Measurement and Modeling of the Hydrogen Distribution in Nuclear Fuel Claddings after Loss of Coolant Accidents

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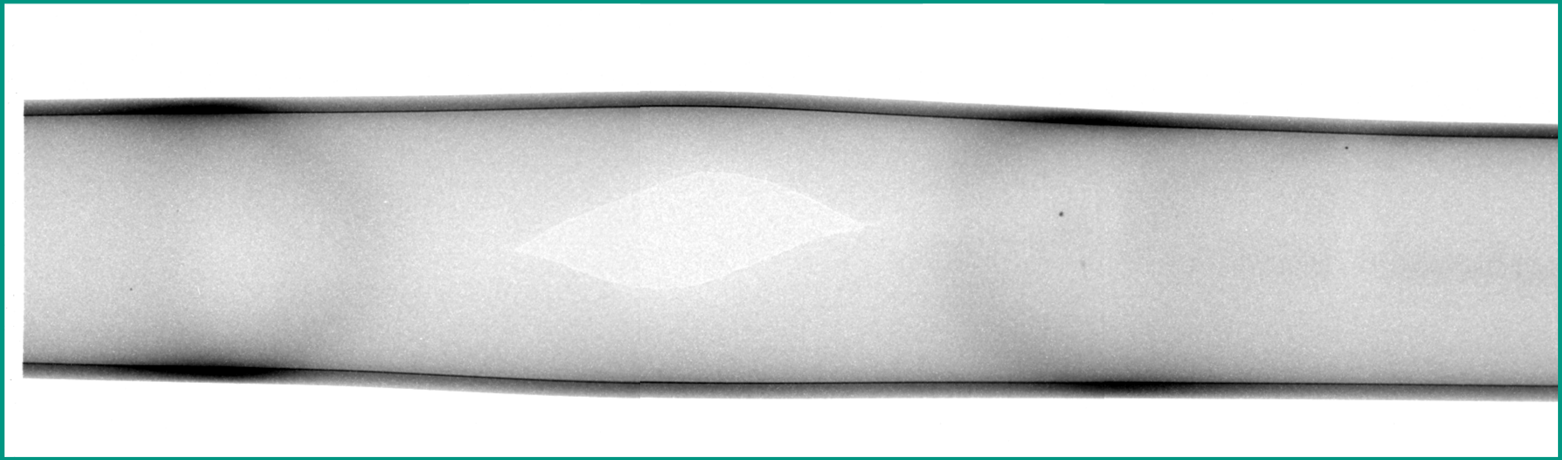
KIT / Institute for Applied Materials / Program NUKLEAR

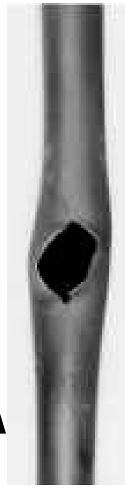
Paul Scherrer Institute Villigen



Outline

- Introduction
  - Processes occuring during loss of coolant nuclear accidents
  - QUENCH-LOCA tests
- Neutron radiography investigations
- Hydrogen distribution in QUENCH-LOCA claddings
- Ab-initio modelling to understand the hydrogen distribution
- Conclusions

Processes occurring during LOCA



Oxidation

$Zr + 2H_2O = ZrO_2 + 2H_2$

Secondary hydrogenation

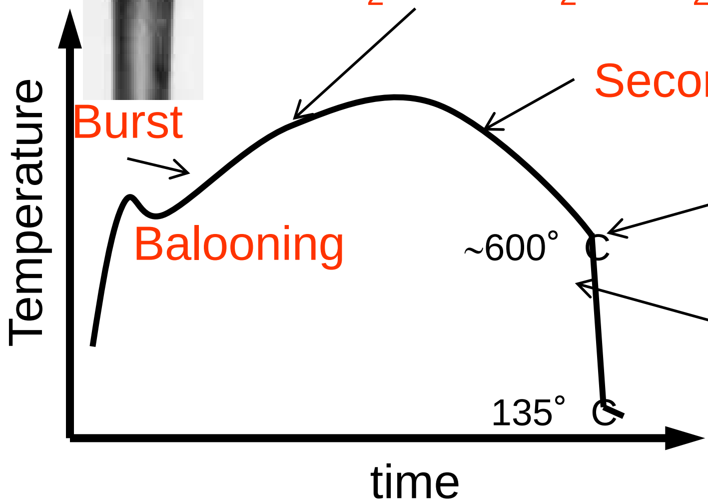
Thermo-shock - Quenching

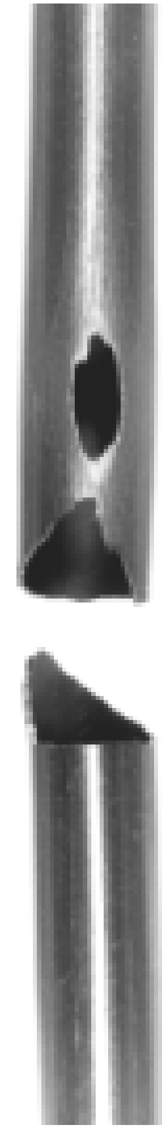
Fragmentation and fuel relocation

coolability???

Burst

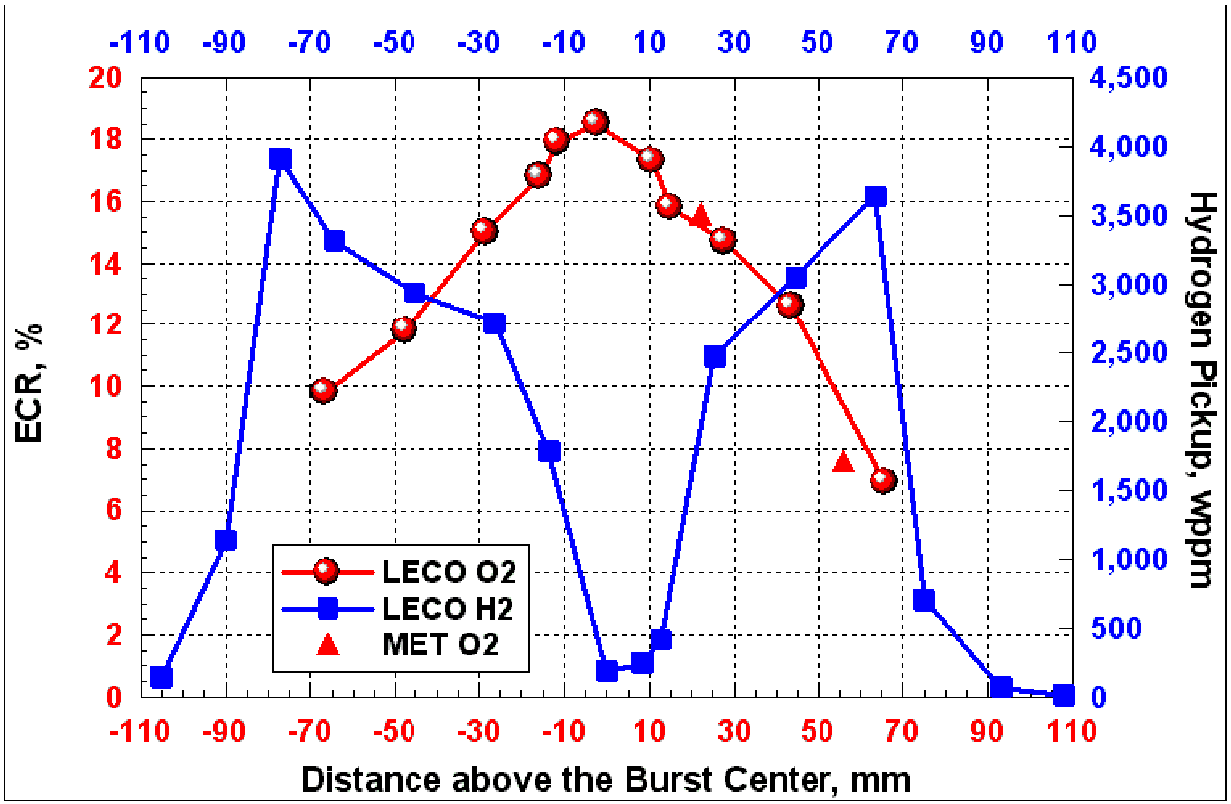
Balooning





Time dependence of the cladding temperature during a loss of coolant accident

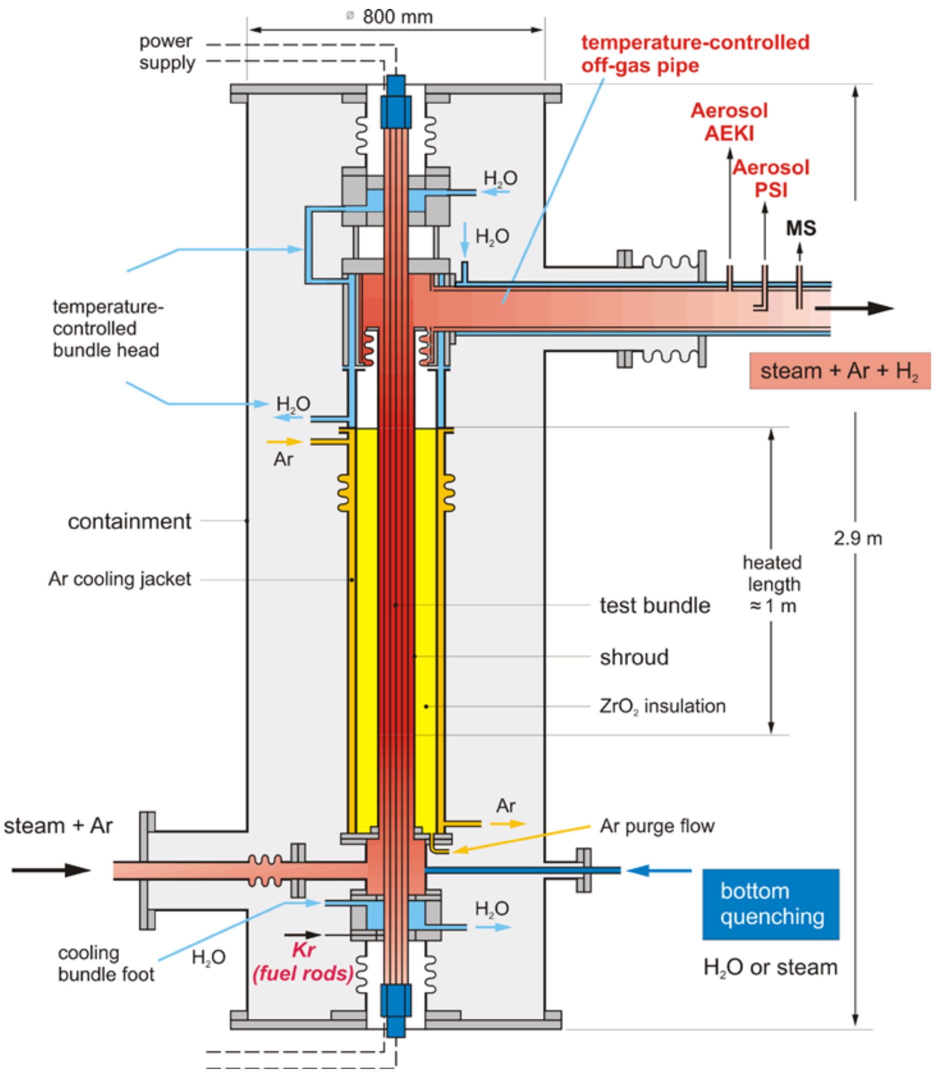
Processes occurring during LOCA



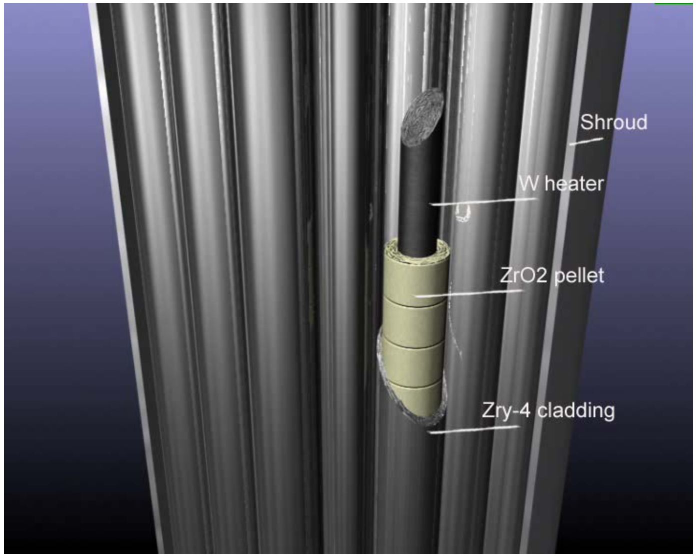
Influence on mechanical propoerties?

M. Billone et al.
NUREG/CR-6967/ANL-07/04

Introduction



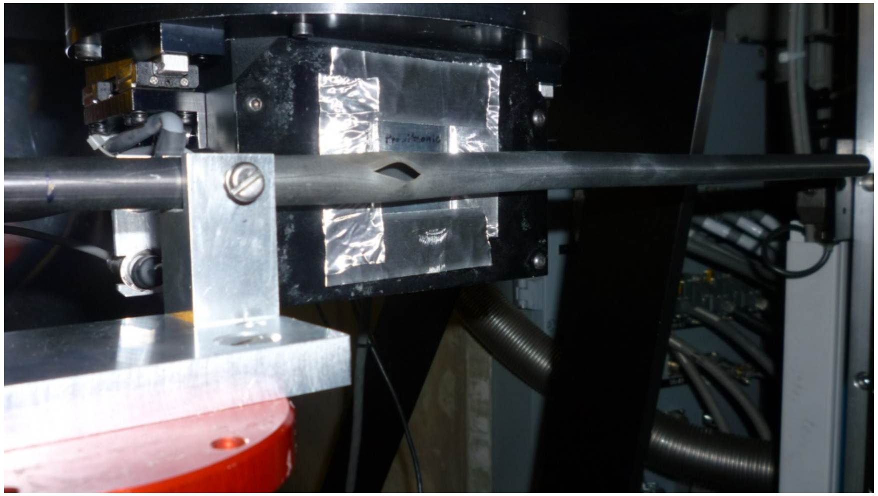
In the framework of the KIT QUENCH program design basis loss of coolant accidents (LOCA) and severe accidents (accidents beyond LOCA) are simulated experimentally on fuel rod bundle scale in large scale tests.

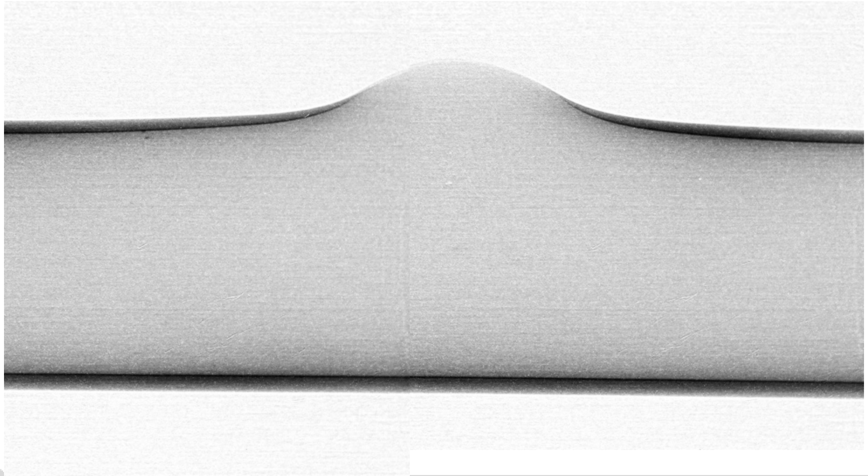


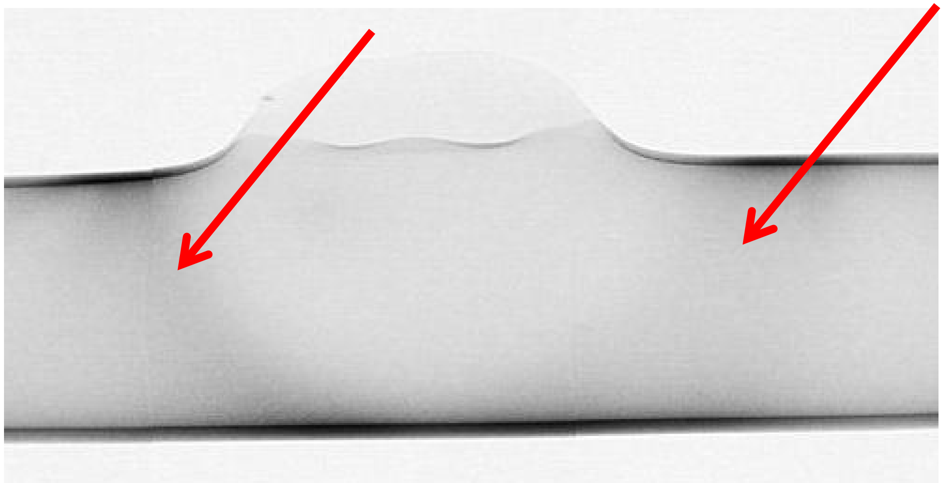
Neutron radiography investigations

Neutron radiography investigations were performed at ICON (PSI Villigen, Switzerland)

Spatial resolution ~ 25 µm
Illumination time: 300 s
L/d: ~ 350
Field of view: 28 mm * 28 mm







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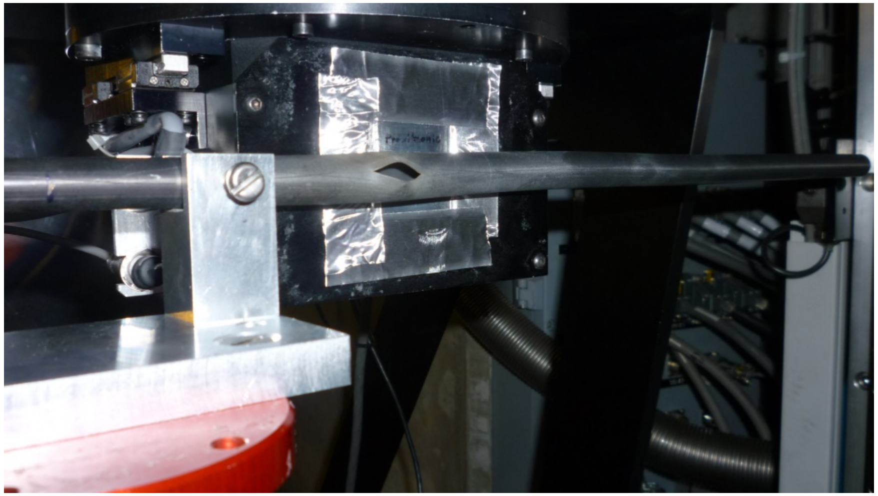
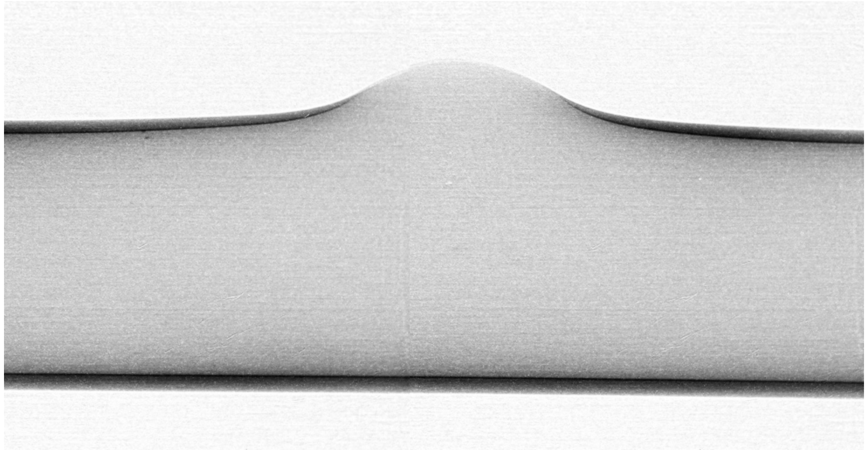
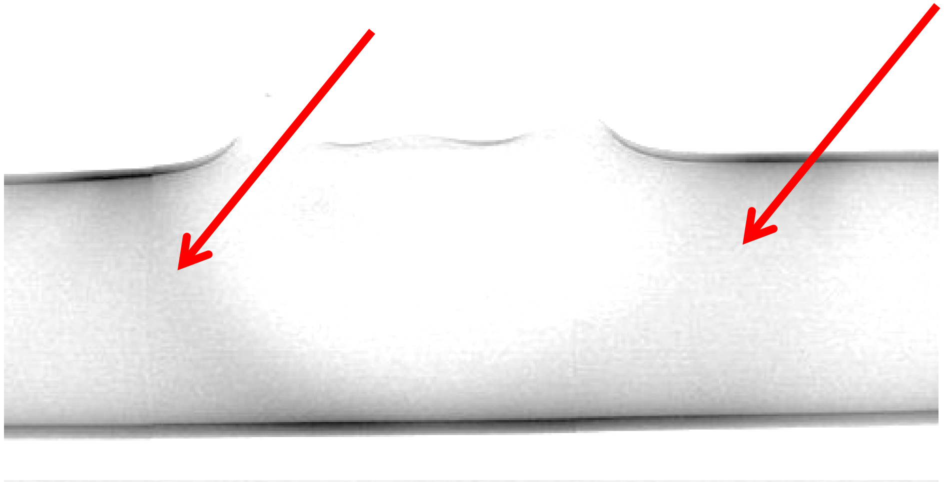


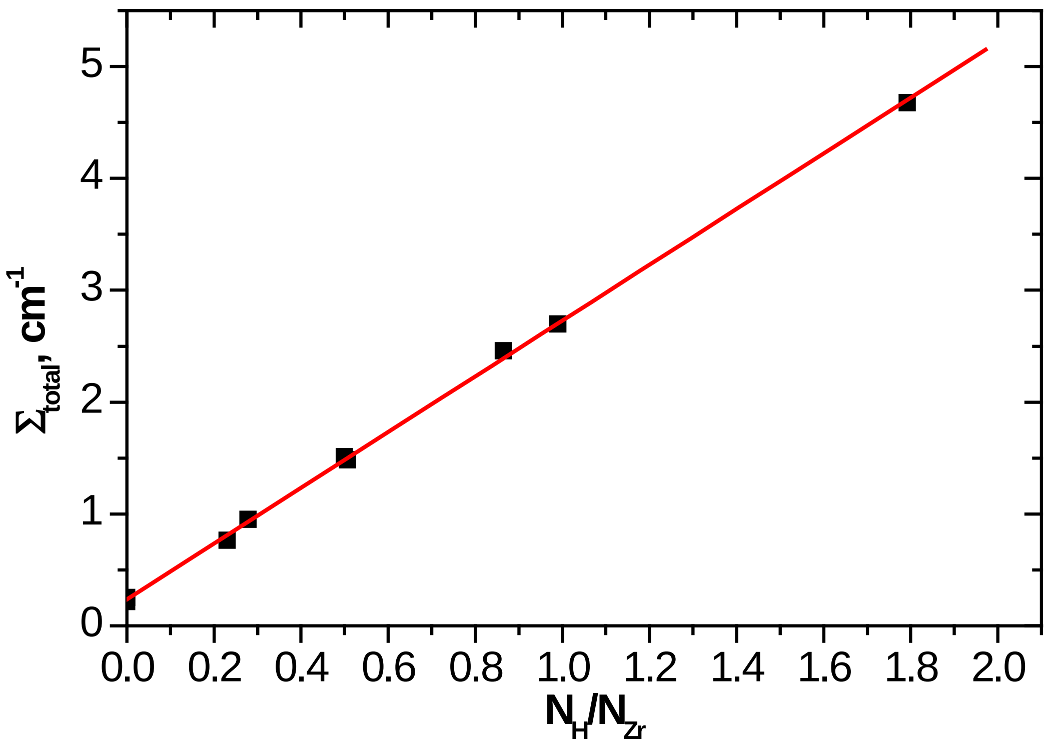




Calibration

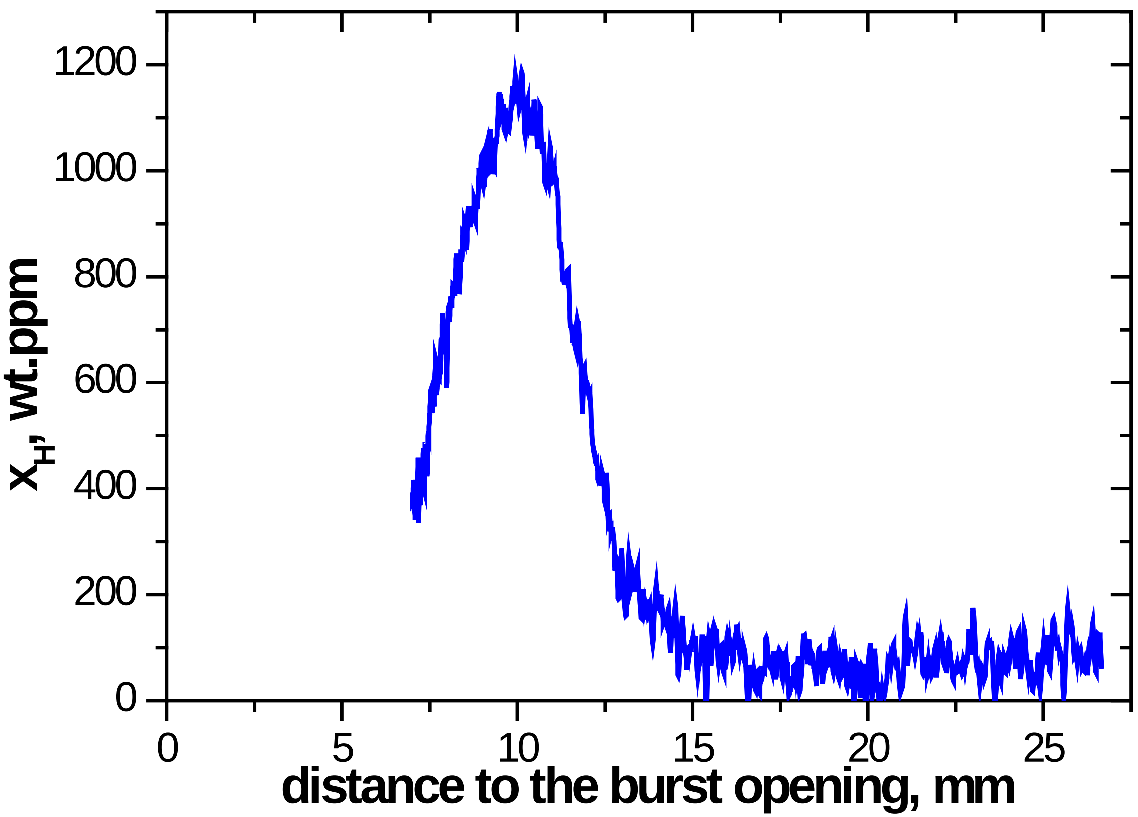
$$T(x,y) = \frac{I(x,y) - I_B(x,y)}{I_0(x,y) - I_B(x,y)} = \exp(-\Sigma_{total}(x,y) \cdot s(x,y))$$

$$\Sigma_{total} = \sum_i N_i \sigma_i = \underbrace{N_{Zr}\sigma_{Zr} + N_{Nb}\sigma_{Nb} + N_{Sn}\sigma_{Sn} + \ldots}_{\Sigma_{cladding\ \ material\ \ as\ \ received}} + N_H \sigma_H + N_O \sigma_O$$



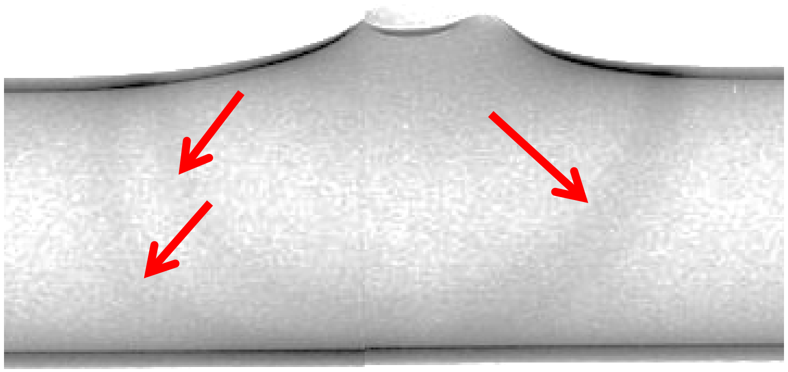
Calibration of the correlation between total macroscopic neutron cross section and H/Zr atomic ratio

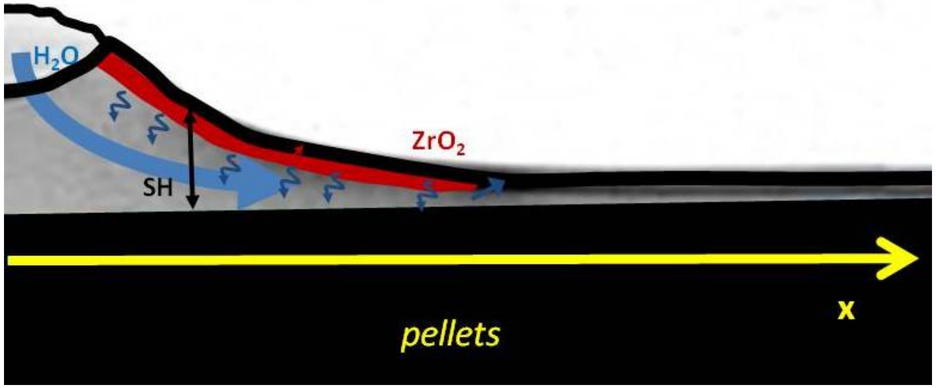
Quantitative analysis of the neutron radiographs



Distribution of absorbed hydrogen in cladding QL0 #03

Modeling of the hydrogen distribution





$$dc_{H_2O}(x) = Max\begin{pmatrix} \left(D\frac{\delta^2 c_{H_2O}}{\delta x^2} - \frac{K_{ox}}{2\sqrt{t}} \right) dt \\ 0 \end{pmatrix}$$

Steam transport and consumption in the gap

$$dc_{H_2}(x) = \left(\frac{K_{ox}}{2\sqrt{t}} + D\frac{\delta^2 c_{H_2}(x)}{\delta x^2} \right) dt$$

Free hydrogen production and transport

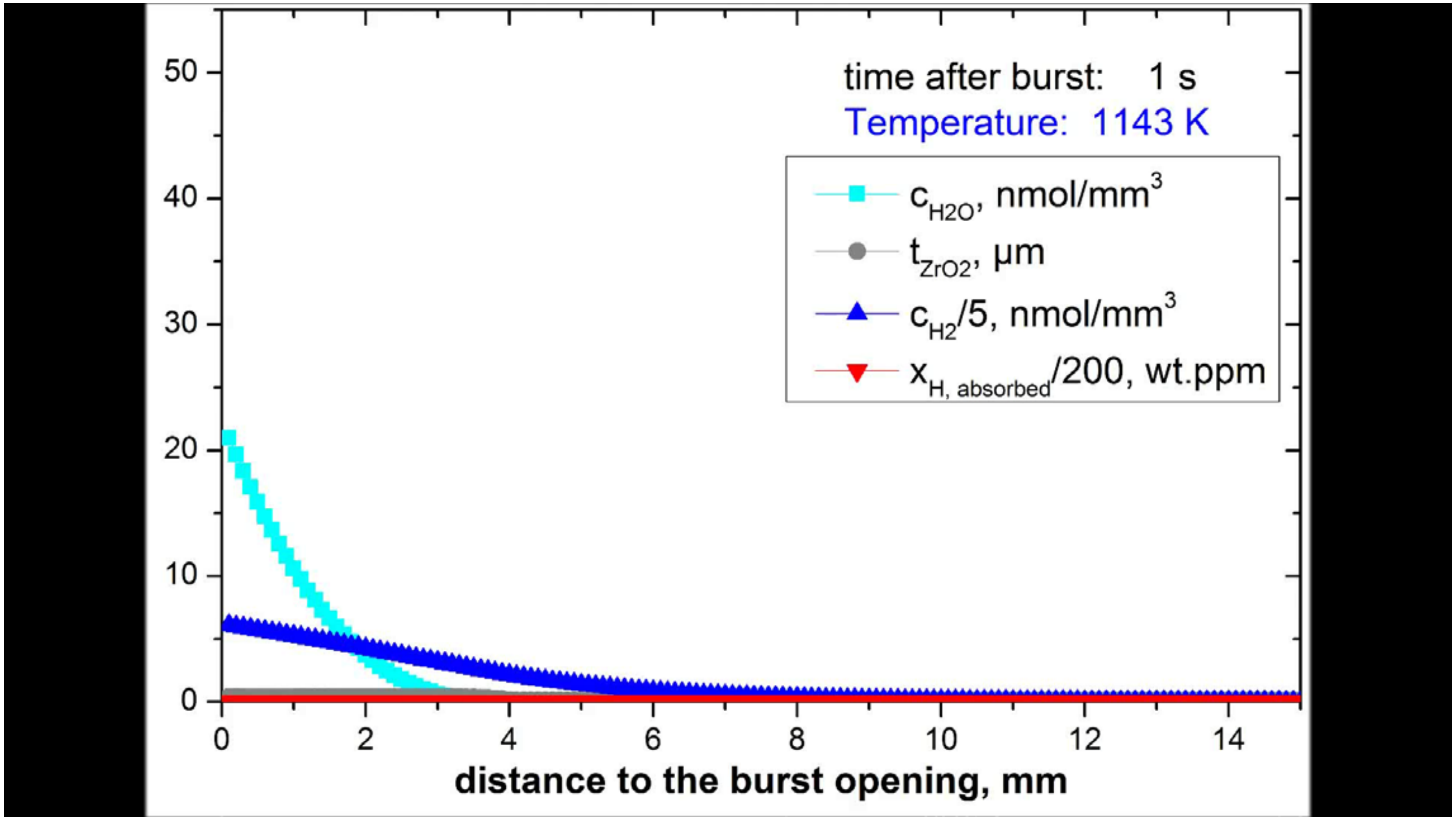
$$c_H^m(x, r=0) = K_S\sqrt{p_{total} * c_{H_2}(x)}$$

Hydrogen uptake (amount of hydrogen in the gap has to be taken into account)

$$dc_H^m(x,r) = D\frac{\delta^2 c_H^m(x,r)}{\delta x^2}$$

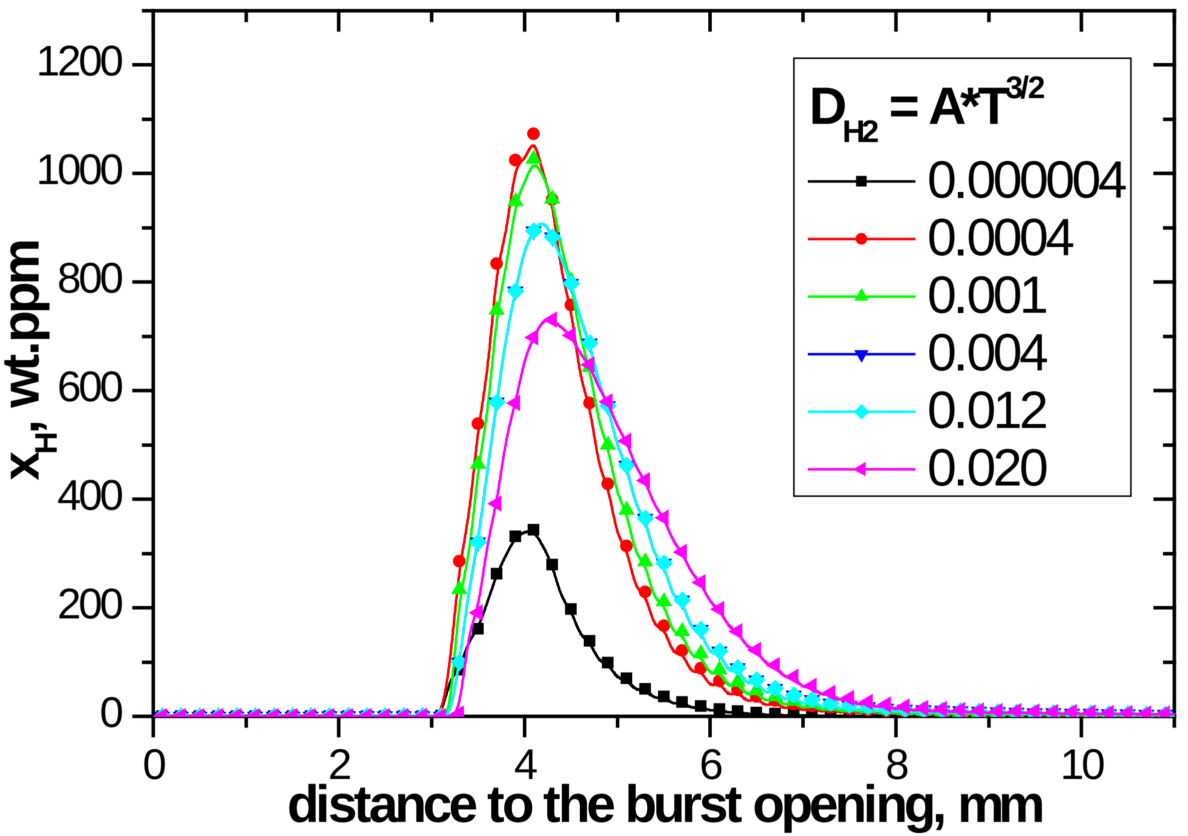
Hydrogen diffusion in the tube wall

Modeling of the hydrogen distribution



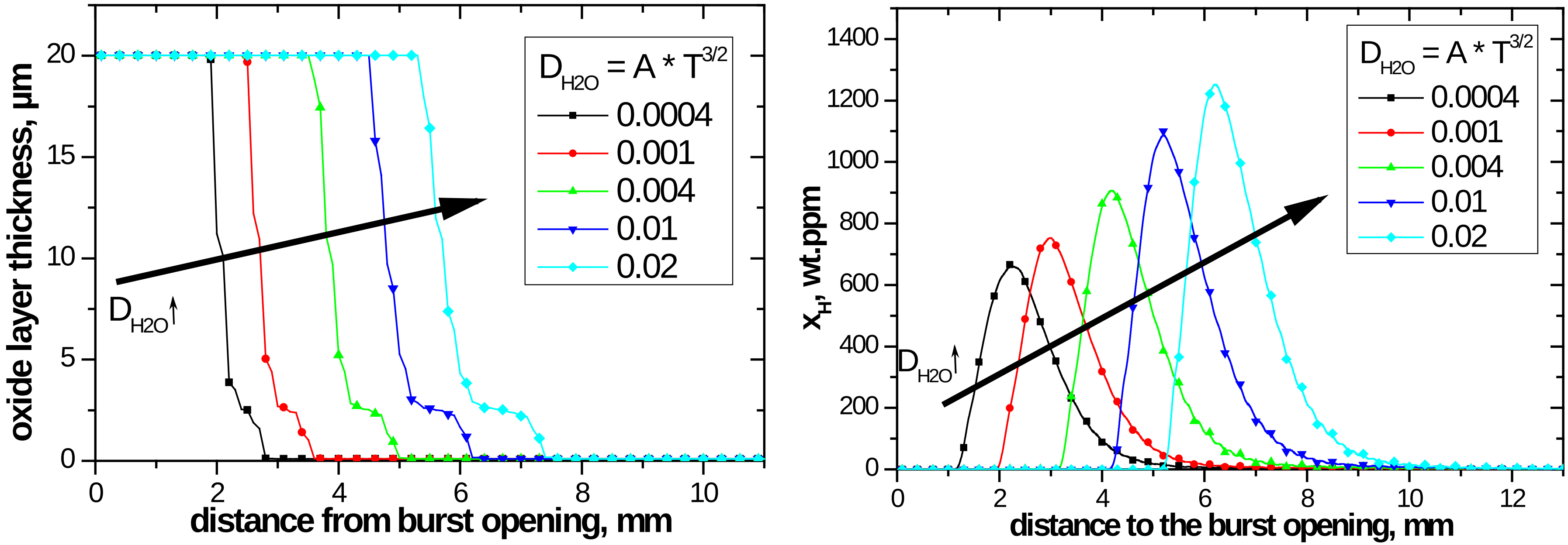
Real time simulation of the development of steam and hydrogen concentration in the gap, oxide layer thickness and hydrogen concentration in the cladding

Modeling of the hydrogen distribution



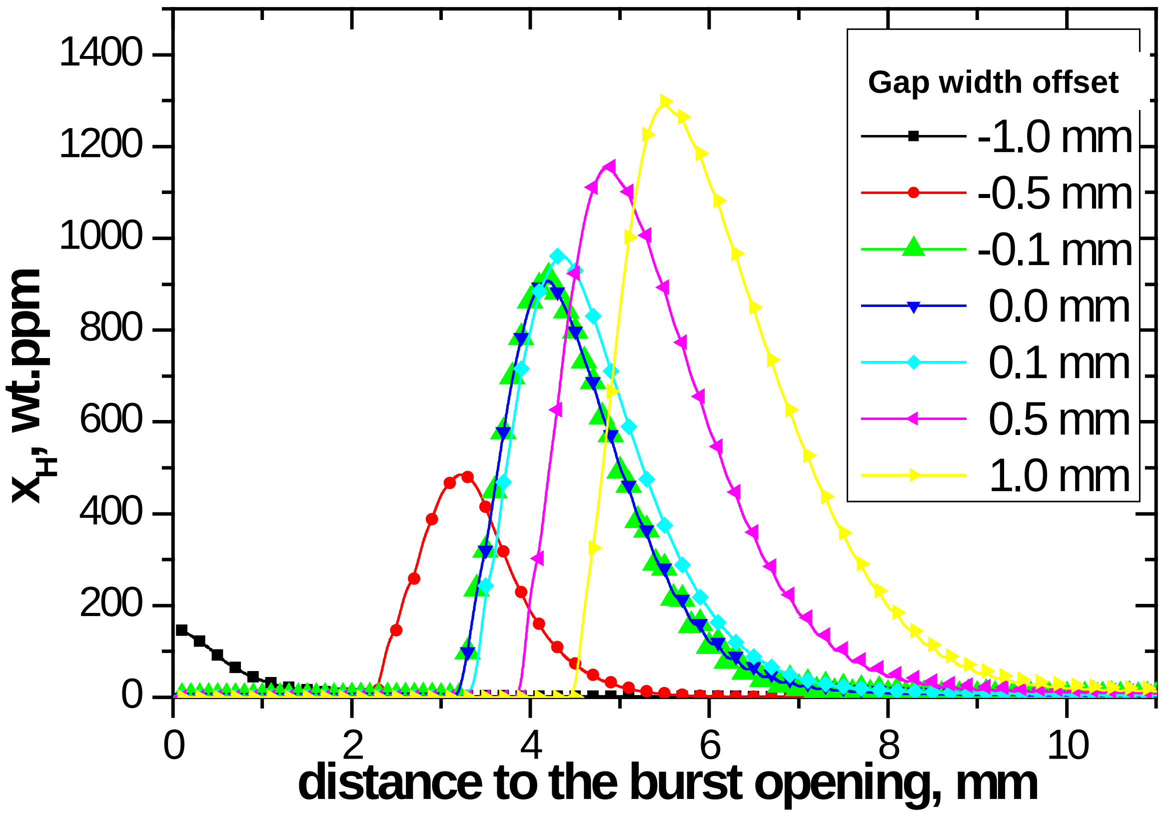
Influence of the hydrogen diffusion coefficient on position of the hydrogen enriched band and the hydrogen concentration in it

Modeling of the hydrogen distribution

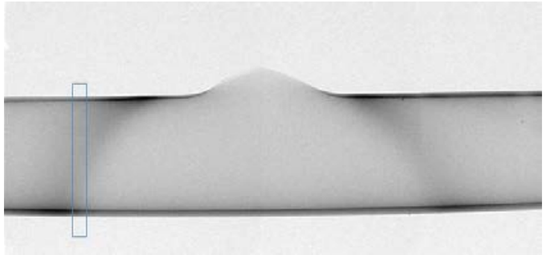


Influence of the steam diffusion coefficient on the position and thickness of the oxide layer and on the position of the hydrogen enriched band and the hydrogen concentration in it

Modeling of the hydrogen distribution



This is the reason for deviations from radial symmetric hydrogen distributions!



Influence of gap width between inner cladding surface and pellets on position of the hydrogen enriched band and the hydrogen concentration in it

Summary and conclusions

- Secondary hydrogenation of cladding tubes during LOCA was studied by means of neutron imaging and ab-initio modeling.
- Hydrogen is concentrated in bended bands oriented non-perpendicular to the tube axis.
- An ab-initio model was developed to describe hydrogen absorption during LOCA.
- The main reason this hydrogen distribution is the obstruction of the hydrogen uptake by the oxide layer formed at the inner cladding surface.
- Parametric studies show that the position of the hydrogen enriched bands mainly depends on the gap width between inner cladding surface and pellets and on the steam transport rate. The amount of absorbed hydrogen depends on the hydrogen and steam transport rates in the gap and on the gap width.

Thanks

The QUENCH-LOCA tests and pre-test investigations are sponsored by the German “Verein der Grosskraftwerksbetreiber“ **VGB**

KIT:

The QUENCH team, particularly C. Goulet, J. Moch, C. Roessger

PSI:

S. Hartmann

Thanks for your attention, questions?

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