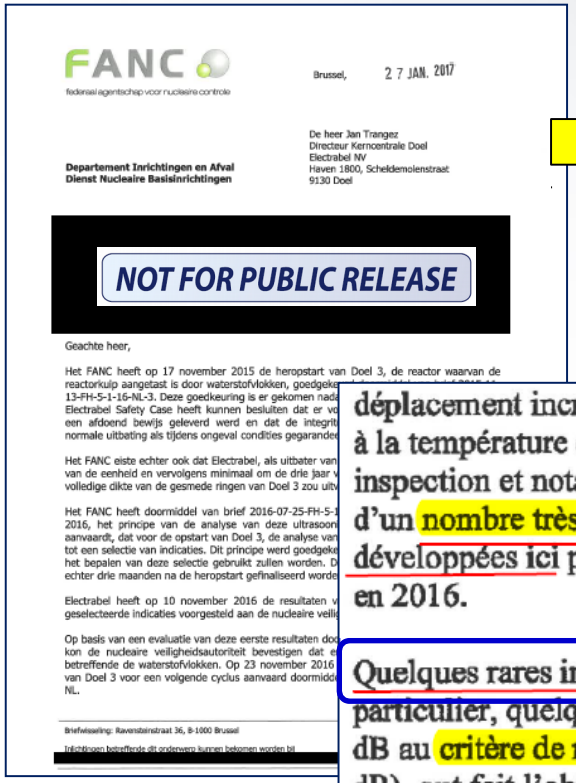
Accueil > Messages publiés

Pas d'évolution des flocons d'hydrogèneà Tihange 2

May 5, 2017

L'analyse des inspections par ultrasons réalisées lors de la révision planifiée de ces dernières semaines révèle que la taille des flocons d'hydrogène constatés dans les parois de la cuve du réacteur de Tihange 2 n'a pas évolué et qu'aucune nouvelle indication n'a été constatée. A l'instar de Doel 3, l'unité de Tihange 2 a été mise à l'arrêt pendant une période prolongée dans le cadre de l'examen des flocons d'hydrogène observés sur les cuves de ces réacteurs.

Inspection Results …



FANC
federaal agentschap voor nucleaire controle

Brussel, 27 JAN. 2017

De heer Jan Trangez
Directeur Kerncentrale Doel
Electrabel NV
Haven 1800, Scheldemolenstraat
9130 Doel

Departement Inrichtingen en Afval
Dienst Nucleaire Basisinrichtingen

NOT FOR PUBLIC RELEASE

Geachte heer,

Het FANC heeft op 17 november 2015 de heropstart van Doel 3, de reactor waarvan de reactorkuip aangetast is door waterstofvlokken, goedgekeurd
13-FH-5-1-16-NL-3. Deze goedkeuring is er gekomen nadat
Electrabel Safety Case heeft kunnen besluiten dat er voldoende
een afdoend bewijs geleverd werd en dat de integriteit
normale uitbating als tijdens ongeval condities gegarandeerd

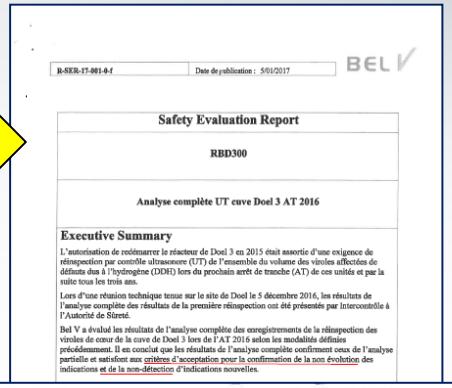
Het FANC eiste echter ook dat Electrabel, als uitbater van
van de eenheid en vervolgens minimaal om de drie jaar
volledige dikte van de gesmede ringen van Doel 3 zou uitvoeren

Het FANC heeft doormiddel van brief 2016-07-25-FH-5-1
2016, het principe van de analyse van deze ultrasoonmetingen
aanvaardt, dat voor de opstart van Doel 3, de analyse van
tot een selectie van indicaties. Dit principe werd goedgekeurd
het bepalen van deze selectie gebruikt zullen worden. De
echter drie maanden na de heropstart gefinaliseerd worden.

Electrabel heeft op 10 november 2016 de resultaten van
geselecteerde indicaties voorgesteld aan de nucleaire veiligheid

Op basis van een evaluatie van deze eerste resultaten door
kon de nucleaire veiligheidsautoriteit bevestigen dat er
betreffende de waterstofvlokken. Op 23 november 2016
van Doel 3 voor een volgende cyclus aanvaard doormiddel
NL.

Briefwisseling: Ravensteinstraat 36, B-1000 Brussel
Inlichtingen betreffende dit onderwerp kunnen bekomen worden bij



R-SER-17-001-0-f | Date de publication : 5/01/2017 | BEL V

Safety Evaluation Report

RBD300

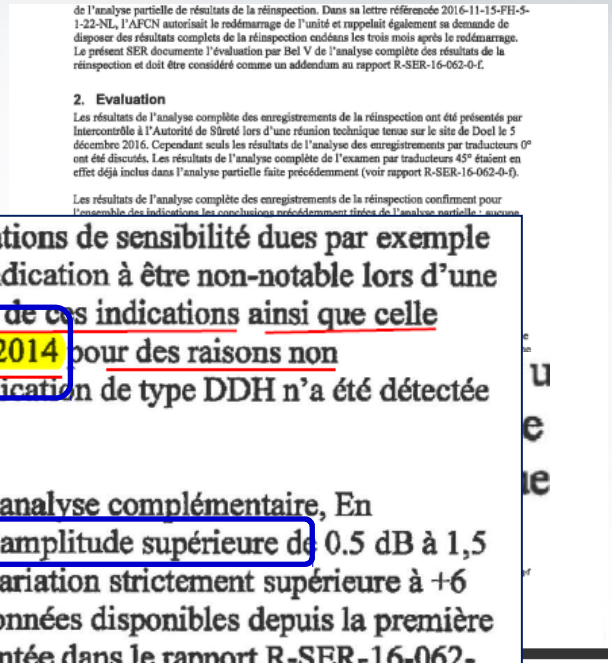
Analyse complète UT cuve Doel 3 AT 2016

Executive Summary

L'autorisation de redémarrer le réacteur de Doel 3 en 2015 était assortie d'une exigence de réinspection par contrôle ultrasonore (UT) de l'ensemble du volume des viroles affectées de défauts dus à l'hydrogène (DDH) lors du prochain arrêt de tranche (AT) de ces unités et par la suite tous les trois ans.

Lors d'une réunion technique tenue sur le site de Doel le 5 décembre 2016, les résultats de l'analyse complète des résultats de la première réinspection ont été présentés par Intercontrôle à l'Autorité de Sûreté.

Bel V a évalué les résultats de l'analyse complète des enregistrements de la réinspection des viroles de cœur de la cuve de Doel 3 lors de l'AT 2016 selon les modalités définies précédemment. Il en conclut que les résultats de l'analyse complète confirment ceux de l'analyse partielle et satisfont aux critères d'acceptation pour la confirmation de la non évolution des indications et de la non-détection d'indications nouvelles.



de l'analyse partielle de résultats de la réinspection. Dans sa lettre référencée 2016-11-15-FH-5-1-22-NL, l'AFCN autorisait le redémarrage de l'unité et rappelait également sa demande de disposer des résultats complets de la réinspection endéans les trois mois après le redémarrage. Le présent SER documente l'évaluation par Bel V de l'analyse complète des résultats de la réinspection et doit être considéré comme un addendum au rapport R-SER-16-062-0-f.

2. Evaluation

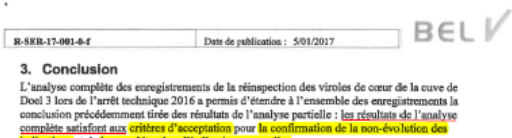
Les résultats de l'analyse complète des enregistrements de la réinspection ont été présentés par Intercontrôle à l'Autorité de Sûreté lors d'une réunion technique tenue sur le site de Doel le 5 décembre 2016. Cependant seuls les résultats de l'analyse des enregistrements par traducteurs 0° ont été discutés. Les résultats de l'analyse complète de l'examen par traducteurs 45° étaient en effet déjà inclus dans l'analyse partielle faite précédemment (voir rapport R-SER-16-062-0-f).

Les résultats de l'analyse complète des enregistrements de la réinspection confirment pour l'ensemble des indications les conclusions précédemment tirées de l'analyse partielle : aucune

déplacement incrémental des traducteurs et les faibles variations de sensibilité dues par exemple à la température de l'eau de la cuve, peuvent amener une indication à être non-notable lors d'une inspection et notable lors d'une autre inspection. L'analyse de ces indications ainsi que celle d'un nombre très faible d'autres indications non notées en 2014 pour des raisons non développées ici permet de conclure qu'aucune nouvelle indication de type DDH n'a été détectée en 2016.

Quelques rares indications ont également fait l'objet d'une analyse complémentaire, En particulier, quelques indications présentant une variation d'amplitude supérieure de 0.5 dB à 1,5 dB au critère de non-évolution en amplitude (évolution si variation strictement supérieure à +6 dB), ont fait l'objet d'une analyse spécifique utilisant les données disponibles depuis la première inspection en 2012. Cette analyse, similaire à celle documentée dans le rapport R-SER-16-062-

+ 6 dB !?...

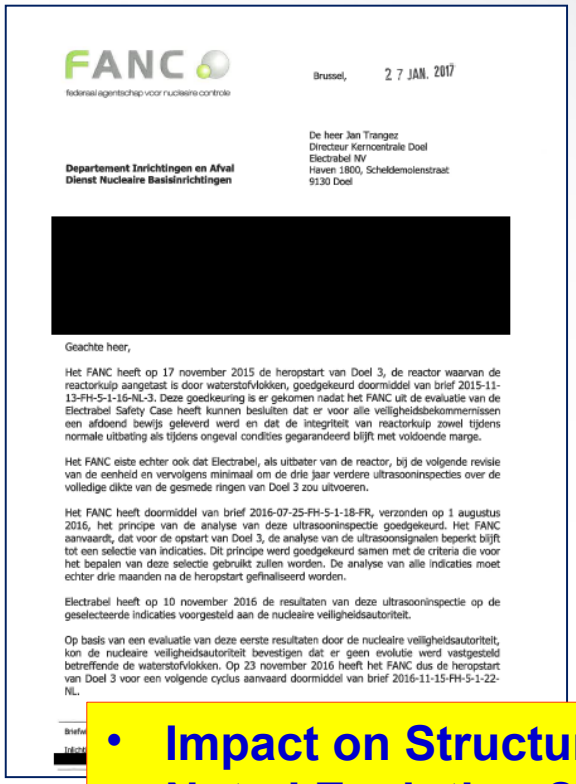


R-SER-17-001-0-f | Date de publication : 5/01/2017 | BEL V

3. Conclusion

L'analyse complète des enregistrements de la réinspection des viroles de cœur de la cuve de Doel 3 lors de l'arrêt technique 2016 a permis d'étendre à l'ensemble des enregistrements la conclusion précédemment tirée des résultats de l'analyse partielle : les résultats de l'analyse complète satisfont aux critères d'acceptation pour la confirmation de la non-évolution des indications et de la non-détection d'indications nouvelles.

Inspection Results – Bis …



FANC

federaal agentschap voor nucleaire controle

Brussel, 27 JAN. 2017

Departement Inrichtingen en Afval
Dienst Nucleaire Basisinrichtingen

De heer Jan Trangez
Directeur Kerncentrale Doel
Electrabel NV
Haven 1800, Scheldemolenstraat
9130 Doel

[redacted]

Geachte heer,

Het FANC heeft op 17 november 2015 de heropstart van Doel 3, de reactor waarvan de reactorkuip aangetast is door waterstofvlokken, goedgekeurd doormiddel van brief 2015-11-13-FH-5-1-16-NL-3. Deze goedkeuring is er gekomen nadat het FANC uit de evaluatie van de Electrabel Safety Case heeft kunnen besluiten dat er voor alle veiligheidsbekommernissen een afdoend bewijs geleverd werd en dat de integriteit van reactorkuip zowel tijdens normale uitbating als tijdens ongeval condities gegarandeerd blijft met voldoende marge.

Het FANC eiste echter ook dat Electrabel, als uitbater van de reactor, bij de volgende revisie van de eenheid en vervolgens minimaal om de drie jaar verdere ultrasooninspecties over de volledige dikte van de gesmede ringen van Doel 3 zou uitvoeren.

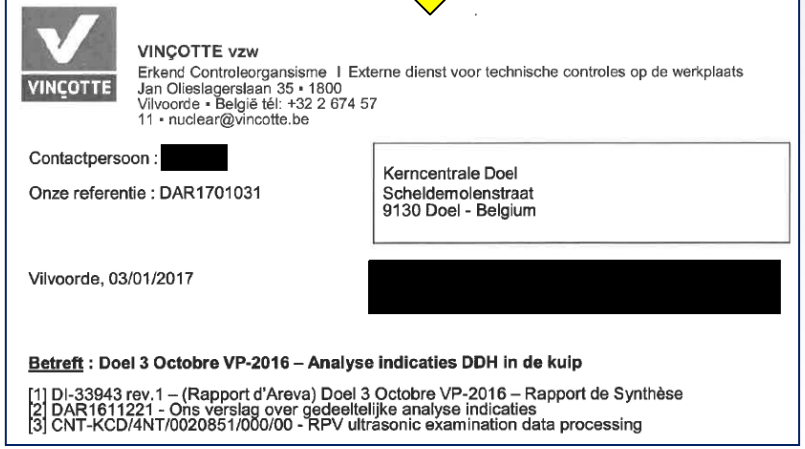
Het FANC heeft doormiddel van brief 2016-07-25-FH-5-1-18-FR, verzonden op 1 augustus 2016, het principe van de analyse van deze ultrasooninspectie goedgekeurd. Het FANC aanvaardt, dat voor de opstart van Doel 3, de analyse van de ultrasoonsignalen beperkt blijft tot een selectie van indicaties. Dit principe werd goedgekeurd samen met de criteria die voor het bepalen van deze selectie gebruikt zullen worden. De analyse van alle indicaties moet echter drie maanden na de heropstart gefinaliseerd worden.

Electrabel heeft op 10 november 2016 de resultaten van deze ultrasooninspectie op de geselecteerde indicaties voorgesteld aan de nucleaire veiligheidsautoriteit.

Op basis van een evaluatie van deze eerste resultaten door de nucleaire veiligheidsautoriteit, kon de nucleaire veiligheidsautoriteit bevestigen dat er geen evolutie werd vastgesteld betreffende de waterstofvlokken. Op 23 november 2016 heeft het FANC dus de heropstart van Doel 3 voor een volgende cyclus aanvaard doormiddel van brief 2016-11-15-FH-5-1-22-NL.

van het Safety Evaluation Report met referentie R-SER-17-001-0-f (bijlage 1), bevestigt dat er geen nieuwe indicaties zijn en dat de indicaties niet groeien ten opzichte van de vooraf overeengekomen acceptatiecriteria.

De onafhankelijke analyse van AIB-Vinçotte, overgemaakt doormiddel van brief met referentie DAR170131 (bijlage 2), stelt ook vast dat er geen reële evolutie van de indicaties is.



VINÇOTTE

VINÇOTTE vzw
Erkend Controleorgansisme I Externe dienst voor technische controles op de werkplaats
Jan Olieslagerslaan 35 ▪ 1800
Vilvoorde ▪ België tél: +32 2 674 57
11 ▪ nuclear@vincotte.be

Contactpersoon : [redacted]

Onze referentie : DAR1701031

Kerncentrale Doel
Scheldemolenstraat
9130 Doel - Belgium

Vilvoorde, 03/01/2017

[redacted]

Betreft : Doel 3 Octobre VP-2016 – Analyse indicaties DDH in de kuip

[1] DI-33943 rev.1 – (Rapport d'Areva) Doel 3 Octobre VP-2016 – Rapport de Synthèse
[2] DAR1611221 - Ons verslag over gedeeltelijke analyse indicaties
[3] CNT-KCD/4NT/0020851/000/00 - RPV ultrasonic examination data processing

- **Impact on Structural Integrity ?**
- **Noted Evolution ???**

We hebben tijdens de revisie van de kuip van Doel 3 in 2016 ook de acquisities van sommige andere indicaties nader geverifieerd. Onze selectie bevatte de indicaties met de grootste impact op de structurele integriteit, enkele willekeurig gekozen indicaties et tenslotte de indicaties met de grootste genoteerde evolutie.

Voor acht indicaties wordt een amplitude boven de criteria [3] vermeld.

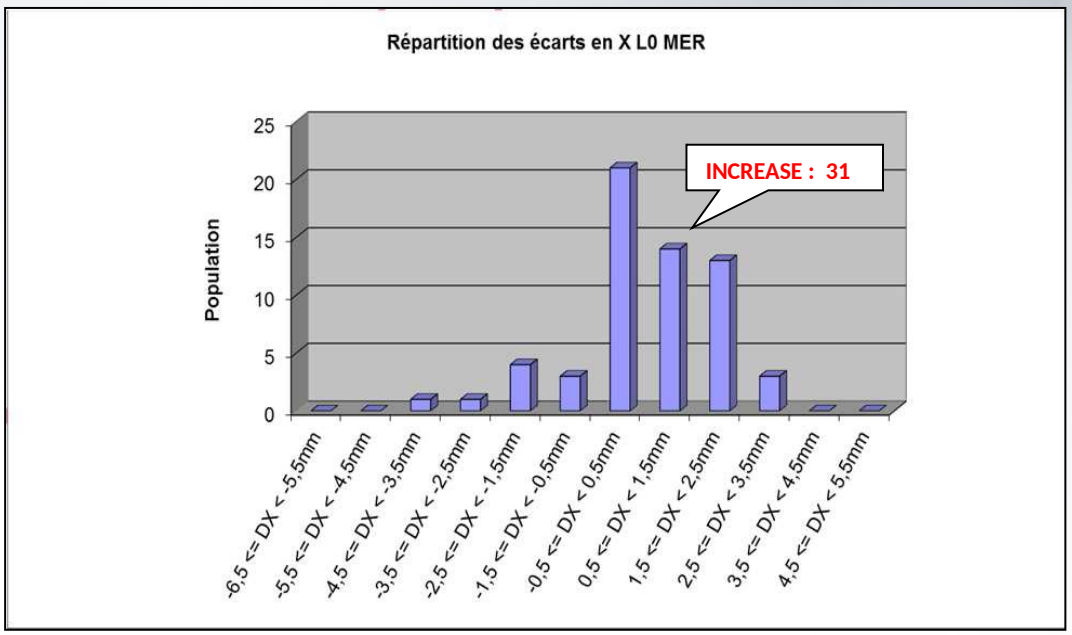
Inspections 2016 / 2017

Real Data

after operation:

Tihange 2

- 60 “new” cracks discovered in 2017
- But: also present in 2014
  (new data analysis)
- Some sizes 5…15… 25% larger



Source: Areva / FANC-AFCN

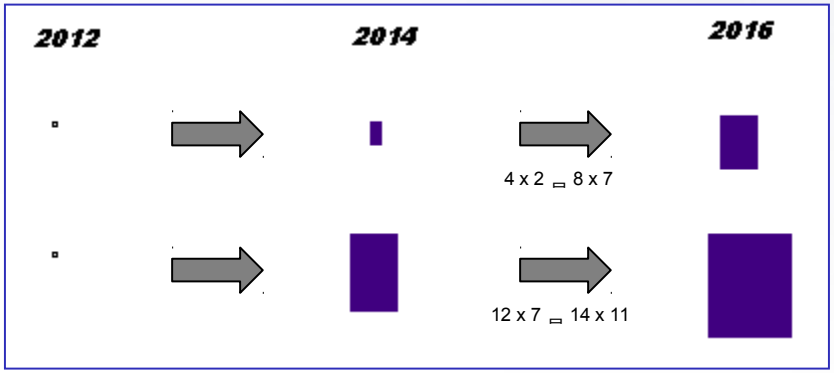
Inspections 2016 / 2017

Real Data

after operation:

Doel 3

- 300 “new” crack discoveries in 2016
- 8 difficult to explain “outlyers”
- Example:
  “Indication nr. 30060”…



Source: Areva / FANC-AFCN

4. ‘D3/T2’ : The Sequel *(2)* …

New Research Results …

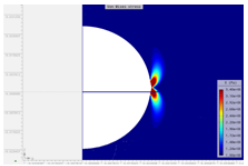
New Studies & Calculations …

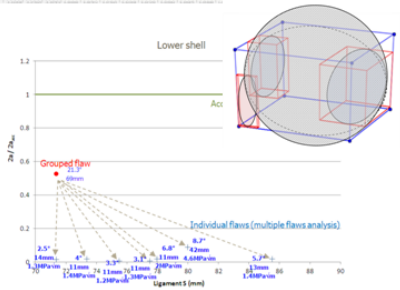
Meanwhile : New Research …

- ***R. Boonen & J. Peirs***
  (Febr. 2017)

> Critical reflections about the integrity of the reactor vessels of the Doel 3 and Tihange 2 nuclear power plants.

  - *Hydrogen as cause of metal cracking ('hydrogen flaking')*
  - *Fracture Mechanics & ASME Code Case N-848 (2 cracks) Doel 3: up to 41/dm³ !…*





> Critical reflections about the integrity of the reactor vessels of the Doel 3 and Tihange 2 nuclear power plants.

Also Nationally / Internationally …

- ***Some German Investigations & Criticisms …***
  (Workshop Aachen, October 4-5, 2016)

- E.g.:
  - D. Majer & I. Tweer: **Conservatism** of approach & Use of **WPS effect** (Warm Pre-Stress effect) with improvement of subsequent apparent thoughness properties = ? Cf. additional ΔRT_{NDT} of 50°C
  - Unclarified **excessive embrittlement** results in SCK*CEN studies of VB395 sample = still not known at this stage

- ***New Vessel Inspections***


FANC

Op basis van de evaluatie door de nucleaire veiligheidsautoriteit van de finale resultaten, kan FANC bevestigen dat er geen evolutie werd vastgesteld betreffende de waterstofvlokken (geen groei van bestaande indicaties, geen nieuwe indicaties).

New Studies & Calculations …

BNEN

Potential effects of process-generated hydrogen on RPV walls during thermal transients

Kristof Dockx
Master Thesis 2016-2017
February 6th, 2017

Universiteit Gent · Université de Liège · UCL Université catholique de Louvain · SCK•CEN · ULB · Vrije Universiteit Brussel · KU LEUVEN

Berkeley UNIVERSITY OF CALIFORNIA

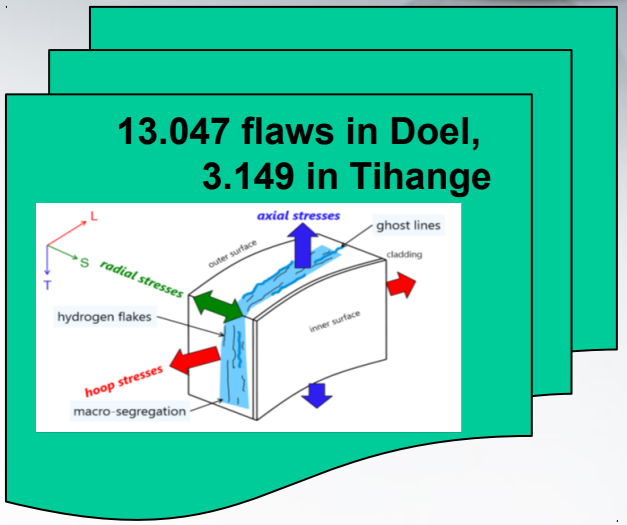
BNEN

Conclusion

- Structural integrity of RPV is very important for safety
- Stability of the hydrogen flakes must be assured
- 3 hydrogen sources:
  - Dissolved hydrogen
  - Corrosion generated hydrogen
  - **Radiolysis generated hydrogen**
- Hydrogen pressure in RPV wall
  - Hot in-service condition → **1,5 10^5 atm H_2**
  - Cold shutdown → **1,65 10^5 atm H_2**
  - PTS → **1,62 10^5 atm H_2**
- Crack growth ~ **GPa = 10^4 atm**
- Not able to assure stability of the hydrogen flakes in the RPV

5. Conclusion

- **UT-inspections:**
  - Acceptance testing (1975 & 1977) : OK !
  - Inspections 2012 vs. Inspections 2014
    - 7775 ⊔ 13.047 flaws detected in Doel,
    - 3.149 flaws detected in Tihange
    - 'More & Larger' ("higher sensitivity") :
      - Typical sizes 'hydrogen flakes': 4 to 15 mm
      - Up to 155 x 71 mm (Tihange)
      - Up to 179 x 72 mm (Doel)
  - Would such results be OK @ acceptance?
- **<u>New UT-inspections</u> after 1 yr operation in 2016** (e.g. Tihange inspection data 2017):
  - 60 "new" defects in Tihange 2
  - Growth in size (?!)
- **Meanwhile:**
  - <u>Industrial experience</u>: CPI (& API)
  - <u>(New) research results</u>: ***Mechanisms for Instability of Hydrogen Flakes During Reactor Operation***

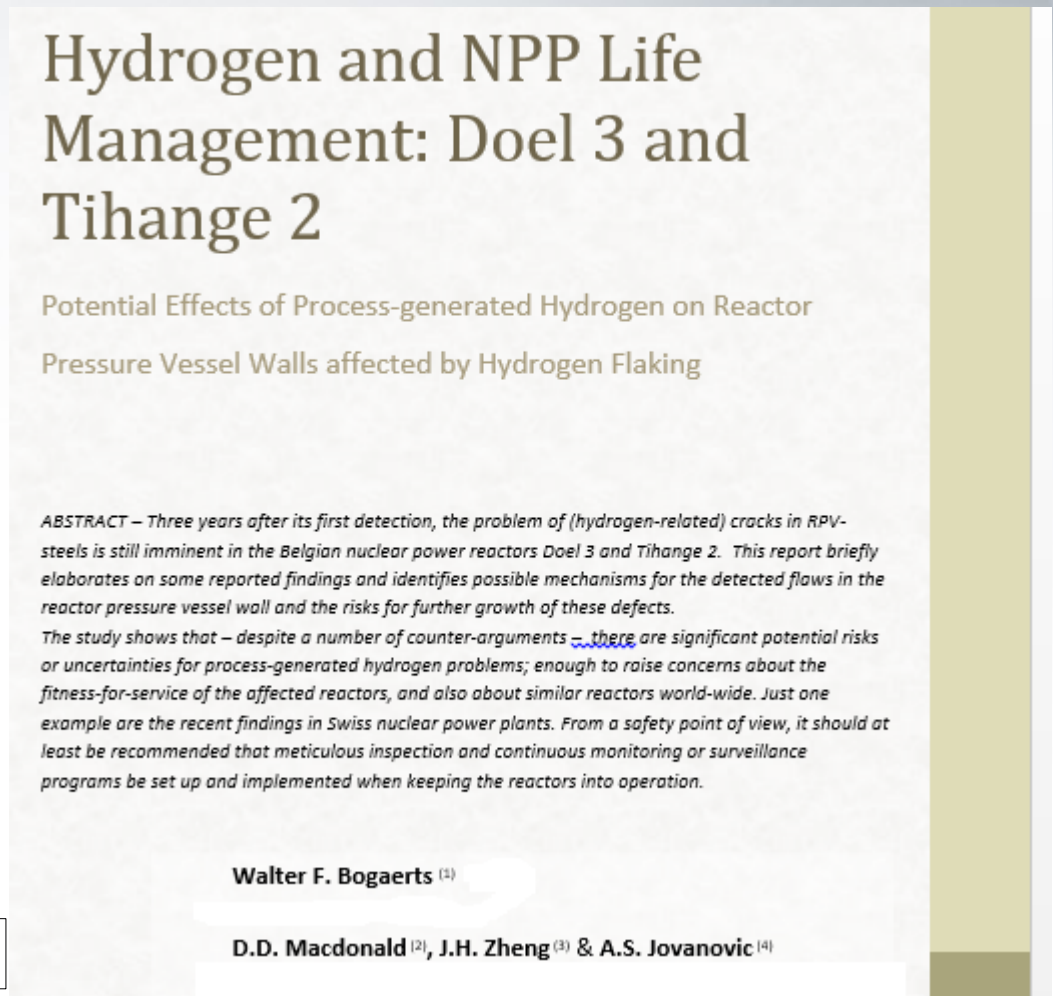


Source: Areva / FANC-AFCN

Questions?

References :

- Various public documents (*e.g.* **www.fanc.be**)
- Older (almost “ancient” – ’70s) literature on hydrogen (embrittlement) and nuclear environments
- Diverse +/- confidential reports and documents



Hydrogen and NPP Life Management: Doel 3 and Tihange 2

Potential Effects of Process-generated Hydrogen on Reactor Pressure Vessel Walls affected by Hydrogen Flaking

ABSTRACT – Three years after its first detection, the problem of (hydrogen-related) cracks in RPV-steels is still imminent in the Belgian nuclear power reactors Doel 3 and Tihange 2. This report briefly elaborates on some reported findings and identifies possible mechanisms for the detected flaws in the reactor pressure vessel wall and the risks for further growth of these defects.
The study shows that – despite a number of counter-arguments – there are significant potential risks or uncertainties for process-generated hydrogen problems; enough to raise concerns about the fitness-for-service of the affected reactors, and also about similar reactors world-wide. Just one example are the recent findings in Swiss nuclear power plants. From a safety point of view, it should at least be recommended that meticulous inspection and continuous monitoring or surveillance programs be set up and implemented when keeping the reactors into operation.

Walter F. Bogaerts [1]

D.D. Macdonald [2], **J.H. Zheng** [3] & **A.S. Jovanovic** [4]

walter.bogaerts@kuleuven.be