What happens during nuclear accidents?
Contributions of neutron imaging to nuclear safety

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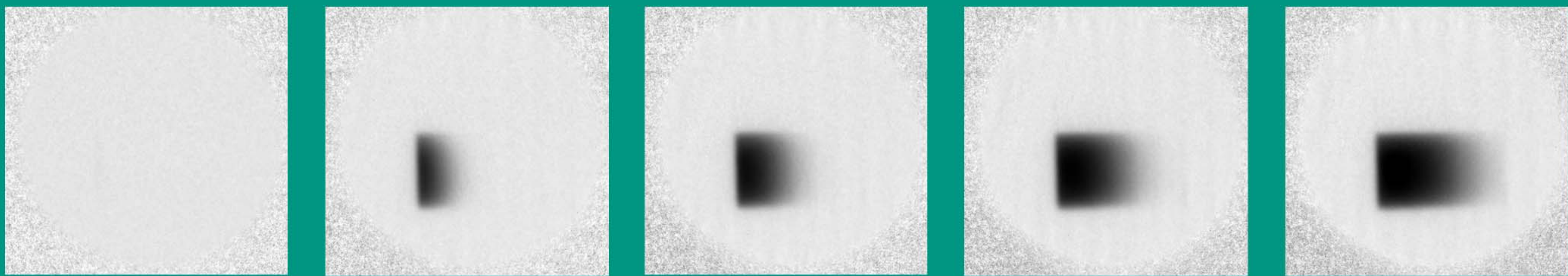

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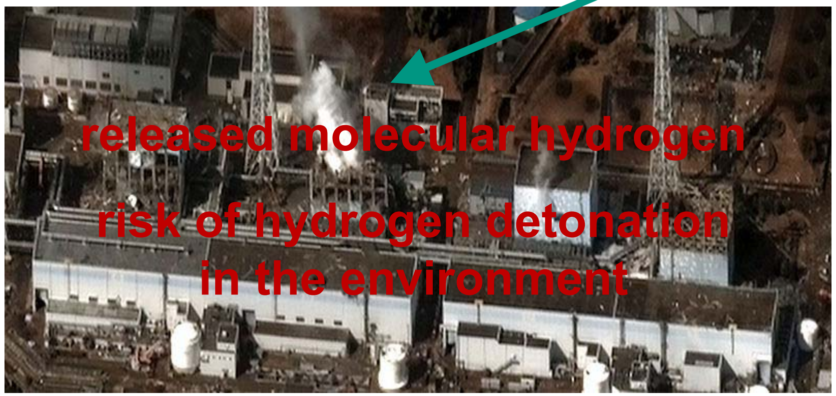
Introduction

At KIT the severe accident of PWR cores are investigated in the QUENCH program.

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

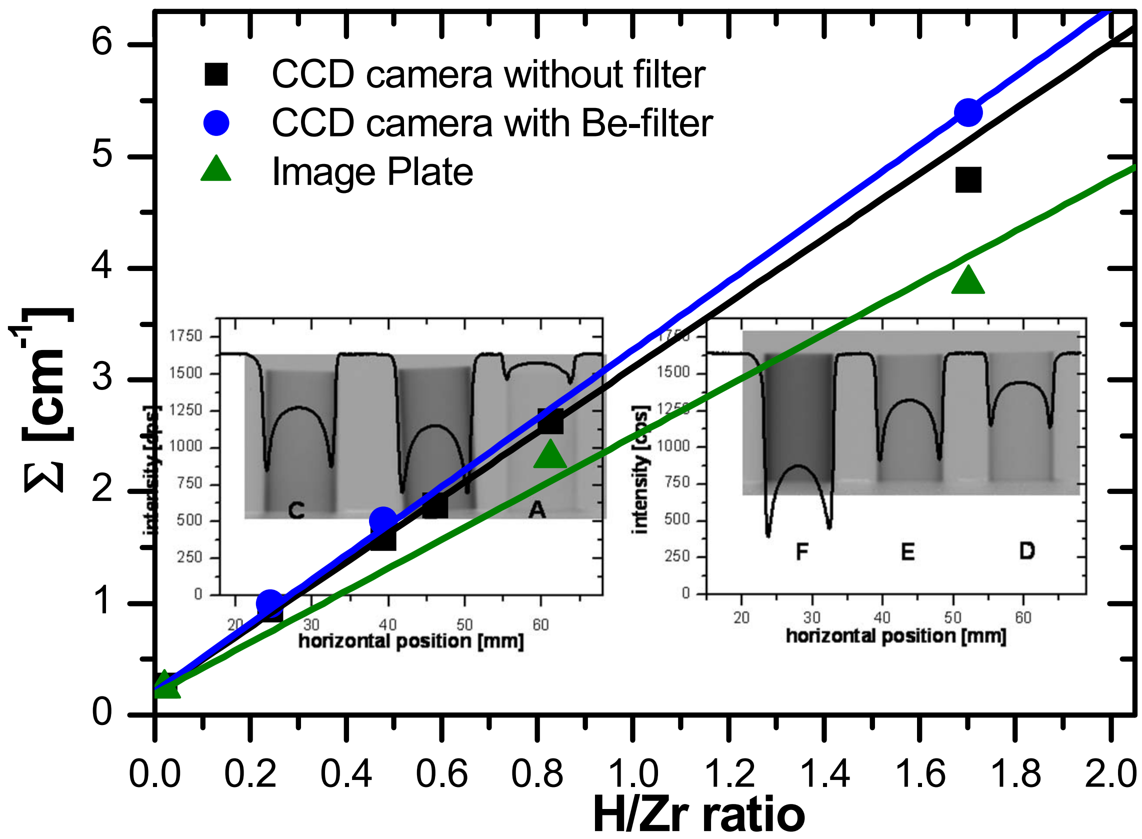
$$2\ H_2O + Zr \rightarrow ZrO_2 + 4\ H \text{ (very simplified)}$$

$$4\ H \rightarrow 2H_2\uparrow\ /\ 4\ H_{absorbed}$$



Kalibrierung

a) Radiography ex-situ



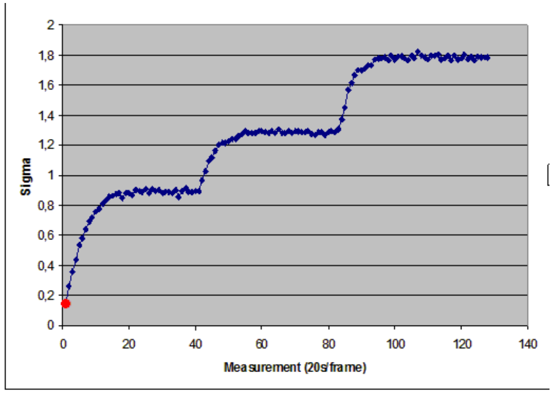
Kalibrierung

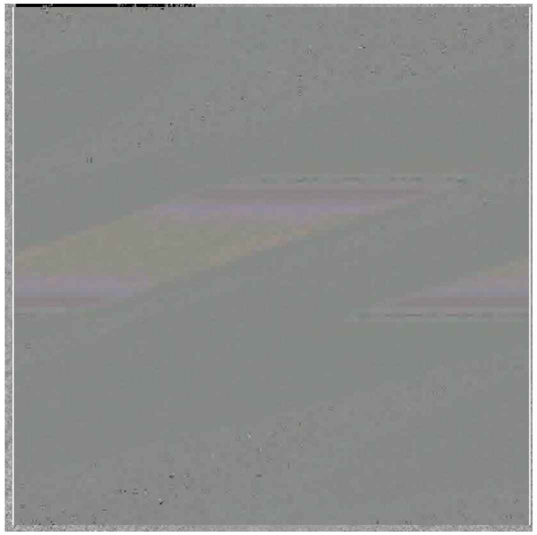
b) Radiography in-situ

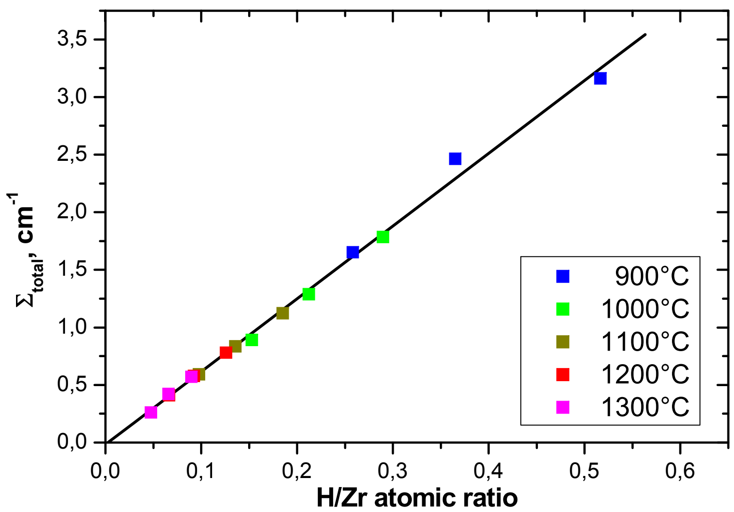
Sieverts´ law:

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

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



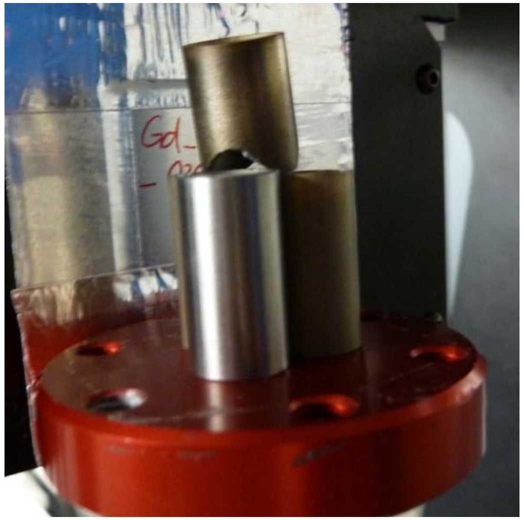


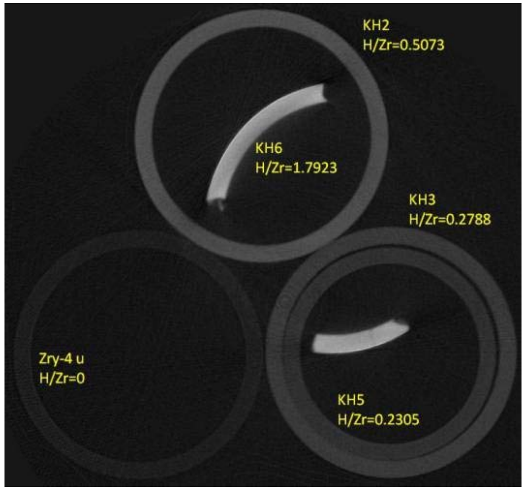


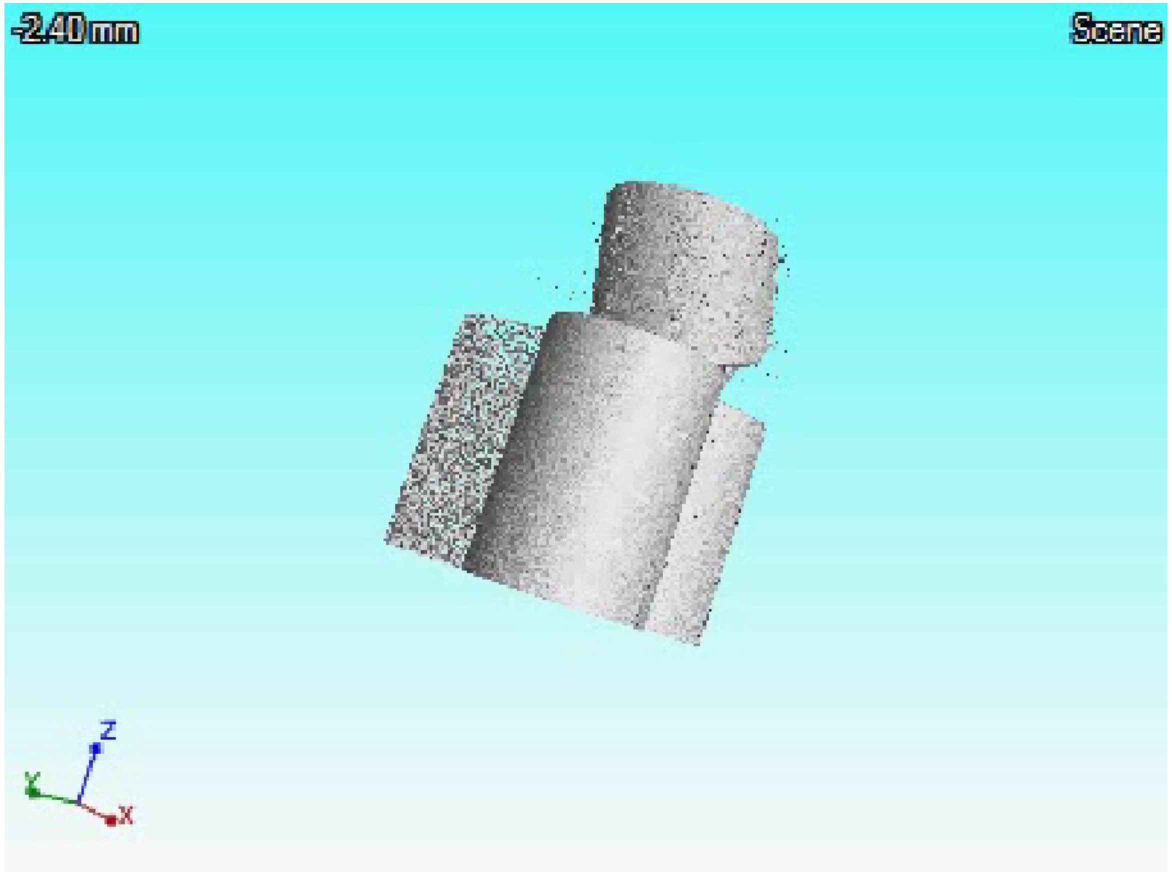
2 l/h 4 l/h 8 l/h H_2,
50 l/h Ar, 1000°C

Kalibrierung

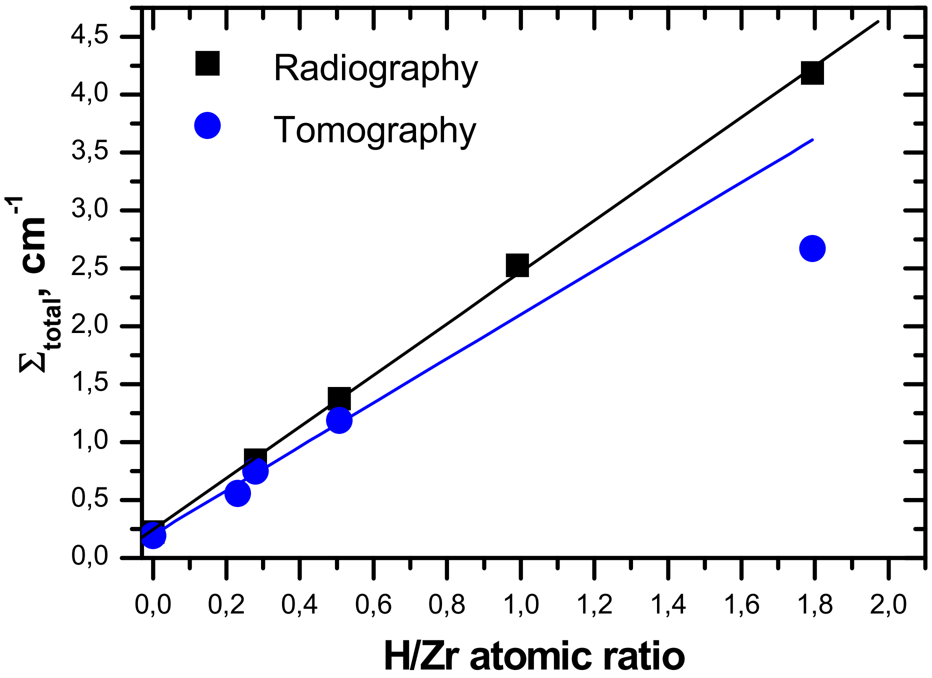
c) Tomography

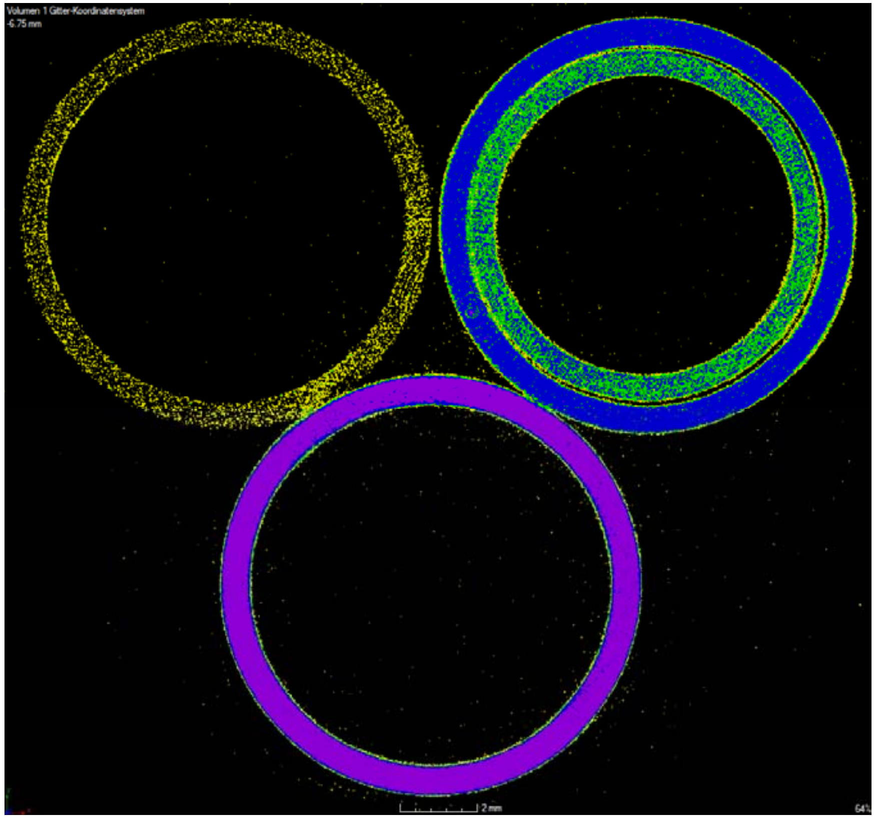




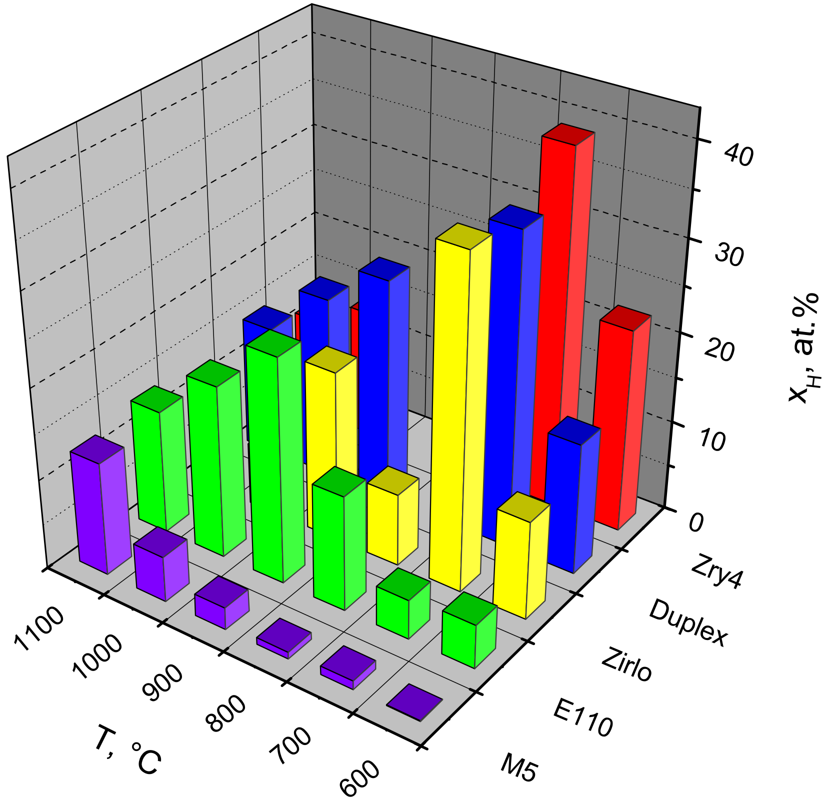


Kalibrierung

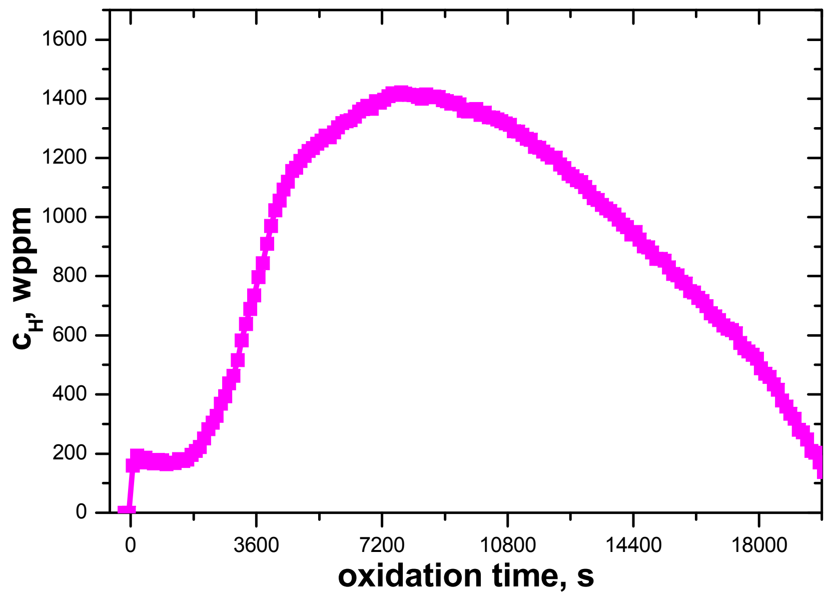




Separate effect tests

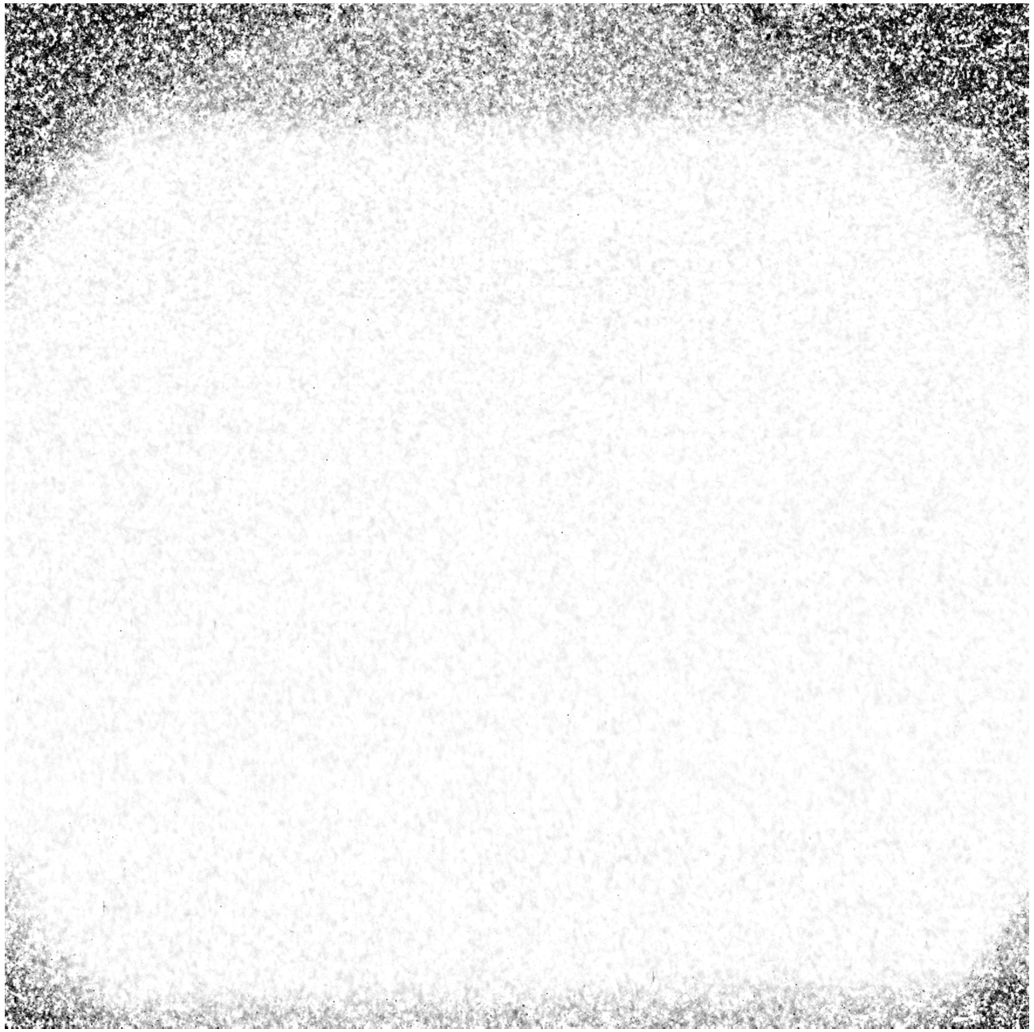


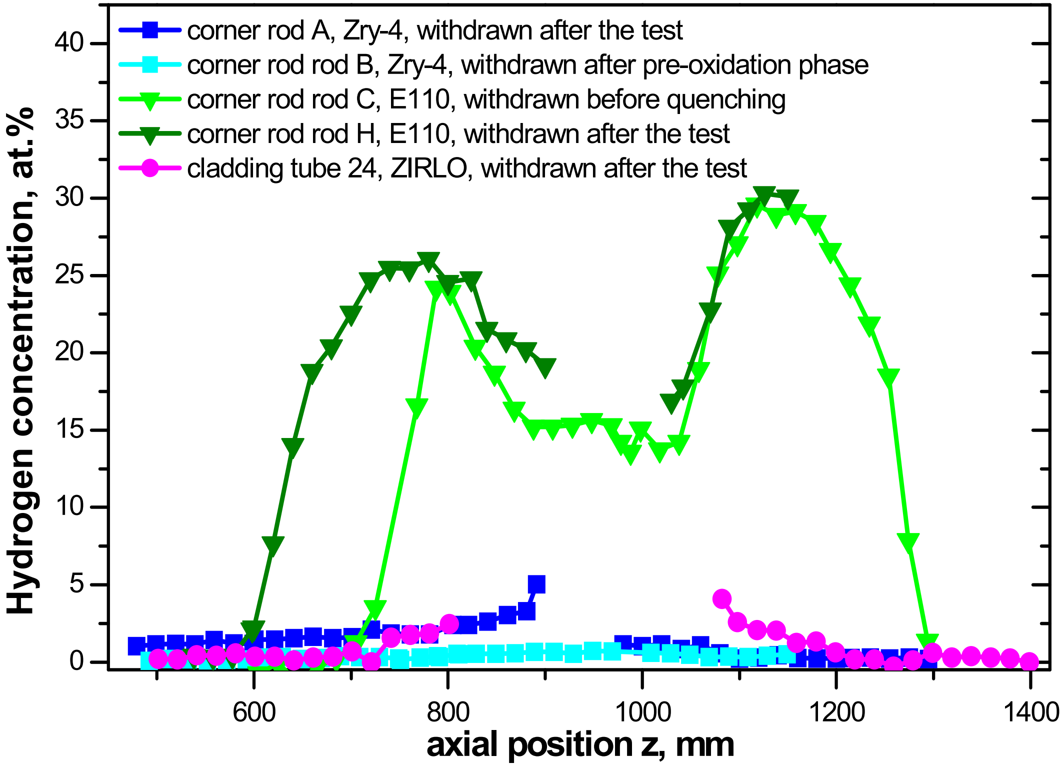
steam oxidation



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

Separate effect tests in-situ investigations of DHC

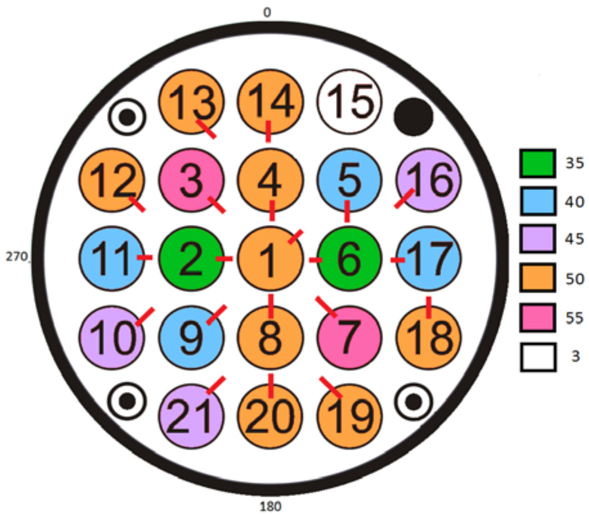


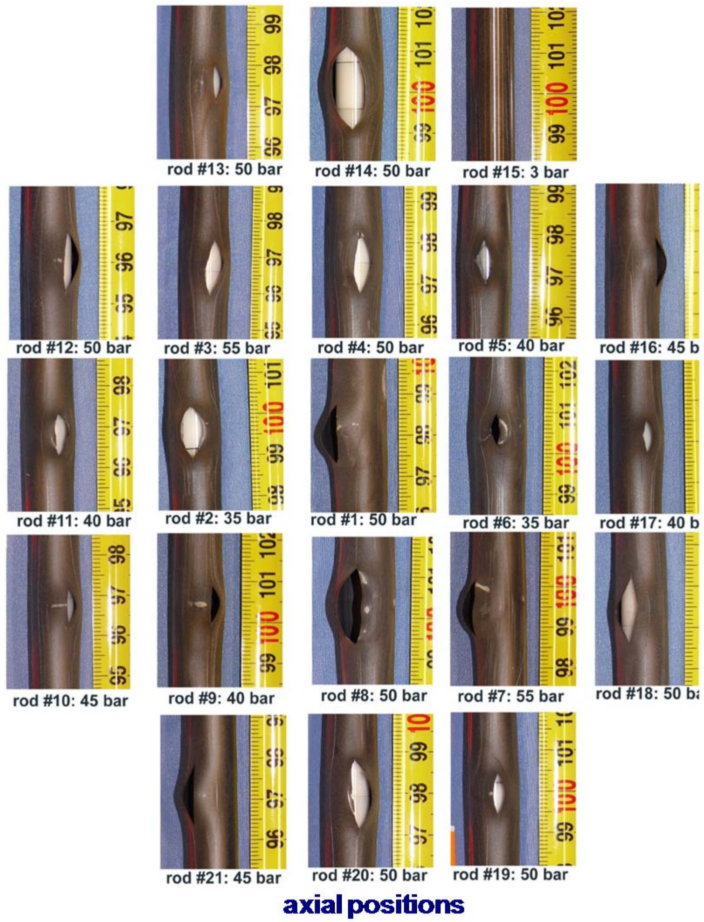


Axial hydrogen distribution in corner rods and a cladding tube of the large scale test QUENCH-15

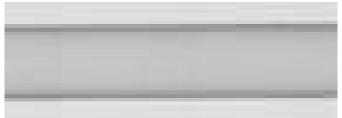
Differences between the materials

Differences for different sample shapes /solid rod and tub

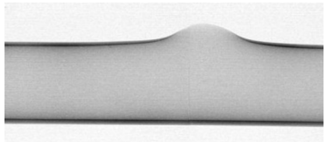

0
270
180
13 14 15
12 3 4 5 16
11 2 1 6 17
10 9 8 7 18
21 20 19
35
40
45
50
55
3


rod #13: 50 bar
rod #14: 50 bar
rod #15: 3 bar
rod #12: 50 bar
rod #3: 55 bar
rod #4: 50 bar
rod #5: 40 bar
rod #16: 45 b
rod #11: 40 bar
rod #2: 35 bar
rod #1: 50 bar
rod #6: 35 bar
rod #17: 40 b
rod #10: 45 bar
rod #9: 40 bar
rod #8: 50 bar
rod #7: 55 bar
rod #18: 50 b
rod #21: 45 bar
rod #20: 50 bar
rod #19: 50 bar
axial positions

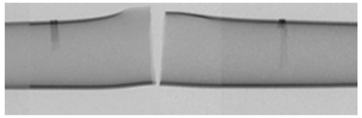
Radiographs of the QUENCH-L0 test arranged in the order of increasing time between burst and quenching



#15, Δt_{b-q}=0 s

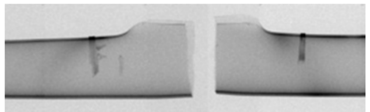


#10, Δt_{b-q}=49 s

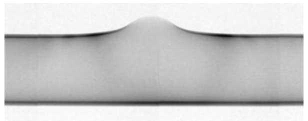


#13, , Δt_{b-q}=61 s

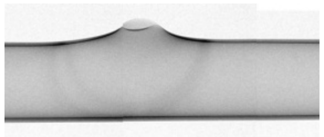
#19, , Δt_{b-q}=63 s



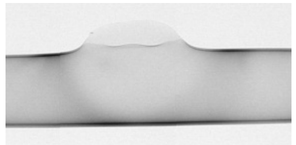
#14, Δt_{b-q}=70 s



#17, Δt_{b-q}=71 s



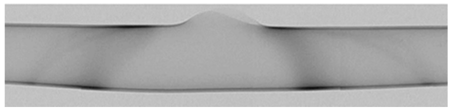
#06, , Δt_{b-q}=93 s,



#08, Δt_{b-q}=101 s

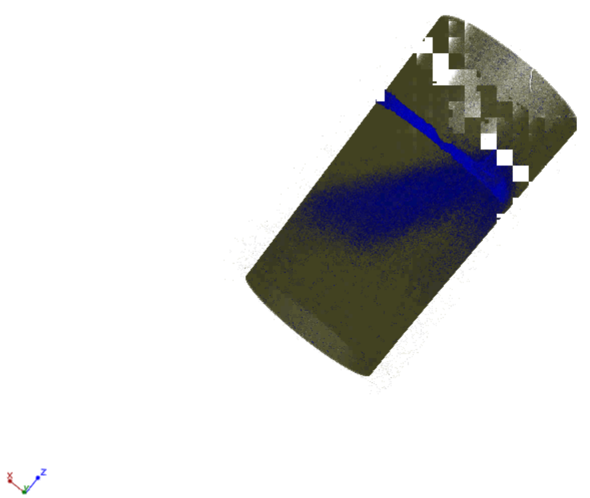
#03, Δt_{b-q}=104 s

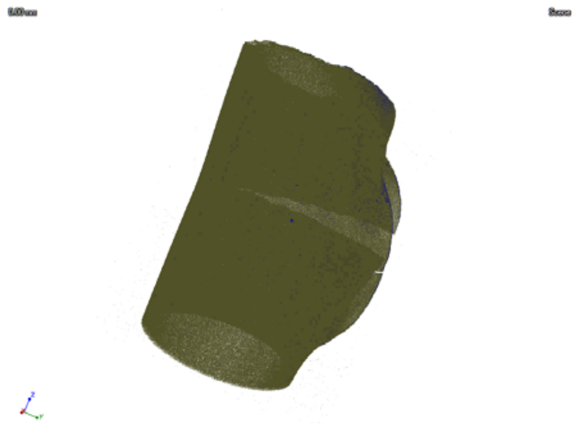
#07, Δt_{b-q}=109 s



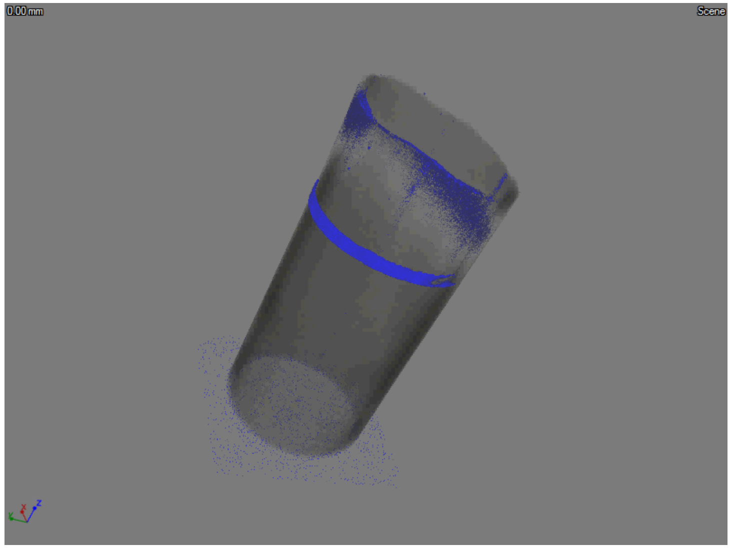
#01, Δt_{b-q}=112 s

Neue Messungen an QL0-Proben

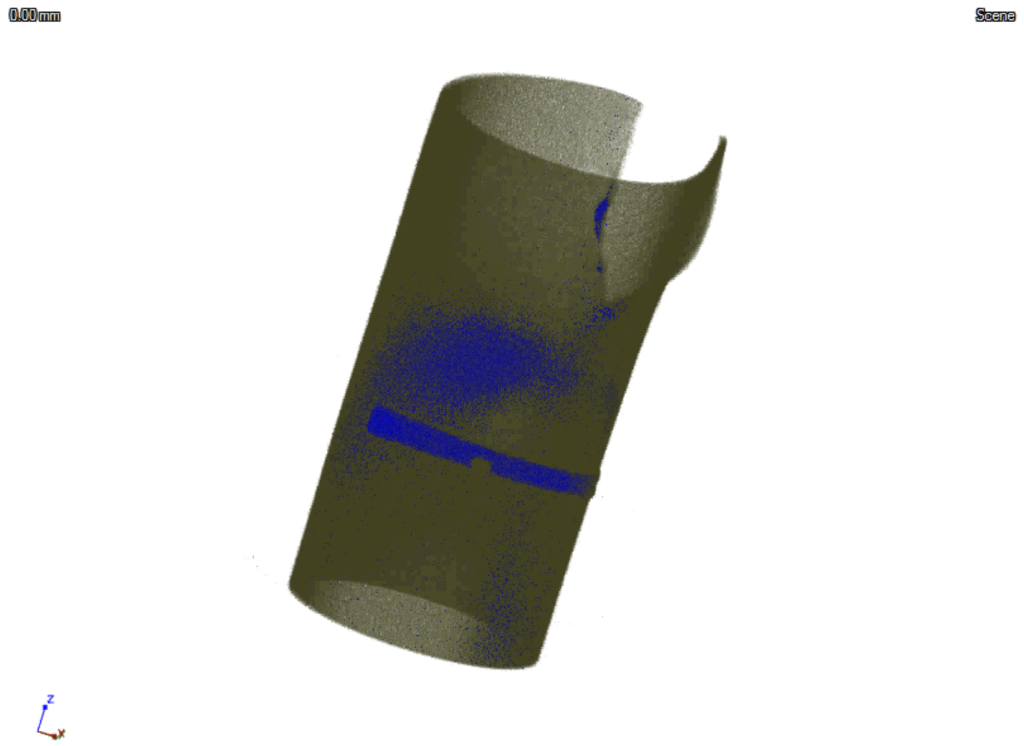




QUENCH-L0 R#07

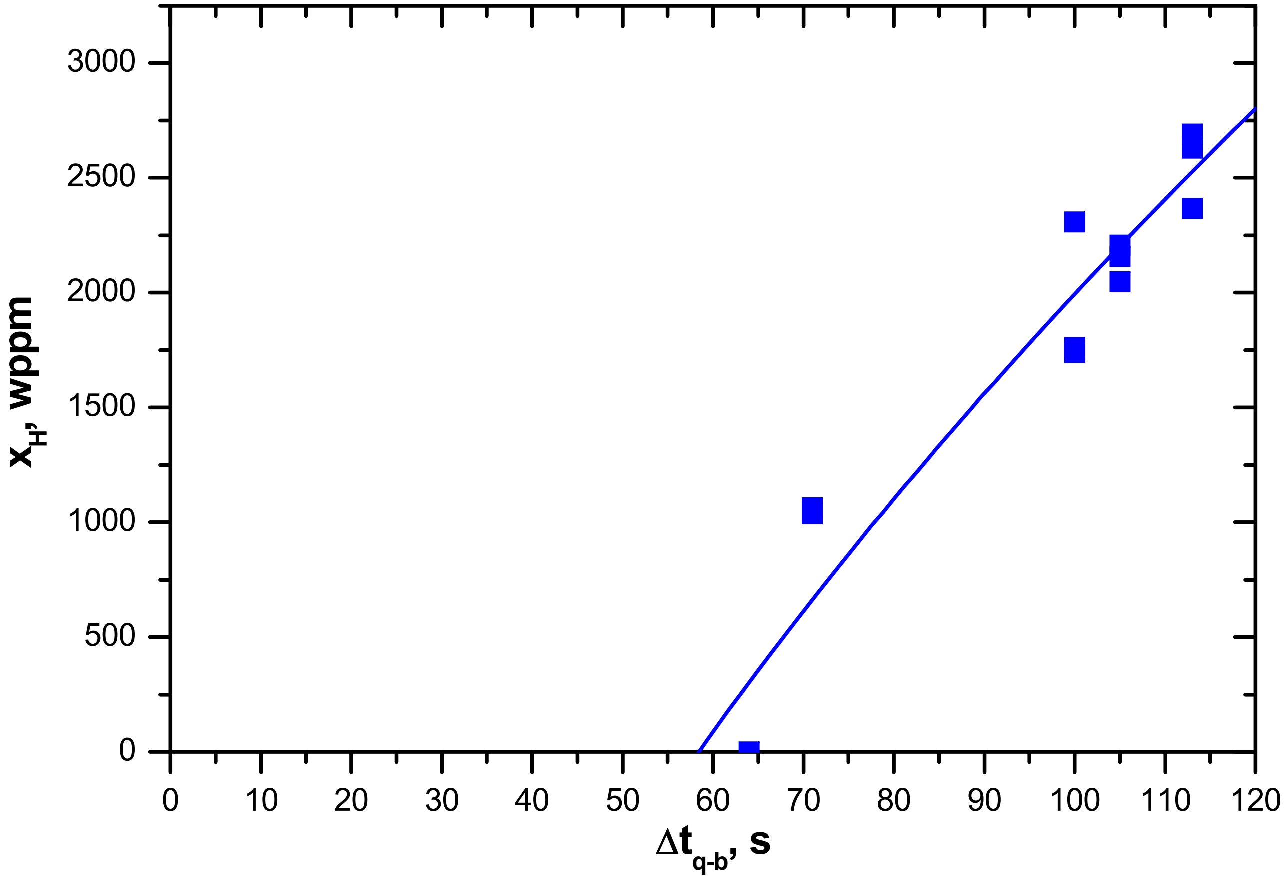


Neue Messungen an QL0-Proben



QUENCH-L0 R#14

Ergebnisse



3000
2500
2000
1500
1000
500
0
0 10 20 30 40 50 60 70 80 90 100 110 120
x_H, wppm
Δt_{q-b}, s

Summary and Conclusions

- Neutron imaging is a powerful tool to investigate the system hydrogen – zirconium.
- 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 hydrogen distribution in nuclear fuel cladding tubes after failure in LOCA tests.

Outlook

Next steps:

- Investigation of different materials applied in different LOCA scenarios.
- Investigations of hydrogen re-distribution during DHC.

Wishes for the future:

- Increase of the neutron flux to reduce illumination times in in-situ experiments.
- Combination with other methods, for instance SANS to study hydride precipitates (monochromatic beams are needed!)

Aknowledgement

- The QUENCH team at KIT, in particular Marius van den Berg and Camille Goulet
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