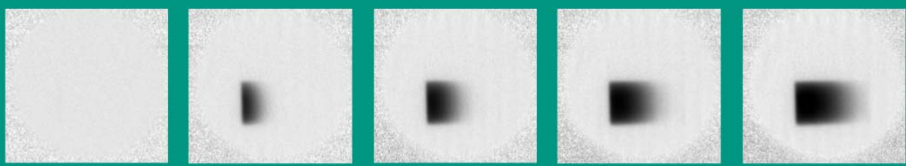
Karlsruhe Institute of Technology

IAM
Institut für Angewandte Materialien

Which processes occurring in the fuel cladding during nuclear accidents? – Contributions of neutron imaging to nuclear safety

Mirco Grosse

Institute for applied materials – applied materials physics / program NUCLEAR



Content

Introduction

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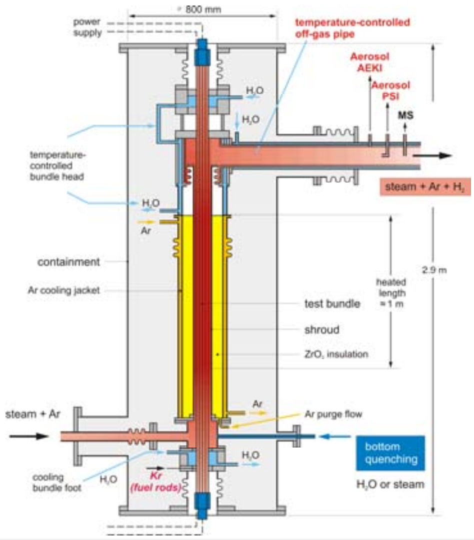
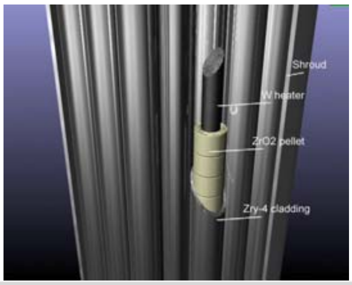


In the framework of the KIT QUENCH program design basis loss of coolant accidents (LOCA) and severe accidents (accidents beyond LOCA) are simulated experimentally on fuel rod bundle scale in large scale tests.



Introduction

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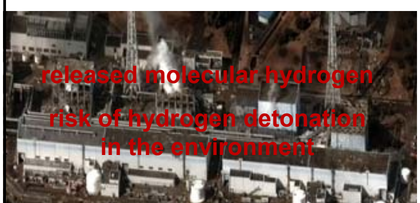
Emerging cooling of the overheated reactor core results in steam oxidation of the zirconium alloys used as fuel rod cladding material:

$$2\ H_2O + Zr \rightarrow ZrO_2 + 4\ H \text{ (very simplified)}$$
$$4\ H \rightarrow 2H_2\uparrow\ /\ 4\ H_{absorbed}$$



Neutron imaging

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X-ray radiography

neutron radiography

GKSS Geesthacht 1991

5/31 Kingston, Canada, June 22, 2012 Mirco Grosse et al.

Institute for Applied Materials
Applied Materials Physics
Program NUCLEAR

Calibration

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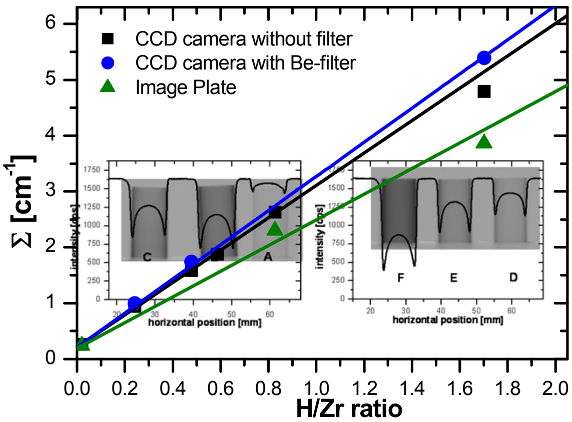
a) Radiography ex-situ



6/31 Kingston, Canada, June 22, 2012 Mirco Grosse

Institute for Applied Materials
Applied Materials Physics
Program NUCLEAR

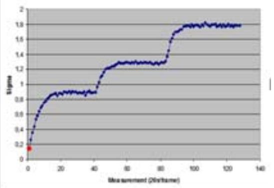
Calibration

b) Radiography in-situ

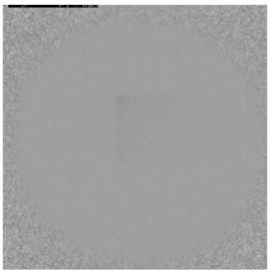
Sieverts´ law:

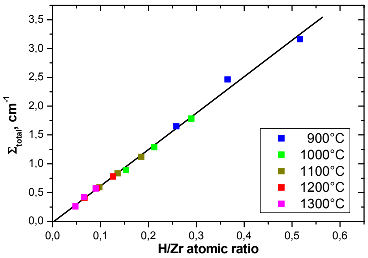
$$C_H^{(m)} = K_S \cdot \sqrt{p_{H_2}}$$

$$K_S = \exp\left(\frac{\Delta_S S}{R} - \frac{\Delta_S H}{R \cdot T}\right)$$



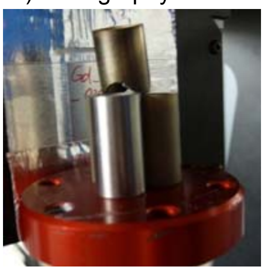
2 l/h 4 l/h 8 l/h H_2,
50 l/h Ar, 1000°C

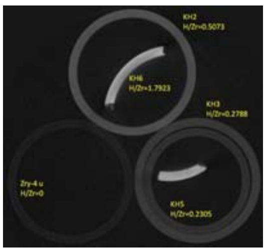


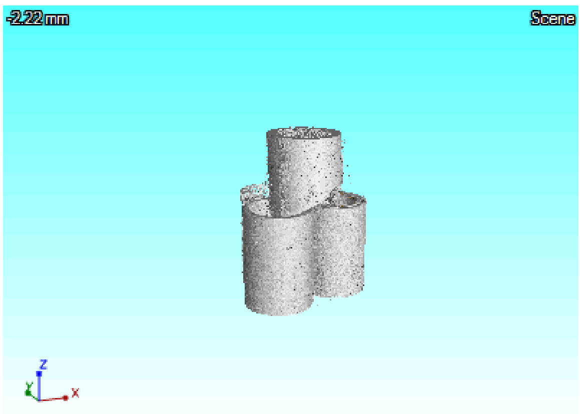


Calibration

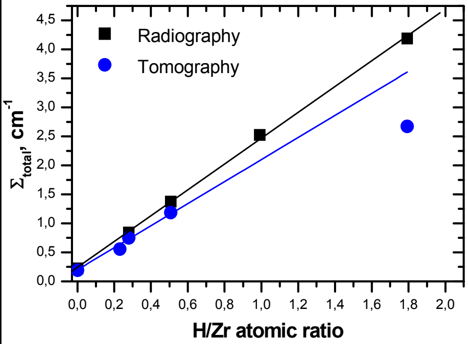
c) Tomography

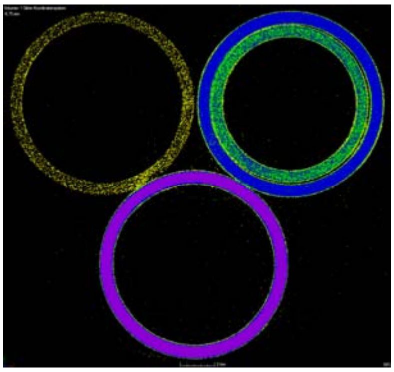






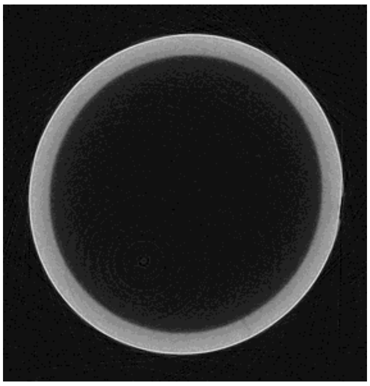
Calibration

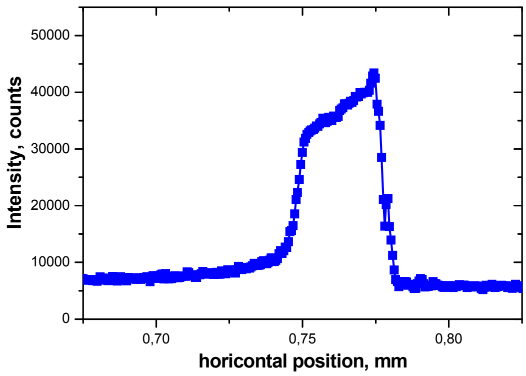




Correlation of total macroscopic neutron cross section and H/Zr atomic ratio

Calibration

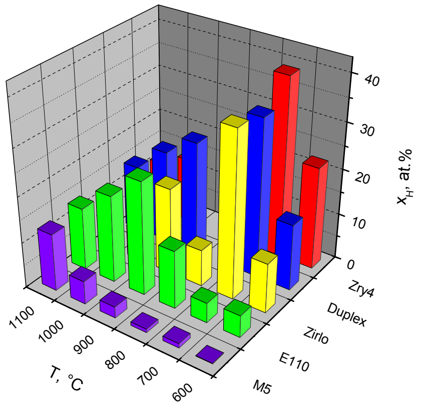




Tomography slice of sample KH6

CT number through the wall distribution in KH6

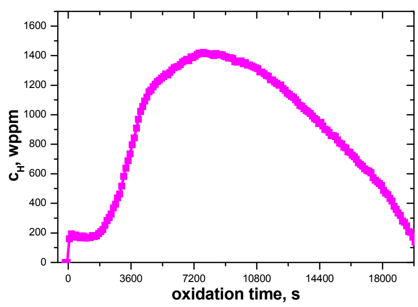
Separate effect tests – ex situ



Comparison of the temperature dependence of the hydrogen uptake of common used cladding alloys

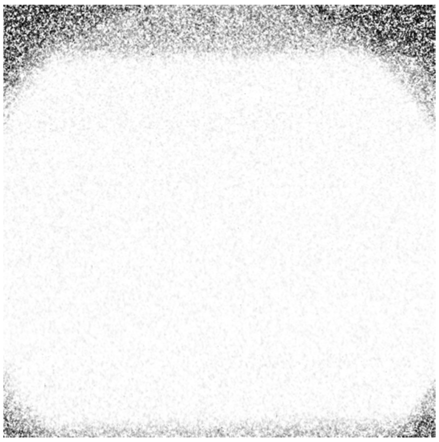
Separate Effect Tests in-situ investigation of H uptake of Zr during steam oxidation

steam oxidation



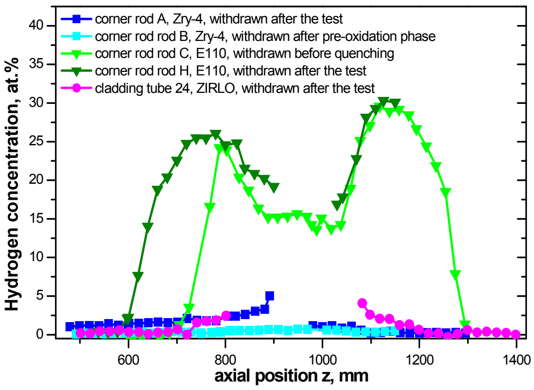
Zry-4, 1000°C, 30 g/h steam, 30 l/h argon

Separate effect tests in-situ investigations of DHC



Hydrogen uptake of a tensiled Zry-4 specimen

Bundle Tests – severe accident

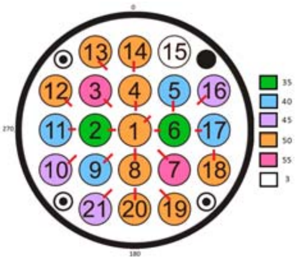


Axial hydrogen distribution in corner rods and a cladding tube of the large scale test QUENCH-15

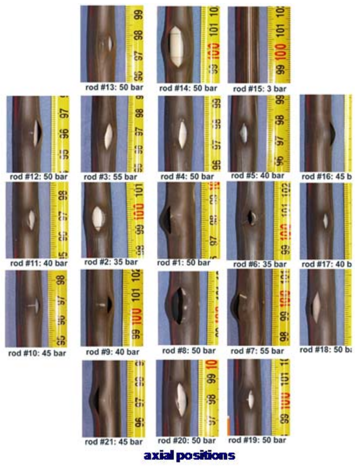
Differences between the materials

Differences for different sample shapes /solid rod and tub

Bundle tests - LOCA

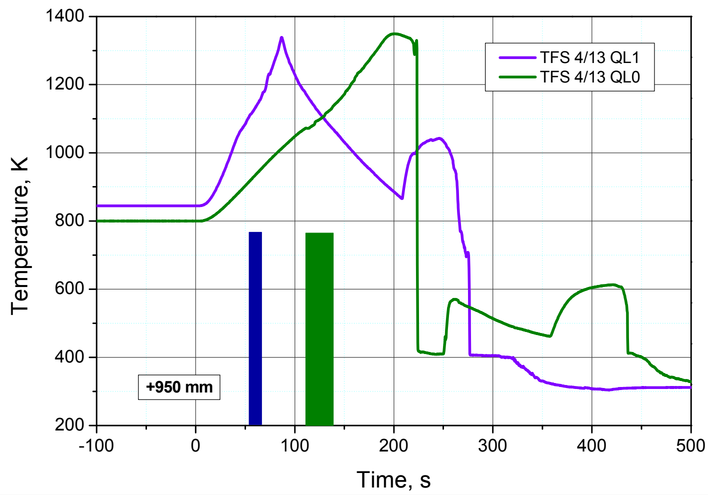


Scheme of the bundle cross section



Burst regions of the rod simulators

Comparison of the temperature scenarios of QUENCH-L0 (commissioning test) and QUENCH-L1 (reference test)

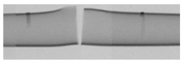


Bundle tests - LOCA

Radiographs of the QUENCH-L0 test arranged in the order of increasing time between burst and quenching


#15, Δt_{b-q}=0 s


#10, Δt_{b-q}=49 s


#13, , Δt_{b-q}=61 s


#19, , Δt_{b-q}=63 s


#14, Δt_{b-q}=70 s


#17, Δt_{b-q}=71 s


#06, , Δt_{b-q}=93 s,

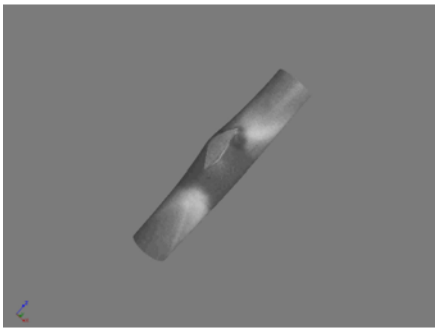

#08, Δt_{b-q}=101 s

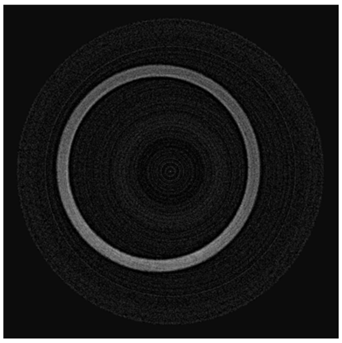

#03, Δt_{b-q}=104 s


#07, Δt_{b-q}=109 s


#01, Δt_{b-q}=112 s

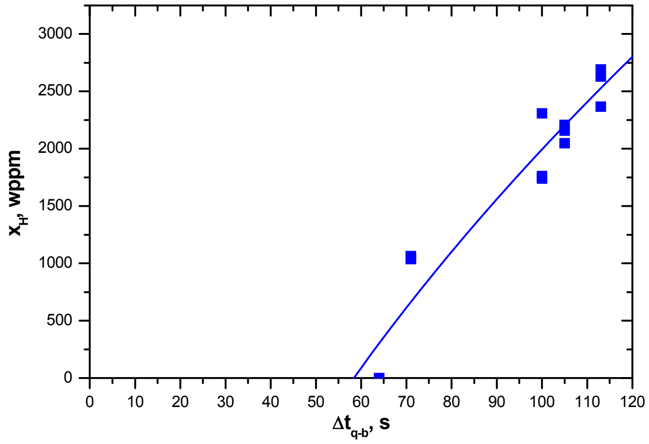
Results Tomography rod QL0-#01 (p_i = 50 bar, Δt = 112 s)





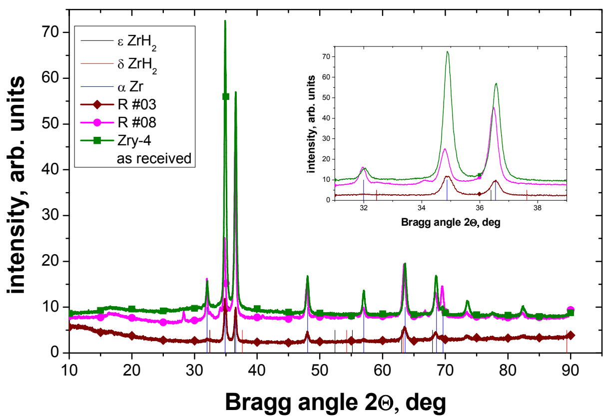
x_H ~ 2700 wppm

Bundle Tests -LOCA



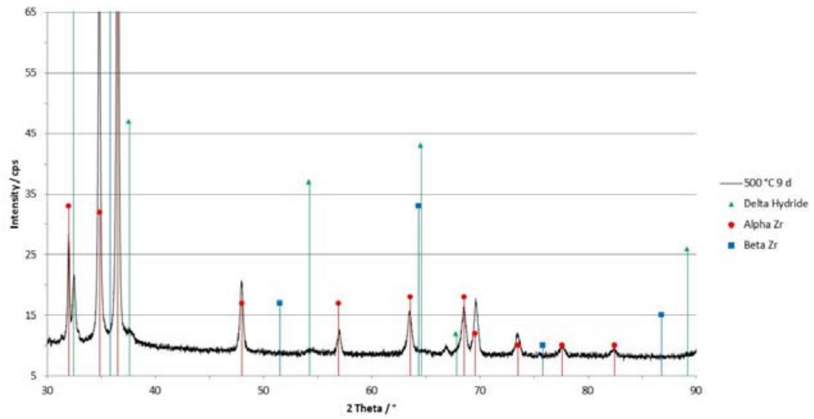
Dependence of the maximal hydrogen concentration on the time between burst and quenching

Results XRD QUENCH-L0



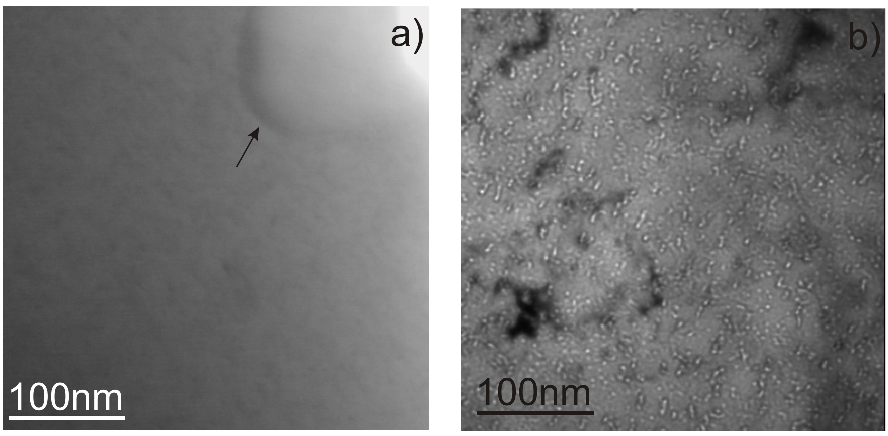
XRD pattern measured at the as-received state and two samples from the QUENCH-L0 test

Comparison with XRD pattern of a laboratory specimen



X-ray diffraction pattern of a laboratory sample cooled with lower cooling rate

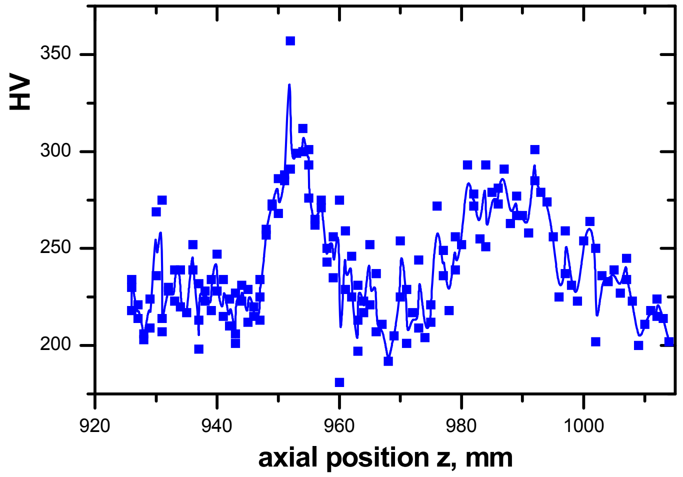
Results TEM QUENCH-L0



as-received

inside the hydrogen enriched bands

Results micro-hardness QL0 rod #03



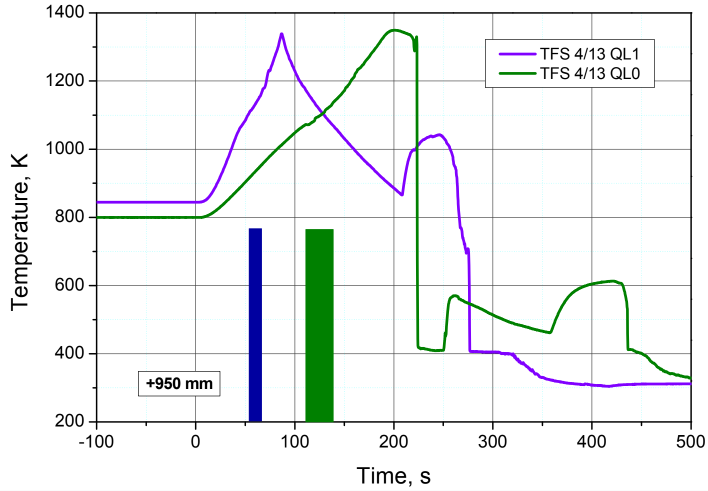
Results tensile tests QL0

Ruptures near to burst opening due to hydrogen embrittlement | Rupture across the burst opening middle due to stress concentration | Rupture near end plugs after plastic deformation

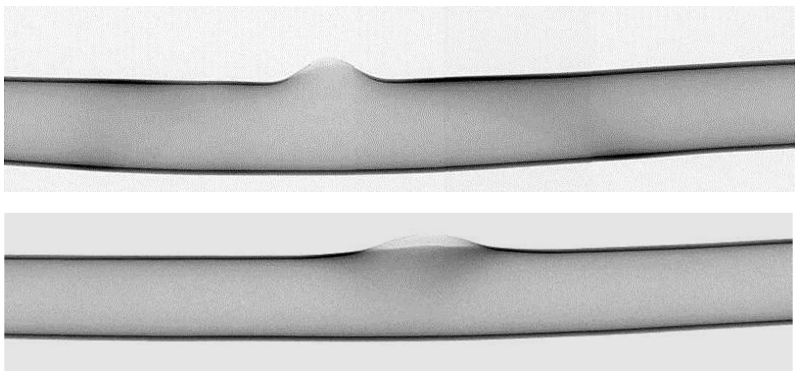
The rods do not show hydrogen bands fail after plastic deformation.

The rods containing hydrogen bands fail by double rupture in the hydrogen bands or by stress concentration at edges of the burst crack

Comparison of the temperature scenarios of QUENCH-L0 (commissioning test) and QUENCH-L1 (reference test)



First glance to the results of n radiography of QL1 samples

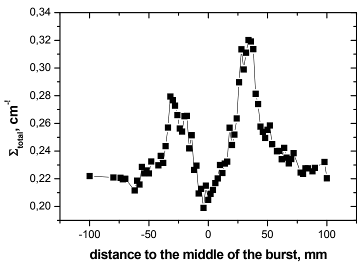


#06

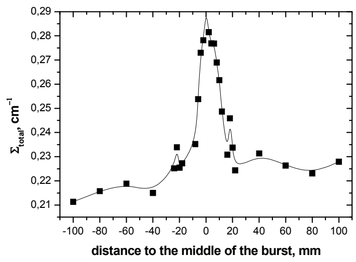
#08

First glance to the results of n radiography of QL1 samples

axial distribution of the total macroscopic neutron cross section



#06



#08

Summary and Conclusions 1

- Neutron imaging is a powerful tool to investigate the system hydrogen – zirconium.
- The calibration of the correlation between hydrogen concentration and total macroscopic neutron cross section allows quantitative analysis of the imaging data.
- The fast and non-destructive character of neutron imaging offers the possibility of in-situ investigations.
- Only neutron tomography is able to provide information about the real 3D hydrogen distribution in nuclear fuel cladding tubes after failure in LOCA tests.

Summary and Conclusions 2

QUENCH-L0

- The hydrogen is enriched in bended bands oriented non-symmetric to the tube axis.
- The extension of the hydrogen enriched bands and the maximal hydrogen concentration in it seems to depend on the time between bursting and quenching and on the temperatures during this time.
- Maximal hydrogen concentrations of ~2600 ppm was determined. No clearly visible hydrogen enriched bands were found for $\Delta t < 70$ s.
- No influence of inner pressure or crack length is obviously.
- Bragg peak shift observed in the XRD investigations give hints for a undercooled solution of hydrogen in the α-Zr lattice.
- Numerous inhomogeneities were found in the hydrogen enriched bands by means of TEM.
- Strong influence of the hydrogen bands on micro-hardness and on the crack positions in the tensile tests.

Summary and Conclusions 3, Outlook

Quench-L1

- Hydrogen bands not clearly visible.
- Different hydrogen distribution because of blockage after bending of the tubes

Next steps:

- QUENCH-DEBRIS test is planed to be performed in summer of this year.
- QUENCH-L2 with a M5® bundle is planed for the end of this year.
- In-situ NR investigations of hydrogen re-distribution during DHC will be performed next month.
- Modeling of the hydrogen distribution in cladding tubes after LOCA?

Aknowledgement

- The QUENCH-LOCA tests are sponsored by the German "Verein der Großkraftwerksbetreiber VGB (association of large power plants operators).
- The QUENCH team at KIT, in particular Marius van den Berg and Camille Goulet, Juri Stuckert, Martin Steinbrück, Conrad Rössger, Jürgen Moch, Ulrike Stegmaier and Ursula Peters
- Stephane Valance from PSI (Cooperation in the investigations of DHC)
- The neutron imaging investigation were performed at the ICON facility at SINQ (PSI) and ANTARES at FRM-2 (TUM).
- Support from PSI in particular Anders Kaestner, Stefan Hartmann, Gabriel Frey and Eberhard Lehmann
- Support from FRM-2: Burkhardt Schilliger and Elbio Calzada

- **Thank you for your attention**

Questions?