

Update of the QUENCH Programme

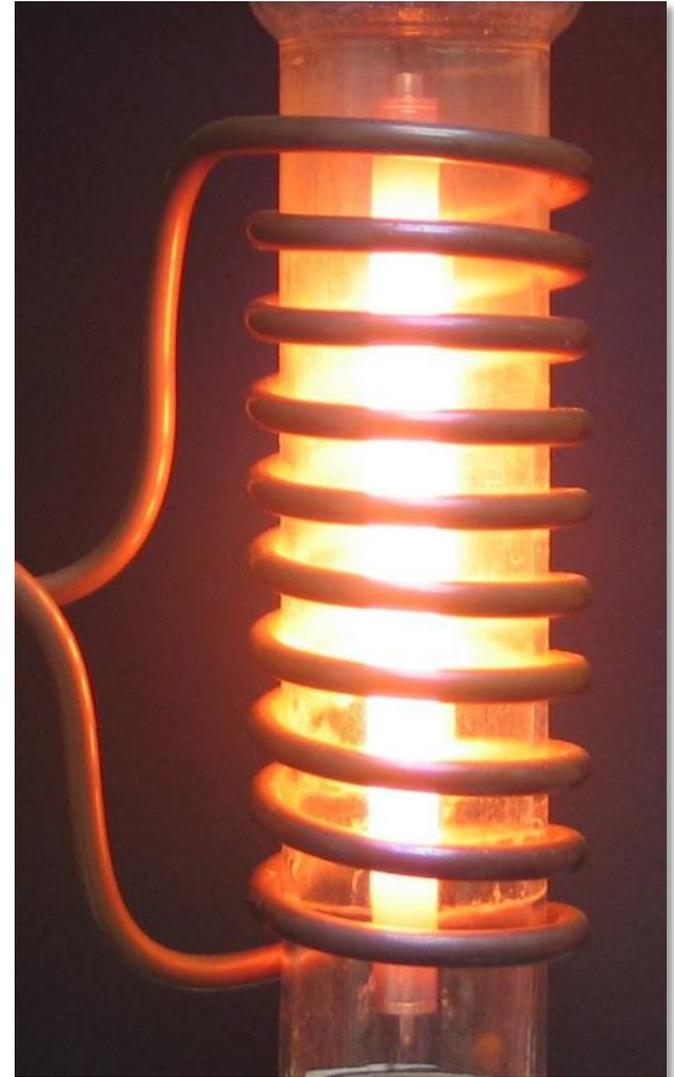
M. Steinbrück, J. Stuckert, M. Große et al.

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

Institute for Applied Materials, Programme NUSAFE



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



- 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

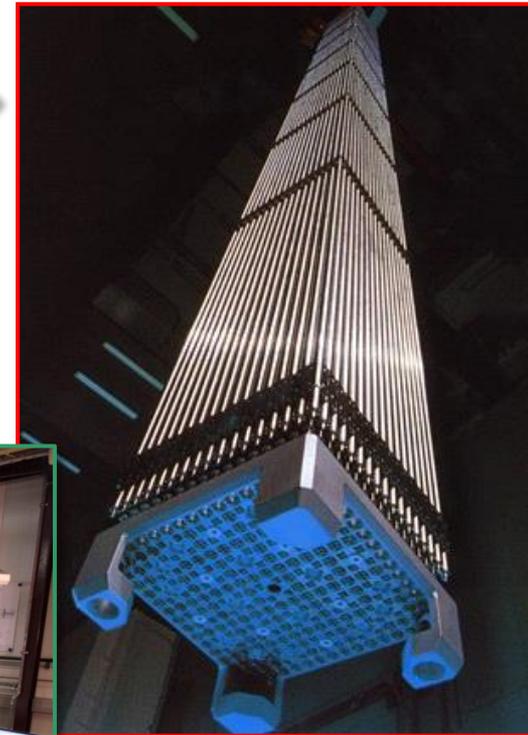
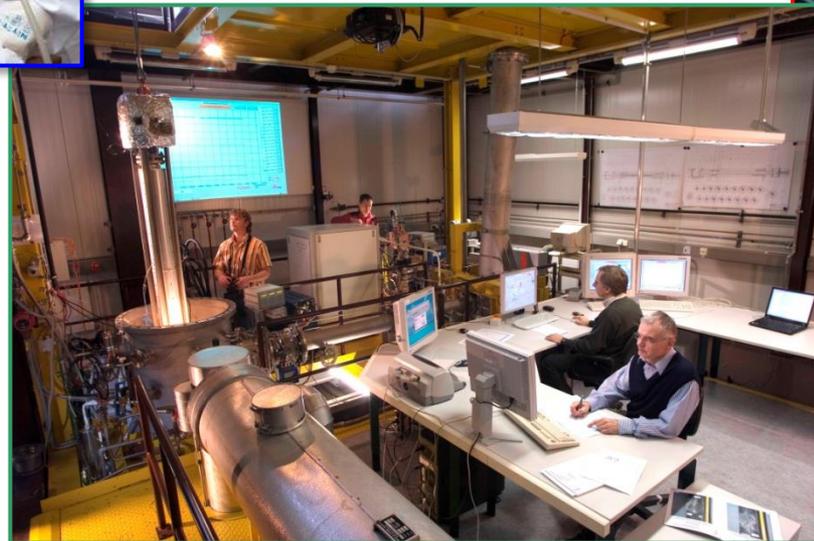
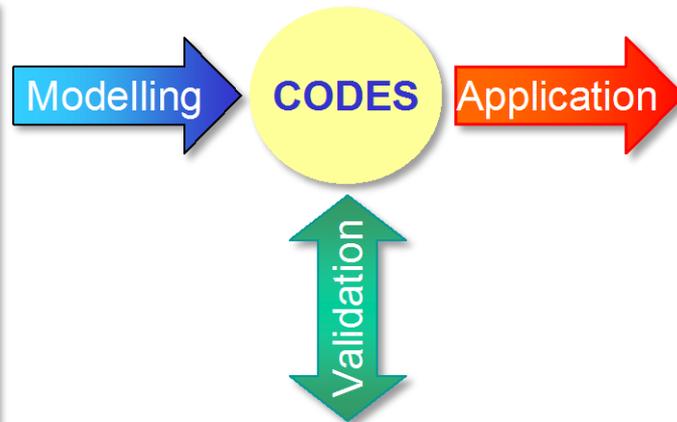
QUENCH Programme

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



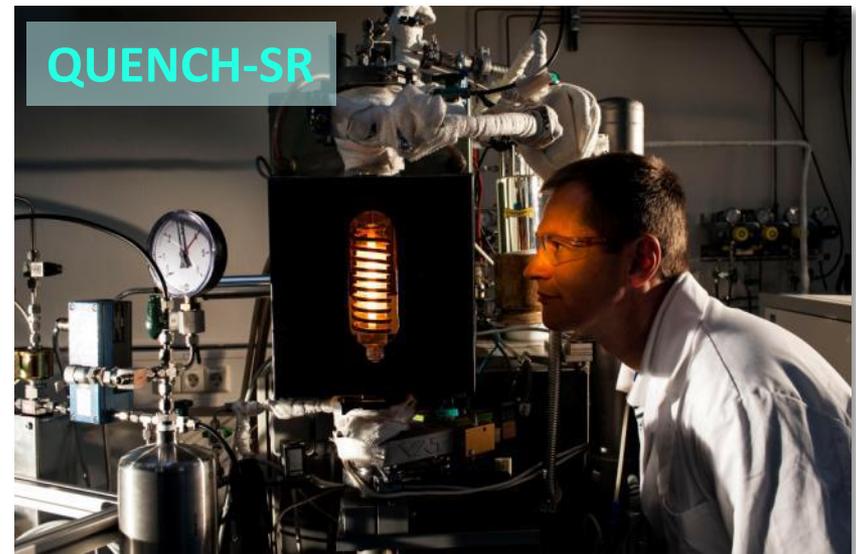
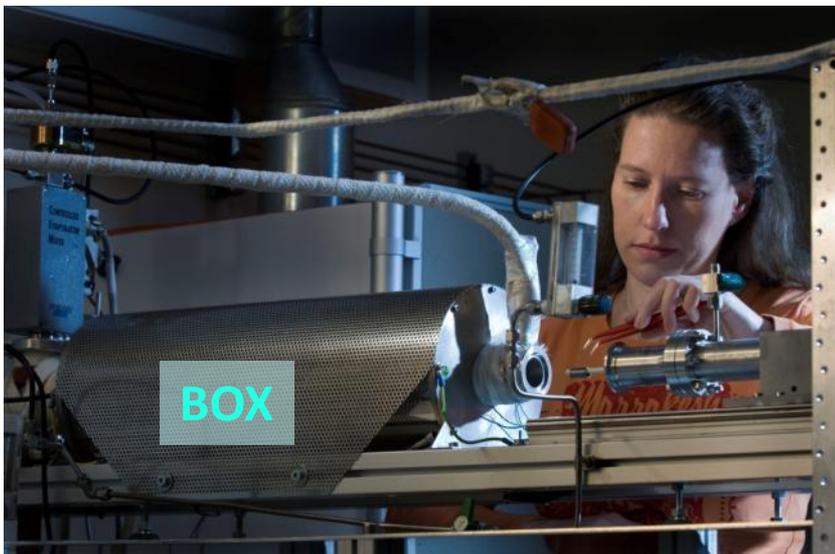
Separate-effects tests

Bundle experiments



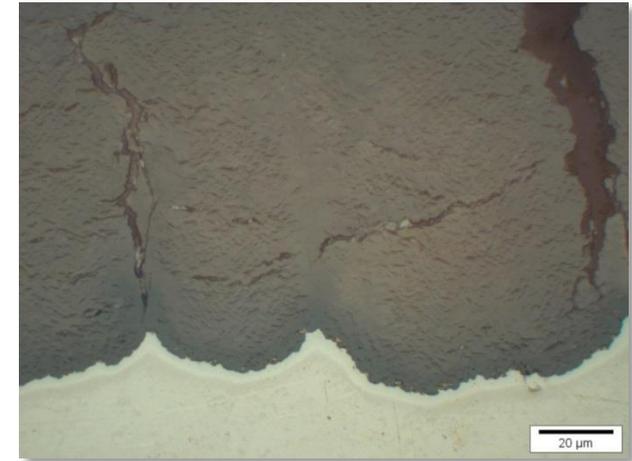
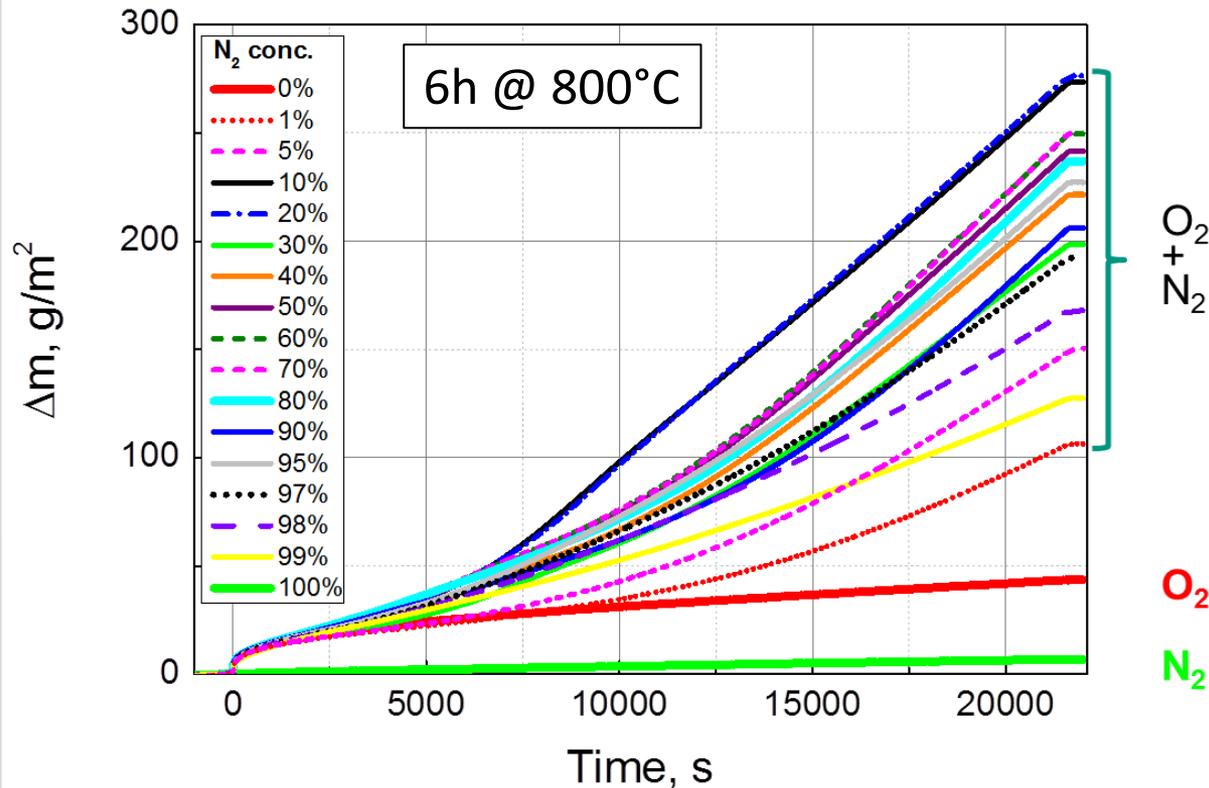
PWR fuel element

QUENCH Separate-effects tests: Main setups

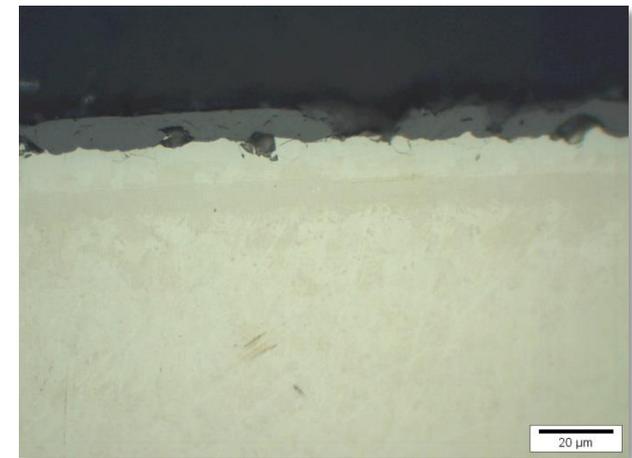


- Experiments on mechanism of air oxidation of Zr alloys
 - Oxidation of Zircaloy-4 in oxygen-nitrogen mixtures
 - In-situ neutron radiography investigations Zr(O)-nitrogen reaction
- Neutron tomography for investigation of hydrogen diffusion in mechanically loaded samples
- Microstructure and mechanical 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 N₂-O₂ mixtures



10% N₂



0% N₂

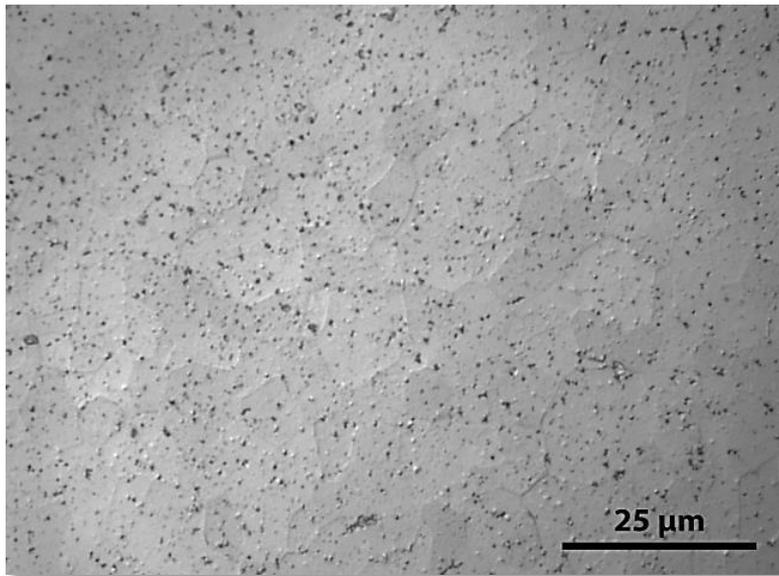
- ➡ Strong effect of nitrogen on oxidation kinetics of Zry-4 in N₂-O₂ mixtures over a wide range of composition

- 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

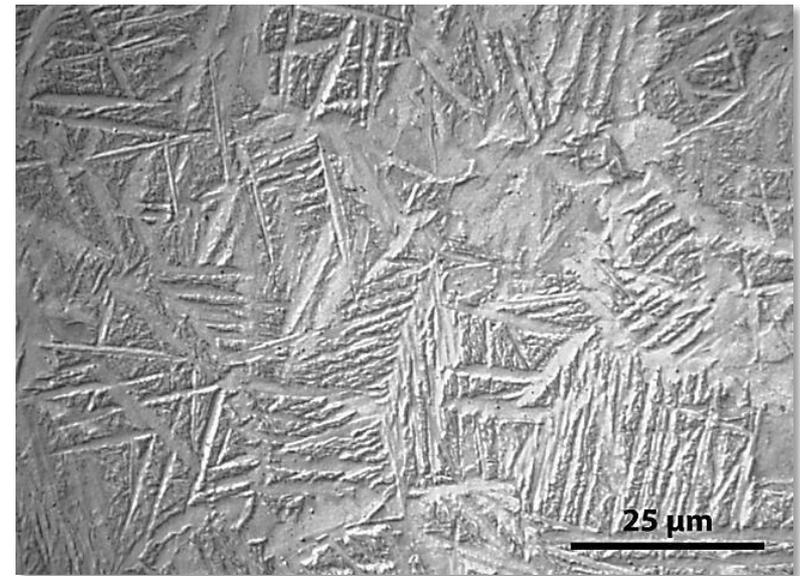
SiC oxidation in steam and quenching from 2000°C



Microstructure of hydrogenated cladding samples

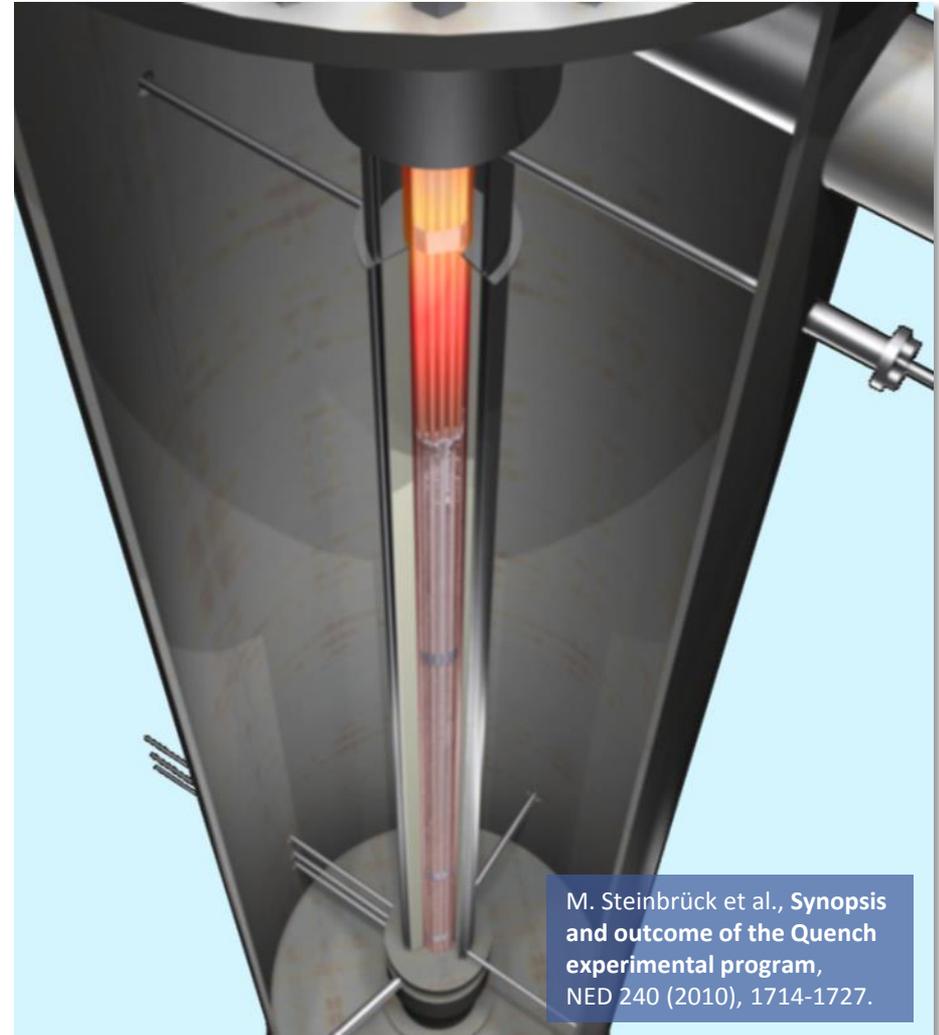


Annealed at 800°C in Ar
(0 wppm H)



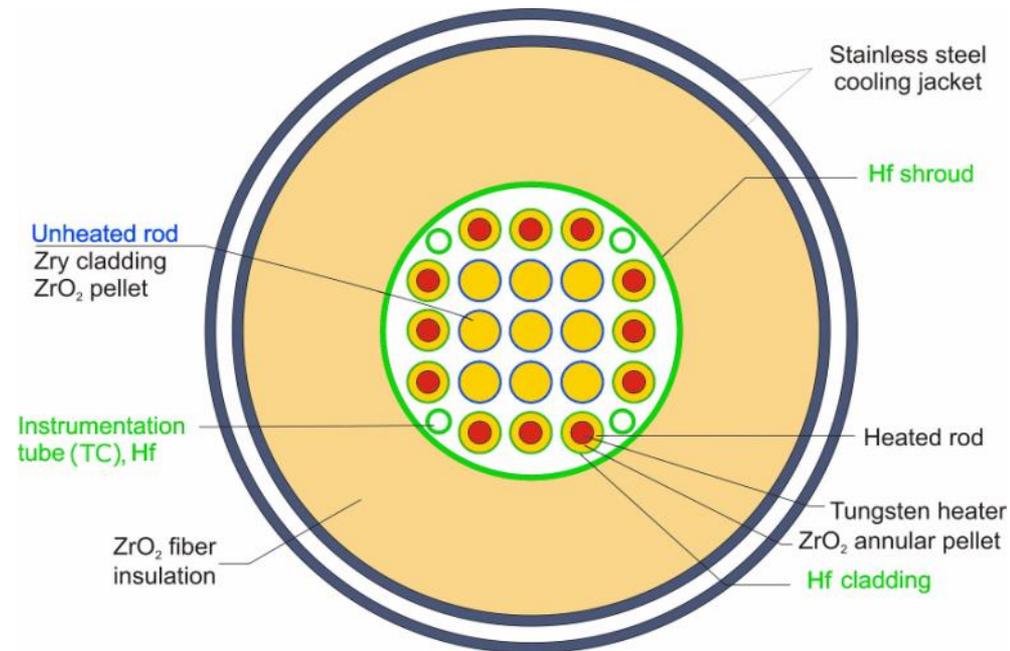
Annealed at 800°C in Ar+H₂
(3000 wppm H)

- Unique out-of-pile bundle facility to investigate reflood of an overheated reactor core
- 21-31 electrically heated fuel rod simulators; T up to $>2000^{\circ}\text{C}$
- 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

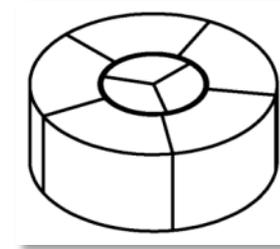


M. Steinbrück et al., *Synopsis and outcome of the Quench experimental program*, NED 240 (2010), 1714-1727.

- 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

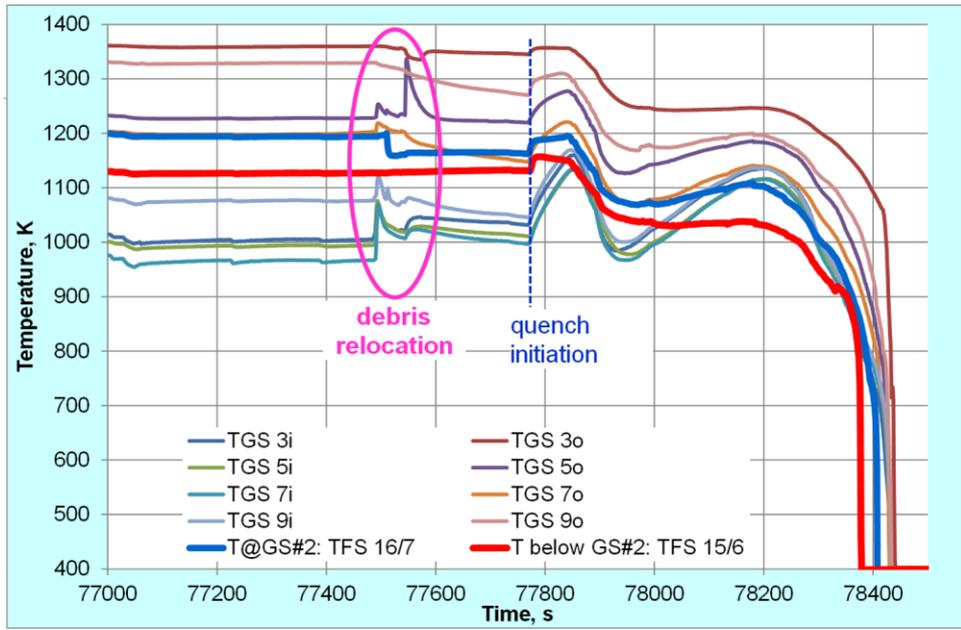


Bundle cross section



Pellet segments

QUENCH-Debris; preliminary results



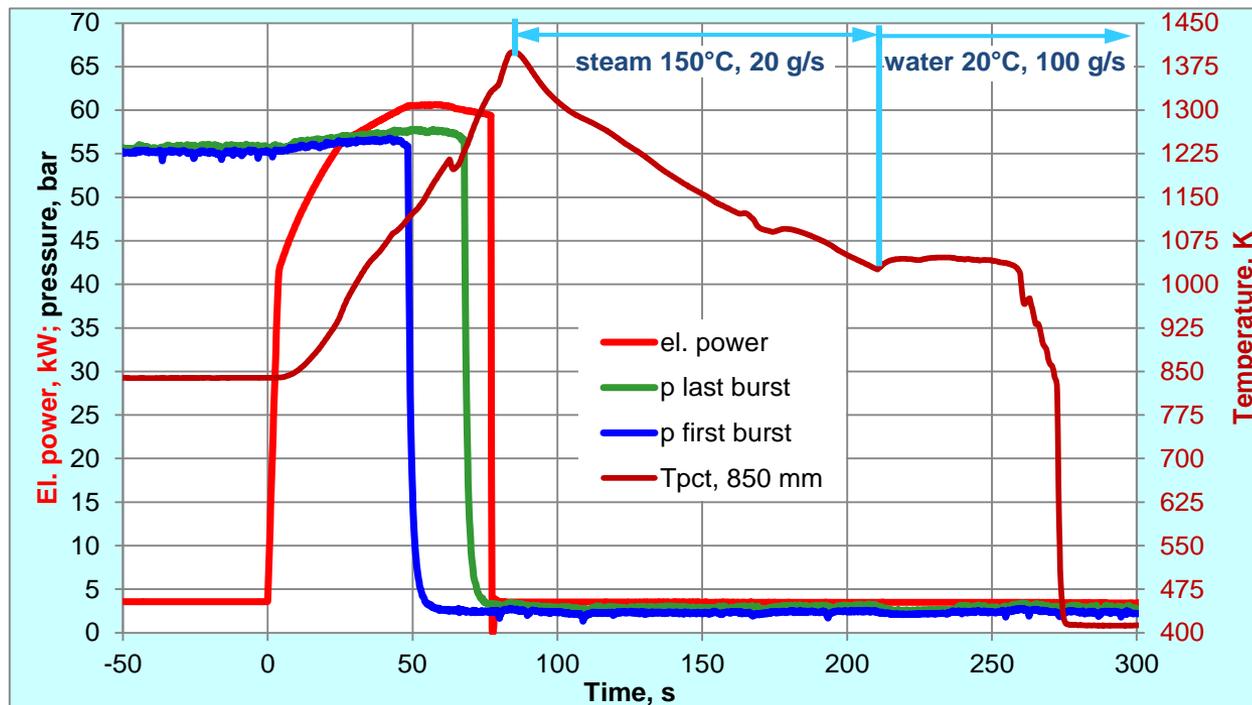
Temperatures in the final phase



Post-test debris

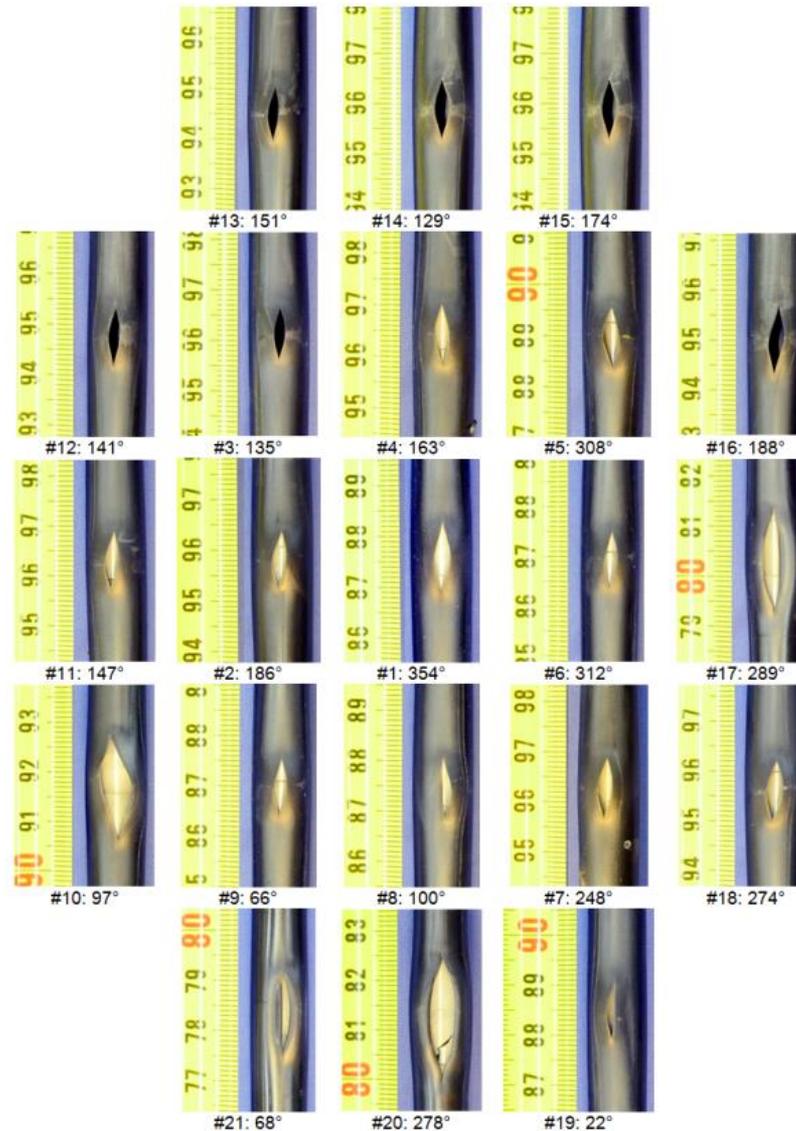
QUENCH-L2

- 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



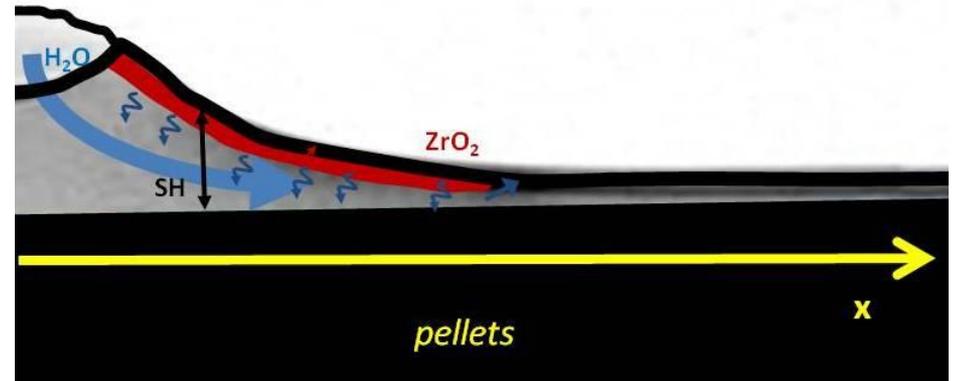
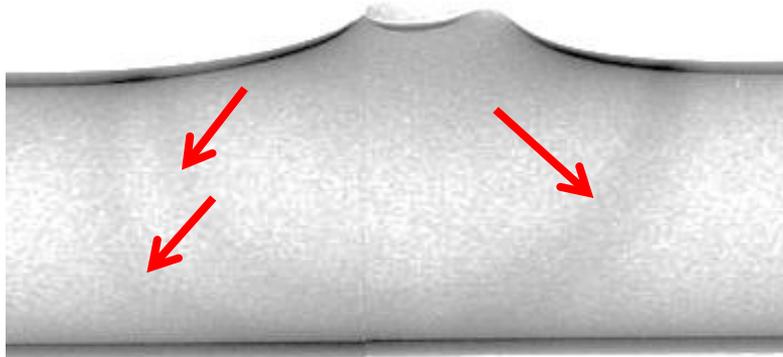
QUENCH-L2
Test conduct

QUENCH-L2; burst positions



- 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



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

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

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

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

- ➊ Steam transport and consumption in the gap
- ➋ Free hydrogen production and transport
- ➌ Hydrogen uptake (amount of hydrogen in the gap has to be taken into account)
- ➍ 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

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The 7th International Topical Meeting on Nuclear Reactor Operations and Safety

Neutron radiography and secondary hydriding of coolant

Mirco K. Grosse*, Juri Stuckert

*Karlsruhe Institute of Technology
*Paul Scherrer Institute

1. Introduction

The motivation for this paper came from progress of the severe nuclear accidents in NPP in March 2011. All affected units the reactors (BWRs) using boron carbide as absorber. Worldwide, many light water reactors use boron carbide as neutron absorbing material (Grosse et al., 1998); details will be given in the next paper. The absorber melt also influences degradation of the fuel elements with release of energy and various gases. Cladding gas release was the potential formation could form volatile organic iodine compounds. B₄C absorber behavior during severe accidents investigated in various CORA tests (Sepold et al., 2012). The presence of B₄C causes the formation of a gas at around 1250 °C that attacks the adjacent rod cladding. The absorber melt also influences its dissolution at low temperatures.

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QUENCH-LOCA program at KIT on secondary hydriding and results of the commissioning bundle test QUENCH-L0

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HIGHLIGHTS

- ▶ Cladding bursts took place during heating at temperatures between 1123 and 1223 K.
- ▶ Around oxide area at inner cladding surface hydrogen-containing bands were formed.
- ▶ Properties of hydrogenated bands: hydrogen content $c_H < 2500$ wppm, hardness 300 HV.
- ▶ Hydrogen is mostly dissolved in the α -Zr lattice.
- ▶ Brittle ruptures along hydrogenated bands with $c_H > 1500$ wppm during tensile tests.

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ABSTRACT

New out-of-pile QUENCH-LOCA bundle tests are being performed in the QUENCH facility within the Nuclear Safety Program of KIT. The overall objective of this bundle test series is the investigation of ballooning, burst and secondary hydrogen uptake of the cladding under representative design basis accident conditions as well as detailed post-test investigation of the mechanical properties of the claddings to check the embrittlement criteria. The program was started in 2010 with the QUENCH-L0 commissioning test using 21 electrically heated rods with as-received Zircaloy-4 claddings followed by the QUENCH-L1 reference test using the same material. Advanced cladding alloys (Duplex DX(D4, M5*, ZIRLO™)) will be applied in further tests. For QUENCH-L0 each rod was separately pressurized with krypton with initial pressures from 35 to 55 bar. The transient phase with heating from 793 K to 1343 K lasted 185 s. The increased ductility of the heated cladding resulted in a progressive ballooning and consequent burst of all of the pressurized rods during the transient. The test was terminated by water quenching of the bundle without the usual intermediate slow cooling phase. Post-test investigations showed circumferential strain values between 20 and 35% at cladding positions with oxidation degree corresponding to 2% ECR. Neutron radiography of cladding tubes showed that at the inner rod simulator groove so called secondary hydriding occurred. Maximal hydrogen concentrations up to 2500 wppm on the boundary of the internal oxidized region around burst positions were determined. These hydrogen containing bands correlate with cladding bulk zones with increased micro hardness. XRD and TEM analysis indicated dissolution of hydrogen in the metal matrix without noticeable zirconium hydrides formation. Tensile tests of claddings with hydrogen containing bands showed simultaneous cladding tube ruptures at these bands below and above the burst opening.

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1. Introduction

Under the licensing procedures for pressurized water reactors (PWR), evidence must be produced that the impacts of all pipe ruptures hypothetically occurring in the primary loop and implying a loss of coolant can be controlled. The double-ended break of the main coolant line between the main coolant pump and the reactor pressure vessel is considered to constitute the design basis for the emergency core cooling system (ECCS) in a loss-of-coolant accident (LOCA). For the successful long-term cooling of the core a reliable sustainment of the reactor core rod geometry is required. To retain the core rod geometry it should be established an acceptable limit of cladding embrittlement, which is increased during oxidation in steam. The current LOCA criteria and their safety goals are applied worldwide with minor modifications since their release by the US NRC in 1973 (Commission, 1973). The criteria are given as limits of peak cladding temperature ($T_{PCT} \leq 1200$ °C) and of oxidation level ECR (equivalent cladding reacted) (calculated as a percentage of cladding oxidized (ECR = 17% calculated using Baker–Just oxidation correlation). These two rules constitute the criterion of cladding

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- 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

- 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

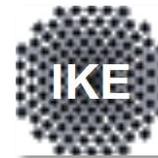
- NUGENIA
- CSARP
- IAEA
- OECD-NEA

Bilateral

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



- ITU
- GRS
- VGB, AREVA, EdF
- CNEA Bariloche



- ENEA
- NECSA, BAM, HMI
- JNES, JEA



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- 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

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