Karlsruhe Institute of Technology

Institute for Applied Materials

Update of the QUENCH Programme

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

20th International QUENCH Workshop, Karlsruhe, 11-13 November 2014

Institute for Applied Materials, Programme NUSAFE

Outlook

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

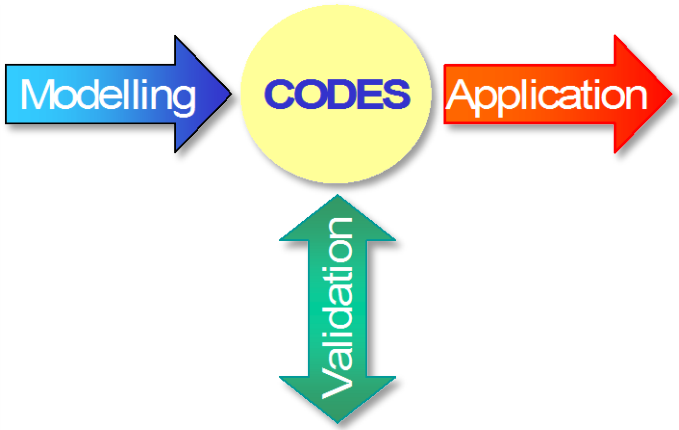
Motivation

- 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

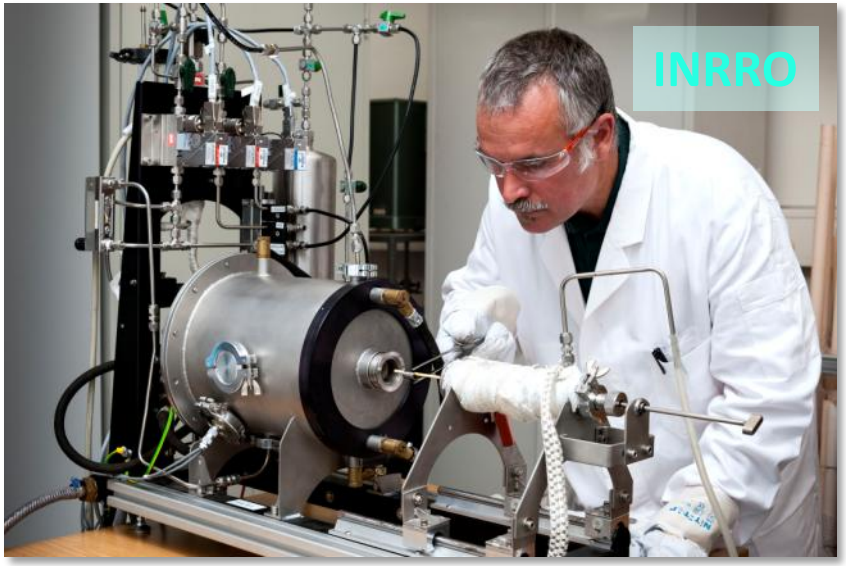
Separate-effects tests

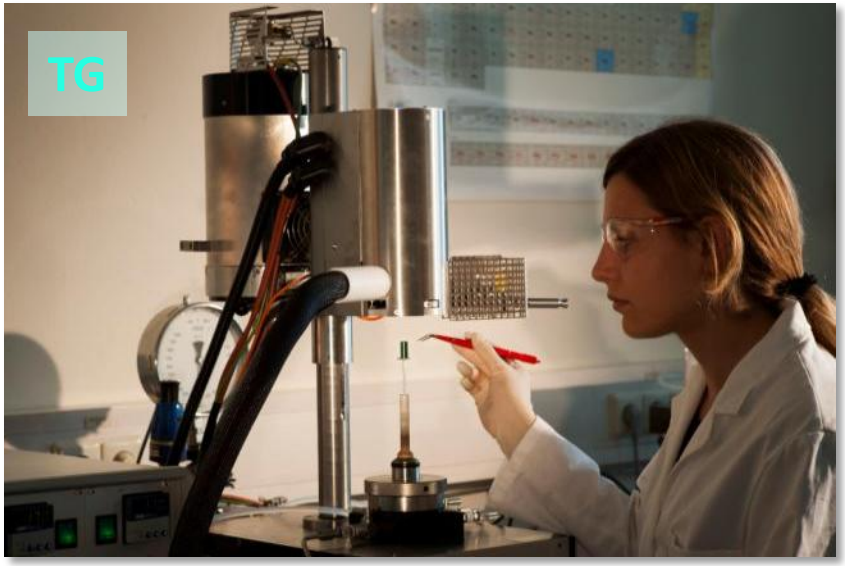


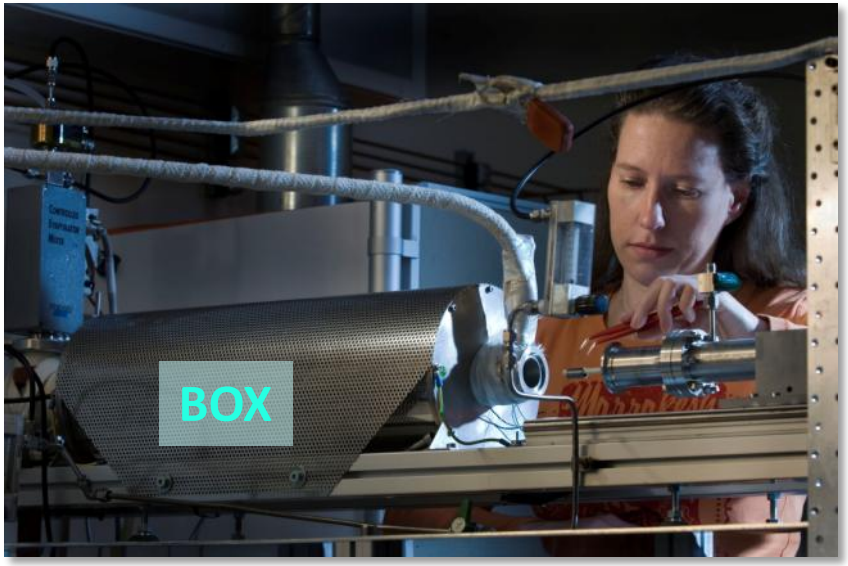
Bundle experiments

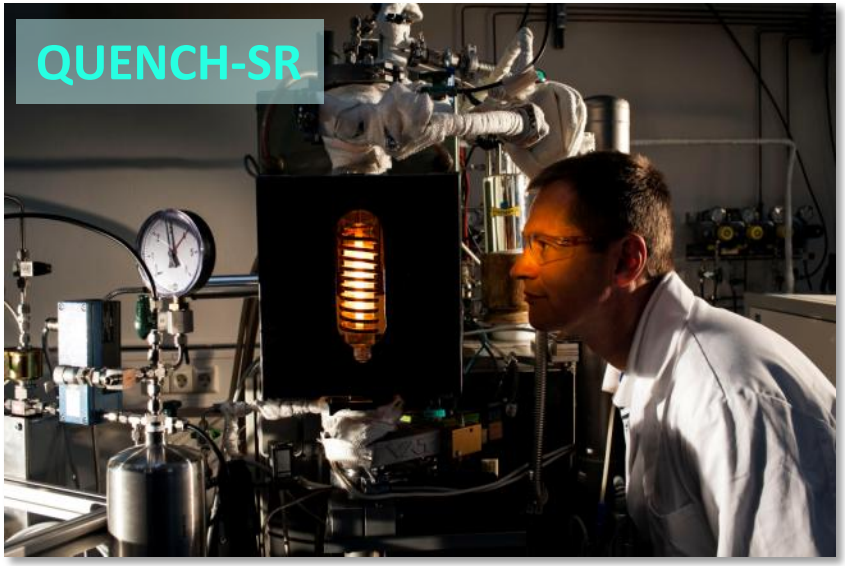
PWR fuel element

QUENCH Separate-effects tests: Main setups





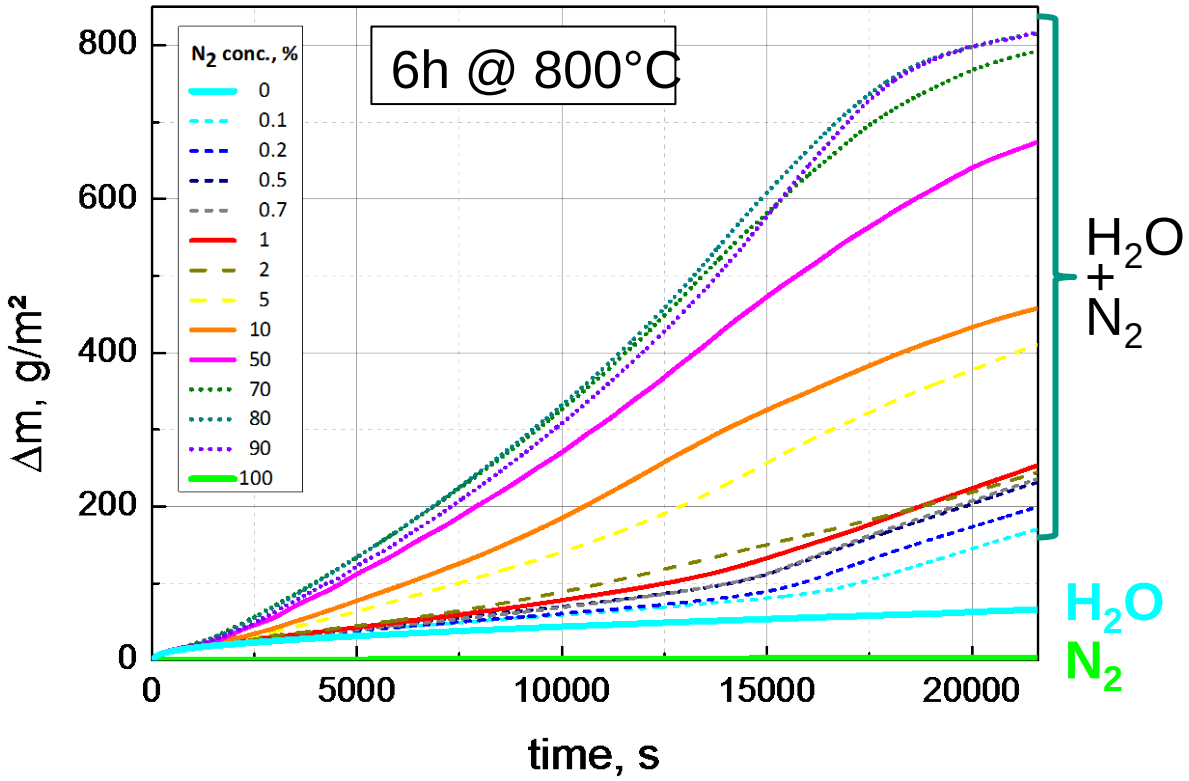


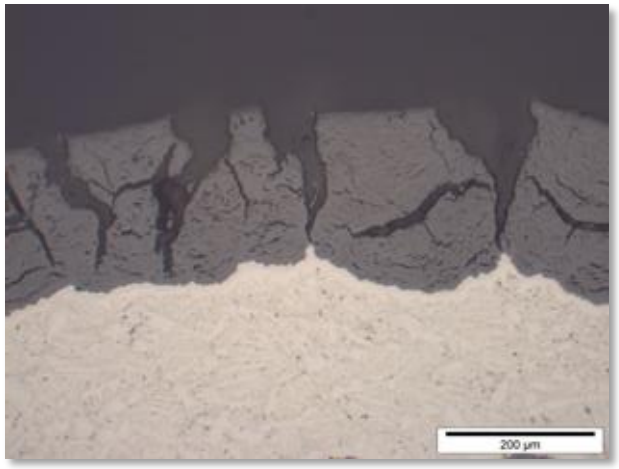


Separate-effects tests in 2014

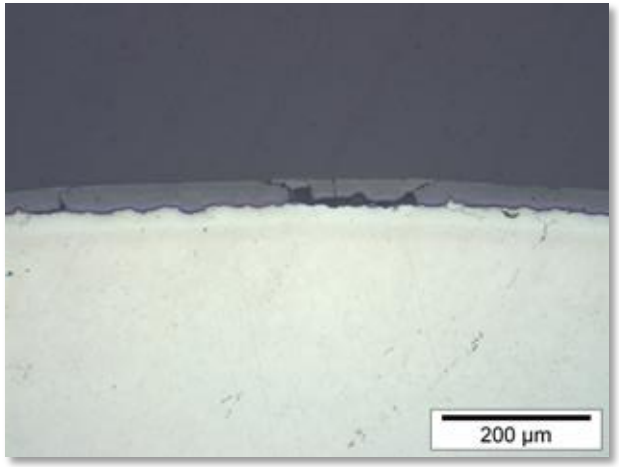
- Experiments on mechanism of air oxidation of Zr alloys
  - Oxidation of Zircaloy-4 in steam-nitrogen mixtures
  - Neutron radiography investigations on hydrogen absorption during oxidation of Zry-4 in steam-nitrogen
- Microstructure and mechanical properties of hydrogenated Zr alloys
- Experiments on high-temperature oxidation, quenching, and joining of silicon carbide
- High-temperature oxidation of tantalum and beryllium
- Dissolution kinetics of oxide layer on cladding surface under oxygen starvation conditions
- ...

Reaction of Zircaloy-4 in steam-nitrogen mixtures





5% N_2

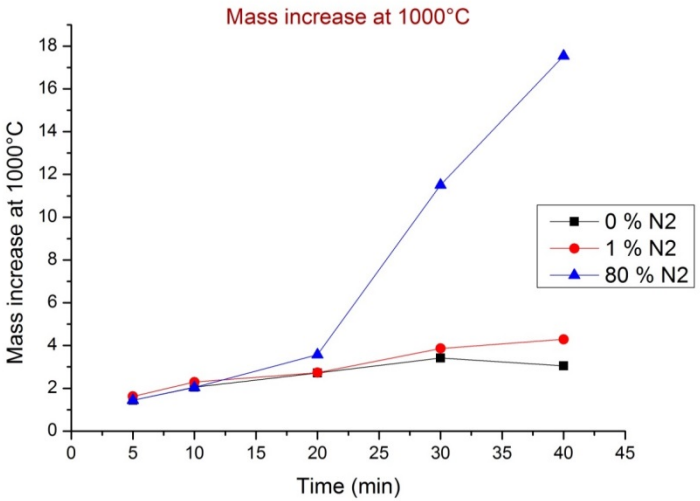


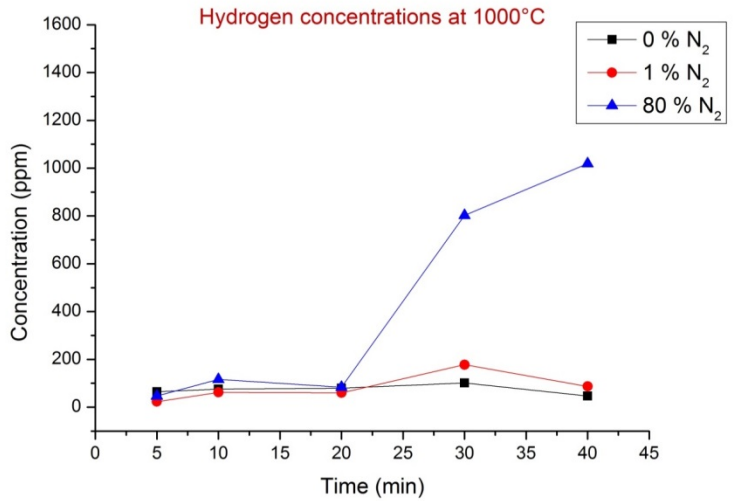
0% N_2

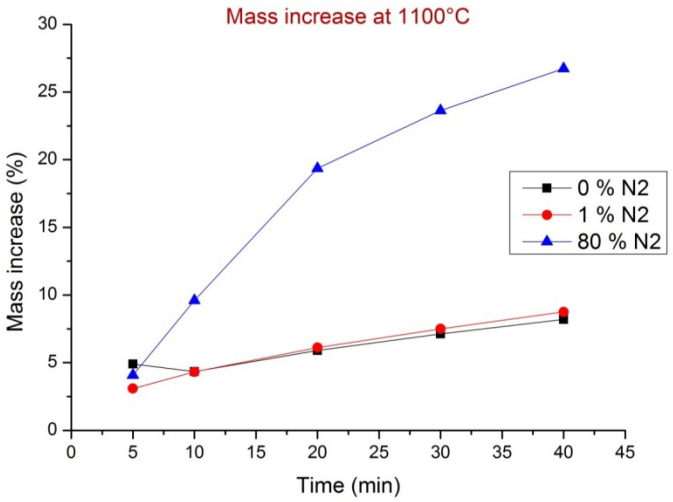
- Strong effect of nitrogen on oxidation kinetics of Zry-4 in N_2-H_2O mixtures over a wide range of composition

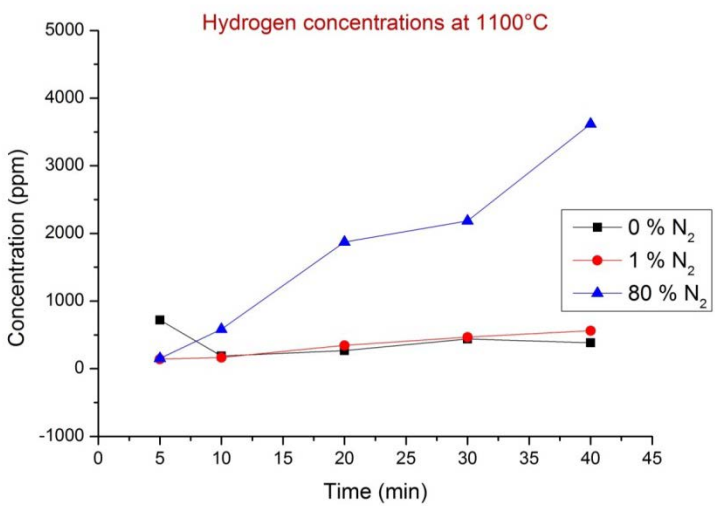
Reaction of Zircaloy-4 in steam-nitrogen mixtures

Mass gain and hydrogen uptake determined by NR



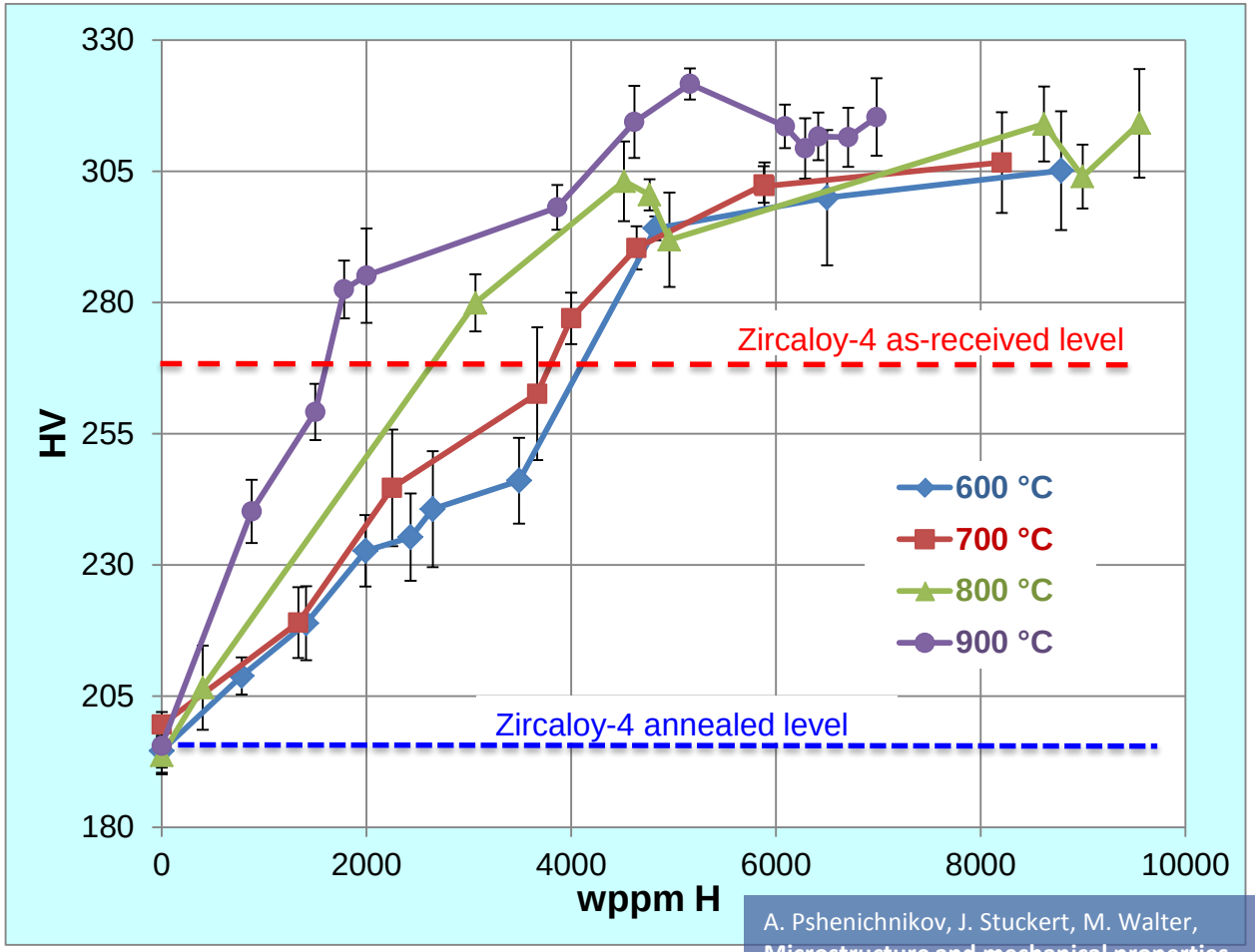






NR image of two samples

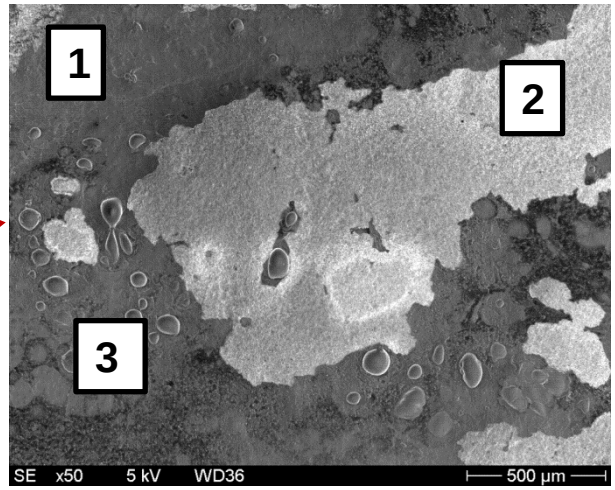
Micro hardness of hydrogenated Zircaloy-4 samples



A. Pshenichnikov, J. Stuckert, M. Walter, **Microstructure and mechanical properties of Zircaloy-4 claddings hydrogenated at temperatures between 900 and 1200 K**, NuMat 2014, Florida.

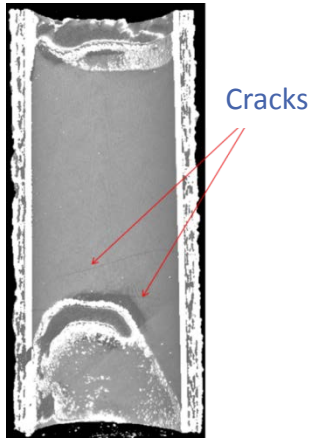
High-temperature oxidation of SiC materials

Oxidation at 2000°C and quench of SiC samples

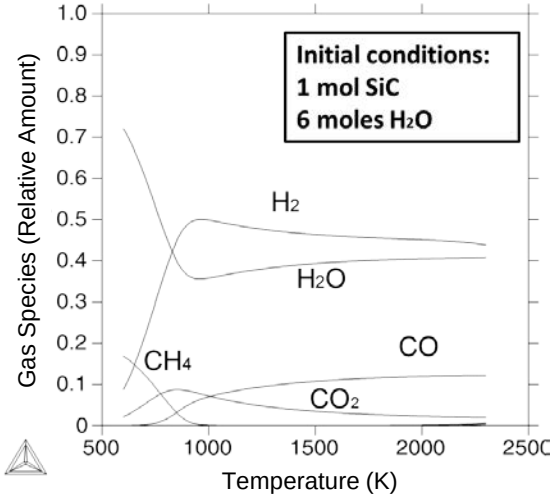


Post analysis:

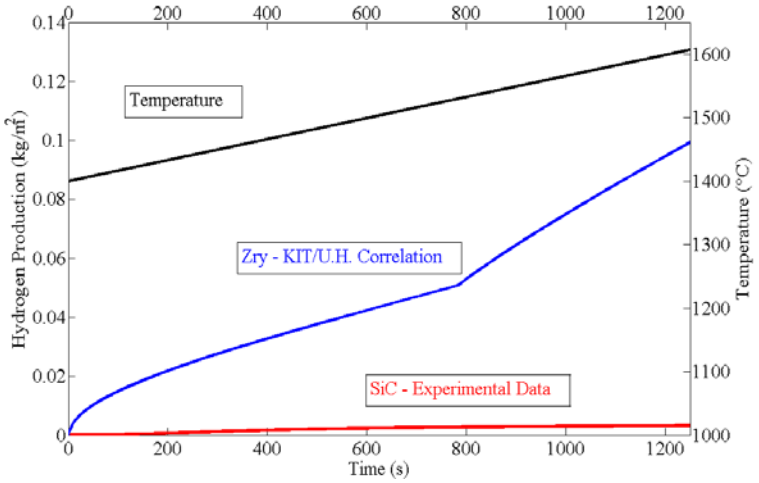
1. Silica
2. Silicon carbide
3. Silica bubbles



Computational thermodynamics

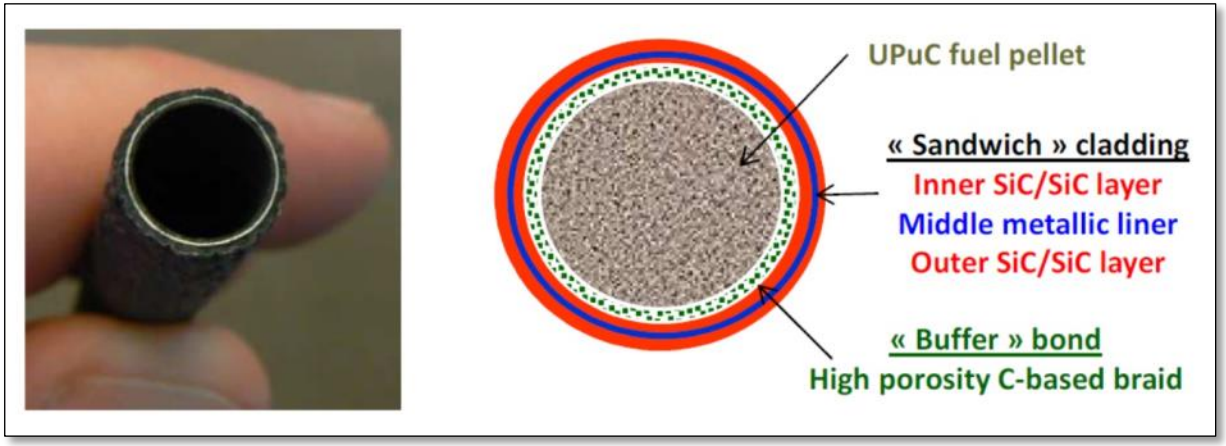


SiC – Zry comparison



High-temperature oxidation of tantalum in steam

Ta is one candidate metal for SiC-M-SiC sandwich claddings

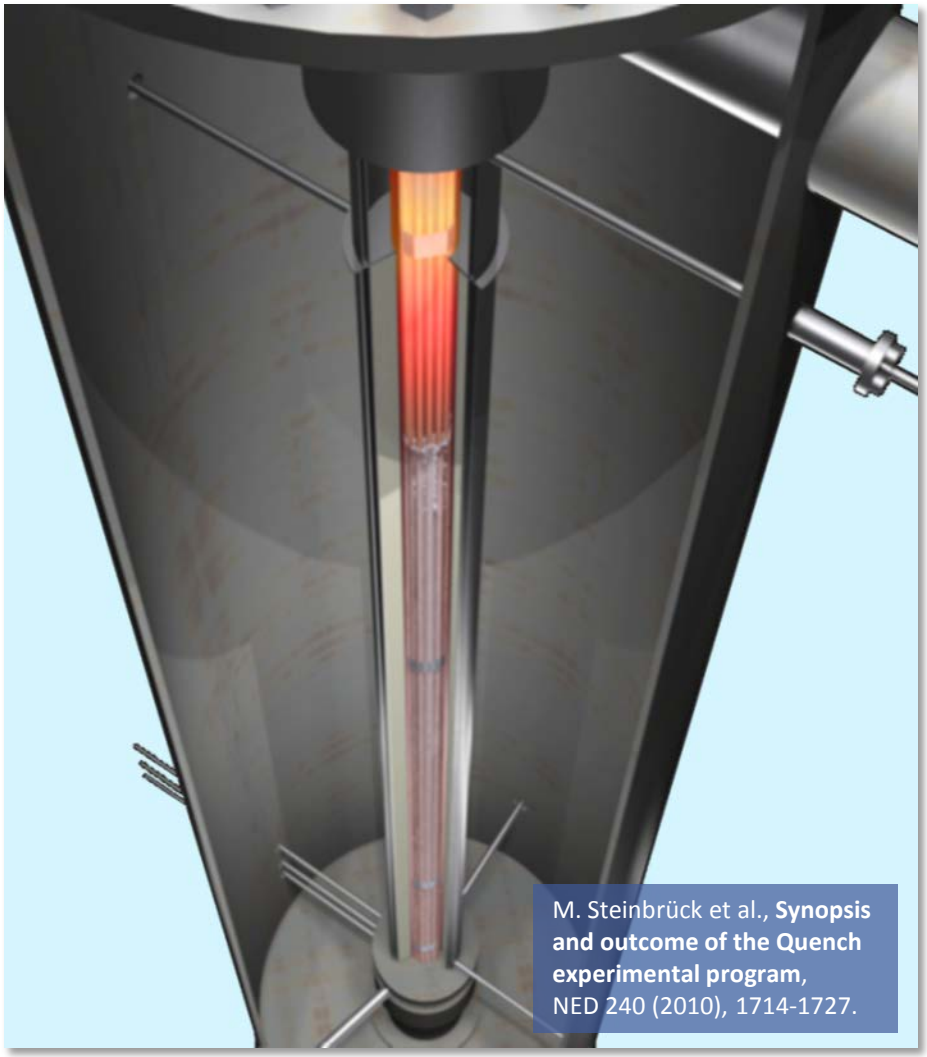


Oxidation in steam

- 600-1100°C
- Varying steam partial pressure
- Plate and tube specimens

QUENCH facility

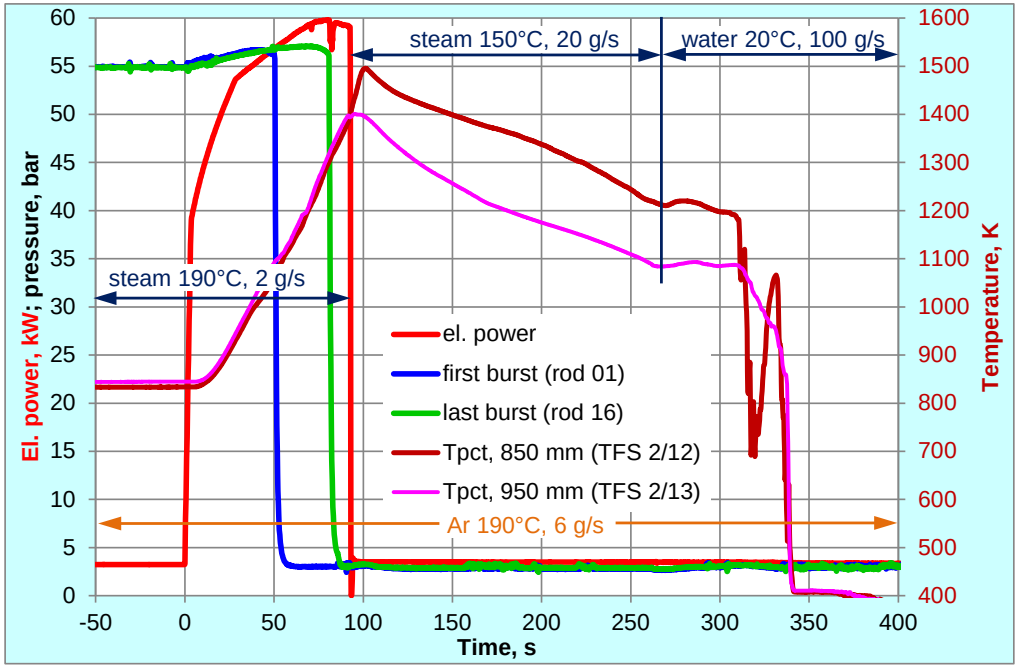
- Unique out-of-pile bundle facility to investigate reflood of an overheated reactor core
- 21-31 electrically heated fuel rod simulators; T up to >2000°C
- Extensive instrumentation for T, p, flow rates, level, etc.
- So far, 17 experiments on SA performed (1996-today)
  - Influence of pre-oxidation, 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.

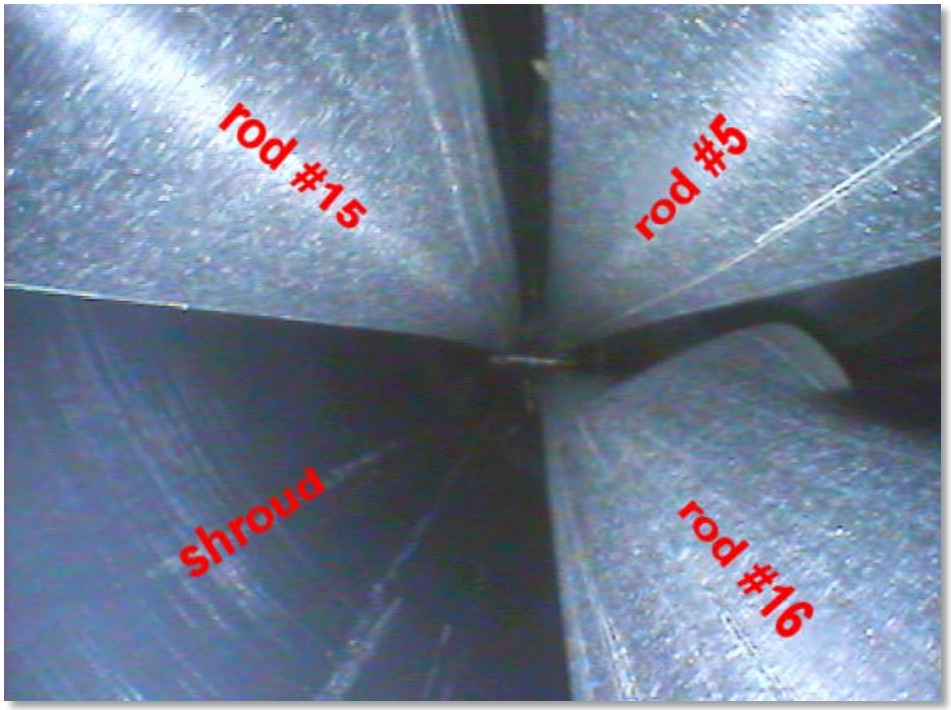
QUENCH-L3HT

- Fourth test of the QUENCH-LOCA series with opt. Zirlo^{TM} cladding
- Conducted on 21 March 2014
- Higher temperature than reference test, provides support for slightly beyond LOCA scenarios, will be repeated
- Post-test examinations in progress, including mechanical testing, metallography, neutron radiography and tomography, micro hardness measurements, XRD, TEM



QUENCH-L3-HT
Test conduct

QUENCH-L3HT



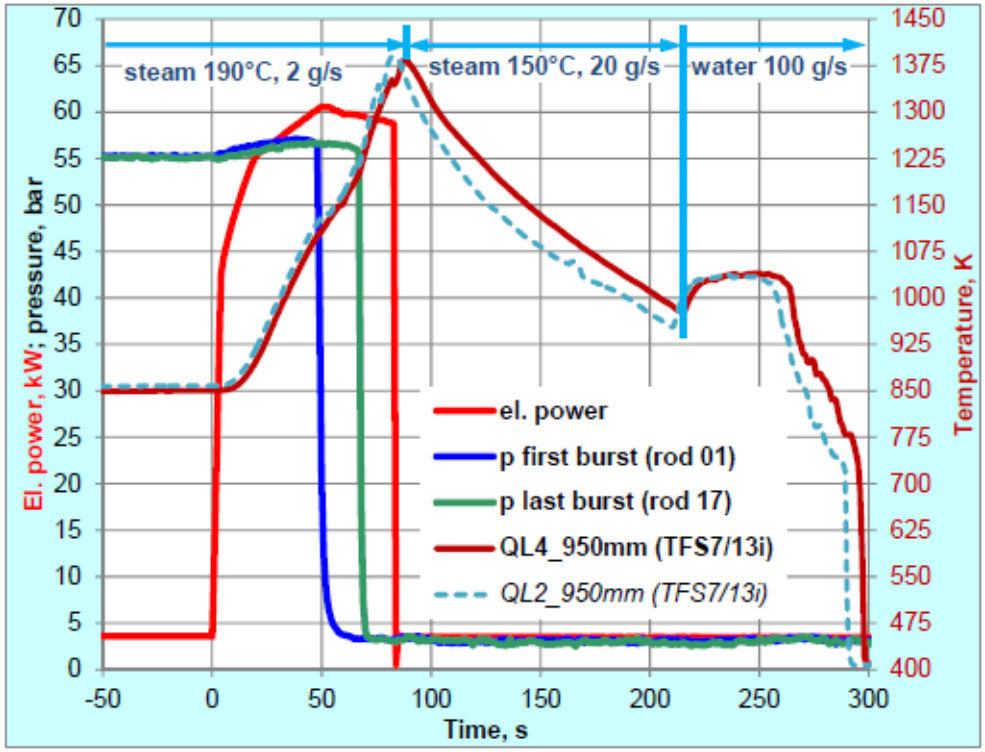
videoscope observation

rod #16:
burst opening

rod #5:
neutron
radiography

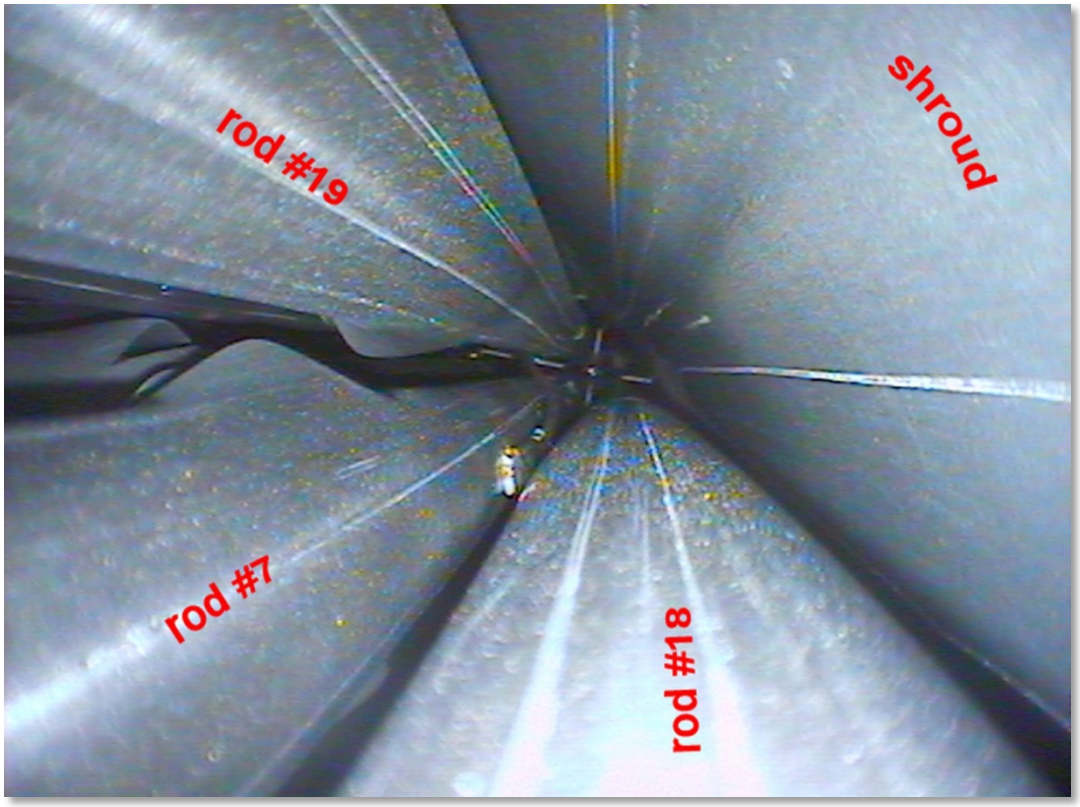
QUENCH-L4

- Fifth test of the QUENCH-LOCA series with pre-hydrided M5® cladding
- Conducted on 30 July 2014
- Post-test examinations in progress, including mechanical testing, metallography, neutron radiography and tomography, micro hardness measurements, XRD, TEM



QUENCH-L4
Test conduct

QUENCH-L4



videoscope observation

rod #7:
burst opening

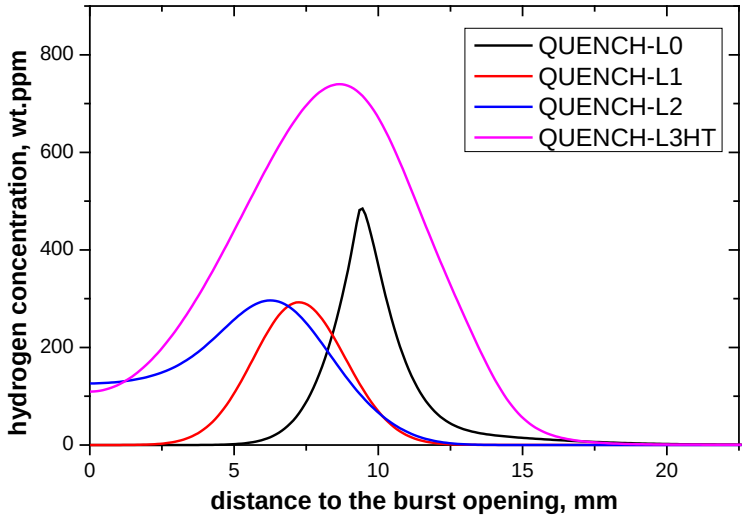
QUENCH activities for Accident Tolerant Fuel Claddings

- Three PhD theses are in progress
  - High-temperature oxidation and quench of SiC
  - Joining of SiC components
  - Development of high-temperature resistant coatings for zirconium alloy cladding tubes
- Participation in the OECD-NEA Expert Group on Accident Tolerant Fuels for LWRs (EGATFL)
- Partner of the EC FALSTAFF project to be proposed in the framework of HORIZON2020
- Participation in the IAEA CRP on Accident Tolerant Fuel Concepts for Light Water Reactors (ACTOF)

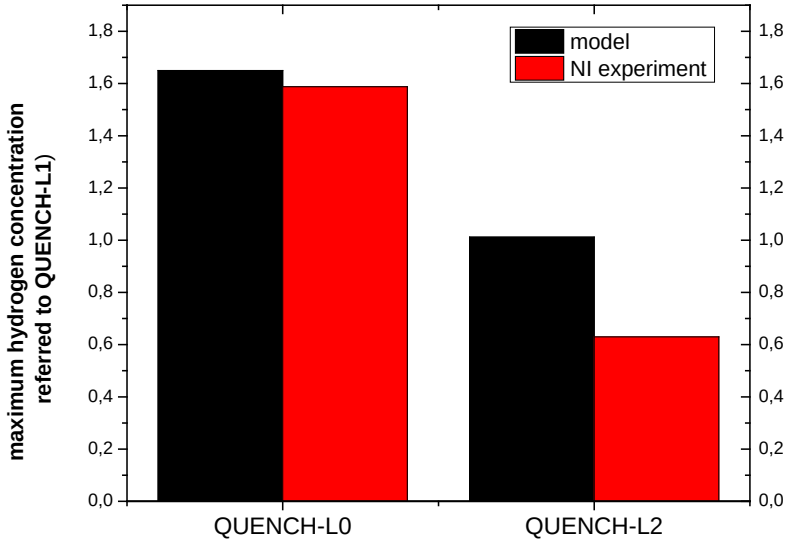
Modelling and code validation

- 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)
- QUENCH data will be used in the frame of IAEA FUMAC project
- Participation in the OECD TMI-2 benchmark
- Further development of 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



Comparison of the computed axial hydrogen distributions



Comparison of the maximal hydrogen concentrations referred to the QUENCH-L1 reference test

Good agreement for Zry-4, unsatisfying agreement for M5®

Differences in material parameters like oxidation kinetics, temperature of monoclinic – tetragonal phase transition has to be included

Reporting

- QUENCH-L1: KIT Scientific Report 7651 published
- QUENCH-L2/3HT: KIT Scientific Reports in preparation
- Numerous papers and conference contributions

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High-temperature reaction of oxygen-stabilized α-Zr(O) with nitrogen

Martin Steinbrück *

Karlsruhe Institute of Technology, Institute of Applied Materials

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1. Introduction

Zirconium alloys are widely used in chem industries because of their excellent mechanic properties at operational conditions and their low tion. Hence, they are applied as fuel cladding tube ture elements in light water reactors (LW temperatures >1000 K, as they are existent dur loss of coolant accidents (LOCA) or beyond design dents, enhanced oxidation leads to degradation tubes, hydrogen release and additional heat prod cal atmosphere during most accident scenarios is sical zirconium alloy for nuclear applications is approx. 1.5 wt.% tin as major alloying element, is available for this alloy regarding oxidation kine a wide range of temperature from operational cor up to temperatures expected for severe accident and references herein].

There are various scenarios where air may h core. Air ingress is possible under shutdown con reactor coolant system is open to the containm Air oxidation of the remaining outer core regi pressure vessel failure in the late phase of core de severe accidents is also possible [3]. Furthermor storage or transportation casks may result in air i sequent interaction with the spent fuel rods, an intensified by the Fukushima Daiichi accidents, spent fuel pool after LOCA is discussed. In compa chemical heat release during oxidation in air is 8

* Tel.: +49 721 608 22517; fax: +49 721 608 24567.
E-mail address: martin.steinbrueck@kit.edu

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Experimental results of the QUENCH-16 bundle test on air ingress

J. Stuckert*, M. Steinbrück

Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

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Oxygen starvation
Zirconium nitride
Core reflood
Hydrogen source term

1. Introduction

Air ingress issues have received considerable attention years in view of the likely acceleration in cladding oxida rod degradation, and the release of some fission produ notable ruthenium. The Paks NPP cleaning tank incident (Project, 2008) and the accidents at Fukushima Daiichi (NI drew attention to the possibility of overheated fuel as becoming exposed to air outside of the reactor.

Experimental and analytical works on air ingress w formed within the EC 4th and 6th Framework Programs (et al., 2000; Albiol et al., 2007). Numerous single effect cladding oxidation in air were performed at ANL (temp 573–1173 K) (Natesan and Soppet, 2004), AEKI (temperatu 1773 K) (Matus et al., 2008), IRSN (temperatures 873– (Duriez et al., 2008; Duriez et al., 2009) and KIT (temp 873–1873 K) (Steinbrück, 2009; Steinbrück and Böttche The current OECD/NEA project SFP investigates the perfor full-scale 17 × 17 PWR assemblies in air with regard to hydraulic and ignition phenomena (SFP, 2013). A nu

* Corresponding author. Tel.: +49 721 608 22558; fax: +49 721 608
E-mail address: juri.stuckert@kit.edu (J. Stuckert).

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A comparison of core degradation phenomena in the CORA, QUENCH, Phébus SFD and Phébus FP experiments

T. Haste[a,*], M. Steinbrück[b], M. Barrachin[a], O. de Luze[a], M. Grosse[b], J. Stuckert[b]

[a] Institut de Radioprotection et de Sûreté Nucléaire, IRSN, BP 3, F-13115 St. Paul-lez-Durance Cedex, France
[b] Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany

HIGHLIGHTS

- The results of the experiments CORA, QUENCH and Phébus SFD/FP are summarised.
- All phenomena expected up to melt movement to the lower head are shown consistently.
- Separate-effect tests performed at KIT and IRSN aid improve their modelling.
- Data from the integral tests help independent validation of new and improved models.
- The improved codes will help reduce uncertainties in safety-critical areas for core degradation.

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ABSTRACT

Over the past 20 years, integral fuel bundle experiments performed at IRSN Cadarache, France (Phébus-SFD and Phébus FP – fission heated) and at Karlsruhe Institute of Technology, Germany (CORA and QUENCH – electrically heated), accompanied by separate-effect tests, have provided a wealth of detailed information on core degradation phenomena that occur under severe accident conditions, relevant to such safety issues as in-vessel retention of the core, recovery of the core by water reflood, hydrogen generation and fission product release. These data form an important basis for development and validation of severe accident analysis codes such as ASTEC (IRSN/GRS, EC) and MELCOR (USNRC/SNL, USA) that are used to assess the safety of current and future reactor designs, so helping to reduce the uncertainty associated with such code predictions.

Following the recent end of the Phébus FP project, it is appropriate now to compare the core degradation phenomena observed in these four major experimental series, indicating the main conclusions that have been drawn. This covers subjects such as early phase degradation up to loss of rod-like geometry (all the series), late phase degradation and the link between fission product release and core degradation (Phébus FP), oxidation phenomena (all the series), reflood behaviour (CORA and QUENCH), as well as particular topics such as the effects of control rod material and fuel burn-up on core degradation. It also outlines the separate-effects experiments performed to elucidate specific phenomena such as the impact of chemical reactions involving boron carbide absorber material. Finally, it indicates the remaining topics for which further investigation is still required and/or is under way.

Education

- AREVA Nuclear Professional School
  - Lectures on Severe Accidents in October 2014
  - Next courses planned for October 2015
  - Information: http://www.anps.kit.edu/
- Organisation of the KTG Technical Meeting on Fuel Assemblies in April 2014
- 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 2014-2016

- QUENCH-LOCA
  - Supported by German VGB PowerTec
  - QUENCH-L3/5 under preparation and planned for end 2014 with opt. Zirlo® and first half of 2015 pre-hydrided opt. Zirlo® claddings
- QUENCH offers one experiment in the framework of the EC supported SAFEST program
- SETs and one bundle experiment 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
- NRA, JAEA

Acknowledgement

- Helmholtz Association for funding program NUSAFE at KIT
- Program NUSAFE and IAM institute's management for broad support of our activities
- 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, A. Pshenichnikov, C. Rössger, U. Stegmaier, M. Walter

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