Belgian R&D on Environmental Effects on Materials Degradation in LWRs

International Workshop on Age-Related Degradation of Reactor Vessels and Internals, USNRC, Washington, 23-24/5/2019

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STUDIECENTRUM VOOR KERNENERGIE
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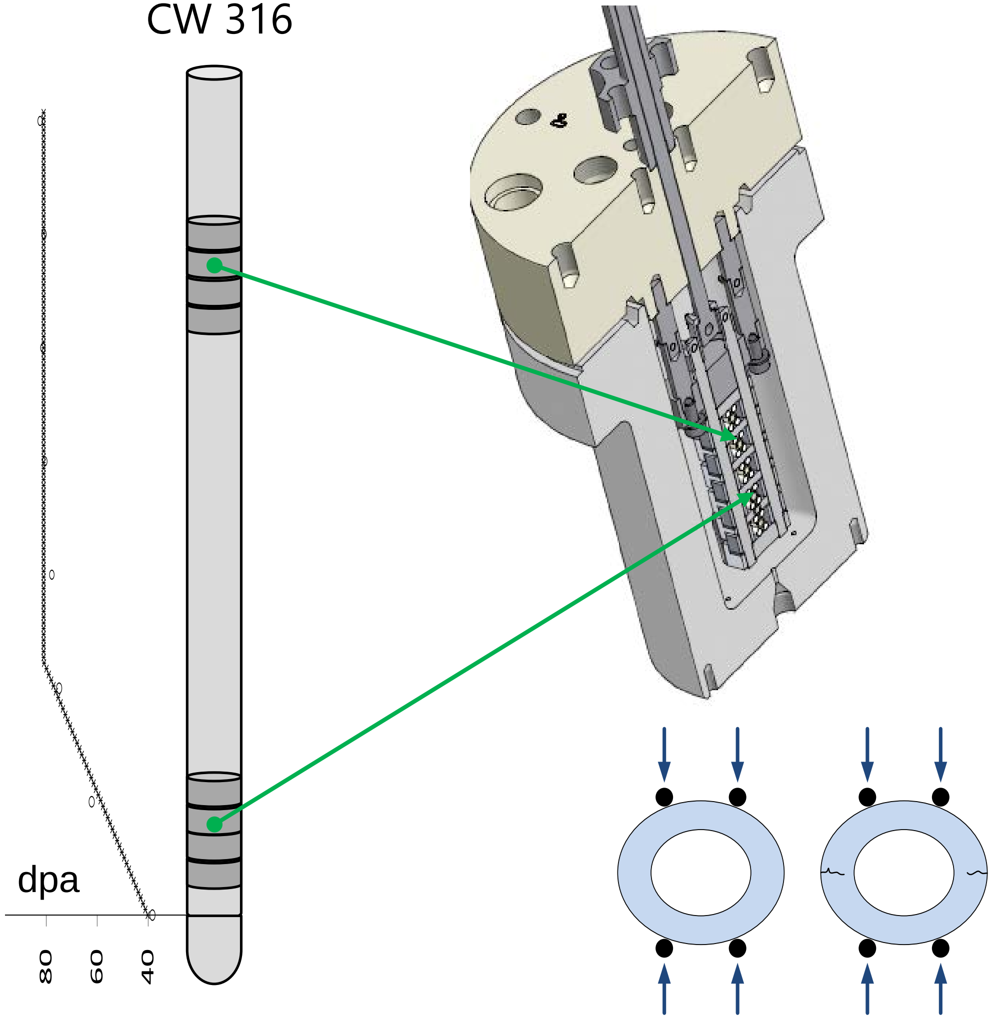
Outline

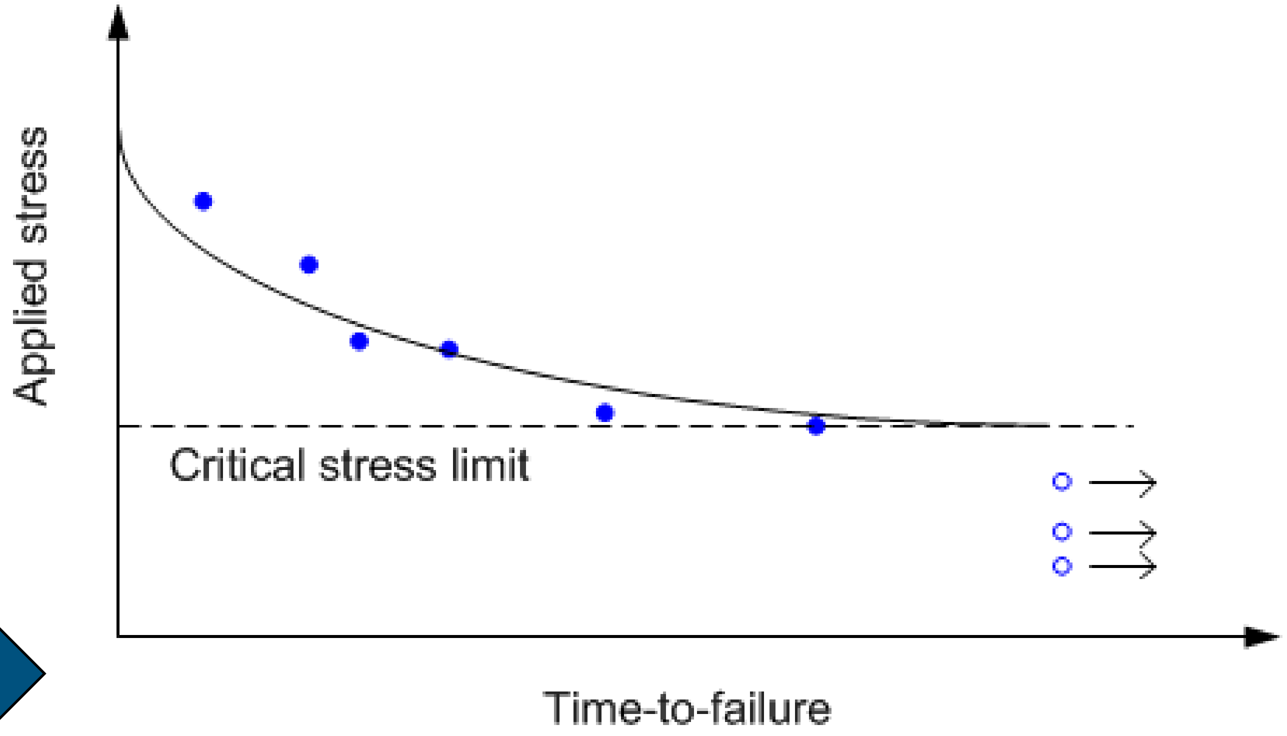
- IASCC
- Hydrogen issues for RPV
- Corrosion fatigue austenitic stainless steels in PWR environment

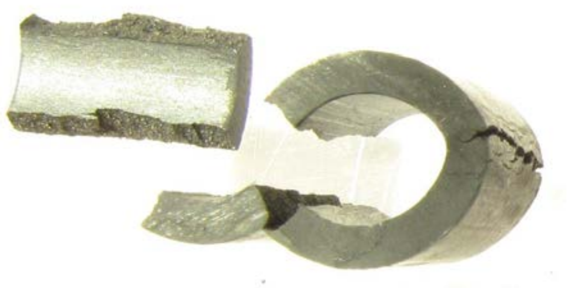
IASCC: experimental program

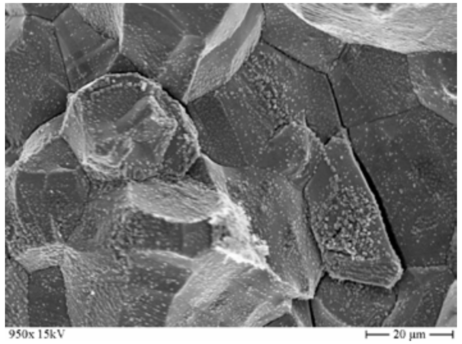
Thimble tube (Thiange 1) CW 316

O-ring compression test in PWR environment

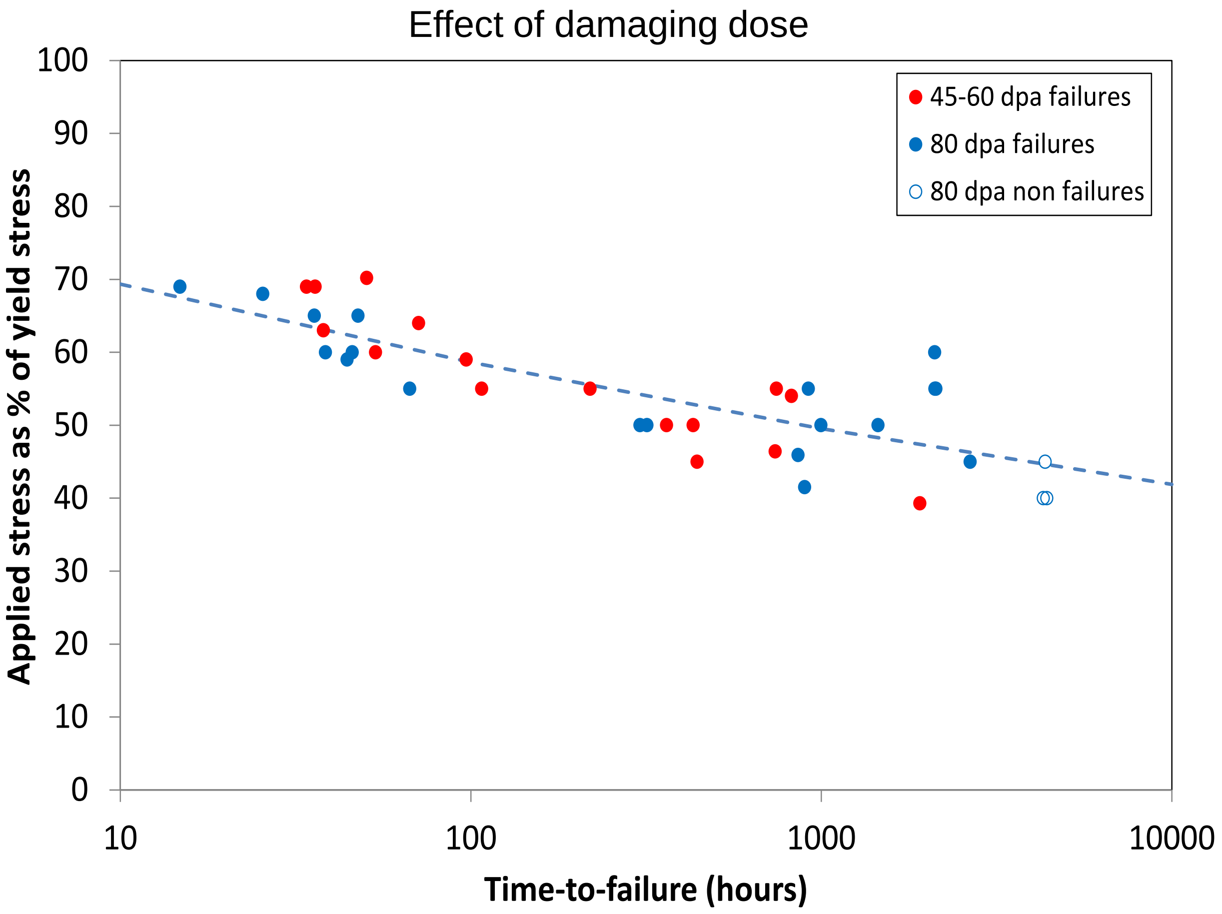


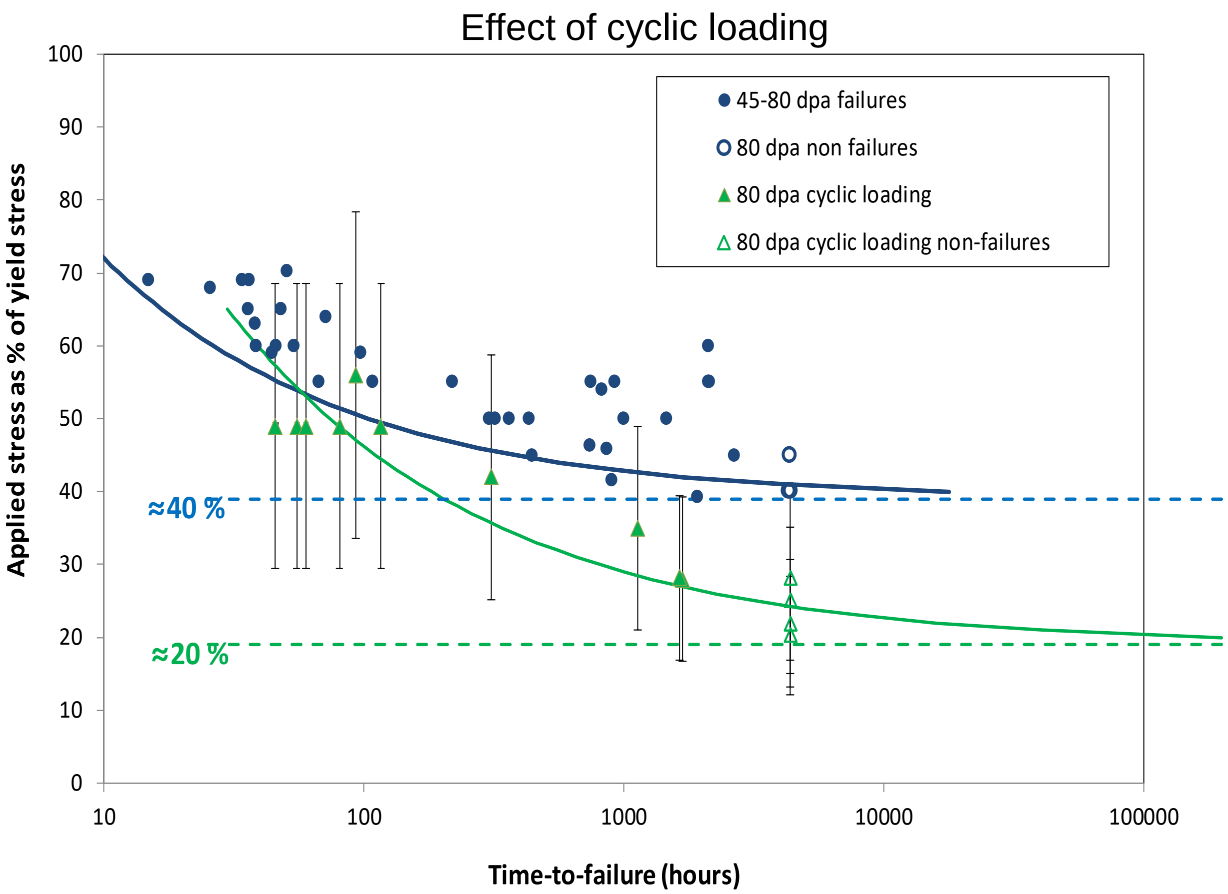






IASCC: Results





R. W. Bosch, M. Vankeerberghen, R. Gérard, F. Somville, IASCC crack initiation testing of thimble tube material with a dose up to 80 dpa under PWR conditions, Fontevraud 8, 2014

R. W. Bosch, M. Konstantinovic, M. Vankeerberghen, R. Gérard, F. Somville, Effect of cyclic loading on IASCC stress threshold of thimble tube material with a dose up to 80 dpa under PWR conditions, Fontevraud 9, 2018

IASCC: Outcome

- No apparent difference of time to failure – stress limit between 45 & 80 dpa -> saturation
- Stress threshold at ≈40 % of yield stress (≈400 Mpa) for time up to 6 months
- Cyclic loading failures occurred at a significantly lower average stress than under constant load conditions, effect was more pronounced at lower stress levels
- On-going: Development of deterministic & probabilistic failure assessments based on experimental results

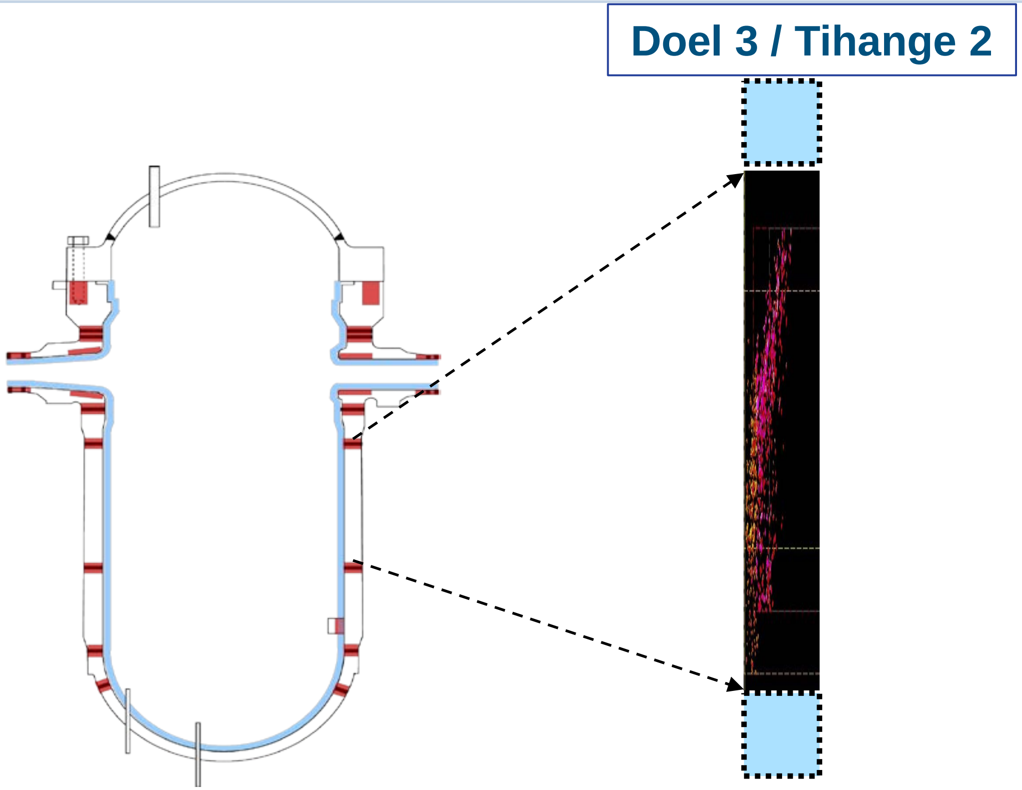
Hydrogen issues

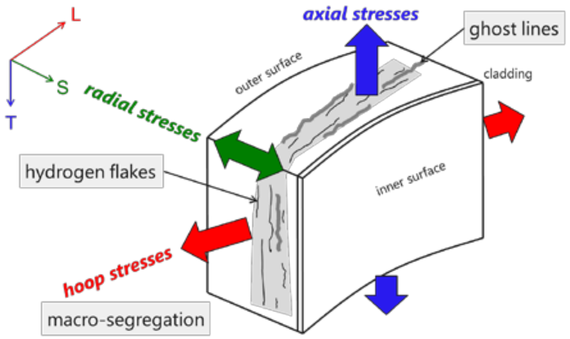
2012 Discovery of flows in RPV of Doel 3 & Thihange 2 NPP identified later as hydrogen flakes formed during fabrication

2015 Hyphothesis of Prof. W. Bogaerts (KU Leuven) with support of Prof. D.D. Macdonald (UC Berkeley) on defects instability (media & press)

2016 Report of Boonen&Peirs on balance of H_2 in ingot: deficit of H_2 to form hydrogen flakes structure

2015-2018 Presentations, papers, invited talks, master thesis on “Mechanisms for Instability of Hydrogen Flakes During Reactor Operation”





2012 UT Doel 2/Tihange2

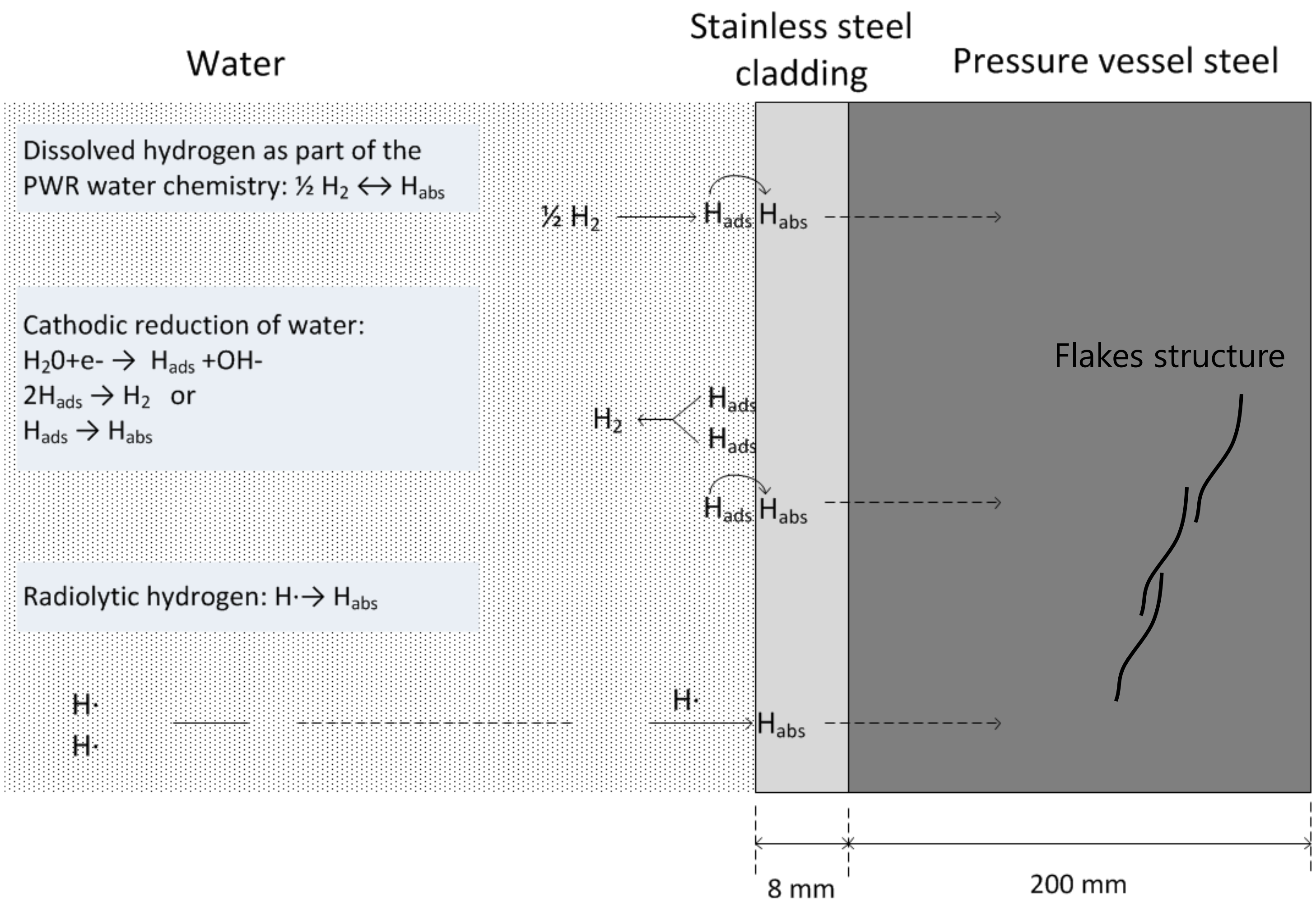
2014 UT Doel 2/Tihange2

2016 UT Doel 2

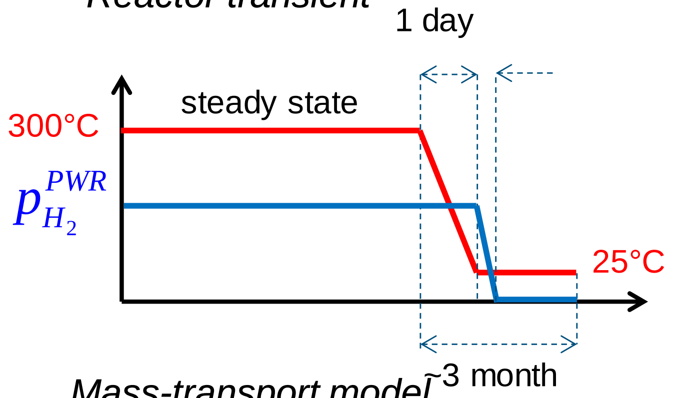
2017 UT Tihange 2

No evidences on further evolution of the defects during operation

Potential sources of hydrogen



Reactor transient



Mass-transport model

- Atomic hydrogen

$$\frac{\partial c_H(x,t)}{\partial t} = -D_H \frac{\partial^2 c_H(x,t)}{\partial x^2} - S_H^{dt}(x,t) - S_H^{ft}(x,t) - S_H^{flake}(x,t)$$

- Flat traps

$$\frac{\partial c_H^{ft}(x,t)}{\partial t} = S_H^{ft}(x,t)$$

- Deep traps

$$\frac{\partial c_H^{dt}(x,t)}{\partial t} = S_H^{dt}(x,t)$$

- Flakes

$$\frac{\partial p_{H_2}^{flake}(x,t)}{\partial t} - \frac{p_{H_2}^{flake}(x,t)}{T(t)} \frac{dT(t)}{dt} = R\,T(t) \frac{\left(k_2^{rpv} \left(c_H(x,t)\right)^2 - k_1^{rpv}\, p_{H_2}^{flake}(x,t)\right)}{2} \left(\frac{S}{V}\right)_{flake}$$

- Additional source term

$$S_H^{flake}(x,t) = \left(k_2^{rpv} \left(c_H(x,t)\right)^2 - k_1^{rpv}\, p_{H_2}^{flake}(x,t)\right) \left(\frac{S}{V}\right)_{flake} f_v^{flake}$$

Significant scatter on mass transport, adsorption/desorption rates and hydrogen trapping parameters in steels reported in literature

Assessment of hydrogen sources, mass transport and pressure build-up

- Assessment of atomic hydrogen sources:
  - Absorption
  - Radiolysis
  - Corrosion reactions
- Mass transport model of hydrogen in RPV structure
- Assessment of pressure built-up during reactor transients
- Critical evaluation of hydrogen balance during flake formation

→

Consistent explanation of formation

No driving force for flake propagation

- Experimental study in representative conditions: on hold

(Corrosion) fatigue

- Horizon 2020 INCEFA-PLUS (Increased safety in nuclear power plants covering deficiencies in the assessment of environmental fatigue) project 2015-2020
  - To address identified gaps and provide more data points on
    - Effects of surface conditions
    - Effect of hold time
    - Effects of mean stress/strain
  - Outcome
    - Protocol for Environment Assisted Fatigue testing (basis for ISO standard)
    - Modified fatigue analysis procedures (with more appropriate conservatism)
    - Fatigue curves for assessment of environmental effect on fatigue endurance (F_{en})

- Doel 1 Upper Plenum Injection line fracture examination (presentation "Doel 1&2 Upper Plenum Injection Line Issue", Michel DE SMET)

Vankeerberghen, M. et al., 2018. "Ensuring data quality for environmental fatigue – INCEFA-PLUS testing procedure and data evaluation", PVP2018-84081, Prague, Czech Republic
Bruchhausen, M., Mottershead, K., Hurley, C., Métais, T., Vankeerberghen, M., Cicero, R., Le Roux, J.C., 2017. "Establishing a multi-laboratory test plan for environmental fatigue", ASTM STP159820160047
M. Vankeerberghen, P. Marmy, L. Bens, PWR Fatigue Testing at SCK•CEN in the Framework of INCEFA+, Proceedings of the 7th International Conference on Fracture Fatigue and Wear, FFW 2018, Ghent, Springer

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