REDUCTION OF RADIOLOGICAL ACCIDENT CONSEQUENCES

Title:	Main issues and model improvement related to defective fuel rod behaviour
Speaker:	C. Leclere
Affiliation:	IRSN
Event:	Open Workshop
When:	November 30th 2023
Where:	IRSN Headquarters

Commission européenne

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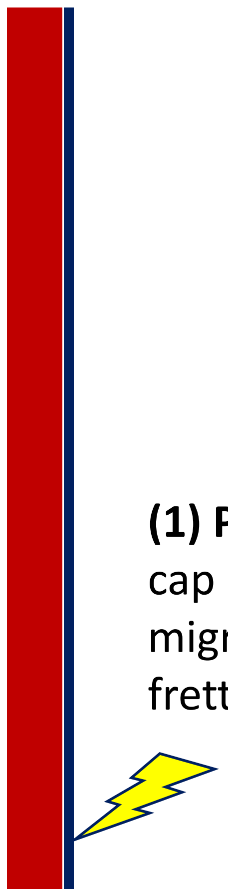
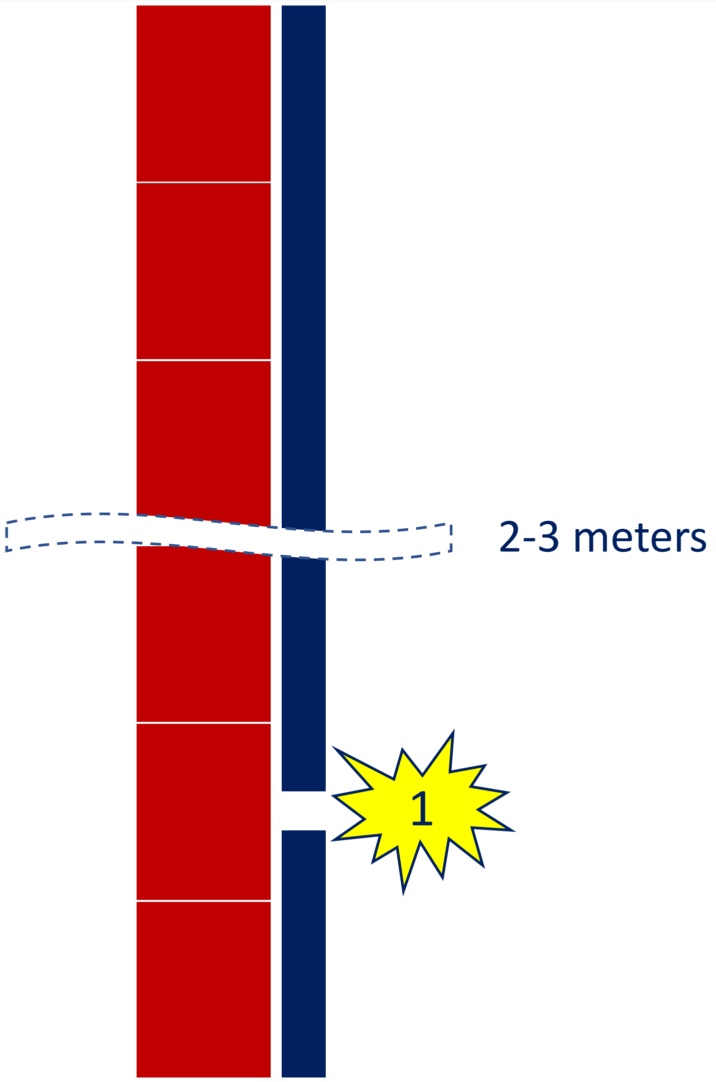
Secondary hydriding phenomena

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS



(1) Primary defect:
cap welding defects,
migrating debris
fretting w/ springs



Secondary hydriding phenomena

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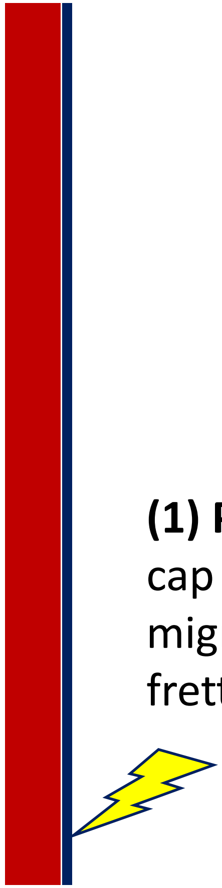

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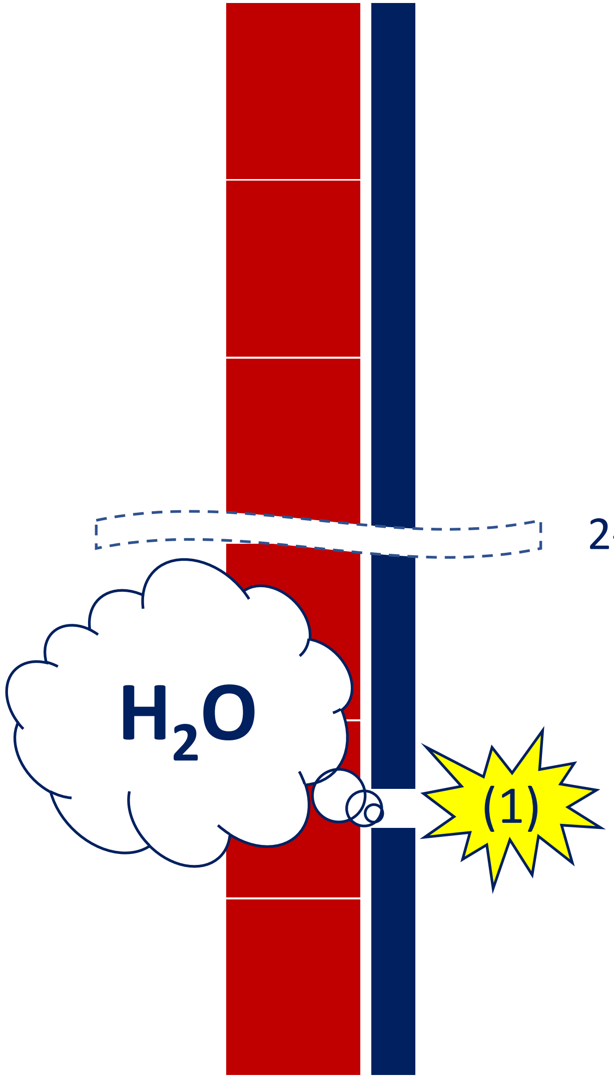

2-3 meters

defective fuel rod
water ingress

Secondary hydriding phenomena

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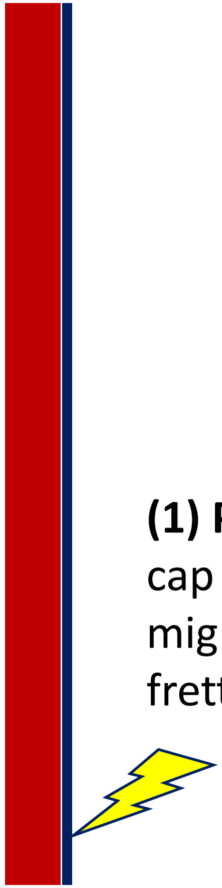

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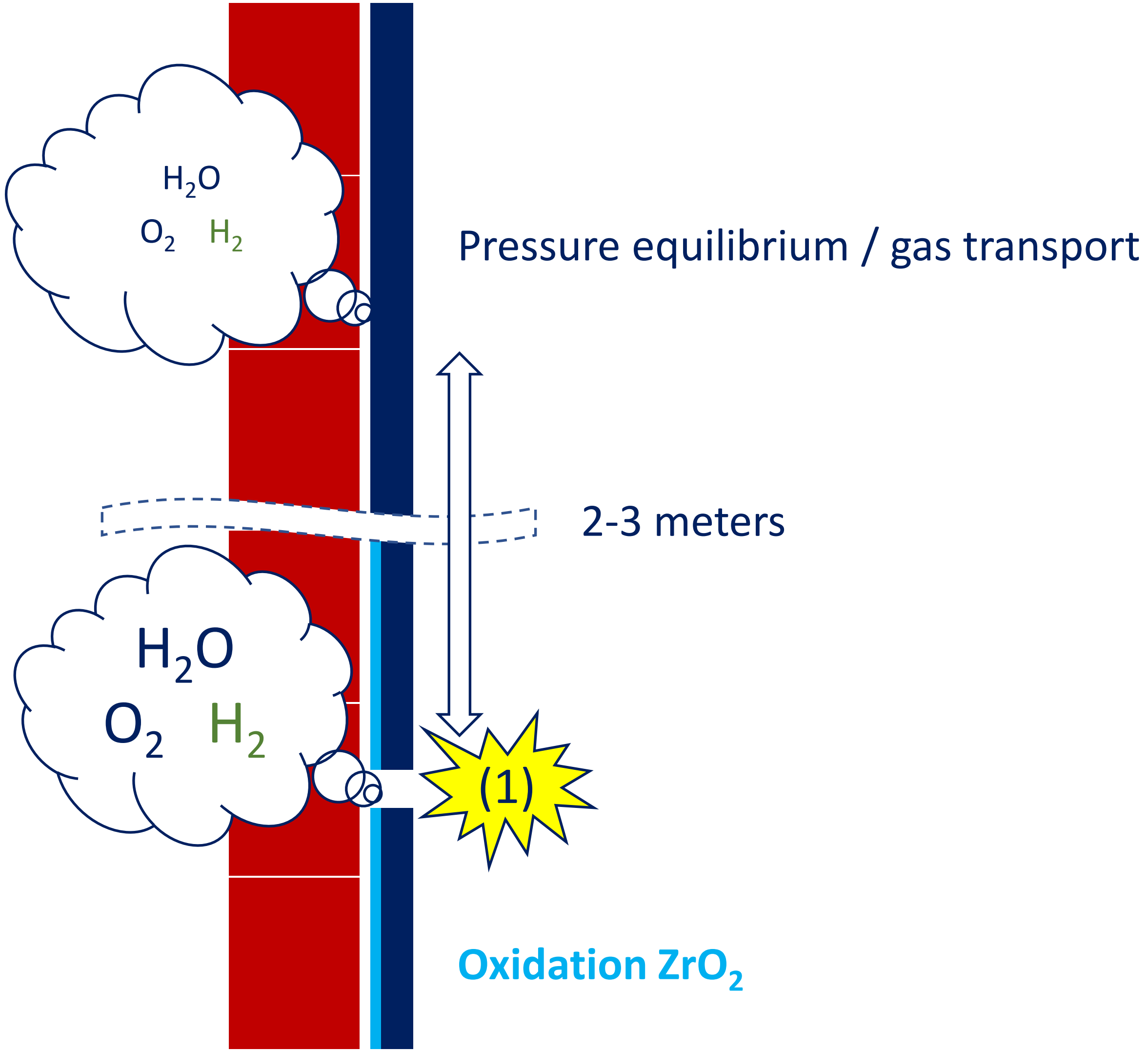

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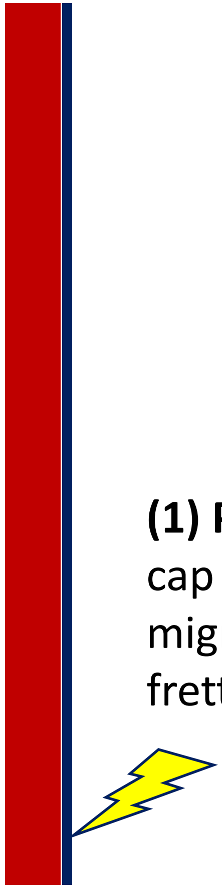

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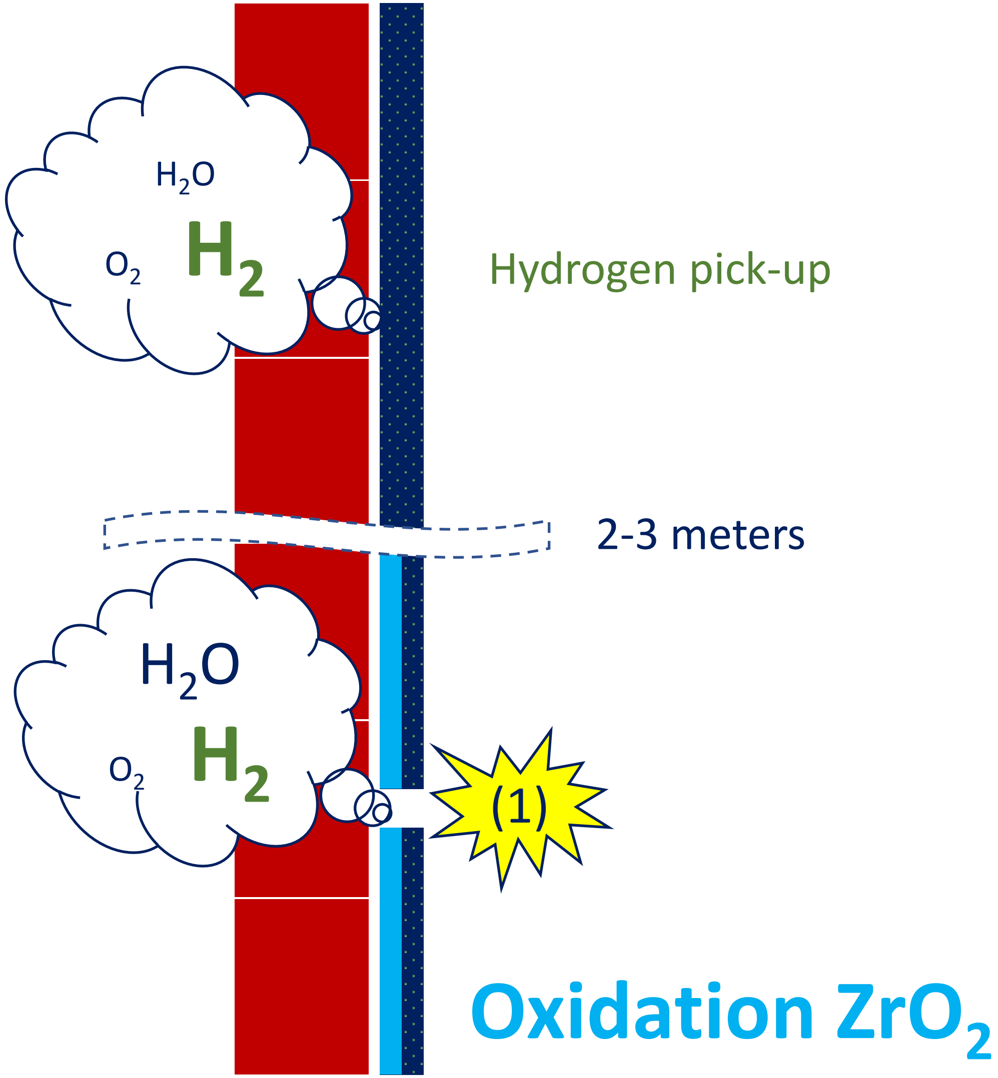

Secondary hydriding phenomena

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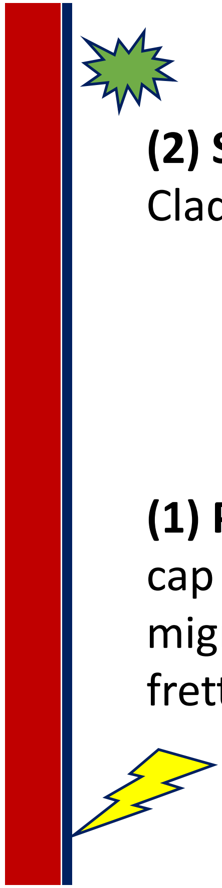
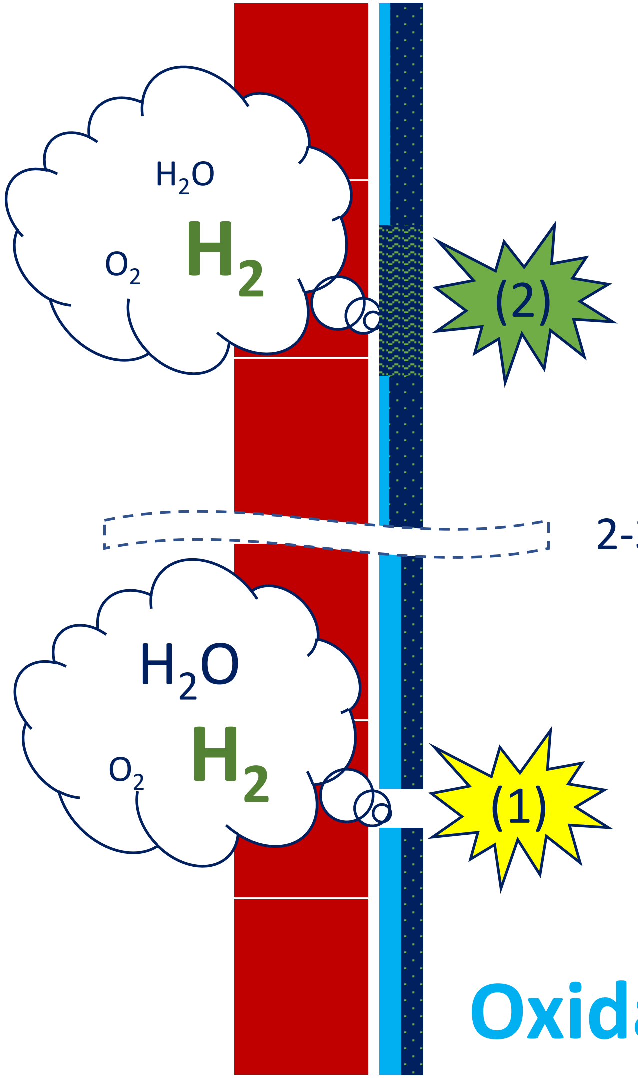


(2) Secondary defect:
Clad Embrittlement

(1) Primary defect:
cap welding defects,
migrating debris
fretting w/ springs



Steam starvation condition critical (pH2/pH2O>>1)

Massive Hydriding

Hydrides sunburst

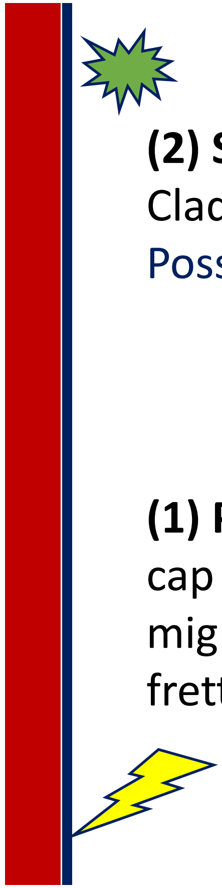
- blisters

2-3 meters

Oxidation ZrO_2

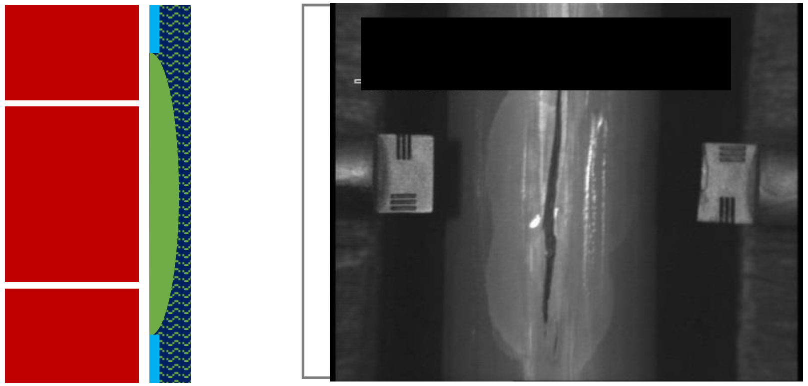
Secondary hydriding phenomena

REDUCTION OF RADIOLOGICAL CONSEQUENCES
OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

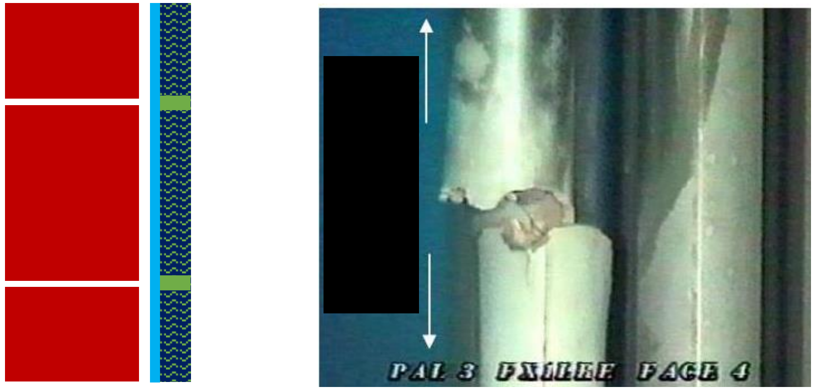


(2) Secondary defect:
Clad Embrittlement
Possible failure

(1) Primary defect:
cap welding defects,
migrating debris
fretting w/ springs



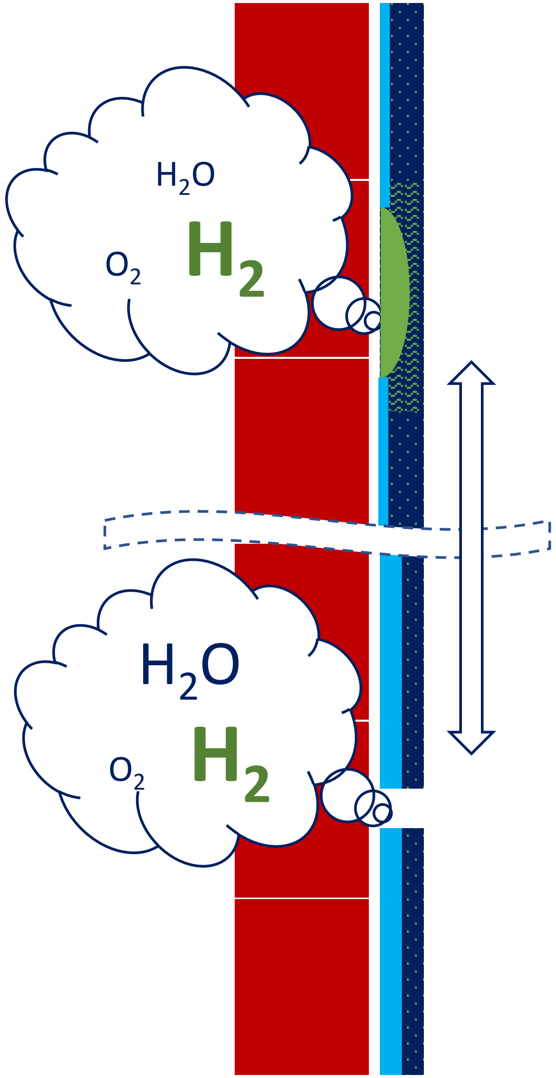
Axial crack due to hydride blister



Inter-pellet « Guillotine » rupture

Secondary hydriding phenomena

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS



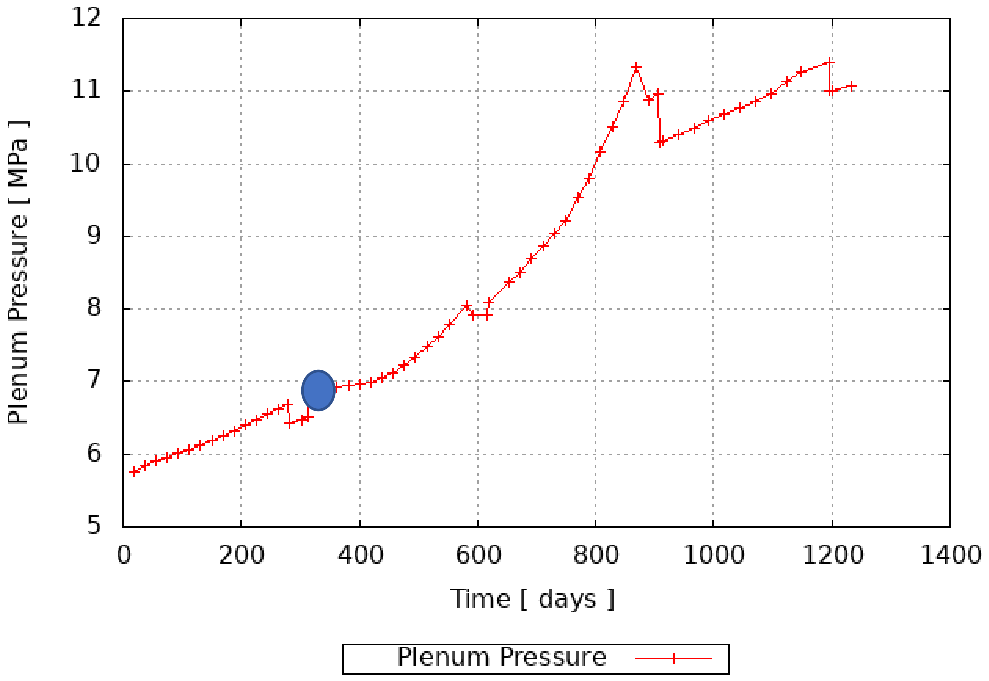
Numerous physical mechanism involved:

- Gas transport in the gap / porous media
- Clad Internal Oxidation
- Hydrogen pick up / steam starvation
- Hydrogen diffusion / precipitation
- Mechanical embrittlement

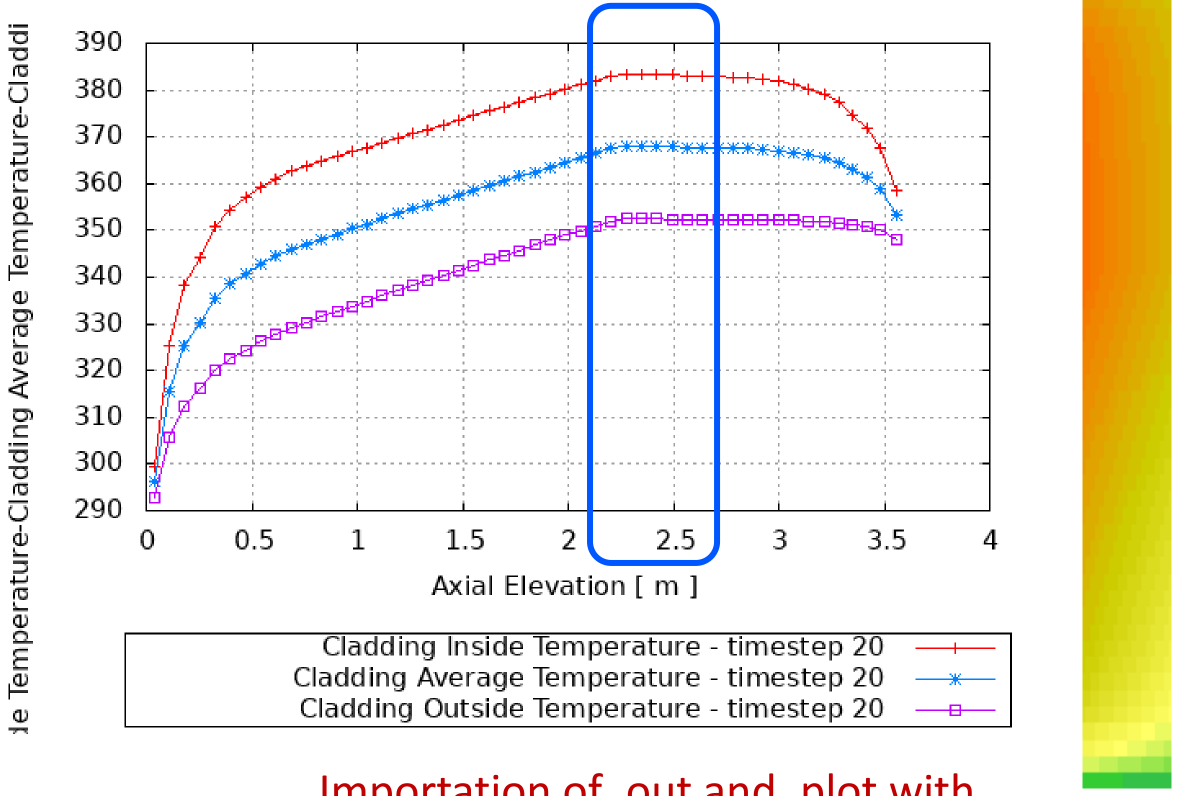
Pre-irradiation scenario

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

IRSN reference case: mixed UO2/MOX core, MOX fuel rod, beginning of cycle 2



Secondary hydriding region:
T_int. 380°C ; T_ext. 350°C



Importation of .out and .plot with MODULE IRRADIAT in SHOWBIZ

Water ingress and gas distribution

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

CHANNEL module in SHOWBIZ model

Gas transport in free volumes modelling

$$\frac{\partial c_i}{\partial t} = \nabla.(D_i \nabla c_i) - \nabla.(\boldsymbol{v} c_i) + Q_i(t))$$

Mass conservation

$$\frac{d}{dt} n^i_{H2O} = \frac{n^i_{H2O}(t+dt) - n^i_{H2O}(t)}{\Delta t} = F^{i-1}_{H2O} - F^i_{H2O} - F^i_{ox} + F^{i_h}_{H2O}$$

$$\frac{d}{dt} n^i_{H2} = \frac{n^i_{H2}(t+dt) - n^i_{H2}(t)}{\Delta t} = F^{i-1}_{H2} - F^i_{H2} + (1-\epsilon) F^i_{ox} - F^i_{pickup(H2)} - F^i_{hy}$$

Inlet steam flow

$$v = \frac{k^{i_h}}{\eta} \frac{(P_{ext} - P^{i_h})}{r_c^{i_h}}$$

Inter-diffusion

$$F^i_l = \frac{2\, S^i}{\frac{\Delta Z^{i+1}}{D^{i+1}_l} + \frac{\Delta Z^i}{D^i_l}} \left(\frac{P^{i+1}_l}{P^{i+1}} - \frac{P^i_l}{P^i} \right)$$

Darcy law

$$v^i = \frac{P^i - P^{i+1}}{R_h} \qquad R_h = \frac{R^i_h}{2} + \frac{R^{i+1}_h}{2} = \frac{R^i_h + R^{i+1}_h}{2} = \frac{1}{2}\left(\frac{\eta^i}{k^i} \Delta Z^i + \frac{\eta^{i+1}}{k^{i+1}} \Delta Z^{i+1} \right)$$

Rh global friction deduced from i/i+1 k permeability, eta viscosity

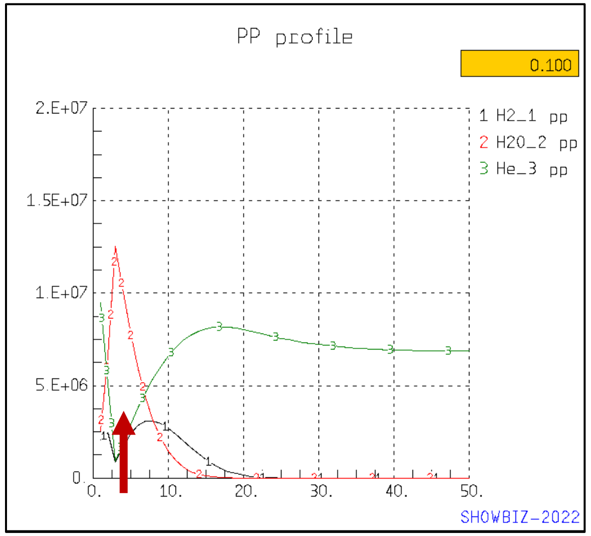
Water ingress and gas distribution

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

First seconds after the primary defect occurence: water ingress

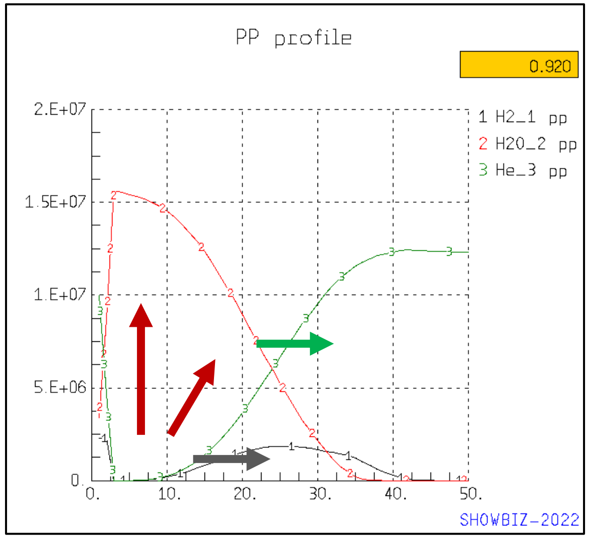
Driving force: pressure difference

Vapor partial pressure / h2 partial pressure / He+others partial pressure



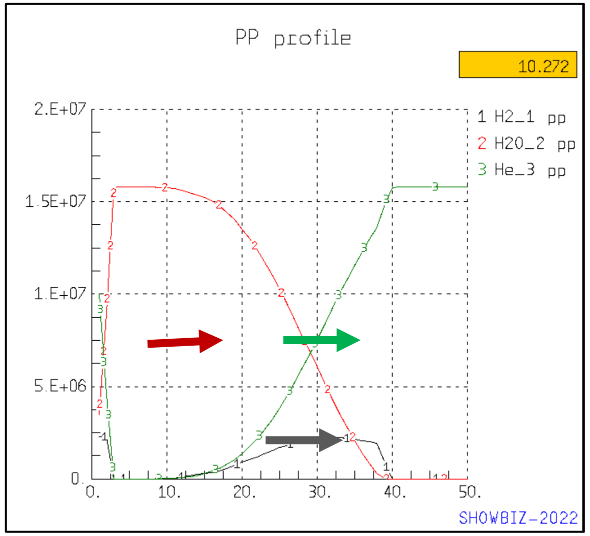
0.1s

- Water peak pressure at the altitude of PD (0.2m)
- Immediate oxidation and H2 release



1s

- Water continue to enter and fill the free volumes
- H2 and He are pushed higher in the rod



10s

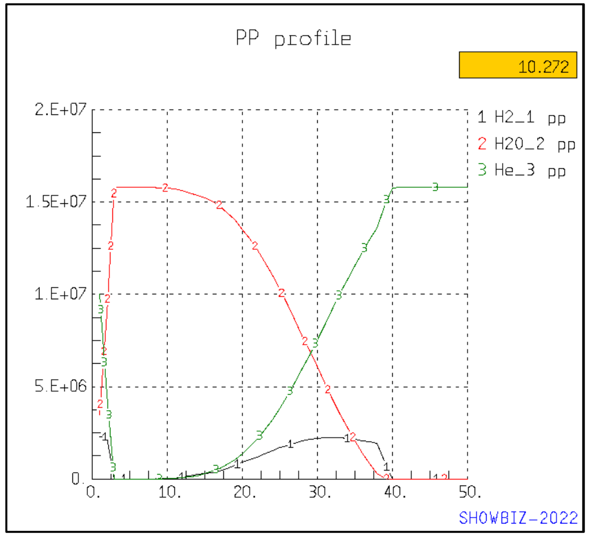
- Pressure equilibrium is reached with coolant

Water ingress and gas distribution

REDUCTION OF RADIOLOGICAL CONSEQUENCES
OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

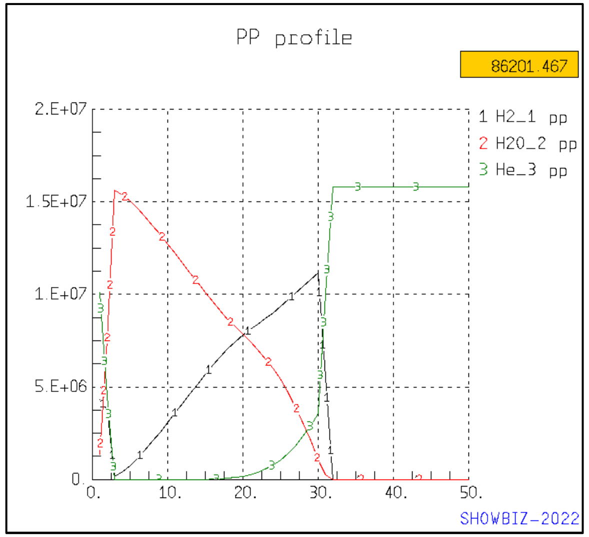
Days after the primary defect occurence: internal oxidation, H2 fillin and massive hydriding

Vapor partial pressure / h2 partial pressure / He+others partial pressure



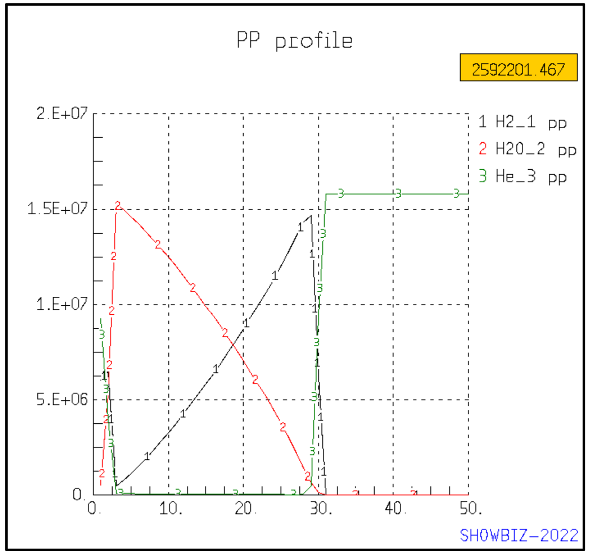
0.001 day

- Oxidation produce H2
- Total pressure decrease
- New entry of water
- H2 pushed higher



1 day

- Rich H2 atmosphere at mesh 30 ie 2,5m from the bottom
- Massive hydriding conditions
- « Secondary hydriding »



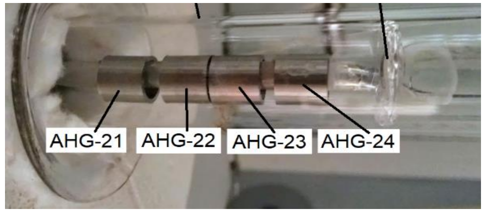
30 days

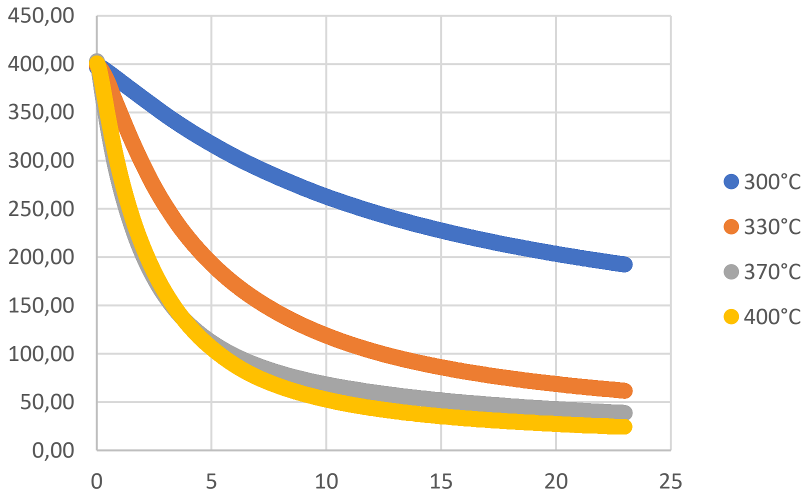
- The partial pressure profile is almost conserved
- Hydriding continue

H2 uptake model

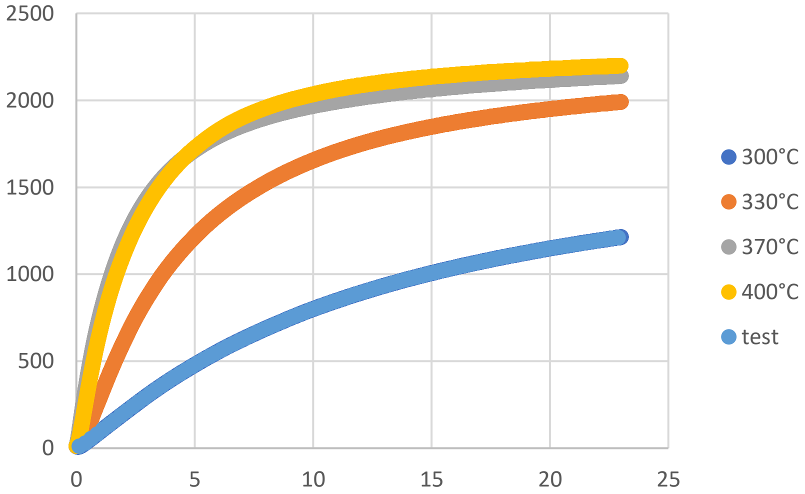
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

MTA-EK experimental data of H2 uptake on Zircaloy-4





H2 pressure drop (mbar)



H content calculation (wppm)

nH2 (mol) from pressure / volume of the chamber
H content from the mass measurement of the 4 samples

Exemple **1213 wppm** for Zry4_300_13_16 experiement

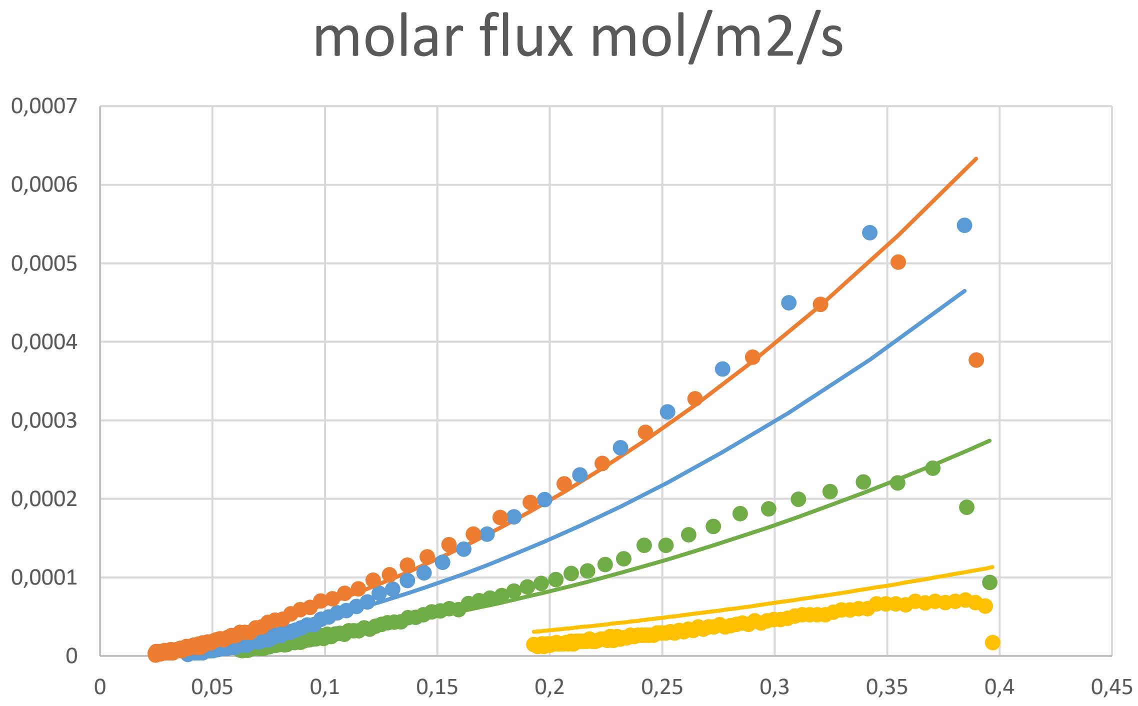
avg. absorbed H (ppm)		**1203**
mass gain (ppm)	ZryH-13	1333
	ZryH-14	1474
	ZryH-15	1047
	ZryH-16	934

H2 uptake model

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

IRSN proposed correlation for H uptake rate:

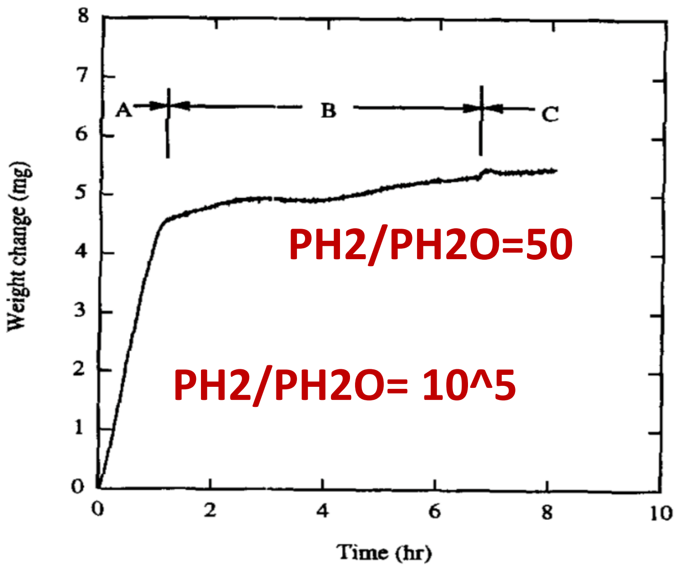
$(aT+b).PH_2 + (cT+d).PH_2^2$



+ condition on H2/H2O pp ratio

$$\beta_{critical} = \left({P_{H_2}}/{P_{H_2O}} \right)_{critical}$$

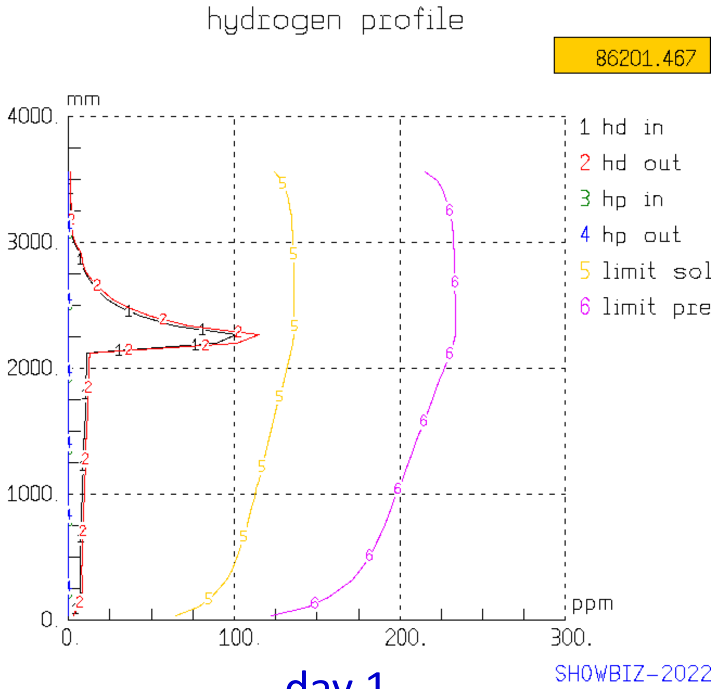
IF $(PH_2./PH_2O)<\beta$ THEN RATE=0



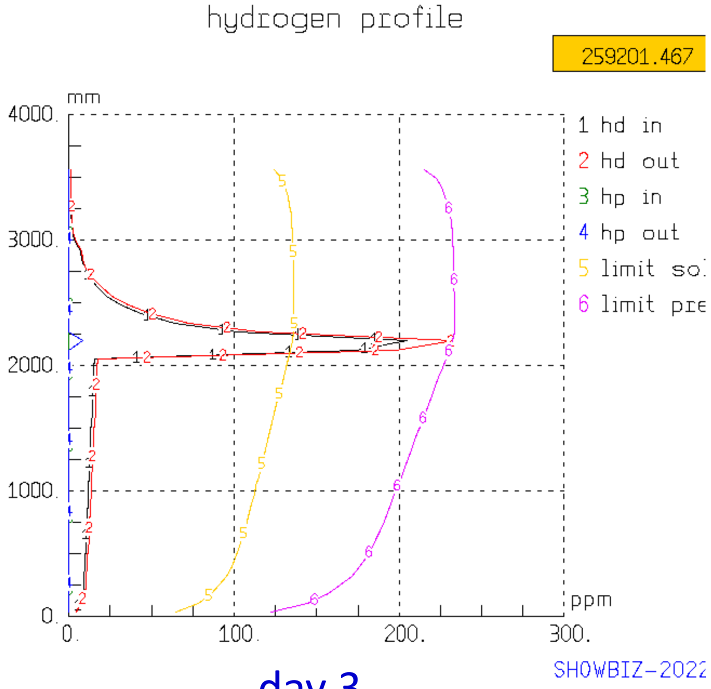
Secondary hydriding results

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

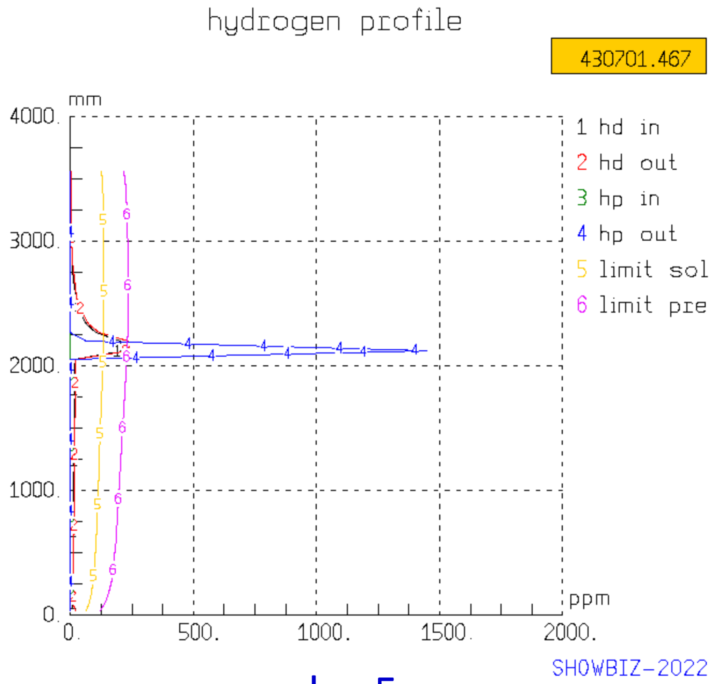
SHOWBIZ calculations



day 1
[H]=100 wppm



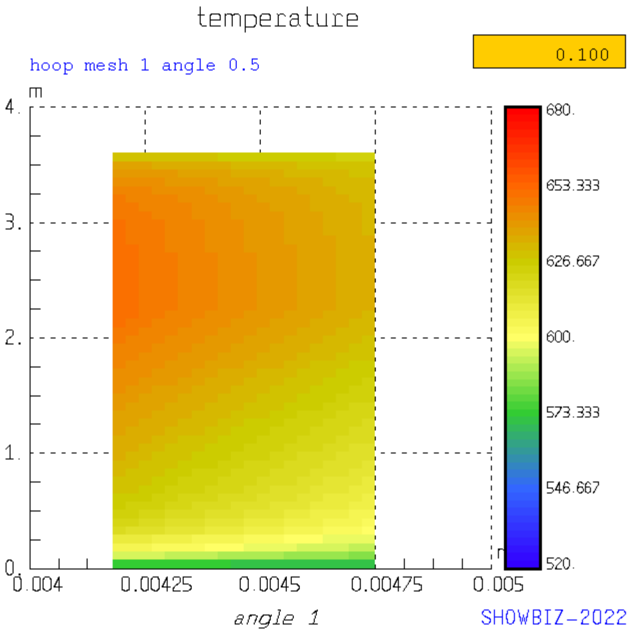
day 3
[H]=250 wppm
Terminal Solid Solubility at precipitation (TSSp) reached at external side -> hydrides formation

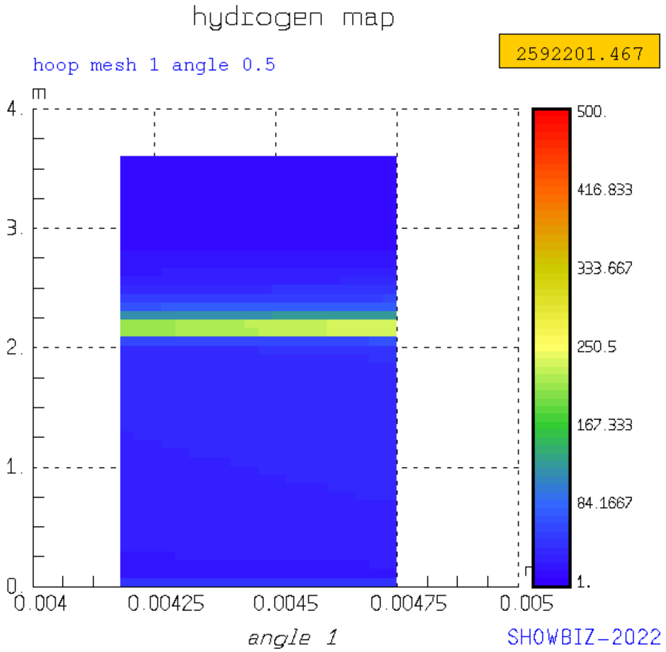


day 5
[H]=1500 wppm (External side)
…
day 10 4500wppm
day 30 12000wppm

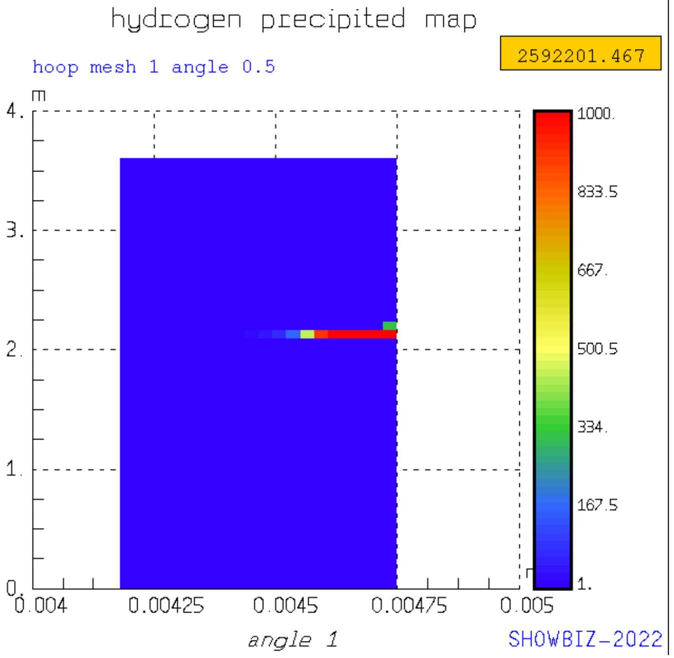
Secondary hydriding results

SHOWBIZ calculations





Hydrogen in solid solution



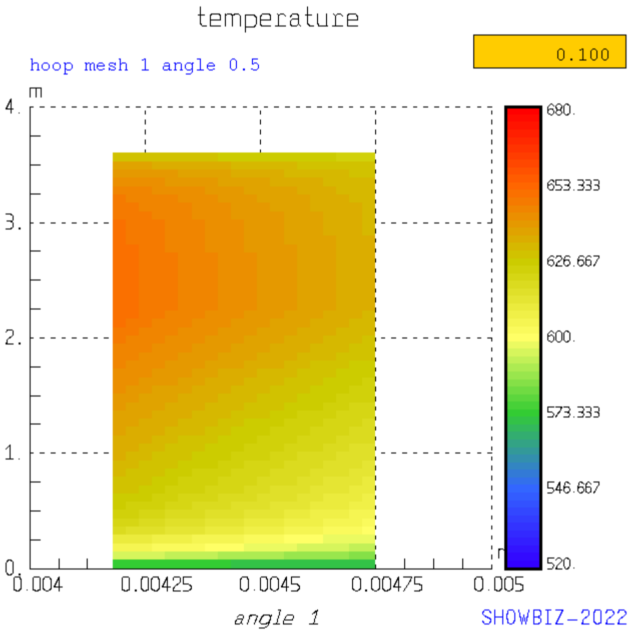
Precipited hydrides

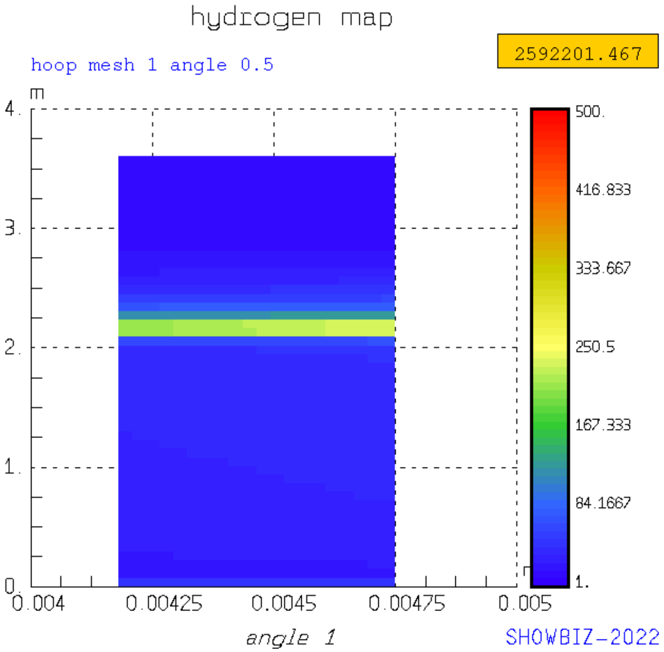
Secondary hydriding results

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

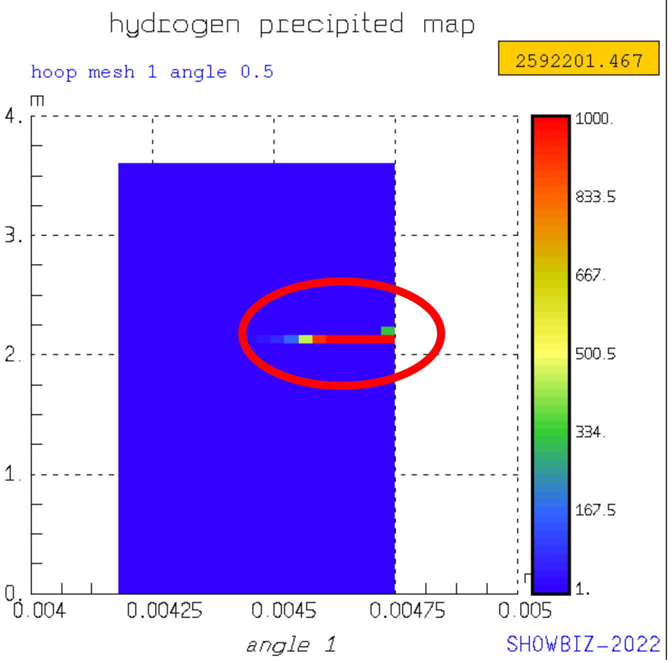
SHOWBIZ calculations

« blister »





Hydrogen in solid solution



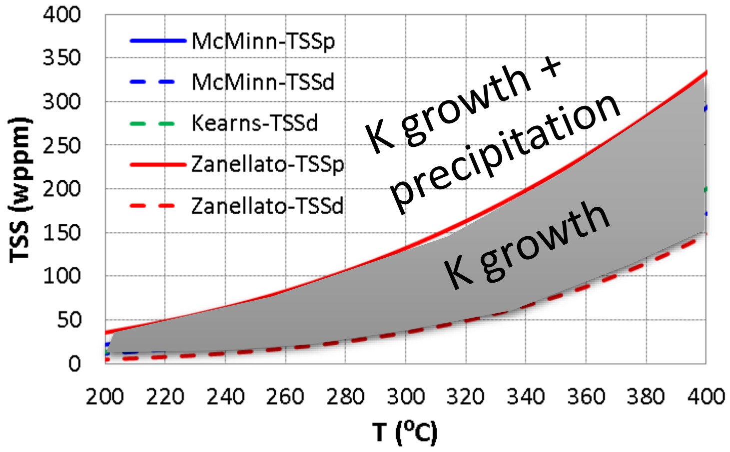
Precipited hydrides

Blister formation: H precipitation model

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

During R2CA project CIEMAT in-clad hydrogen model (coupled with FRAPCON) was adapted, enhanced and verified. Implementation based on the HNGD model

$$\frac{dH_p}{dt} = \begin{cases} k_p \cdot (H_d - TSS_p) \; if \; H_d > TSS_p \\ 0 \; if \; TSS_p \geq H_d > TSS_d \\ k_d \cdot (H_d - TSS_d) \; if \; H_d \leq TSS_d \; and \; H_p > 0 \\ 0 \; if \; H_d \leq TSS_d \; and \; H_p = 0 \end{cases}$$

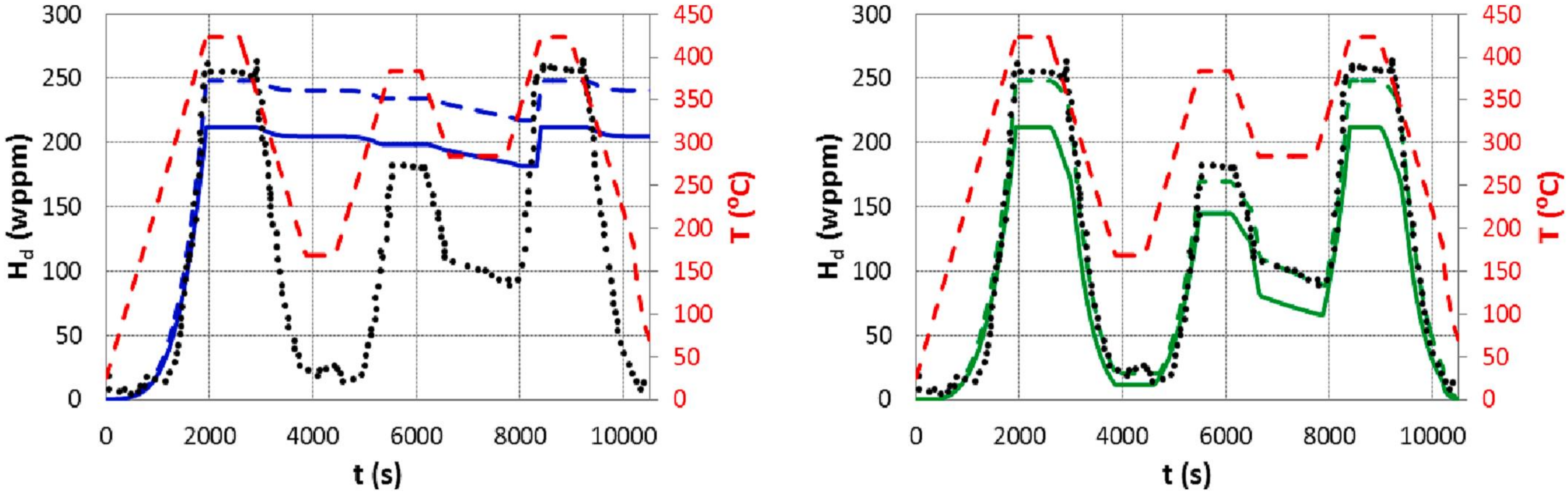


$$\frac{dH_p}{dt} = \begin{cases} k_N \cdot (H_d - TSS_p) + k_G \cdot (H - TSS_d) \cdot p \cdot (1-x) \cdot (-ln(1-x))^{1-1/p} \; if \; H_d > TSS_p \\ k_G \cdot (H - TSS_d) \cdot p \cdot (1-x) \cdot (-ln(1-x))^{1-1/p} if TSS_p \geq H_d > TSS_d \\ k_D \cdot (H_d - TSS_d) \; if \; H_d \leq TSS_d \; and \; H_p > 0 \\ 0 if H_d \leq TSS_d \; and \; H_p = 0 \end{cases}$$

Blister formation: H precipitation model

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

HNGD model very important for 150-200wppm H content and 200-400°C temperature range



Blister formation: H precipitation model

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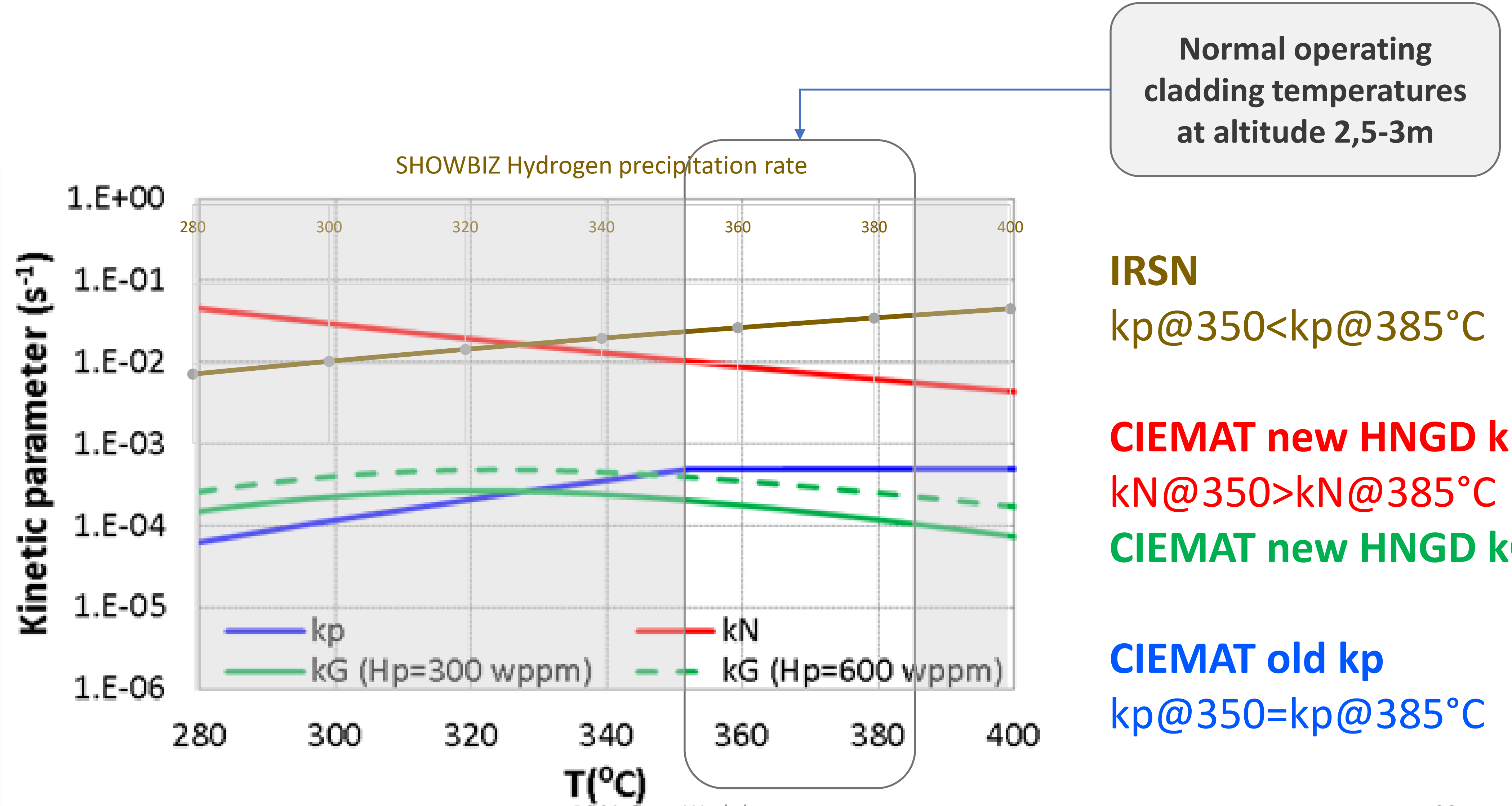


IRSN

kp@350<kp@385°C

CIEMAT new HNGD kN

kN@350>kN@385°C

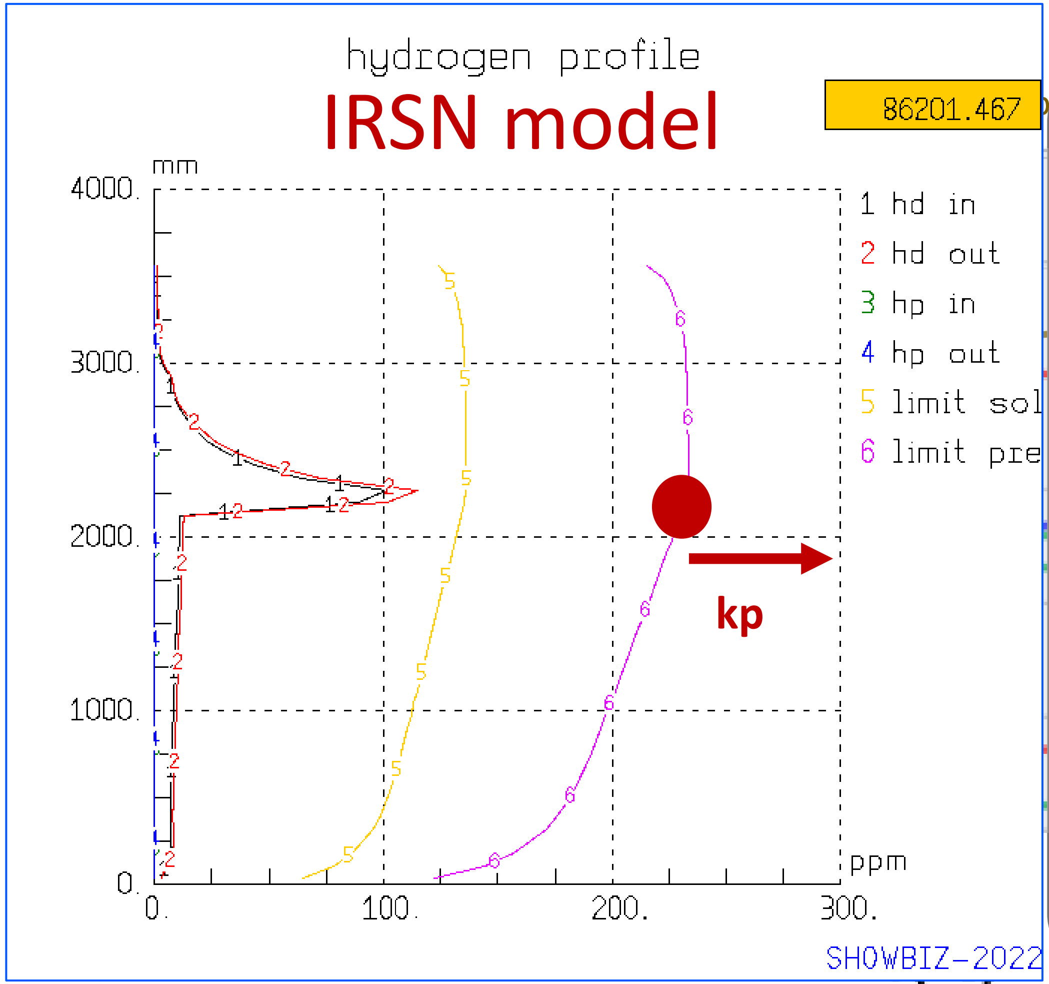
CIEMAT new HNGD kG

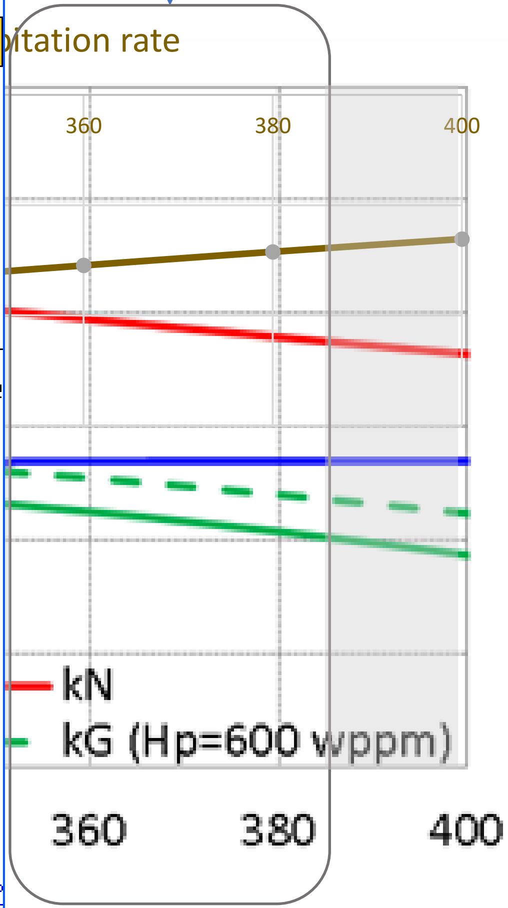
CIEMAT old kp

kp@350=kp@385°C

Blister formation: H precipitation model

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS





Normal operating cladding temperatures at altitude 2,5-3m

IRSN
kp@350<kp@385°C

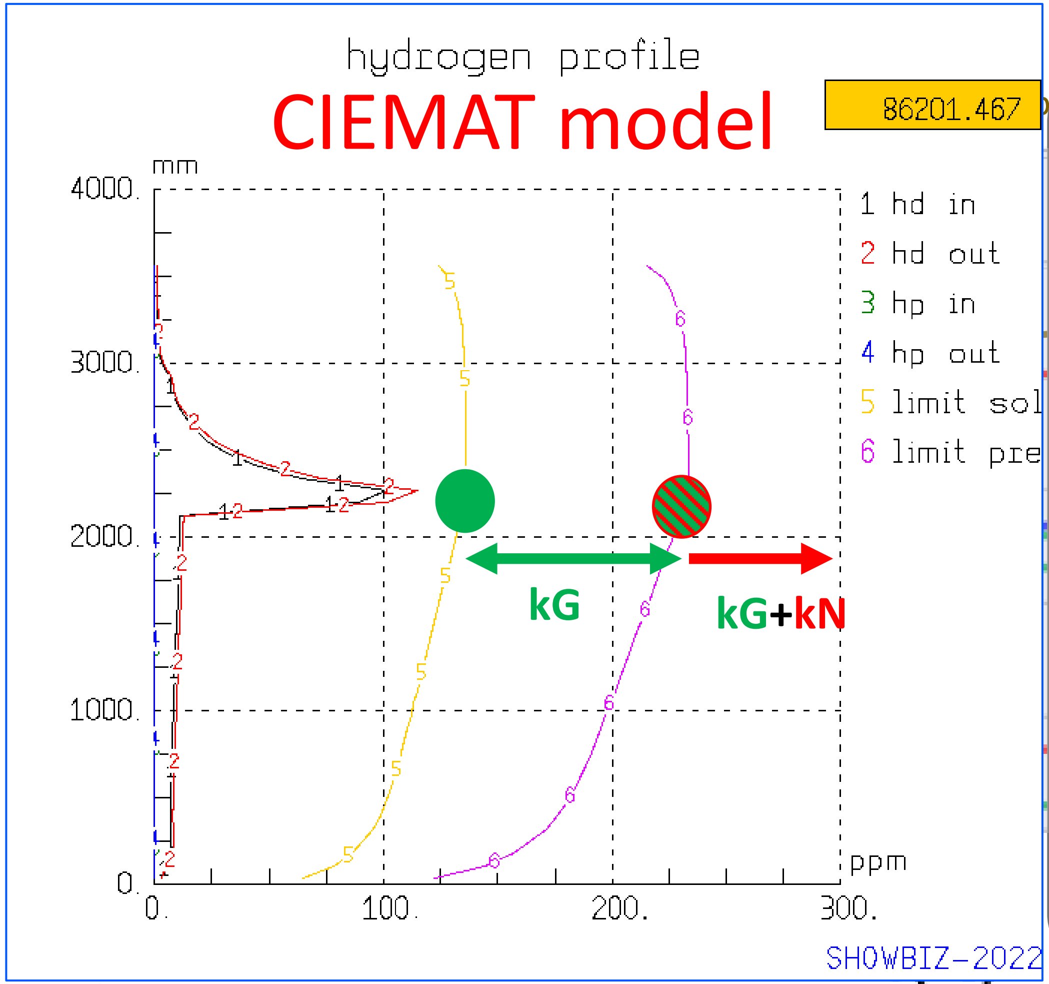
CIEMAT new HNGD kN
kN@350>kN@385°C

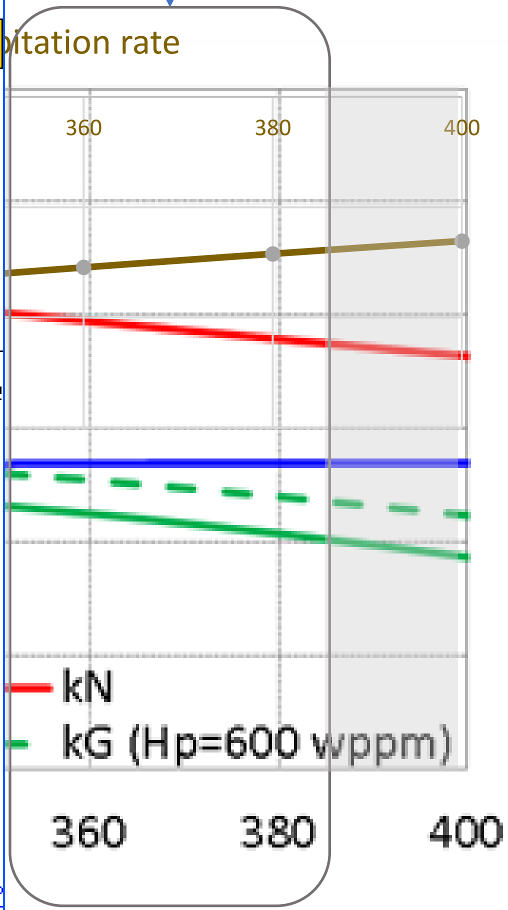
CIEMAT new HNGD kG

CIEMAT old kp
kp@350=kp@385°C

Blister formation: H precipitation model

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS





Normal operating cladding temperatures at altitude 2,5-3m

IRSN

kp@350<kp@385°C

CIEMAT new HNGD kN

kN@350>kN@385°C

CIEMAT new HNGD kG

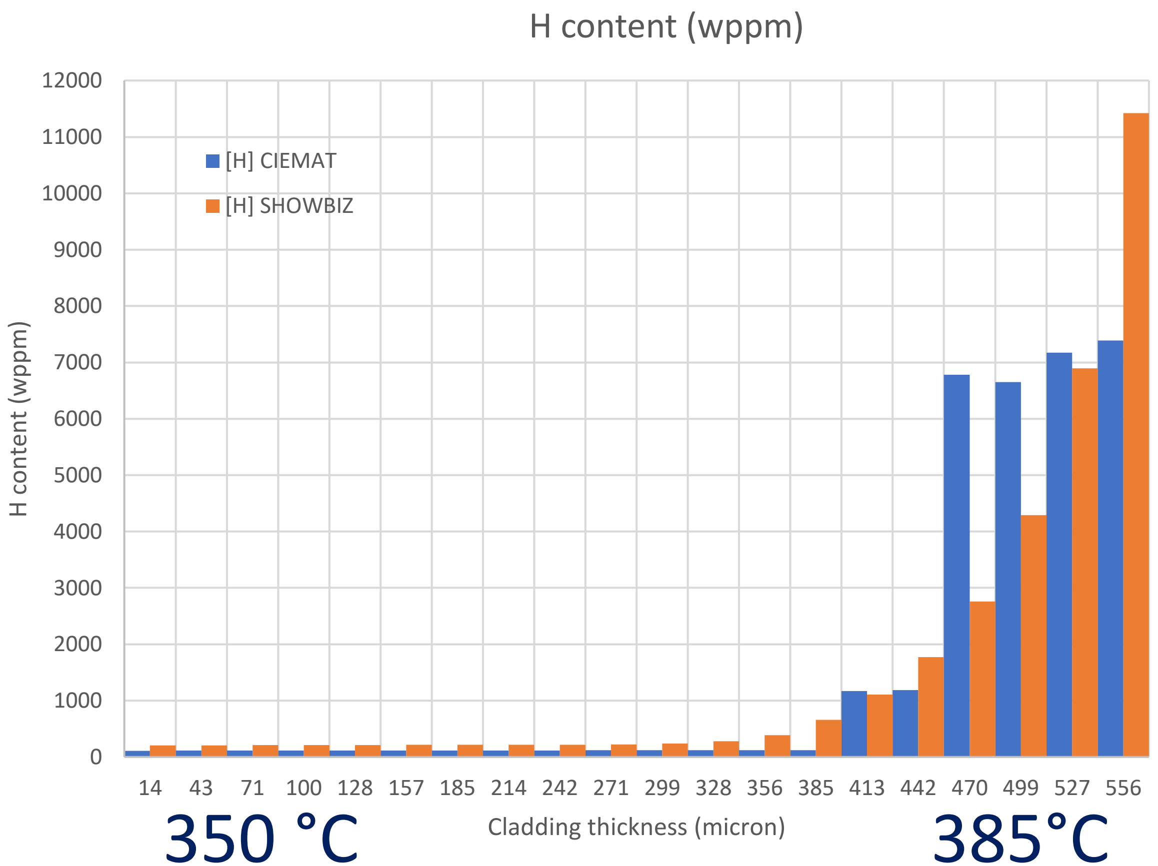
CIEMAT old kp

kp@350=kp@385°C

Blister formation: H precipitation model

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Comparison between CIEMAT / IRSN model: goal = thickness of the blister?



350 °C — 385°C

IRSN

kp@350**<**kp@385°C

CIEMAT new HNGD kN

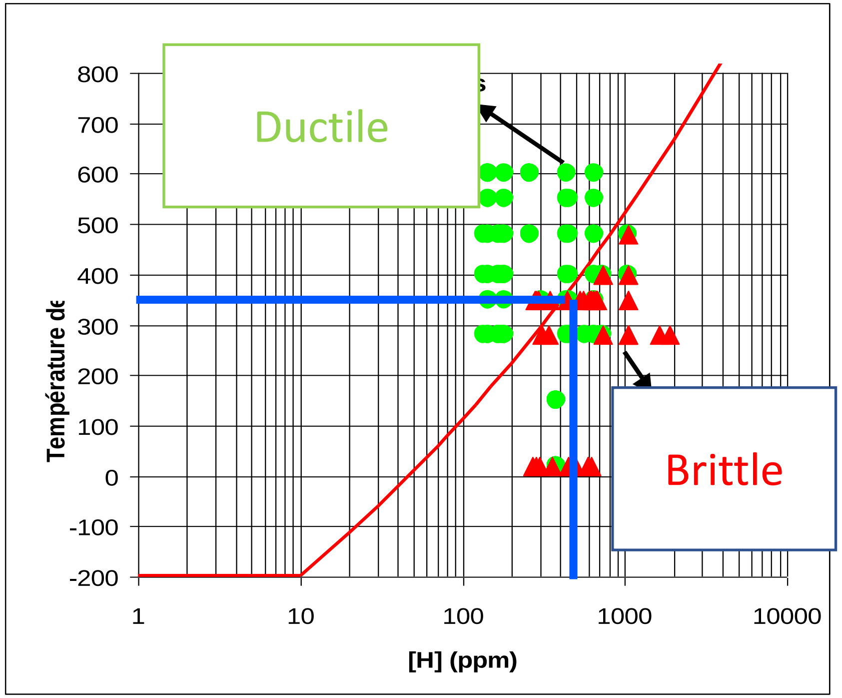
kN@350**>**kN@385°C

Towards a failure criteria

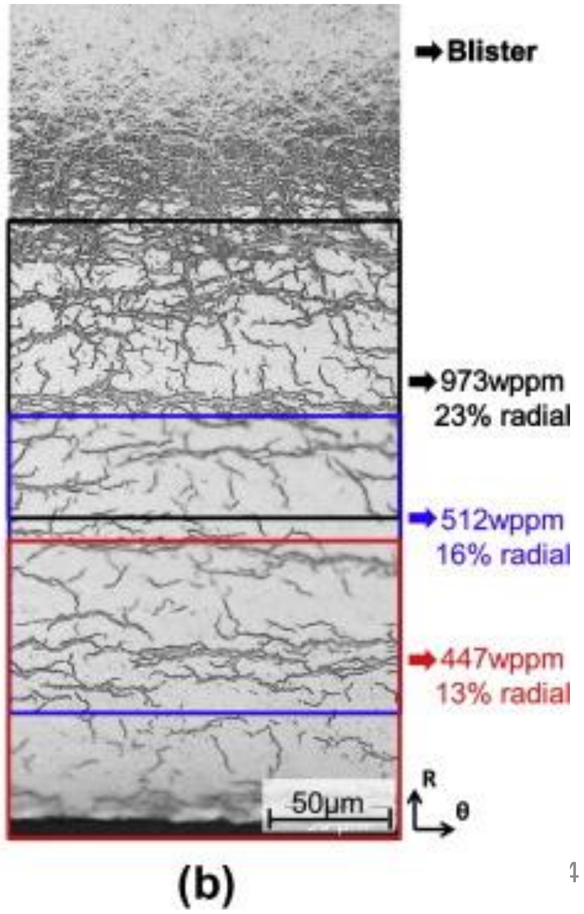
REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Blister thickness based on [H] content threshold

« Blister » can be considered above 500-1000wppm, here 20-30% of the cladding



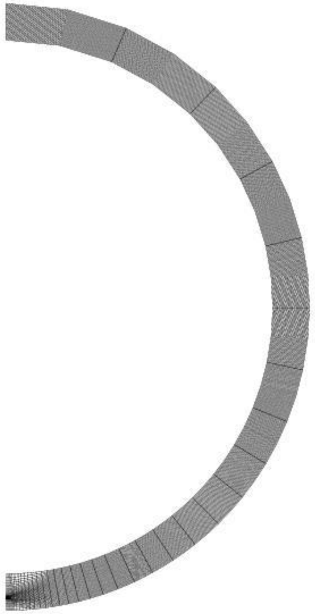
Brittle region

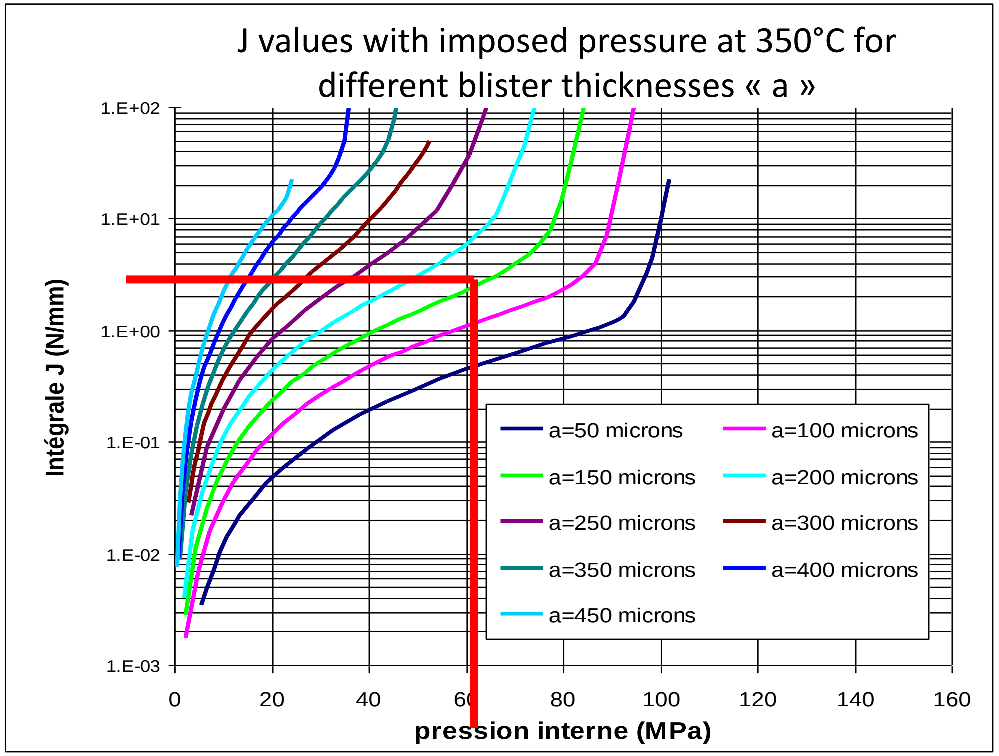


Pure massive hydride blister is 17000wppm but the sunburst region with radial hydrides have also to be taken into account

Towards a failure criteria

Does the remaining sound clad will crack with SGTR depressurisation?





Linear Elastic Fracture Mechanical theory:

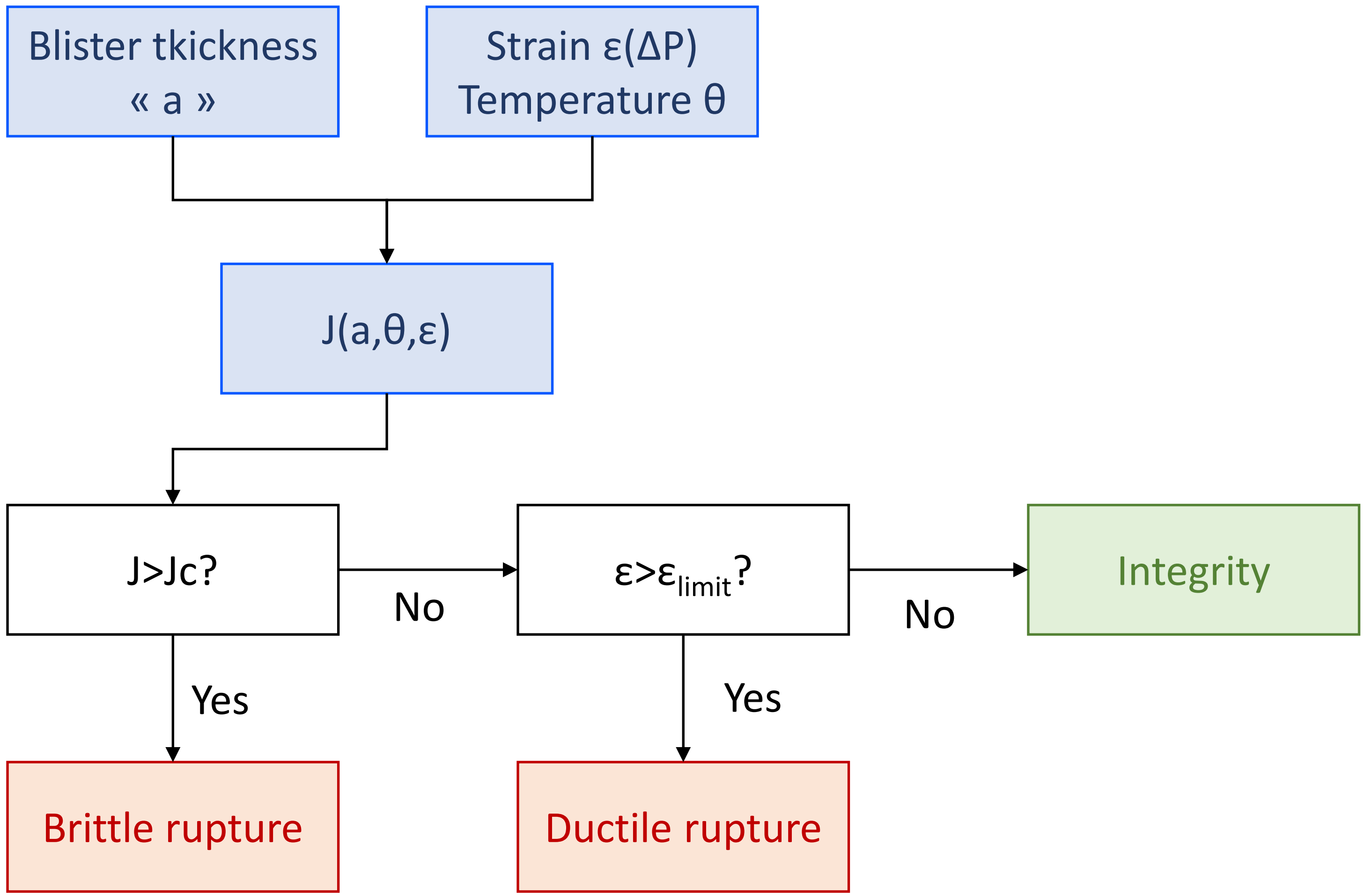
- Integral J evaluation with FEM calculation
- Comparison with toughness of the material

$$K_I = \sqrt{\frac{EJ}{1-\nu^2}}$$

Blister max 150micron
RLCP deltaP=70bar

Towards a failure criteria

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS



Conclusion

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- **First simulation of secondary hydriding from water ingress to blister formation**
  - Validation of the scenario with identified mechanism
  - Reproduction of representative altitude of secondary hydriding

- Uncertainties remains on:
  - Axial gas transport
  - Oxidation cinetic in vapor phase at low temperature with presence of H
  - Hydriding cinetic with presence of oxygen

- Comparison of H redistribution models planned
- Failure criteria based on fracture mechanical theory can be applied
  - Implementation in SHOWBIZ software envisaged at IRSN

- Full release of fission gas with primary defect too concervative (gas pushed higher in clad)
- Secondary defect can be « through wall » without SGTR
- SGTR depressurisation not instantaneous

Thanks for your attention!

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