Update of the QUENCH Programme

M. Steinbrück, J. Stuckert, M. Große et al.

19th International QUENCH Workshop, Karlsruhe, 19-21 November 2013

Institute for Applied Materials, Programme NUSAFE

Outlook

- Motivation
- Separate-effects tests
- Bundle experiments
- Modelling / Code validation
- Education
- Future prospects

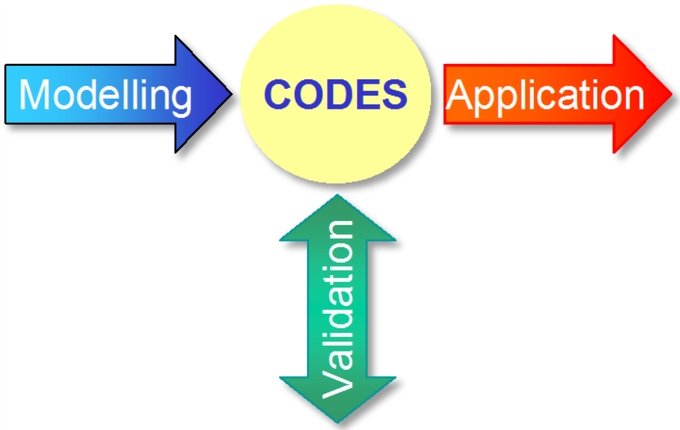
Motivation

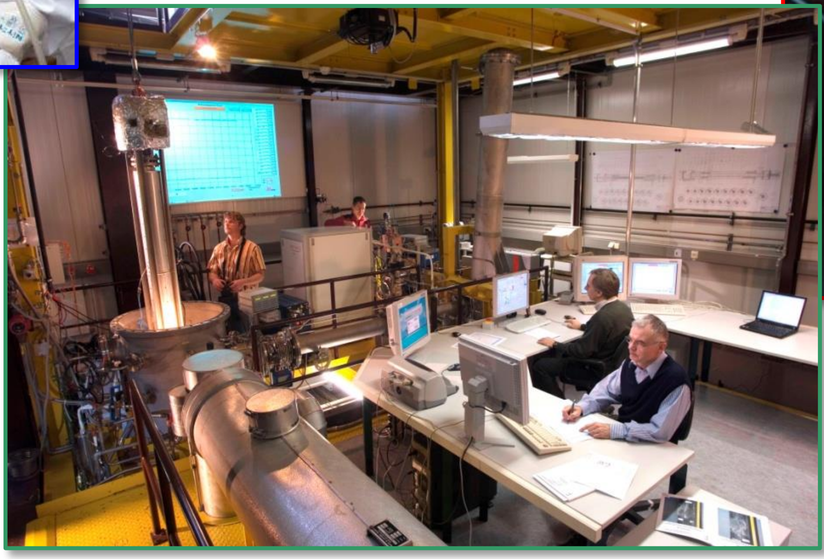
- Reflood is a prime accident management measure to terminate a nuclear accident
- Reflood may cause temperature excursion connected with increased hydrogen and FP release (severe accidents) and embrittlement of cladding and secondary hydriding (LOCA)
- Coolability of a degraded core is a matter of high priority (SARNET-SARP, OECD-GAMA, Fukushima)
- ➡ QUENCH experiments (bundle+SET) provide data for development of models and validation of SFD code systems

QUENCH Programme

Investigation of hydrogen source term and materials interactions during LOCA and early phase of severe accidents including reflood

Separate-effects tests

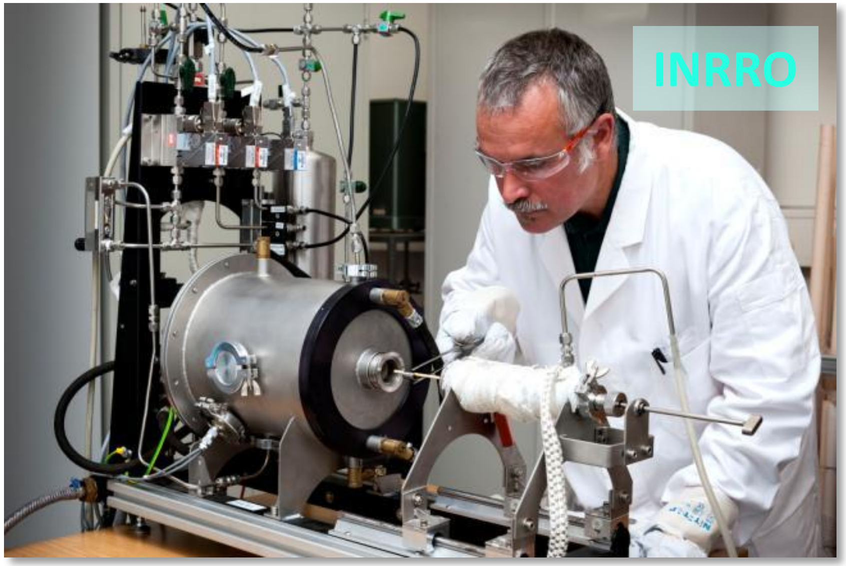


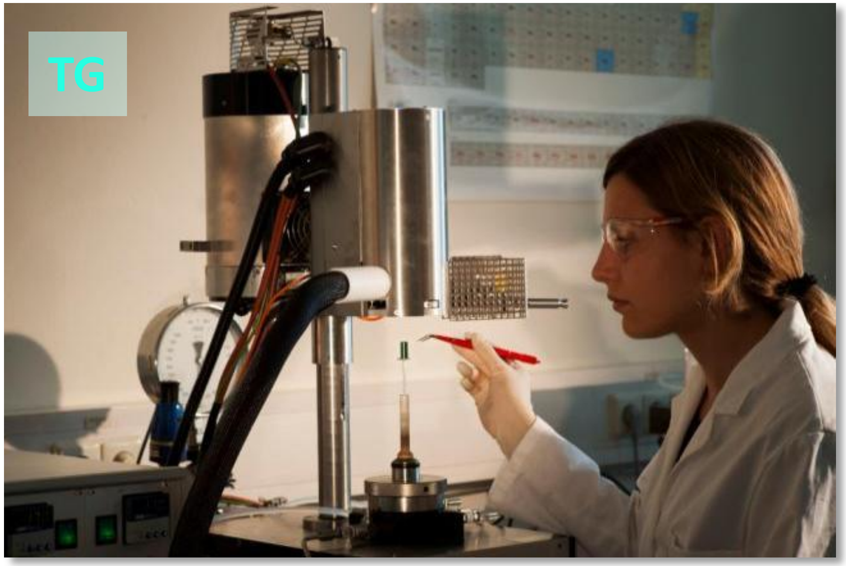


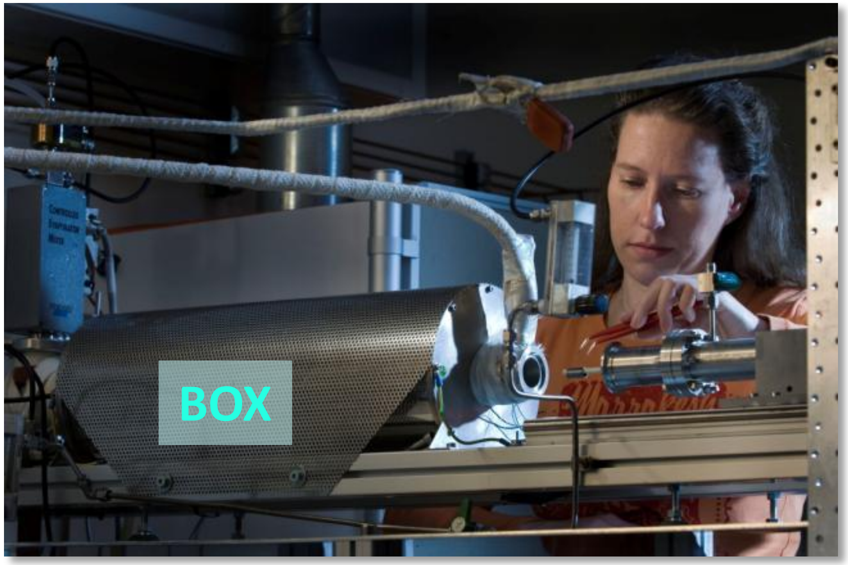
Bundle experiments

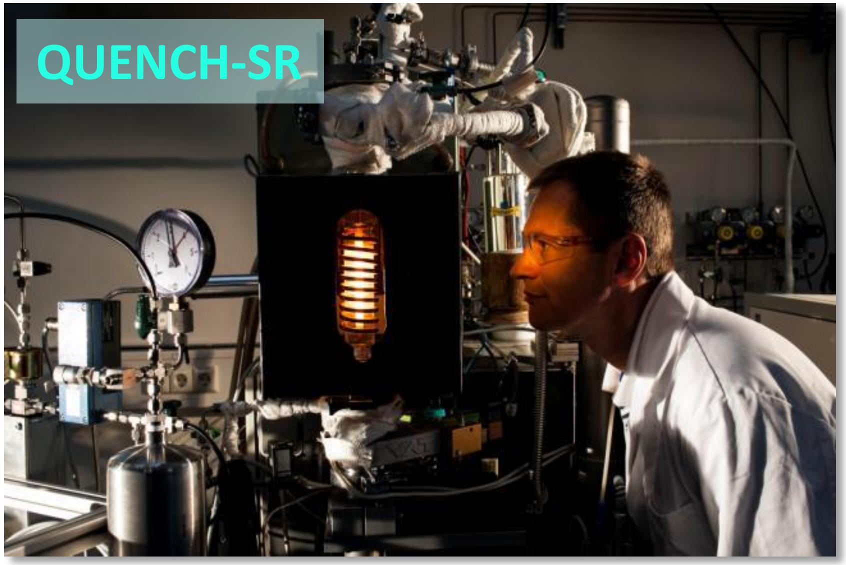
PWR fuel element

QUENCH Separate-effects tests: Main setups





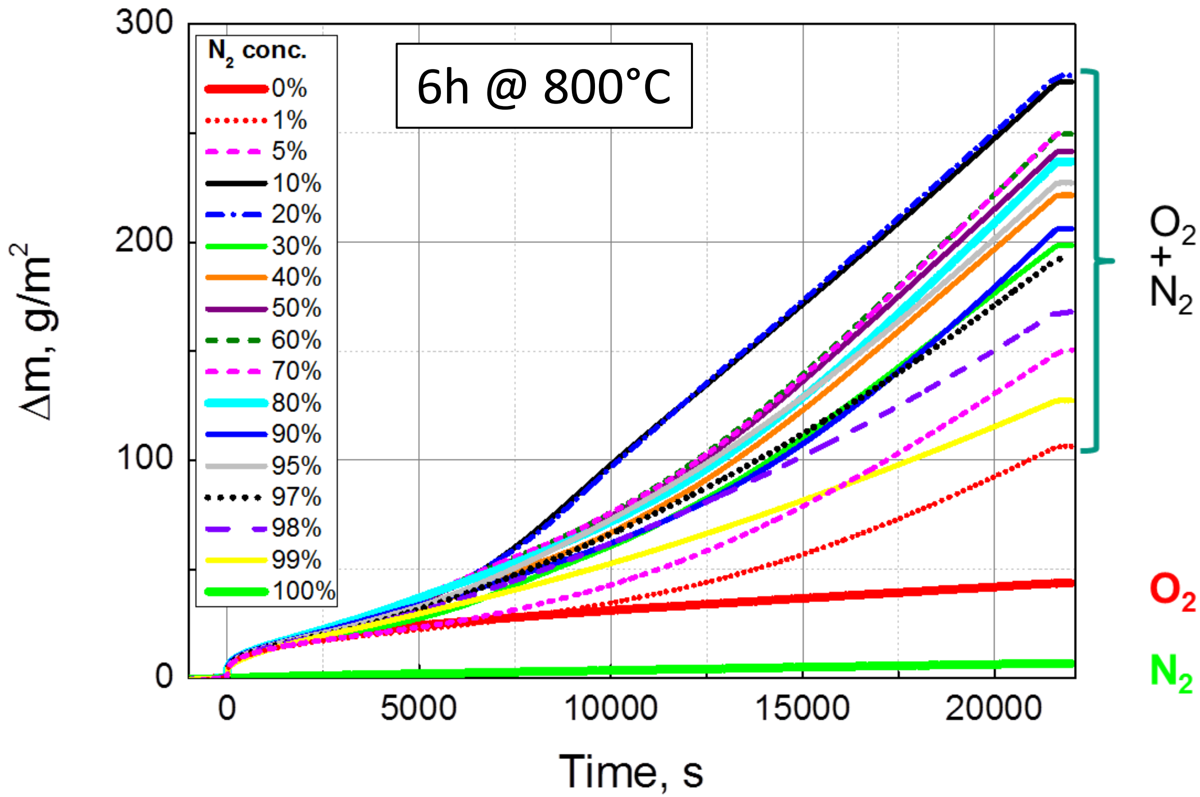




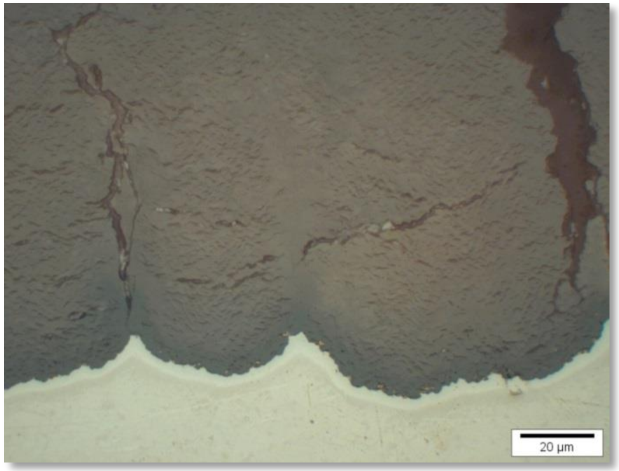
Separate-effects tests in 2013

- Experiments on mechanism of air oxidation of Zr alloys
  - Oxidation of Zircaloy-4 in oxygen-nitrogen mixtures
  - In-situ neutron radiography investigations Zr(O)-nitrogen reaction
- Neutron tomography for investigation of hydrogen diffusion in mechanically loaded samples
- Microstructure and mechanical properties of hydrogenated Zr alloys
- Experiments on high-temperature oxidation and quenching of silicon carbide
- Brazing tests on tungsten samples for fusion application
- …

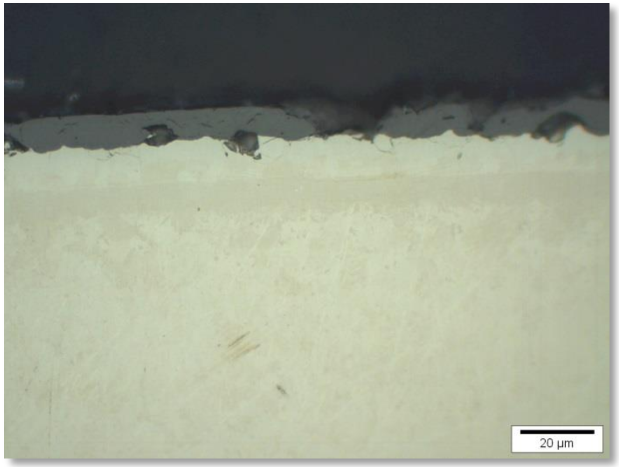
Reaction of Zircaloy-4 in N_2-O_2 mixtures



- Strong effect of nitrogen on oxidation kinetics of Zry-4 in N_2-O_2 mixtures over a wide range of composition



10% N_2



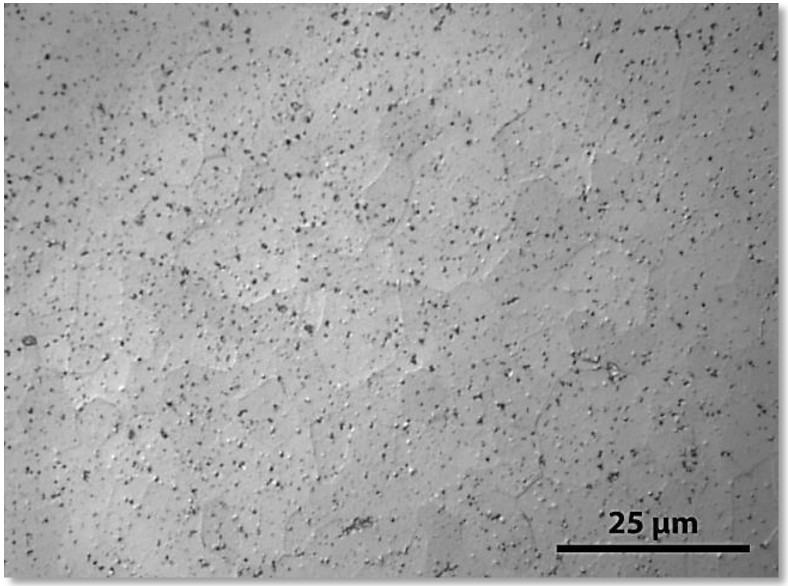
0% N_2

High-temperature oxidation of SiC materials

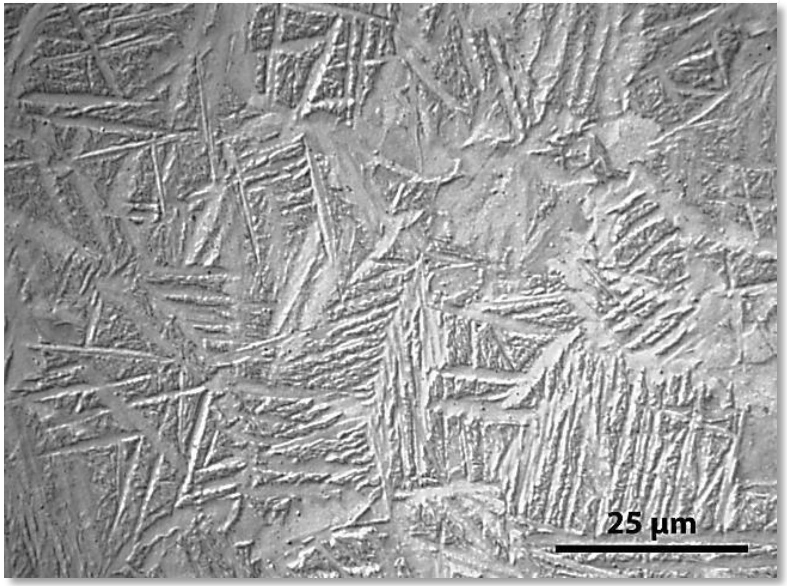
- PhD thesis started 04/2012 “**High temperature oxidation in corrosive atmospheres and quenching of silicon carbide**”
- Partner of the EC MatISSE program
- Materials:
  - Commercial α-SiC cylindrical samples (ESK Ekasic F-plus)
  - SiC-SiC cladding tubes provided by CEA and CTP
- Atmospheres:
  - Argon-oxygen mixtures
  - Helium-impurities mixtures
  - Steam
- Experiments with final quench phase from up to 2000°C

SiC oxidation in steam and quenching from 2000°C

Microstructure of hydrogenated cladding samples



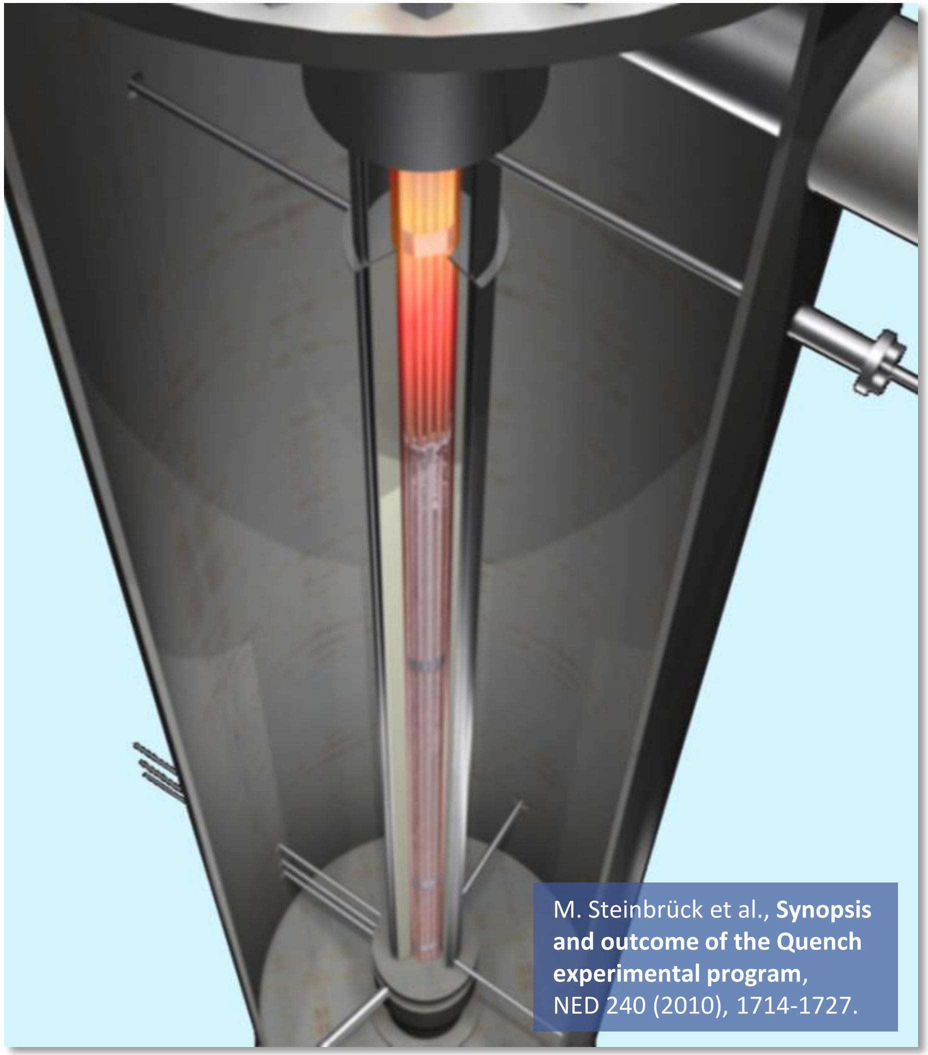
Annealed at 800°C in Ar
(0 wppm H)



Annealed at 800°C in Ar+H_2
(3000 wppm H)

QUENCH facility

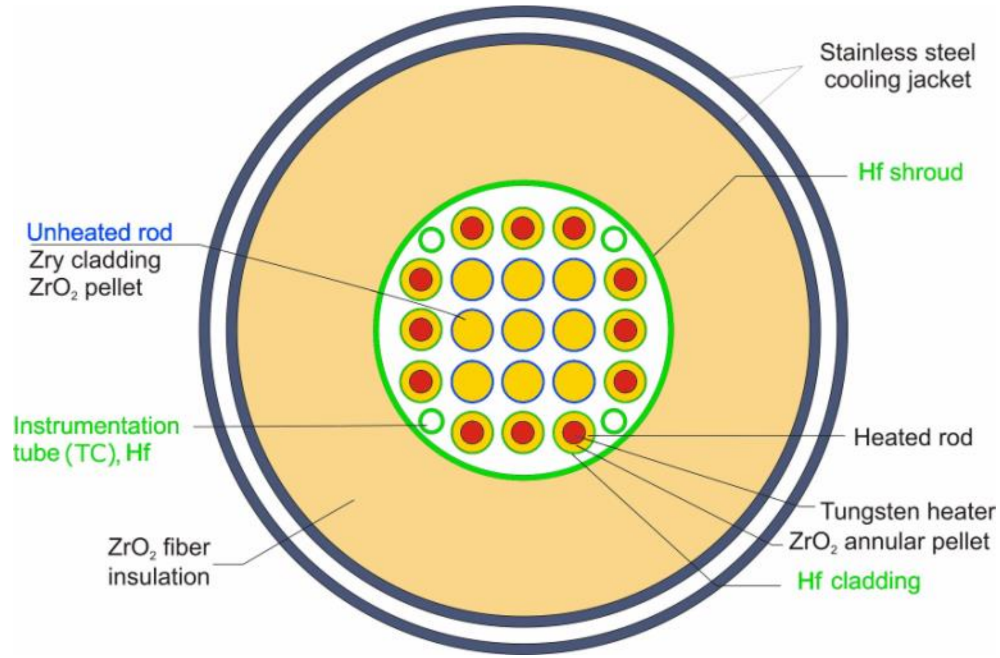
- Unique out-of-pile bundle facility to investigate reflood of an overheated reactor core
- 21-31 electrically heated fuel rod simulators; T up to >2000°C
- Extensive instrumentation for T, p, flow rates, level, etc.
- So far, 17 experiments on SA performed (1996-today)
  - Influence of pre-oxidation, initial temperature, flooding rate
  - B_4C, Ag-In-Cd control rods
  - Air ingress; debris formation
  - Advanced cladding alloys
- DBA LOCA experiments with separately pressurized fuel rods



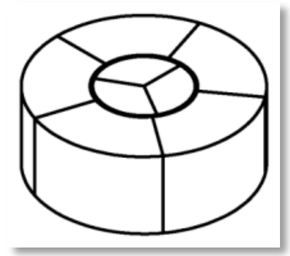
M. Steinbrück et al., **Synopsis and outcome of the Quench experimental program**, NED 240 (2010), 1714-1727.

QUENCH-Debris

- Conducted at 30/31 Jan 2013
- Investigation of formation and coolability of debris and melt in the core
- In the framework of the SARNET-2 program
- Post-test examinations underway

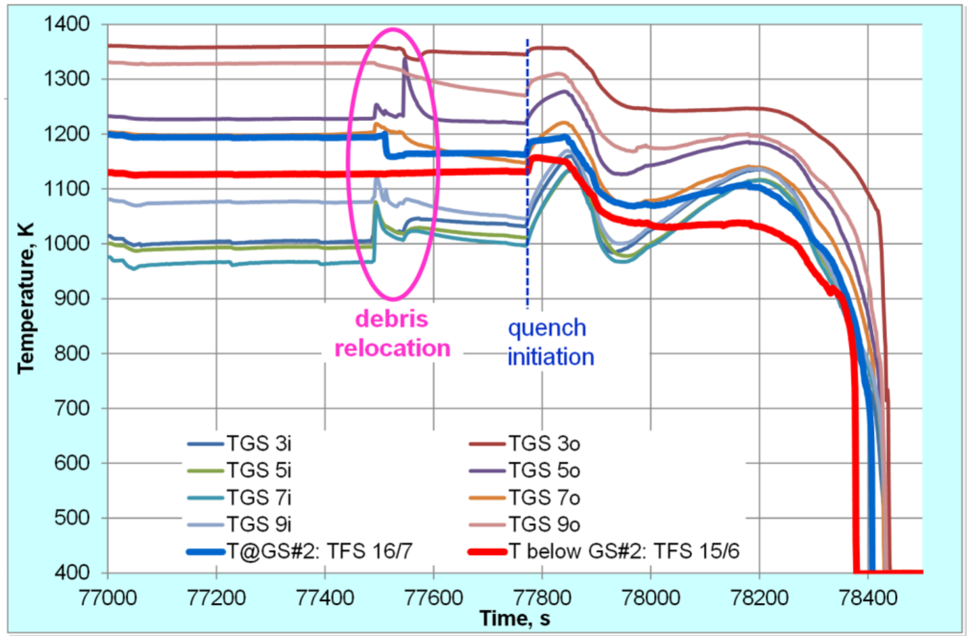


Bundle cross section



Pellet segments

QUENCH-Debris; preliminary results

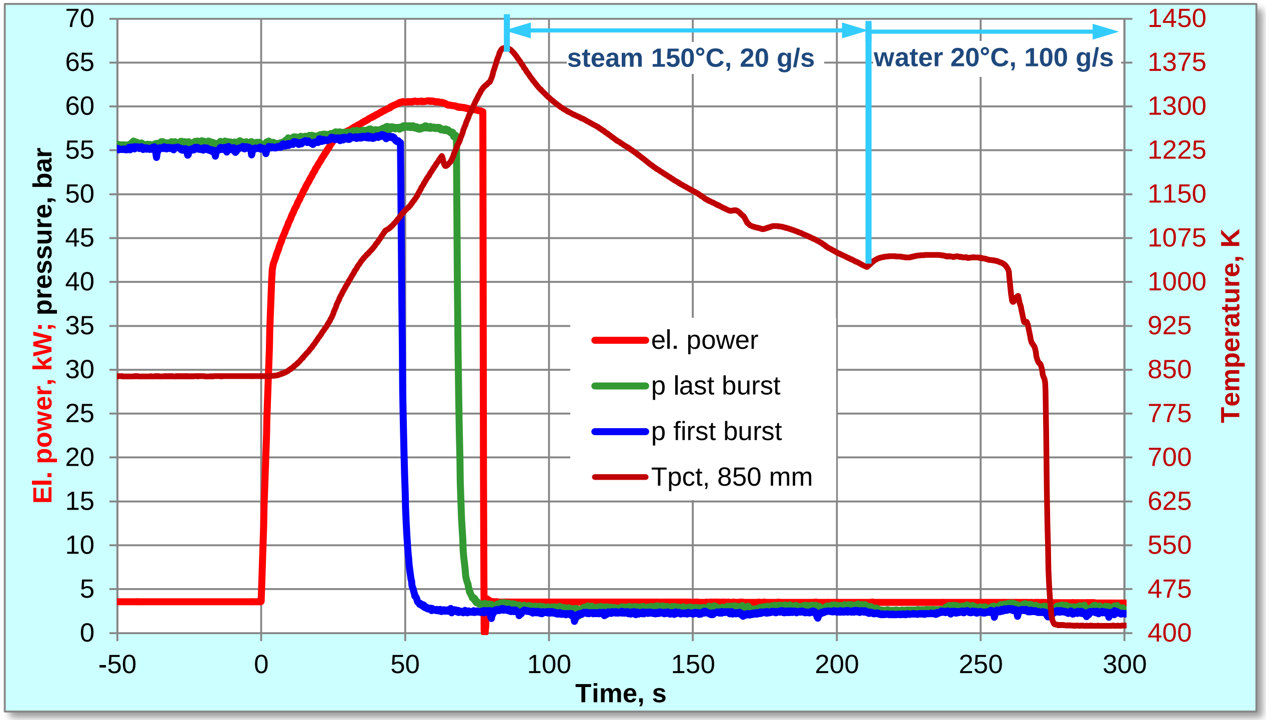


Temperatures in the final phase

Post-test debris

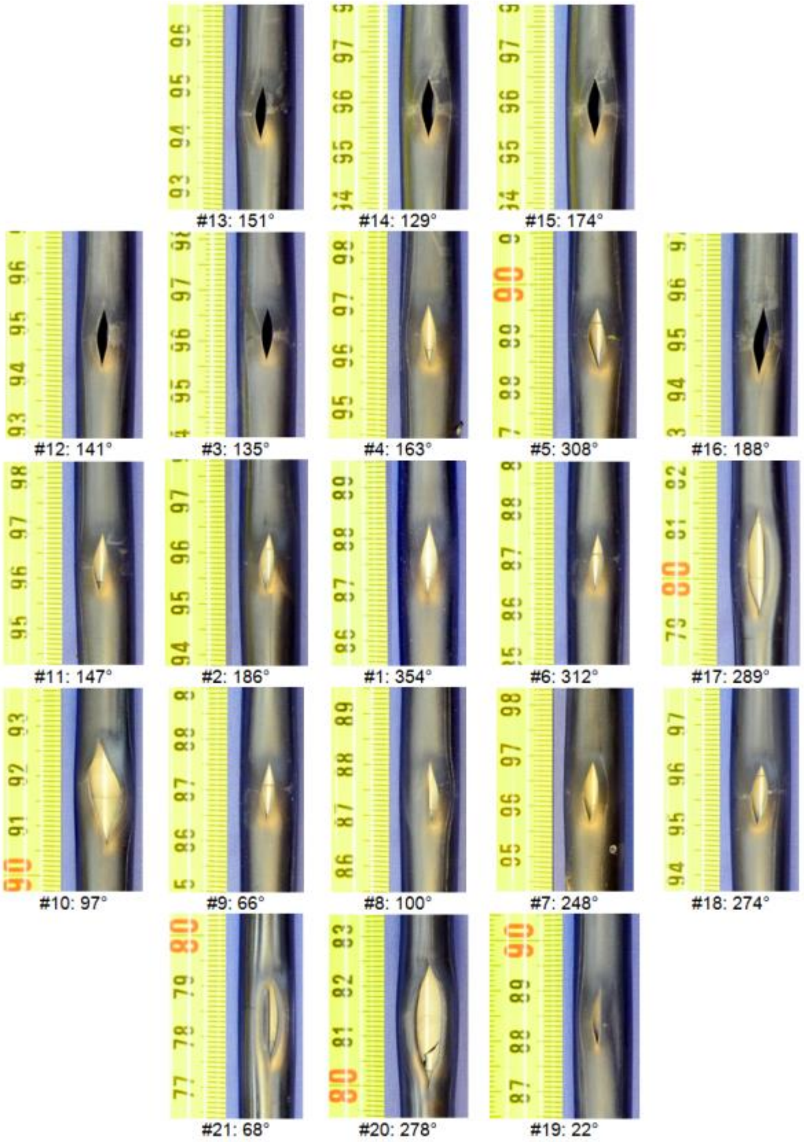
QUENCH-L2

- Third test of the QUENCH-LOCA series with M5® cladding
- Conducted at 30 July 2013
- Post-test examinations are underway, including mechanical testing, metallography, neutron radiography and tomography, micro hardness measurements, XRD, TEM



QUENCH-L2
Test conduct

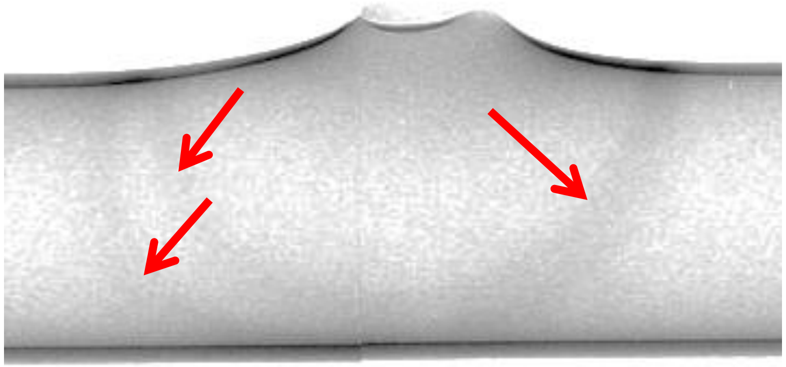
QUENCH-L2; burst positions

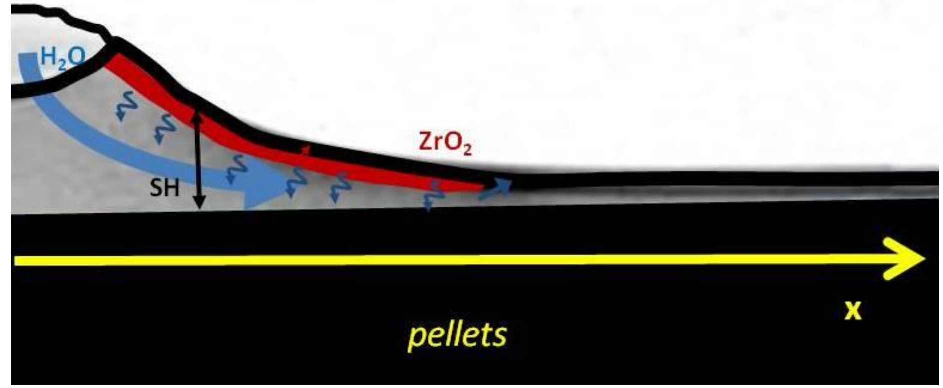


Modelling and code validation

- QUENCH bundle tests are part of validation matrices of most SFD code systems
- SCDAP/R5 and MELCOR used for pre-test calculations (PSI), SOCRAT used for LOCA preparation (IBRAE)
- Participation in the OECD TMI-2 benchmark
- QUENCH-10/-16 benchmark in the framework of SARNET
- New model for description of secondary hydriding during LOCA
- Separate-effects test data on air oxidation of Zr alloys are used by PSI, RUB, EdF and others for model development

Model for hydrogen distribution after secondary hydriding





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

- 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

Reporting

- QUENCH-16: KIT Scientific Report 7634 published
- QUENCH-L0: KIT Scientific Report 7571 published
- Numerous papers and conference contributions

Education

- AREVA Nuclear Professional School
  - Lectures on Severe Accidents in October 2013
  - Next courses planned for October 2014
  - Information: http://www.anps.kit.edu/
- QUENCH group hosts guest scientists, and supervises students during placements, bachelor, master, and PhD thesis
- Two agreements for common mentoring of PhD thesis at PSI and EdF

Outlook 2013-2015

- Evaluation of the HGF Program Nuclear Safety in January 2014
- QUENCH-LOCA
  - Supported by German VGB PowerTec
  - QUENCH-L3-5 under preparation and planned for 2014 with opt. Zirlo® and M5® claddings
  - Two tests planned with hydrogen preloading for simulation of high burnup
- Bundle experiments and SETs on high-temperature oxidation and quenching of accident tolerant claddings (ATF)
- Cooperation with Japanese organizations for Fukushima-related experiments are under discussion
- SETs on various further topics

Co-operations

Programs

- NUGENIA
- CSARP
- IAEA
- OECD-NEA

Bilateral

- PSI
- AEKI
- IRSN, CEA
- IBRAE, KI
- RUB-LEE, IKE
- ITU
- GRS
- VGB, AREVA, EdF
- CNEA Bariloche
- ENEA
- NECSA, BAM, HMI
- JNES, JEAE

Acknowledgement

- IAEA and EC JRC for support of the 2013 QUENCH workshop
- Helmholtz Association for funding program NUSAFE at KIT
- Program NUSAFE and IAM institute's management for broad support of our activities
- EC SARNET2 program for supporting QUENCH-Debris experiment
- VGB for supporting QUENCH-LOCA test series

- And last but not least the QUENCH team:
  V. Avincola, M. Heck, J. Laier, J. Moch, H. Muscher, U. Peters, Pshenichnikov, Anton (IAM), A. Pshenichnikov, C. Rössger, U. Stegmaier, M. Walter

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