Neutron Radiography Investigations to Study the Material Behaviour in Loss of Coolant Nuclear Accidents

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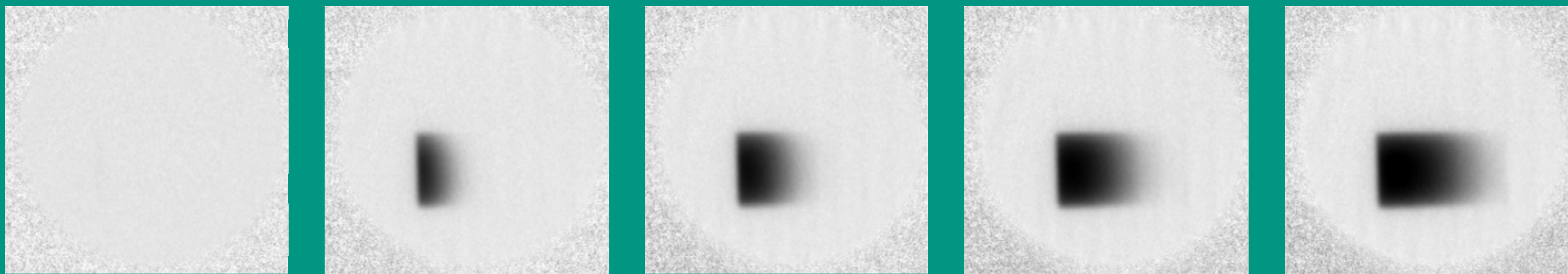
Institute for applied materials / Program NUCLEAR



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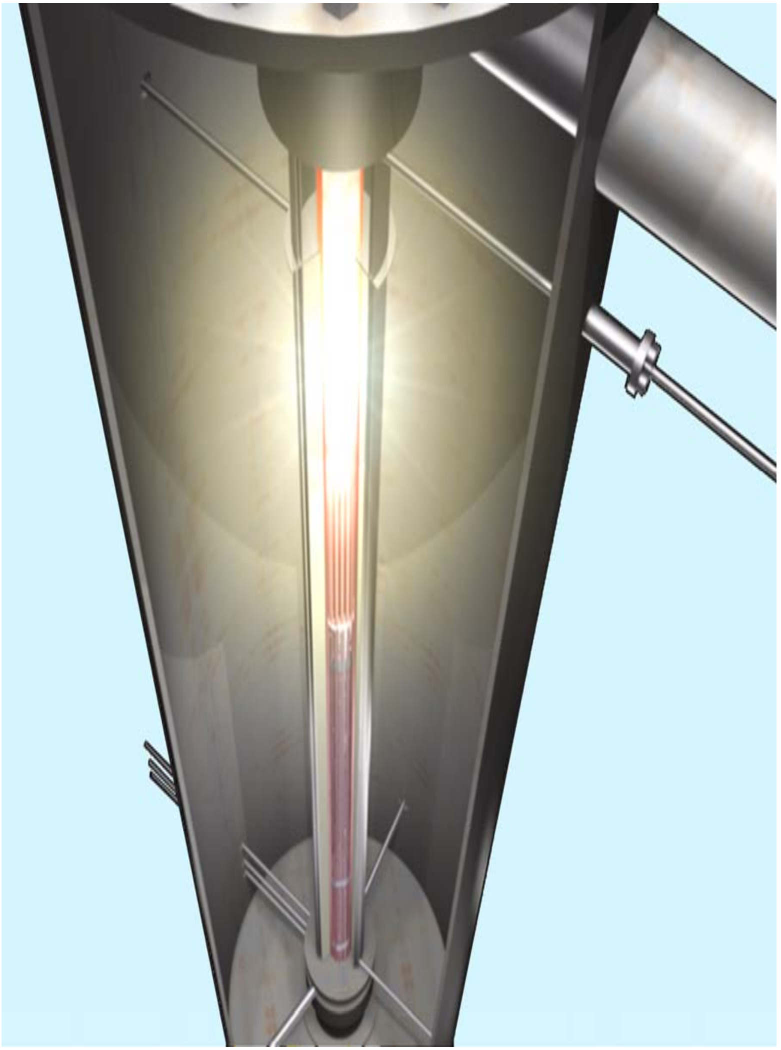
Introduction: The QUENCH program at KIT



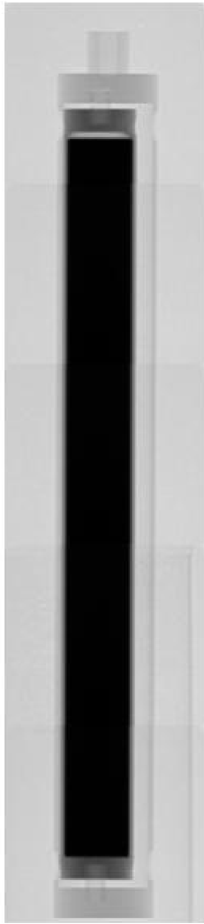
At KIT the severe accident of PWR cores are simulated experimentally in the large scale QUENCH facility.

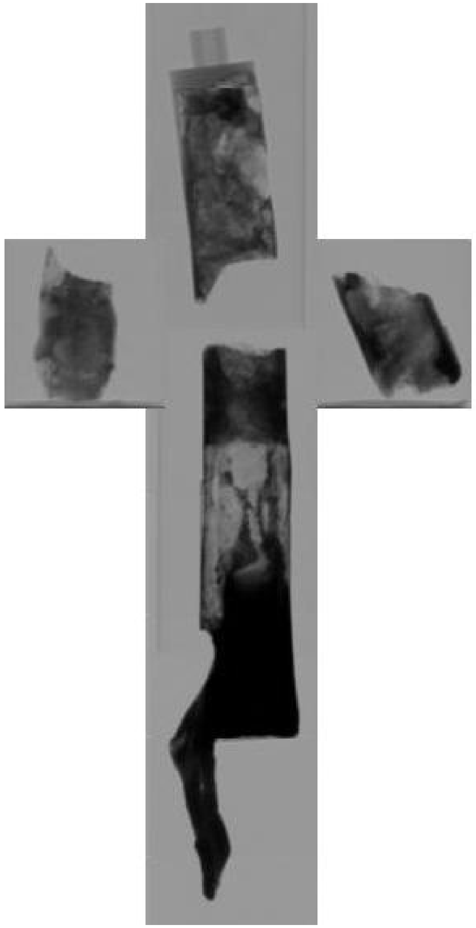
Emerging cooling of the overheated reactor core results in steam oxidation of the zirconium alloys used as fuel rod cladding material:

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

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

Investigations of control rod failure

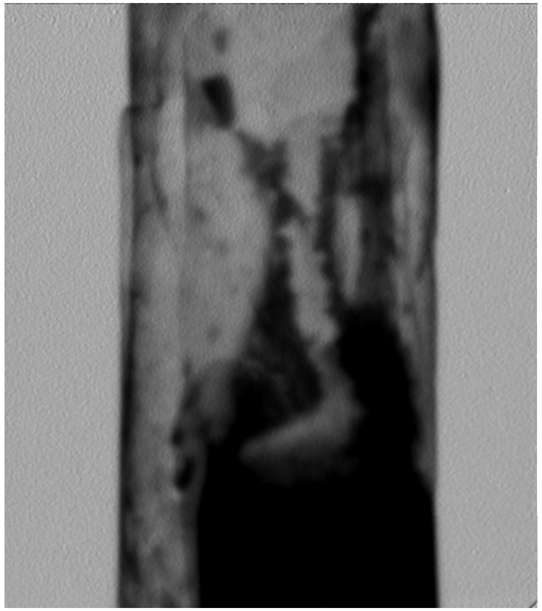




Information coming from structure materials (SS, Zry-4) and absorber material (AgInCd) has to be separated.

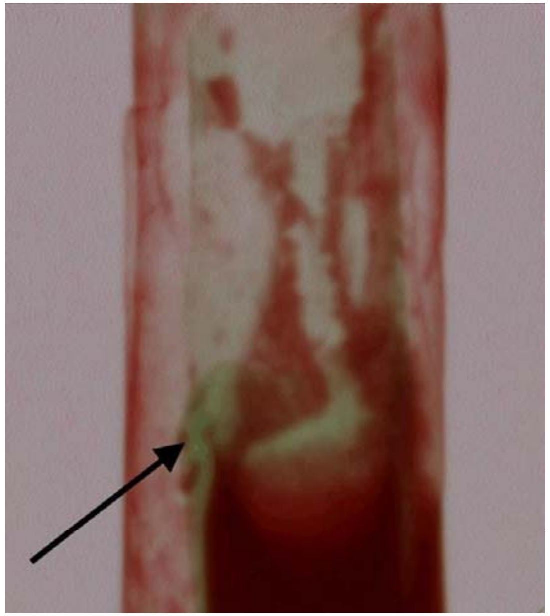
Application of different neutron spectra

Investigations of control rod failure



a) without Cd filter
12 s

b) with Cd filter
600 s



c) False color mix of the two radiographs

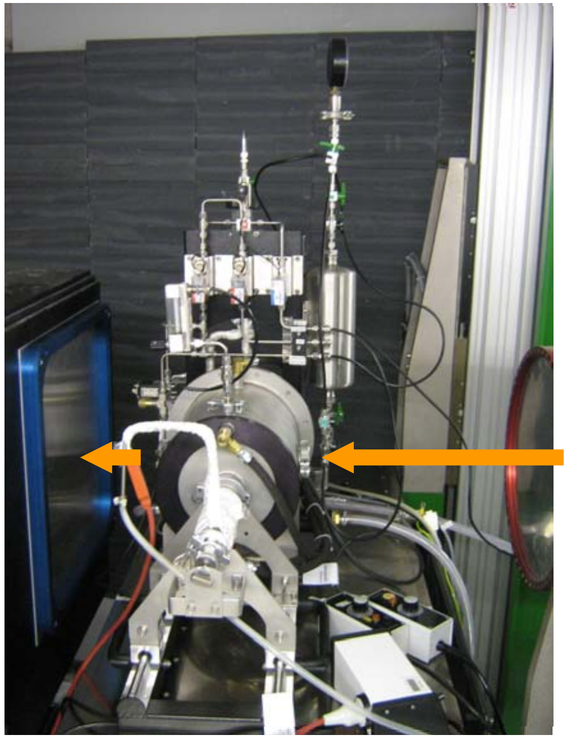
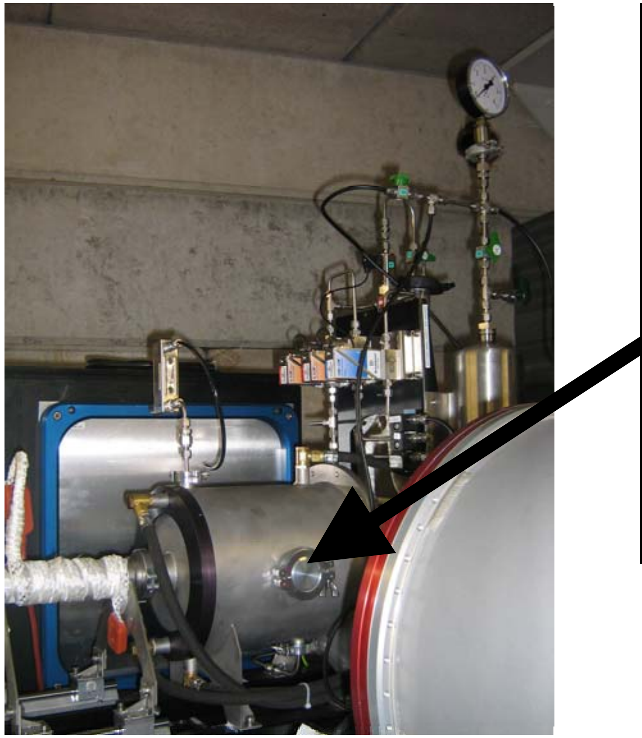
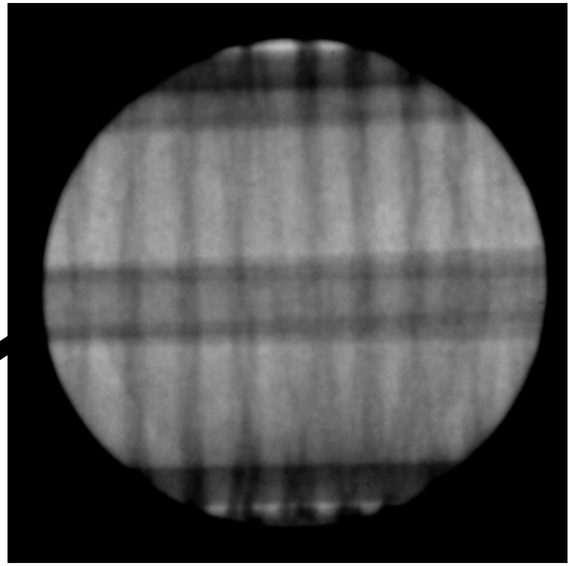
In-situ investigations

Why measure the hydrogen concentration in zirconium by means of neutron radiography?

- spatial resolution up to 25 µm
- strong contrast between hydrogen and zirconium
- fully quantitative analysis is possible by calibration
- non-destructive
- fast (5 .. 120 s per frame)

} possibility of in-situ investigations (non-destructive, fast)

In-situ neutron radiography experiments

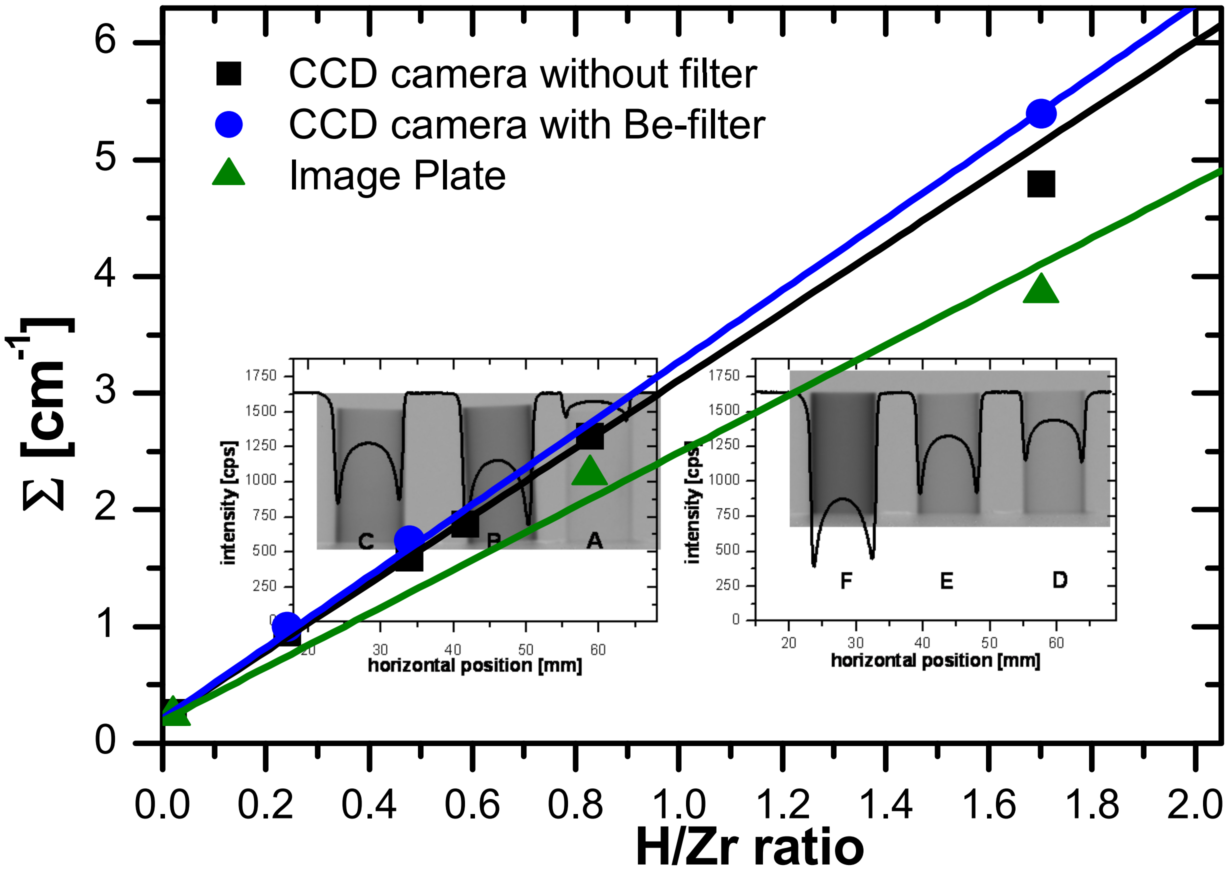




INRRO facility

In-situ-**N**eutronen-**R**adiographie-**R**eaktions-**O**fen

(in-situ neutron radiography reaction furnace)

Calibration ex-situ

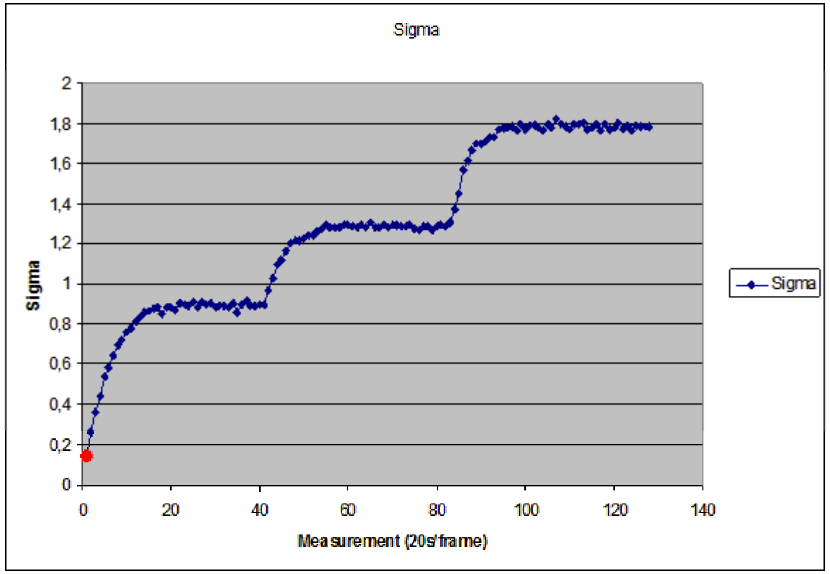


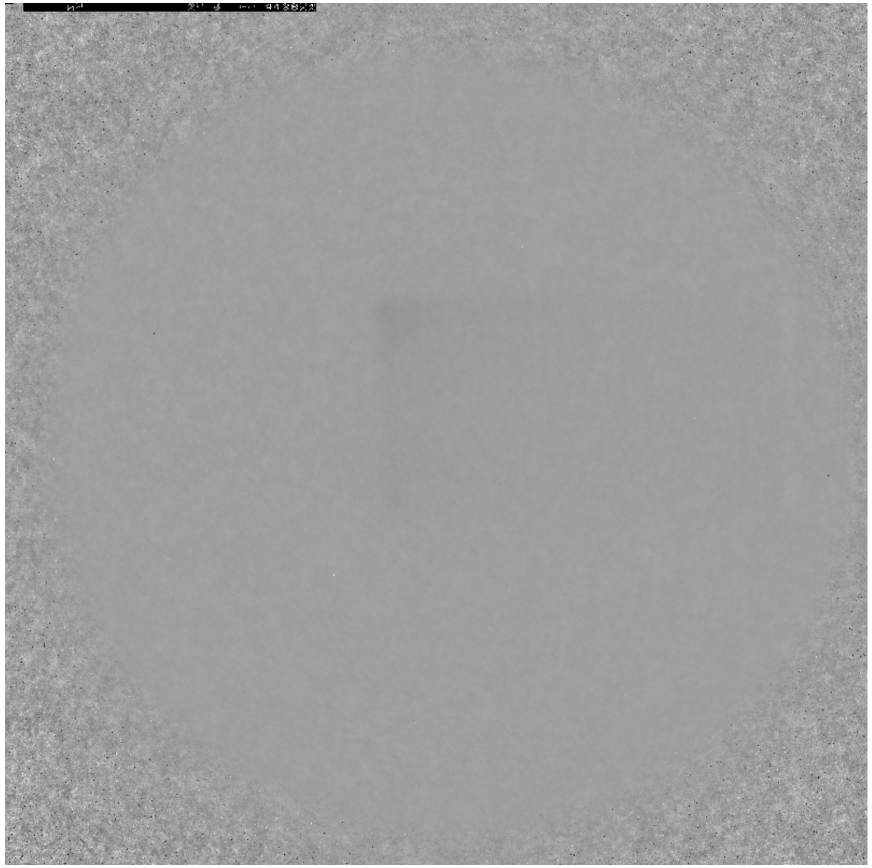
Calibration in-situ

Sieverts´ law:

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

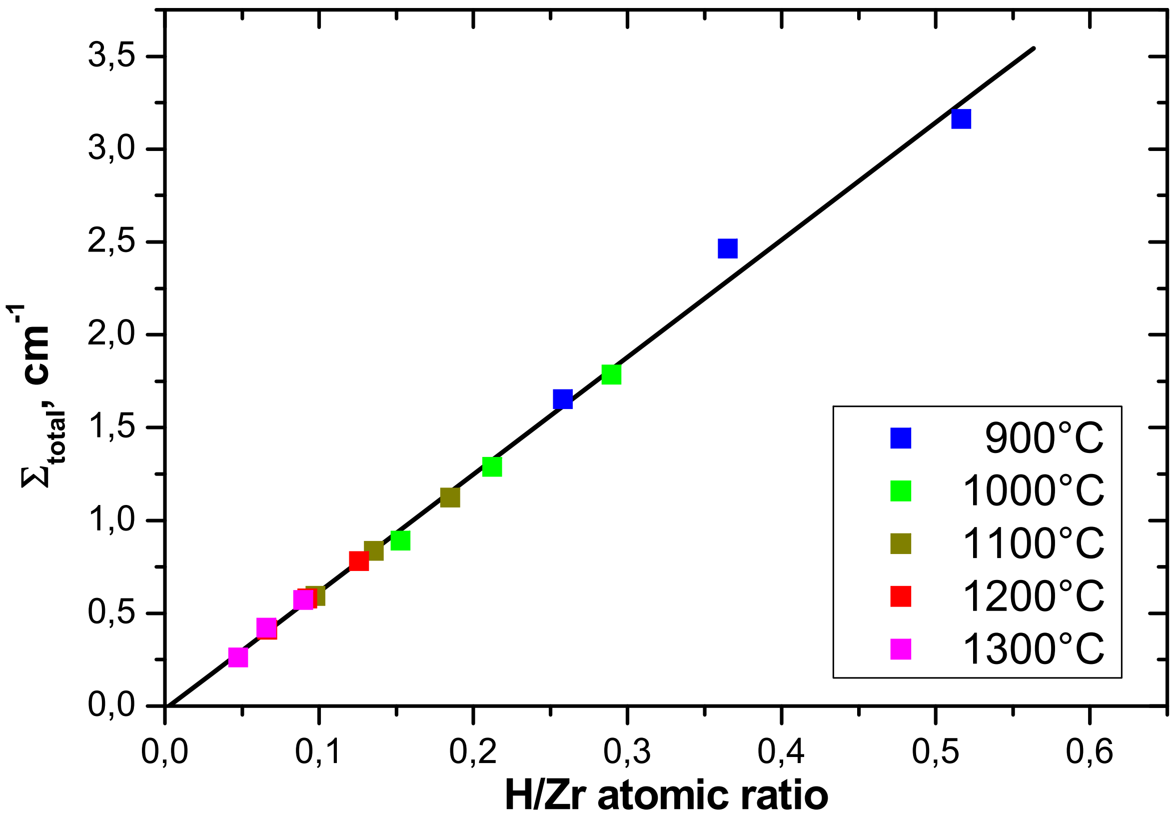
$$K_S \quad = \exp\left(\frac{\Delta_S S}{R} - \frac{\Delta_S H}{R \cdot T}\right)$$





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

Calibration in-situ



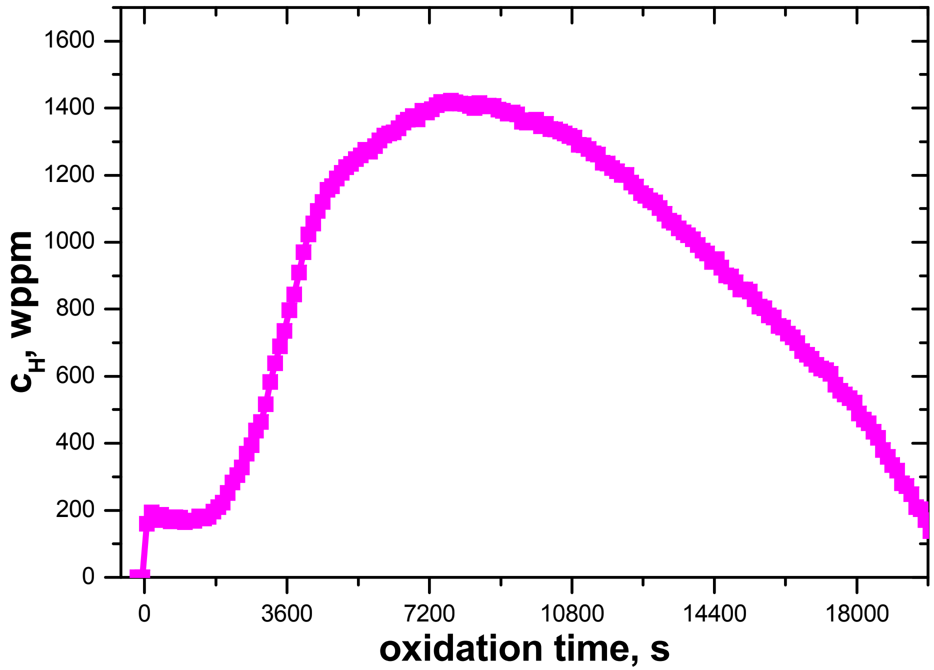
- Linear dependence between H/Zr ratio and Σ_{total}
- No significant temperature dependence
- : $\Sigma_{total} = 6.32 \pm 0.12$ H/Zr

This corresponds with: σ_{total}, H = 149 barn

Thermal neutrons: 82.4 barn

In-situ investigation of steam oxidation

steam oxidation



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

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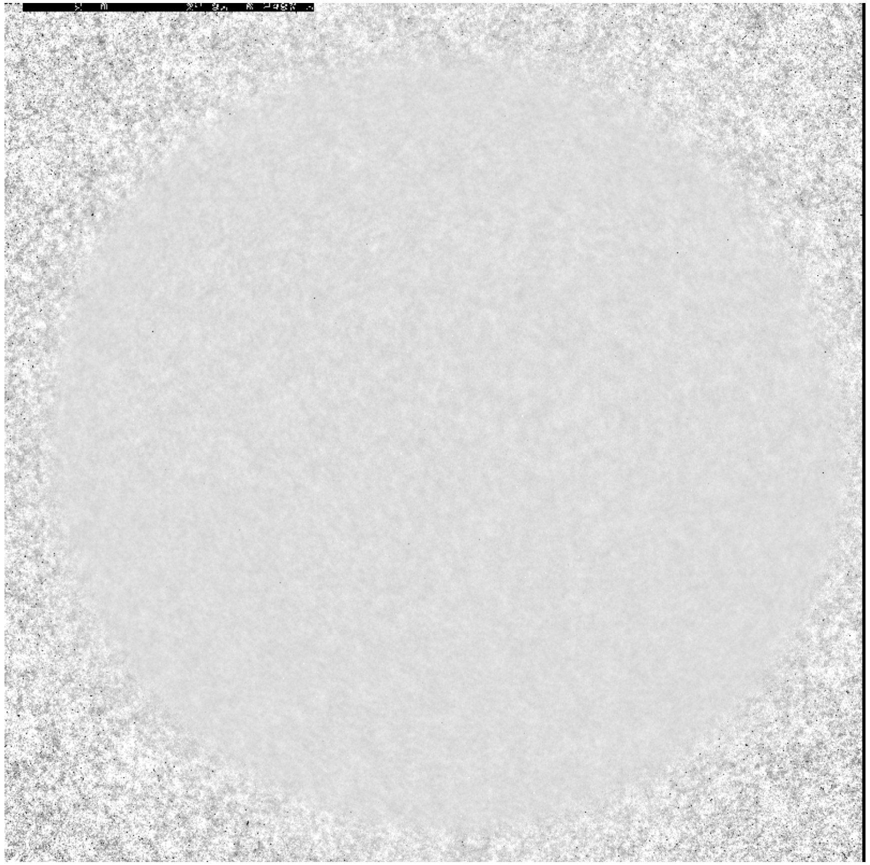
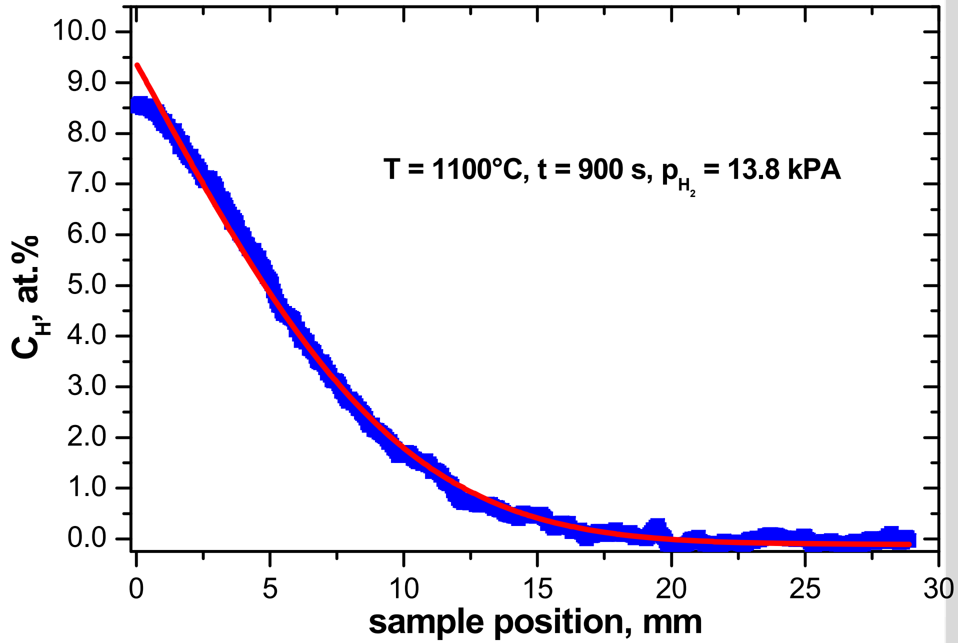
in.-situ investigations of hydrogen diffusion

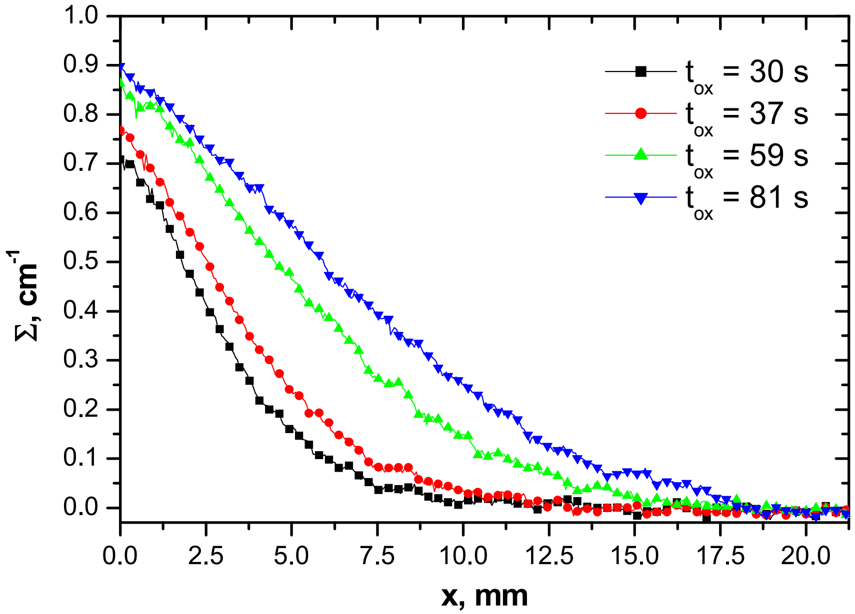
Hydrogen diffusion into a solid Zry-4 cylinder (Ø =12mm, l = 20 mm) at 1100°C (time ratio: 1 : 100)

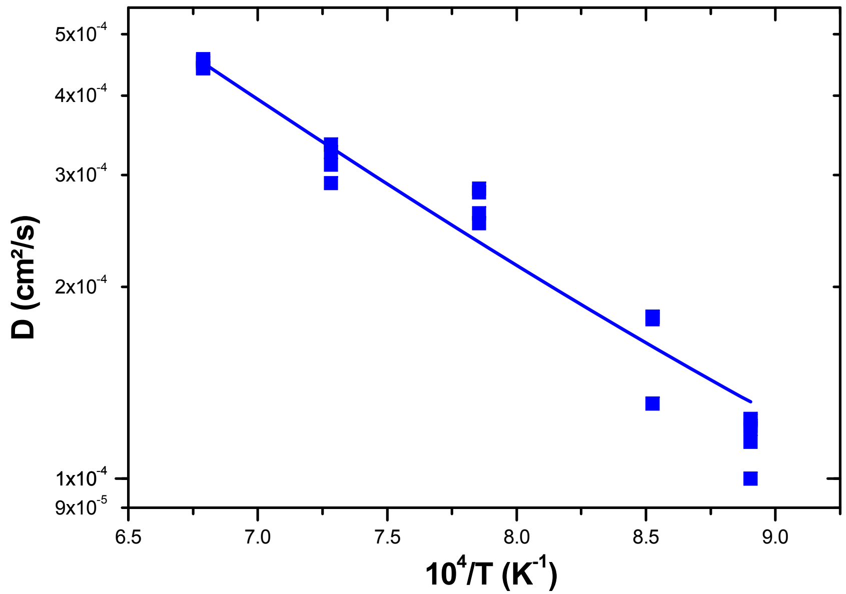




$$D_H(T = 1373\,K) = 3.39 \cdot 10^{-4}\,\frac{cm^2}{s}$$

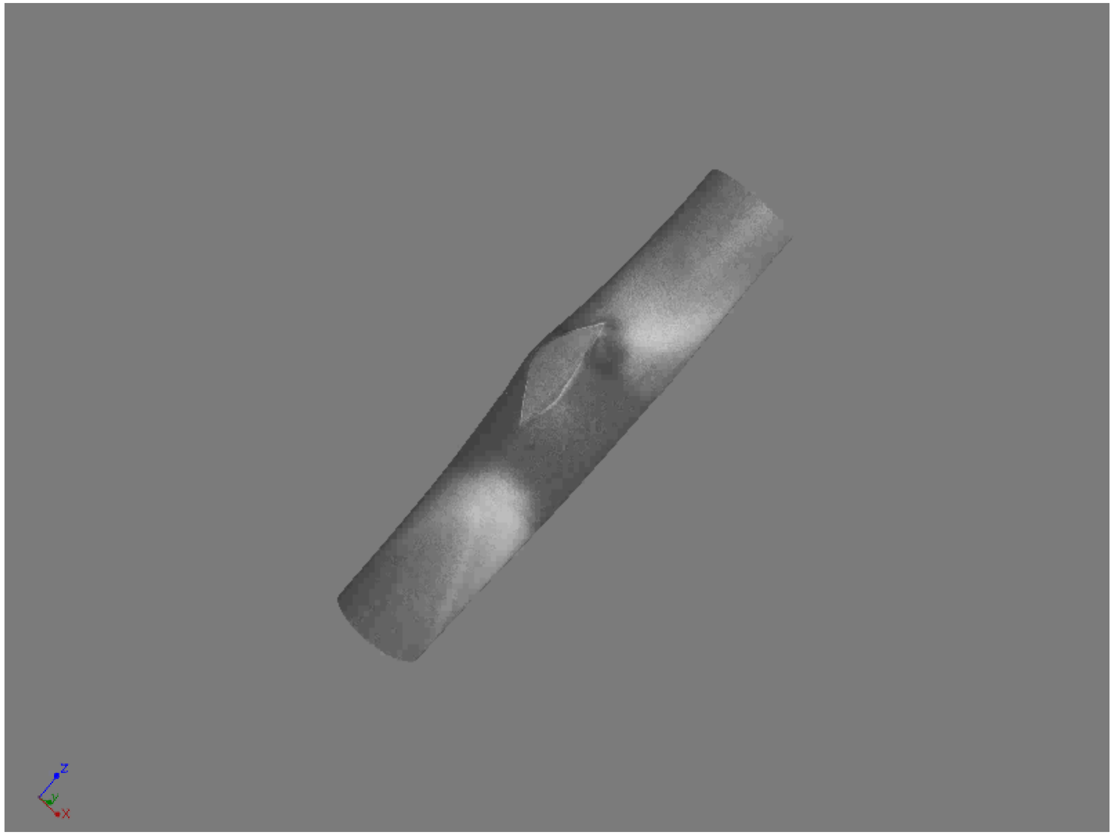
Hydrogen diffusion





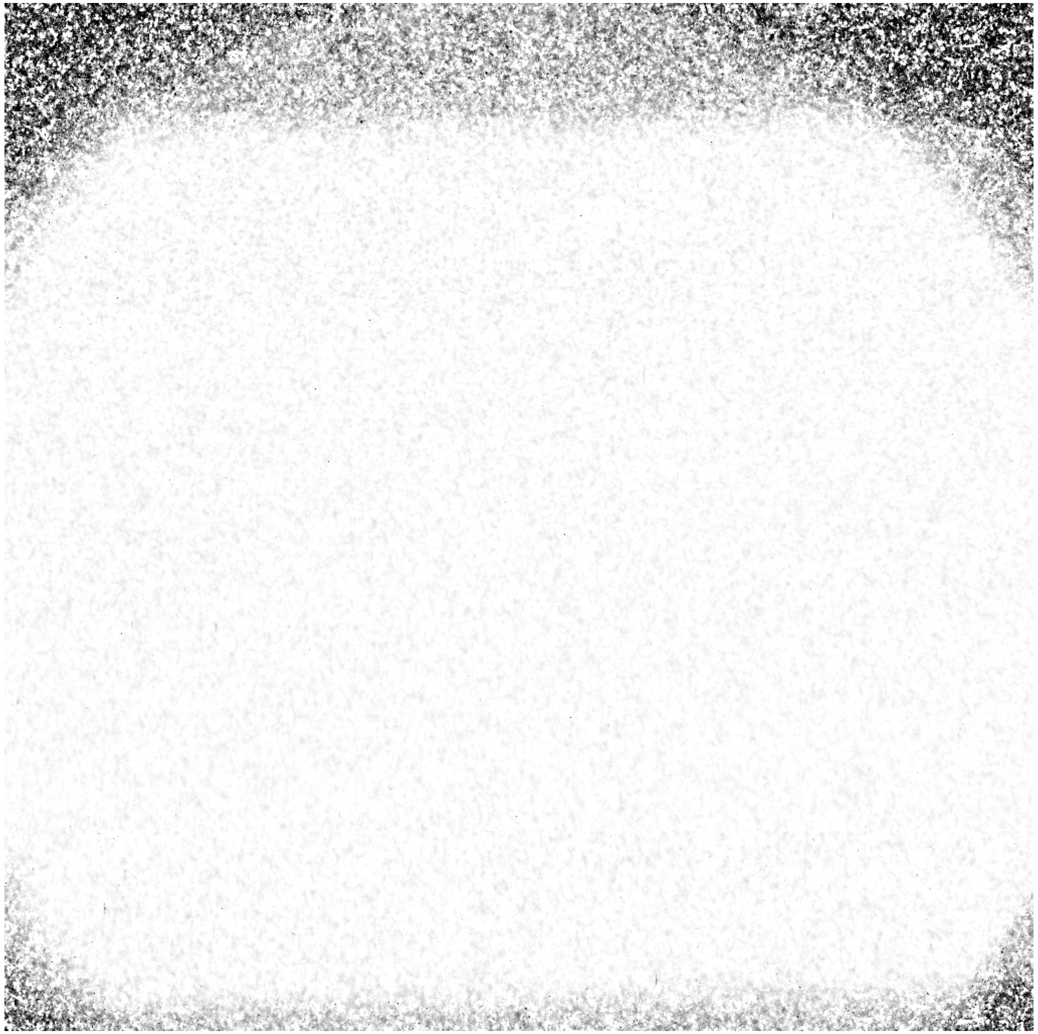
Activation energy: 55.43 kJ/mol

Ex-situ investigations of specimens prepared from LOCA simulation tests



Neutron tomography of cladding tubes failed in large scale LOCA simulation experiments

In-situ investigations of the delayed hydride cracking



Tensile loaded Zry-4 sample in Ar/H_2 atmosphere at 350°C

Movie is speeded up by a factor of 1000

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Conclusions

- Neutron radiography is a powerful tool to investigate material processes in zirconium alloys occuring during LOCA and severe accidents.
- NR is fast and non-destructive. These properties provides the possibility of in-situ investigations.
- Calibration can be performed. Quantitative analysis of hydrogen concentration in zirconium is possible.
- Diffusion of hydrogen in zirconium alloys was studied. The activation energy was determined.
- The neutron radiography investigations have provide new information about material processes during nuclear accidents never obtained by any other methods before.

Thanks

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