Update of the QUENCH Program

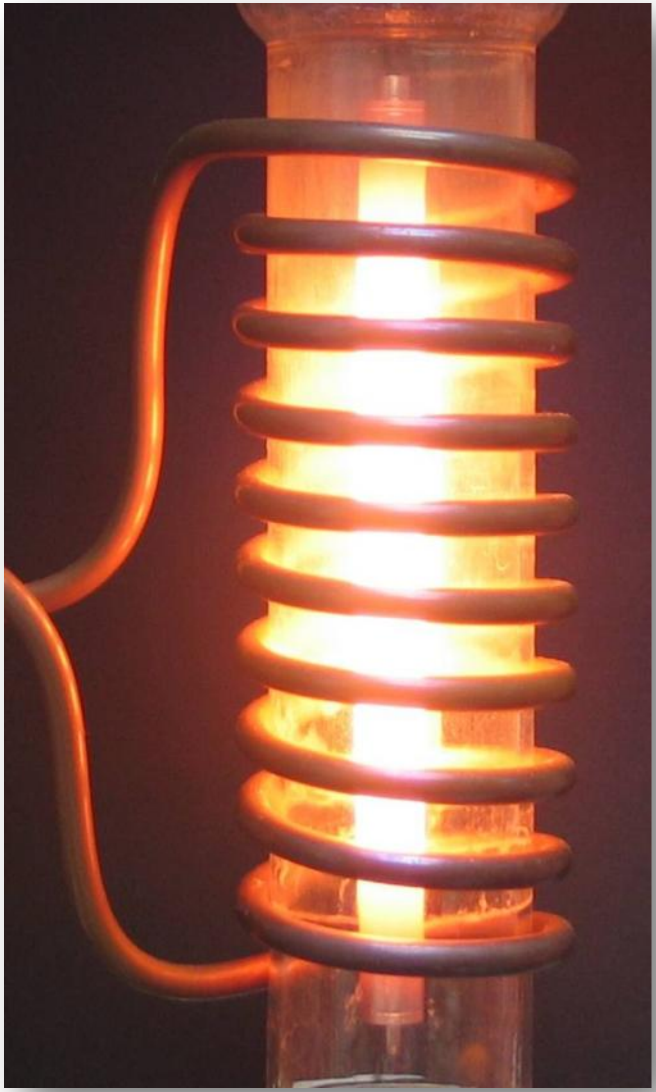
M. Steinbrück, J. Stuckert, M. Große et al.

24th International QUENCH Workshop, Karlsruhe, 13-15 November 2018

Institute for Applied Materials, Programme NUSAFE

Outlook

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



Motivation

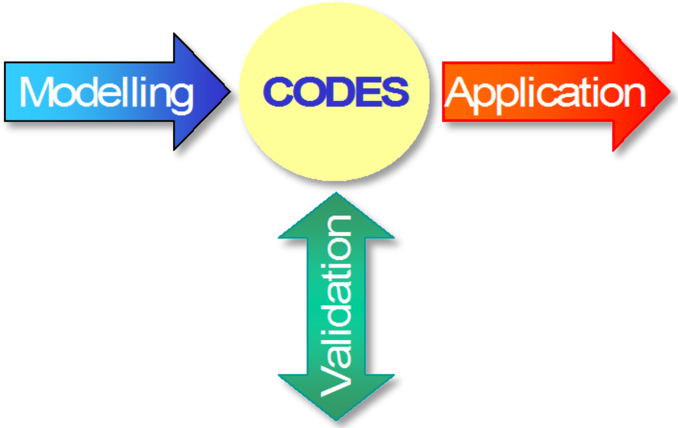
- Reflood is a prime accident management measure to terminate a nuclear accident
- Reflood may cause temperature excursion connected with increased hydrogen and FP release (severe accidents) and embrittlement of cladding and secondary hydriding (LOCA)
- Coolability of a degraded core is a matter of high priority (Fukushima)

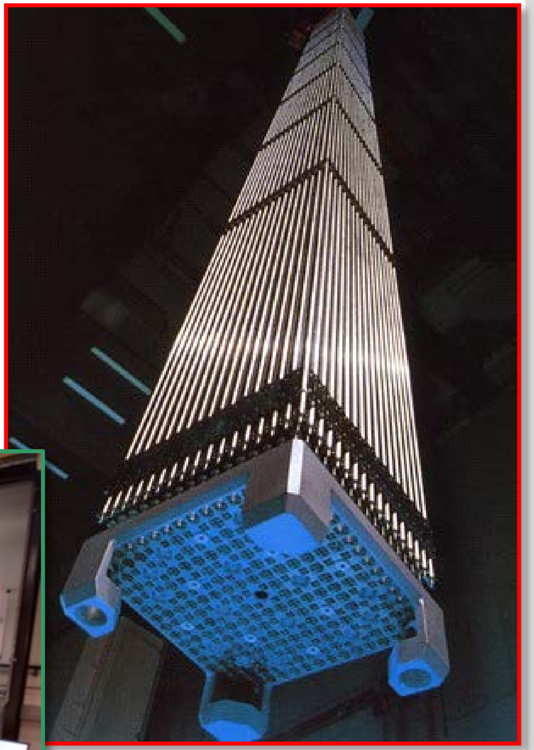
➡ QUENCH experiments (bundle+SET) provide data for development of models and validation of SFD code systems

QUENCH Programme

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

Separate-effects tests



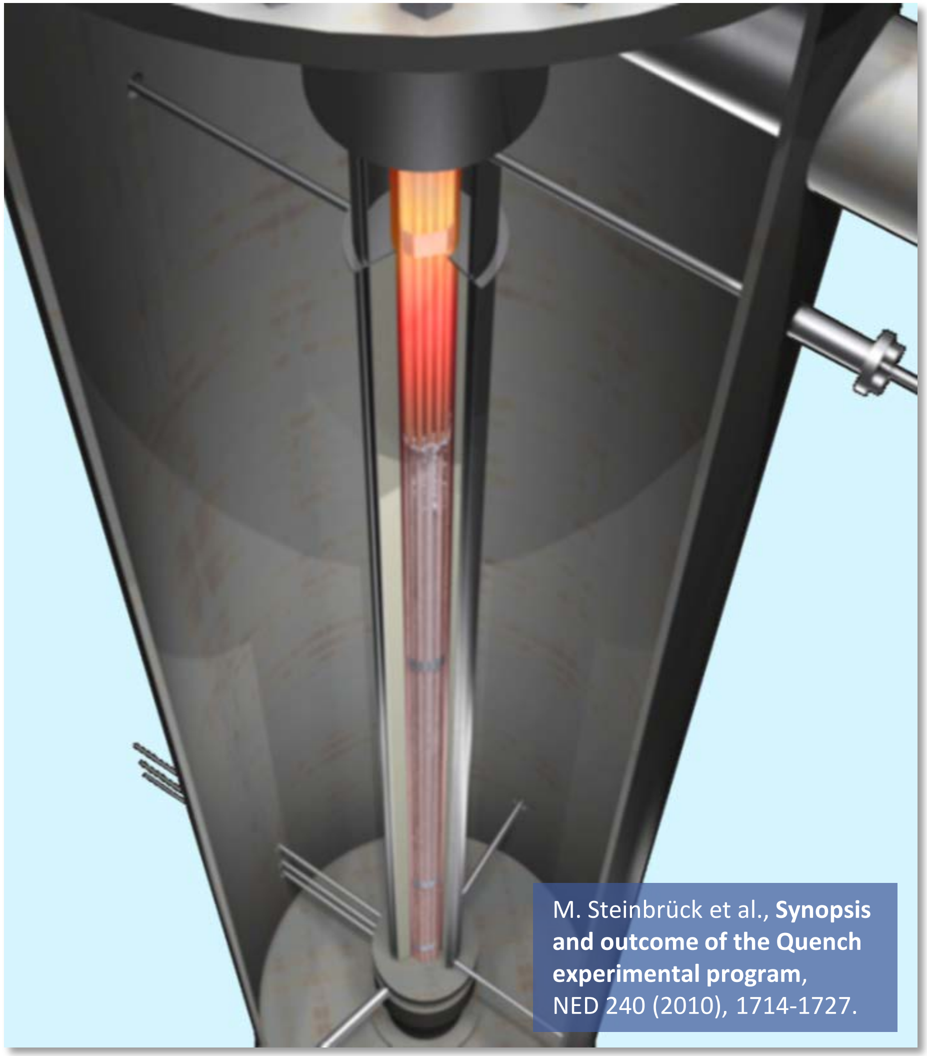


PWR fuel element

Bundle experiments

QUENCH facility

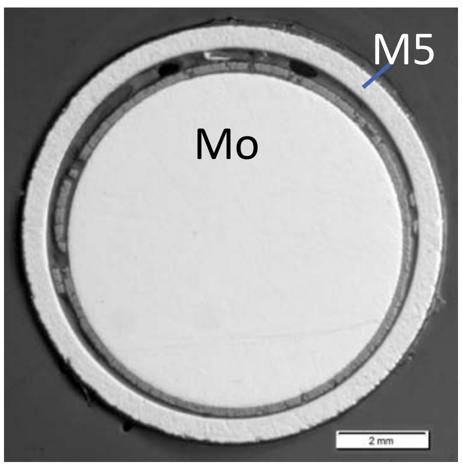
- Unique out-of-pile bundle facility to investigate reflood of an overheated reactor core
- 21-31 electrically heated fuel rod simulators; T up to >2000°C
- Extensive instrumentation for T, p, flow rates, level, etc. + MS
- So far, 19 experiments on SA performed (1996-today)
  - Influence of pre-oxidation, initial temperature, flooding rate
  - B_4C, Ag-In-Cd control rods
  - Air ingress; debris formation
  - Advanced cladding alloys
- 7 DBA LOCA experiments with separately pressurized fuel rods

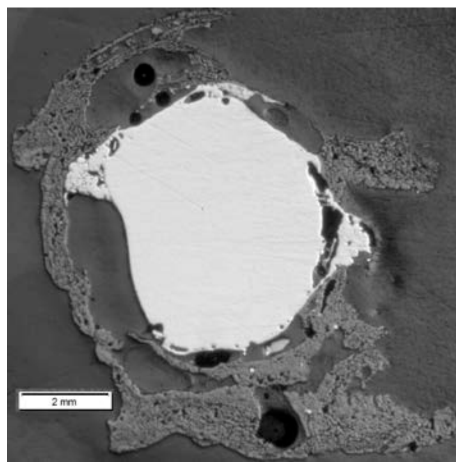


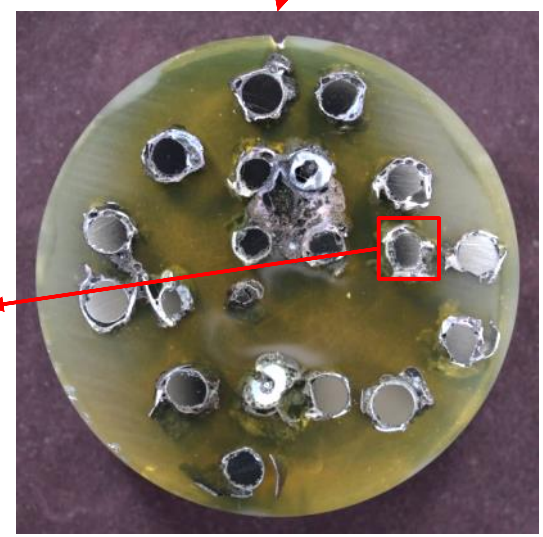
M. Steinbrück et al., **Synopsis and outcome of the Quench experimental program**, NED 240 (2010), 1714-1727.

QUENCH-18

- Successfully conducted in Sept 2017
- In the framework of the EC-China ALISA project
- With M5® cladding, two pressurized rods, two Ag-In-Cd absorber rods, and air ingress
- Strongly degraded bundle
- PTE of the main bundle part still pending
- Issue with MS measurements of O_2 concentration in presence of H_2O





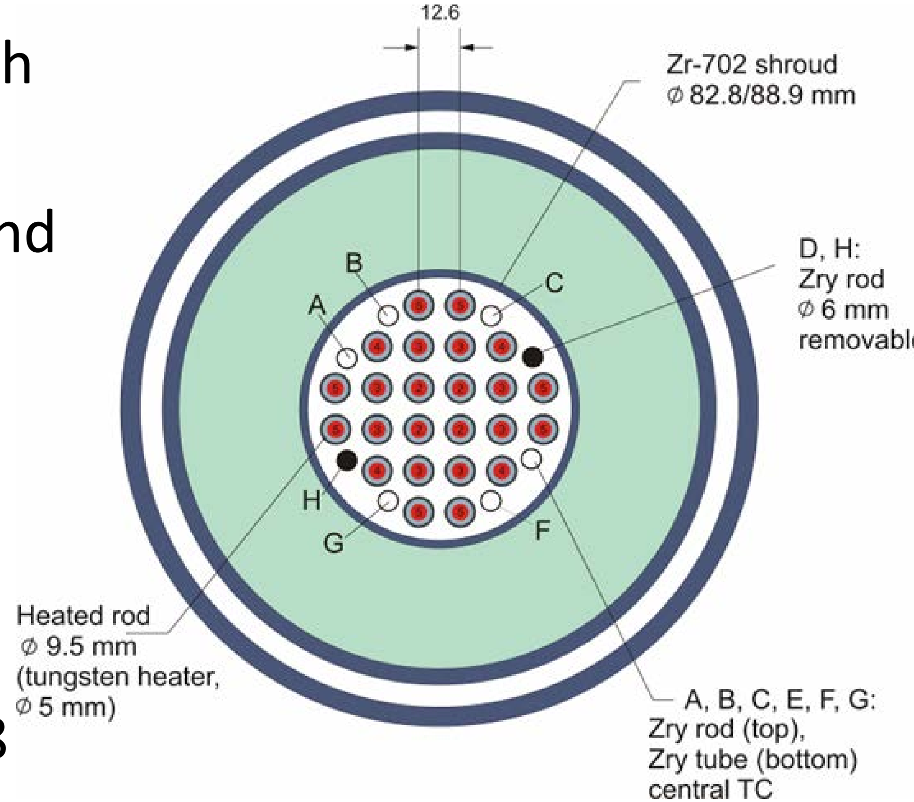


Intact rod at 1450 mm

Strongly degraded bundle at 1250 mm

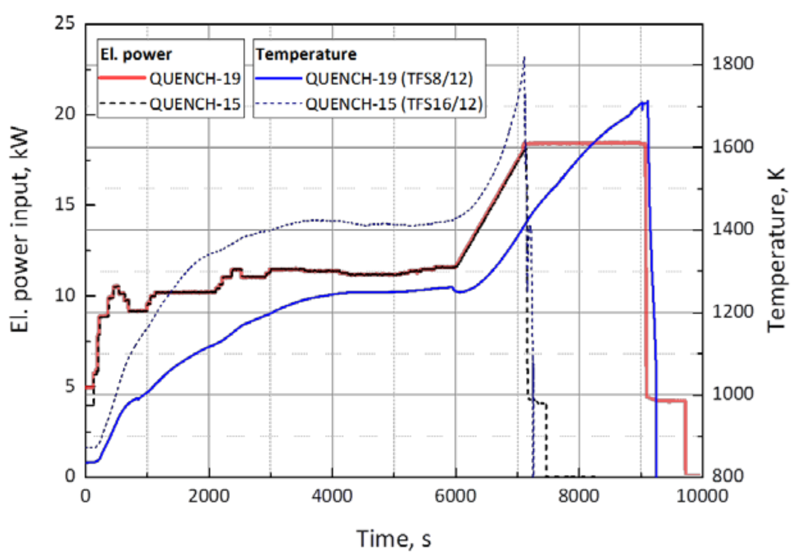
QUENCH-19

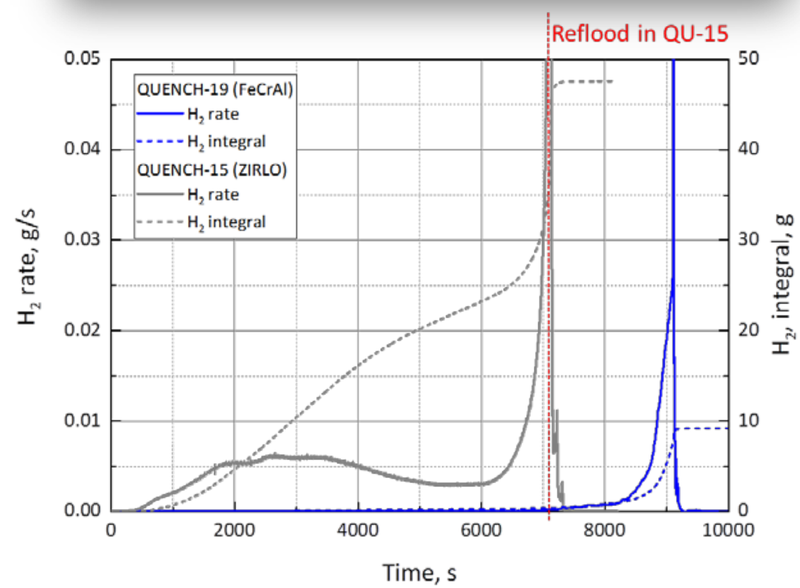
- Worldwide first bundle test with ATF cladding
- With FeCrAl cladding, shroud and spacer grids
- In cooperation with ORNL
- Scenario similar to QUENCH-15 (same bundle geometry, same electrical power input)
- Conducted on 29th August 2018



QUENCH-19

- 100x less hydrogen released up to quenching time of Q-15
- Melting temperature of FeCrAl locally reached
- Significant gain of coping time with FeCrAl compared to Zr alloy



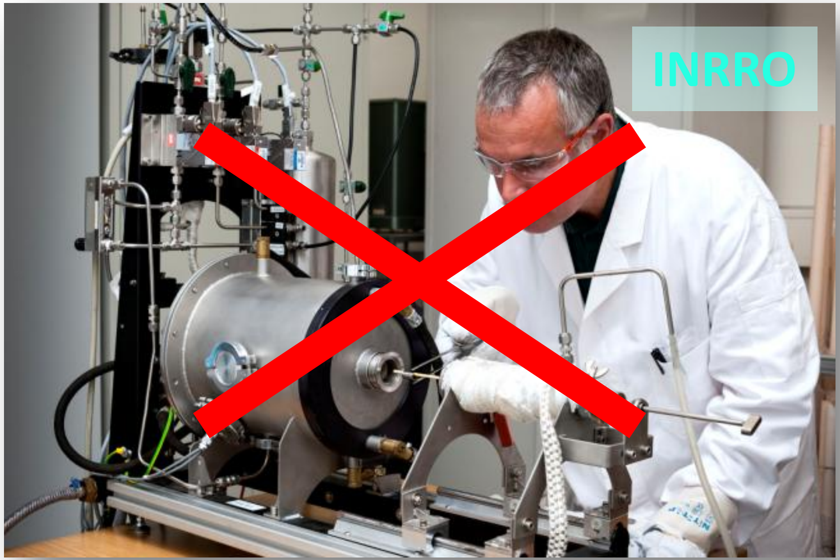


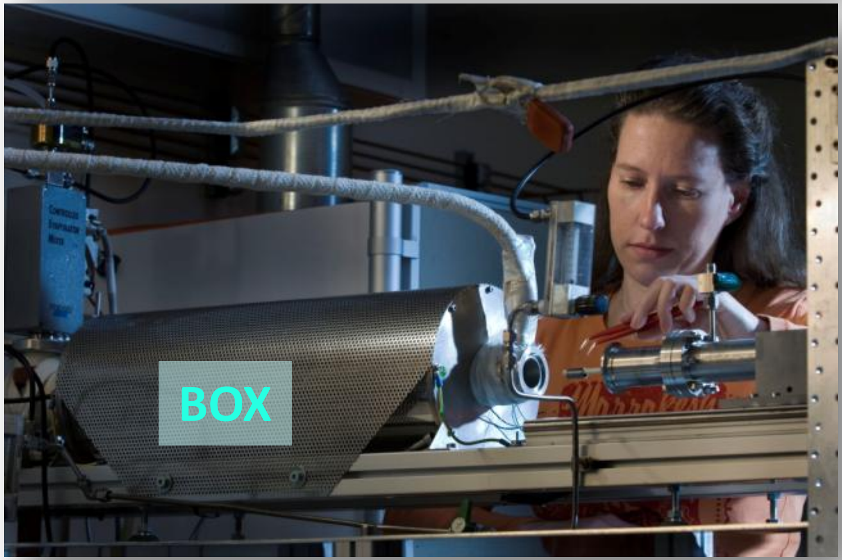
Separate-effects tests in 2018

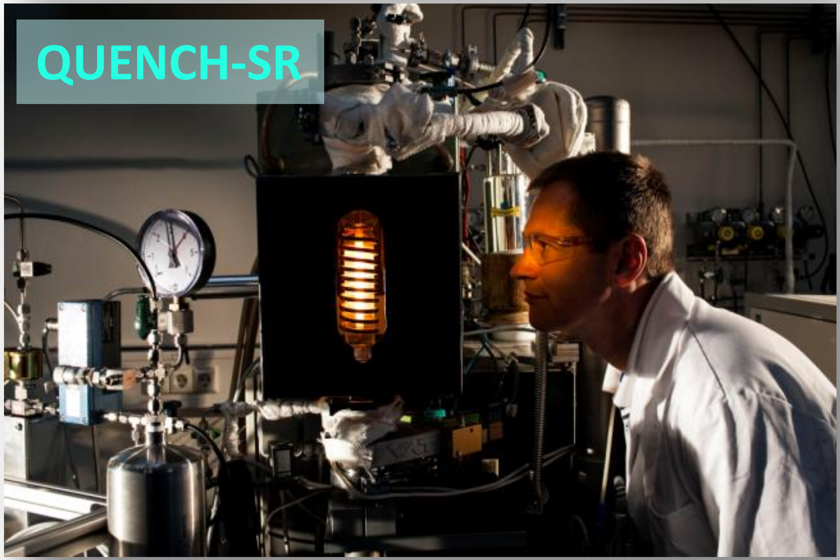
- Experiments on high-temperature oxidation of silicon carbide ceramic-matrix-composites in various atmospheres for different applications
- Optimization of Cr_2AlC MAX phase coatings on Zry
- Autoclave tests with MAX phase coatings at Westinghouse, USA
- High-temperature oxidation of various ATF cladding materials (Fe alloys, MAX phases, coated Zr alloys…) in the framework of international cooperations
- Interaction between SiC and Zry

- CODEX-AIT3 at MTA Budapest proposed by KIT (SAFEST)

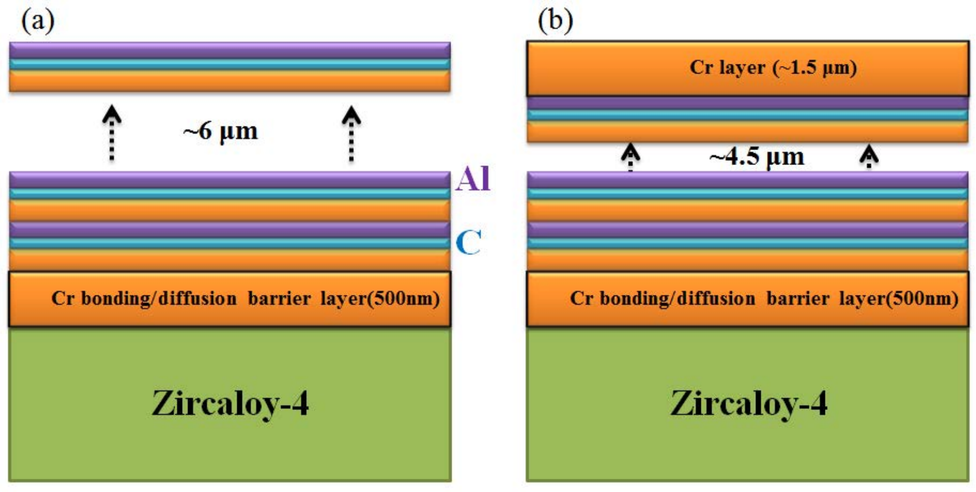
QUENCH Separate-effects tests: Main setups



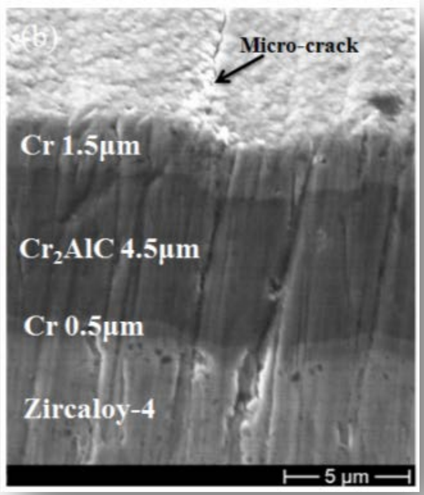




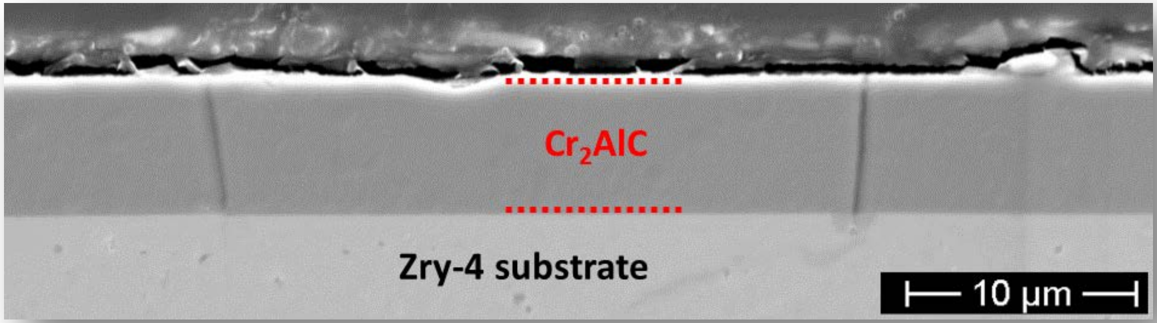
Cr_2AlC MAX phase coating on Zry-4

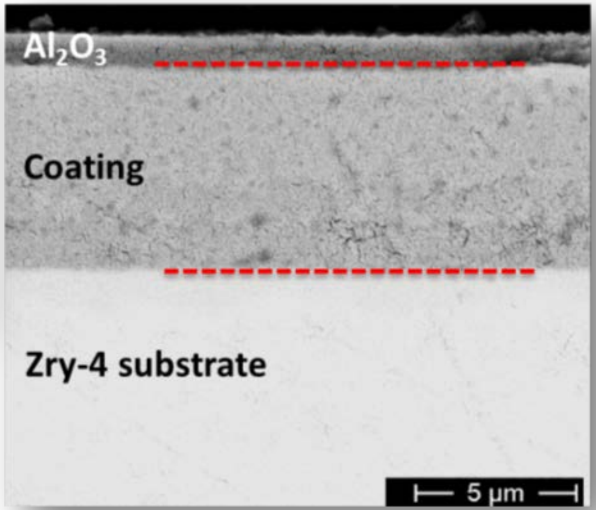


Magnetron sputtered Cr/C/Al nano layers



Pure MAX phase

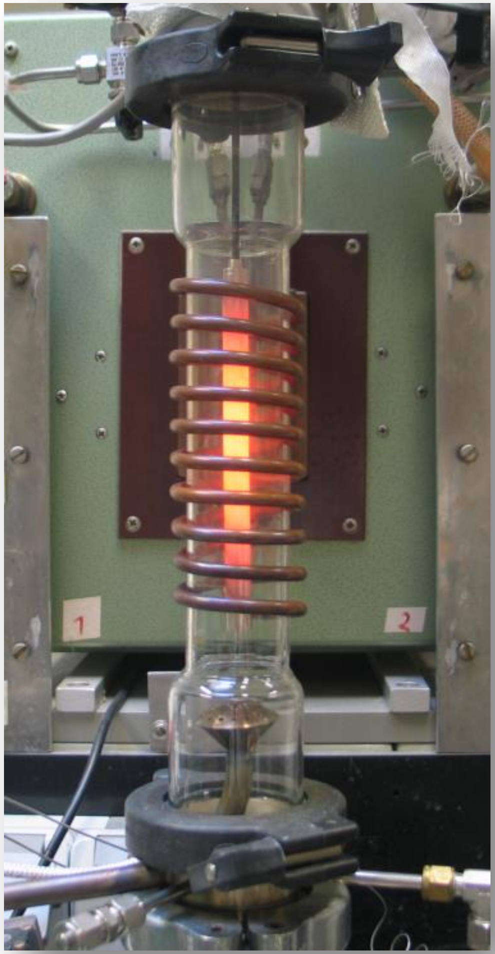




- Excellent behavior of coatings during autoclave tests (↑) and HT oxidation in steam up to 1200°C (→)

HT oxidation in steam of SiC_f-SiC cladding

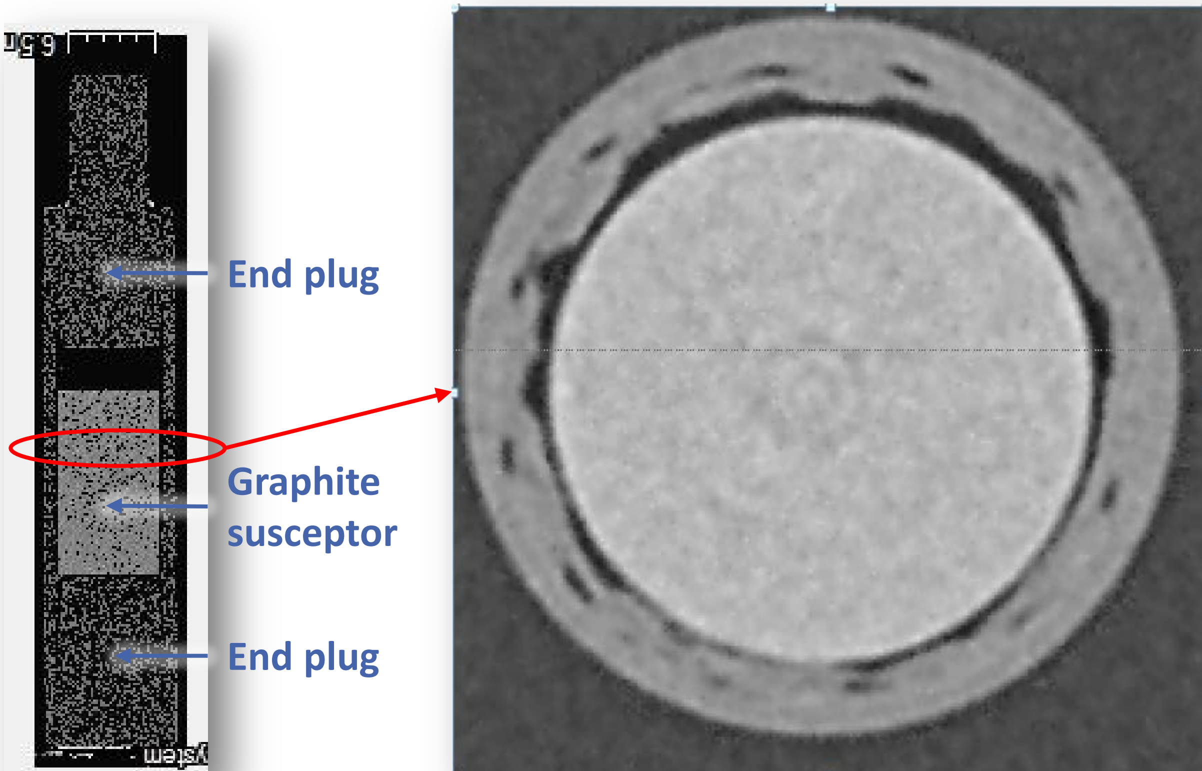
- QUENCH-SR rig with inductive heating of graphite as susceptor
- Two samples
- Four experiments
  - Transient test with target temperature 2200°C (sample 1)
  - Three subsequent isothermal tests at 1600, 1700, and 1750°C terminated by quenching with water (sample 2)



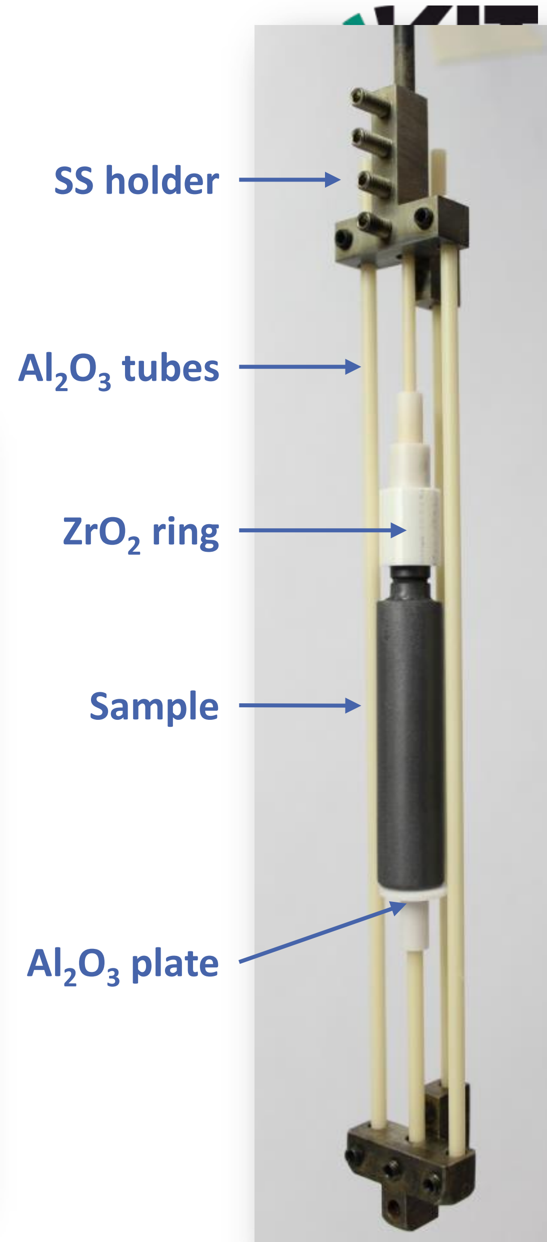
QUENCH-SR with inductive heating

SiC_f-SiC samples

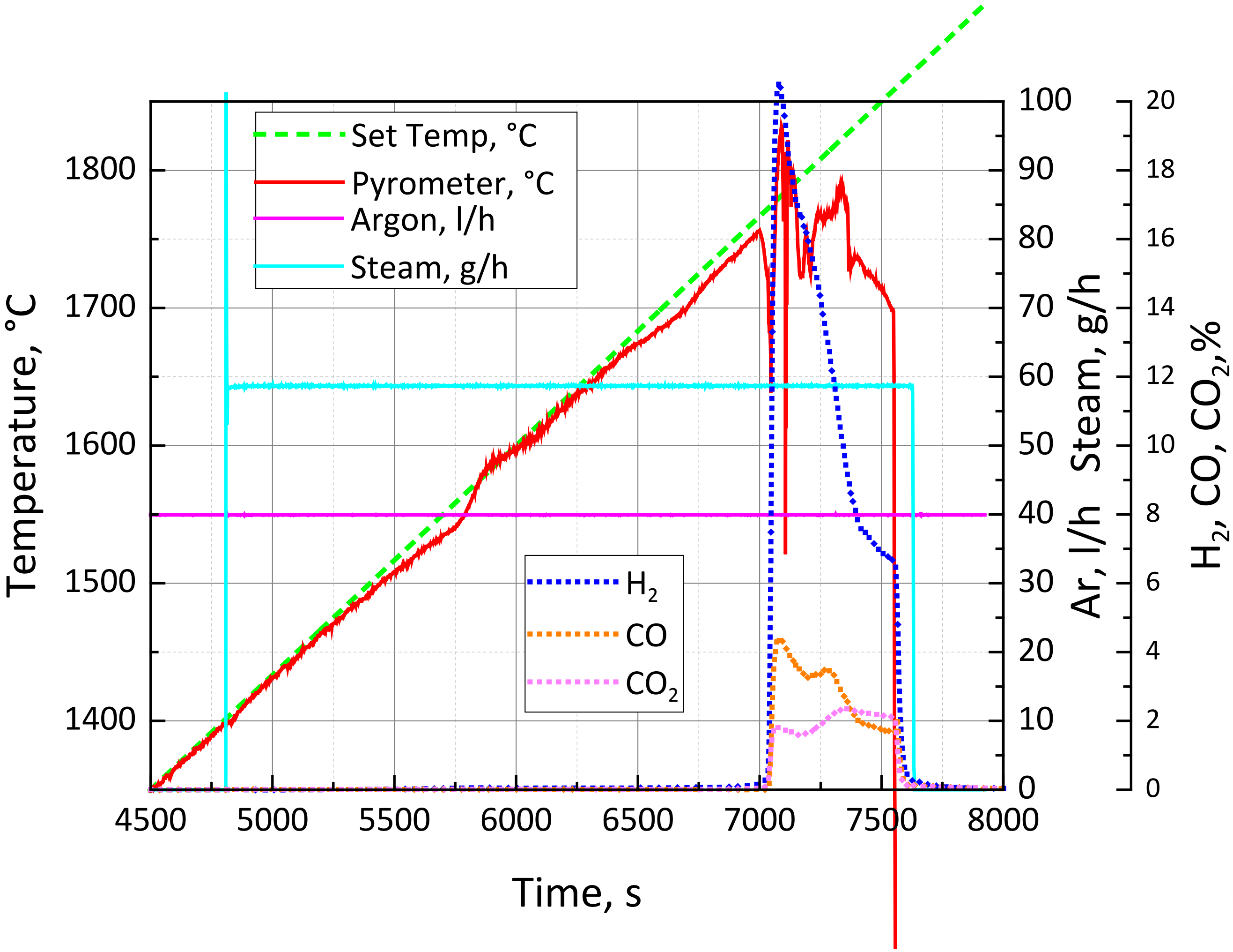
- Provided by General Atomics
- Leak tight with welded end plugs and filled with graphite

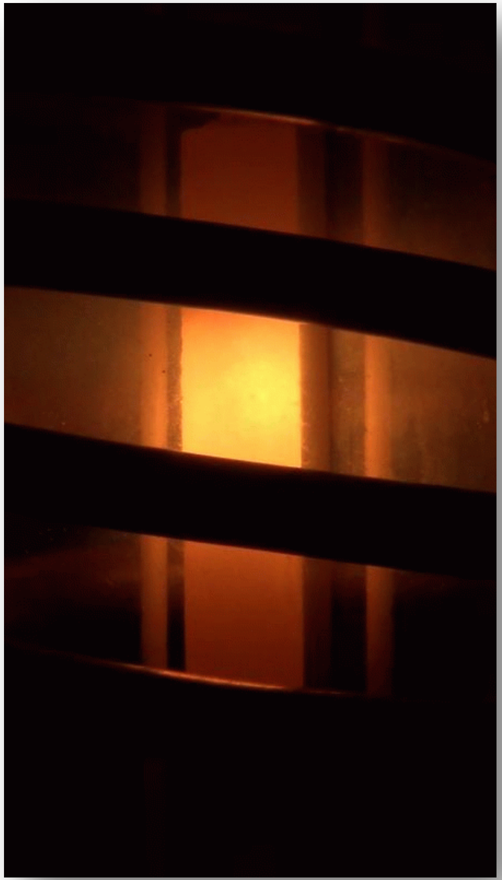


Neutron tomography of as-received sample



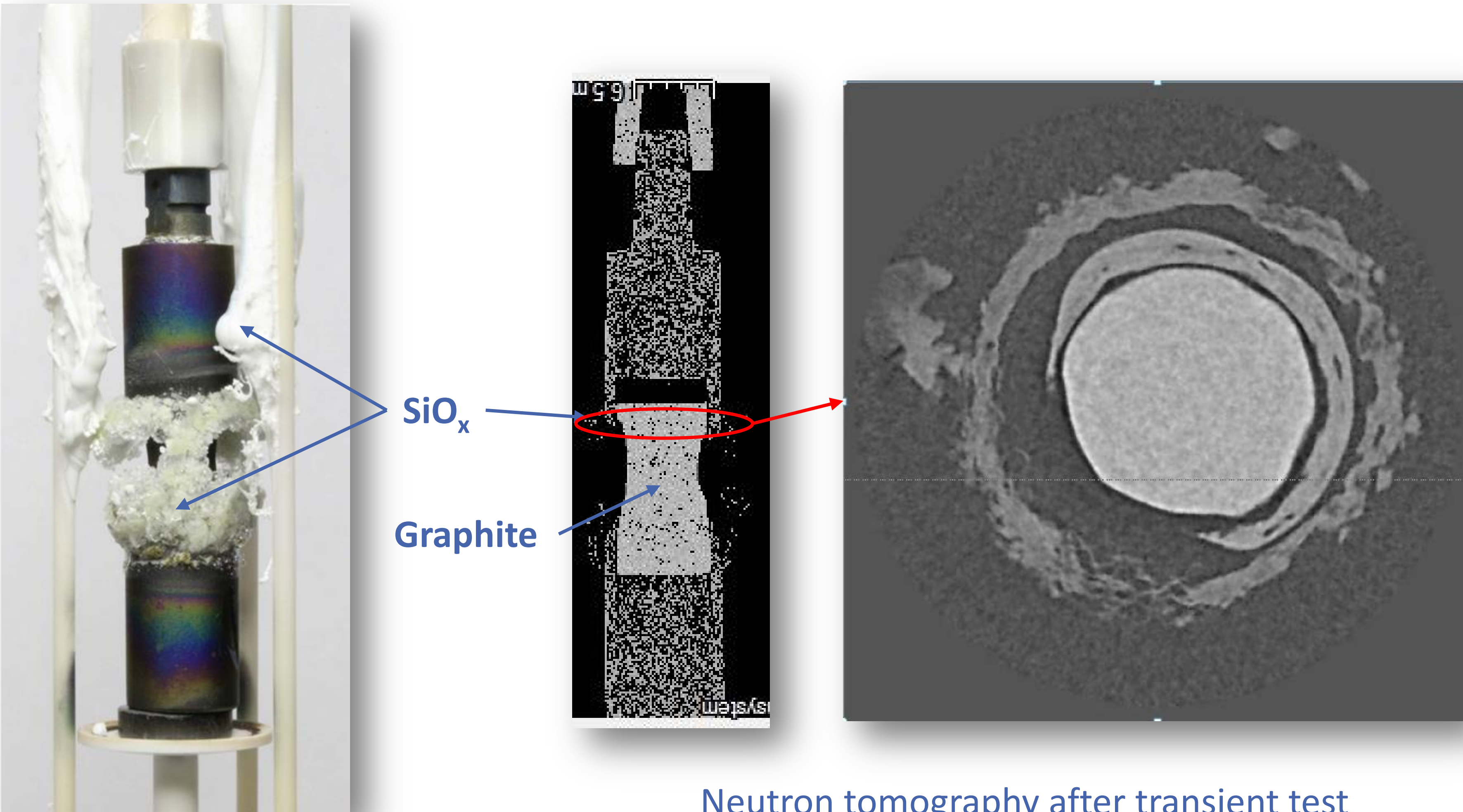
Transient test: Conduct and MS results





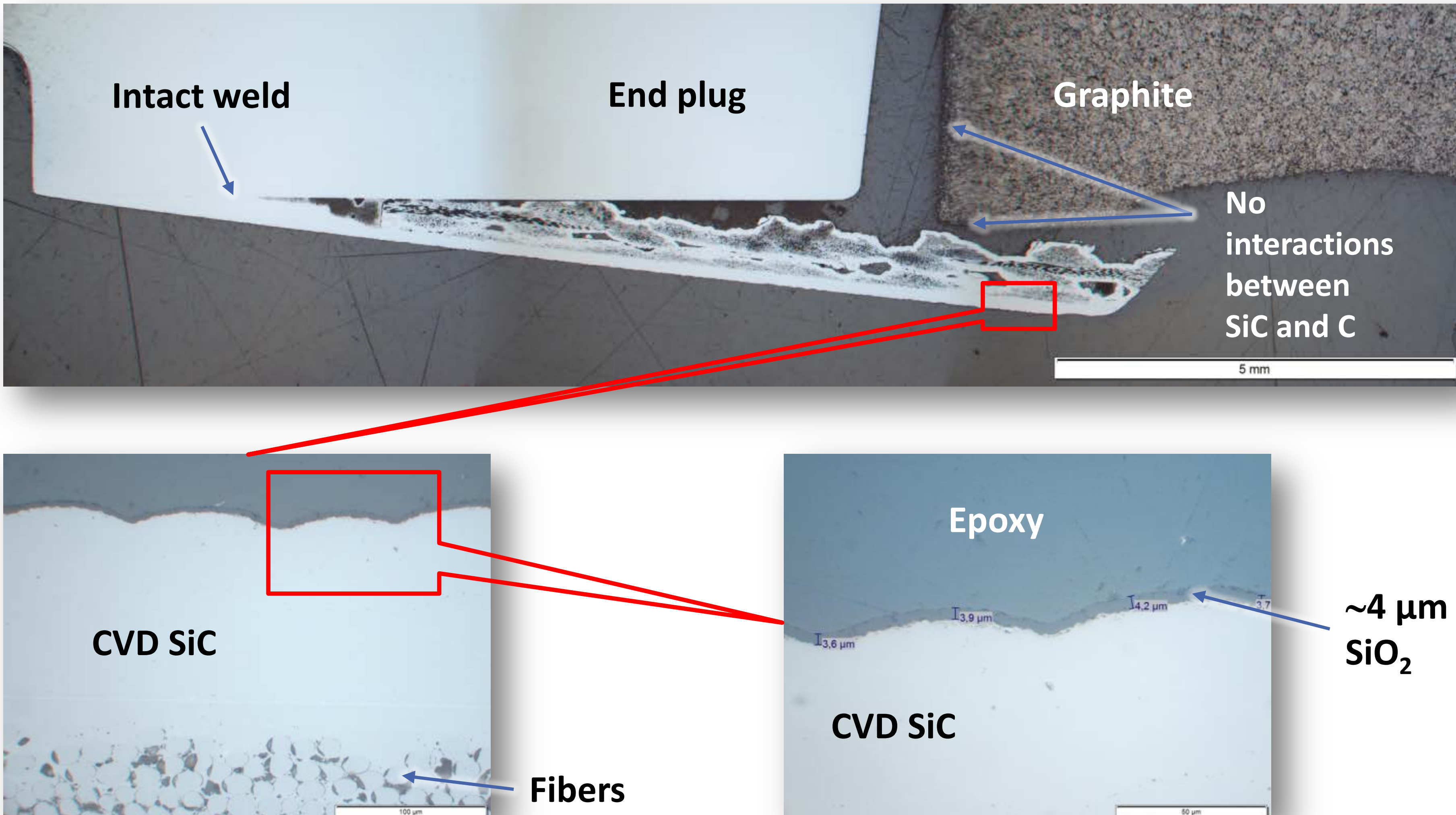
- Bubble formation, strong gas release, SiO_x volatilization above ~1750°C

Transient test: Post-test appearance



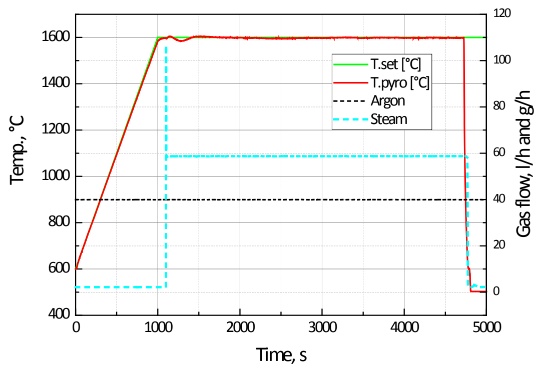
Neutron tomography after transient test

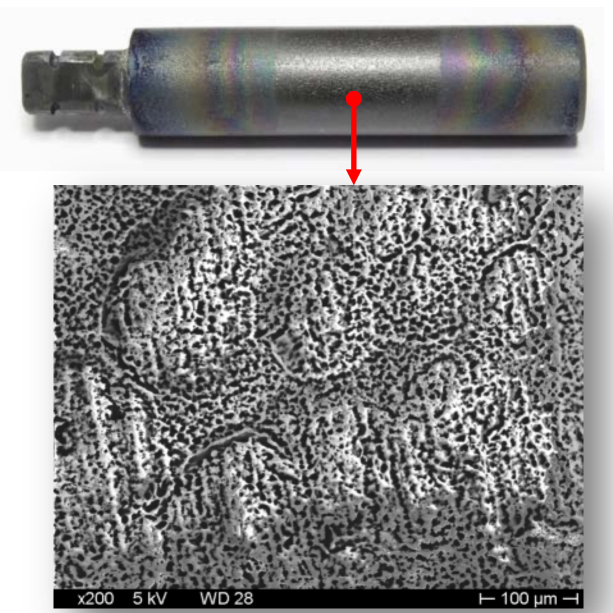
Transient test: Micrographs of longitudinal cross section



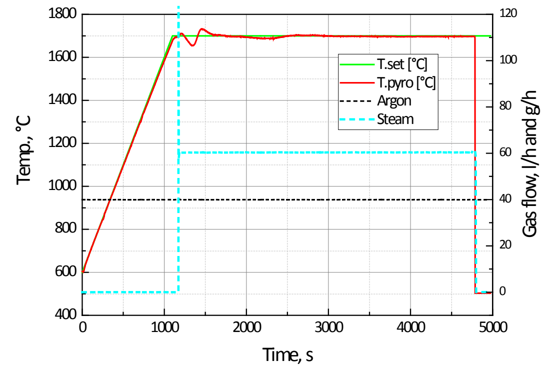
Isothermal tests: conduct and post-test appearance

1 h @ 1600°C

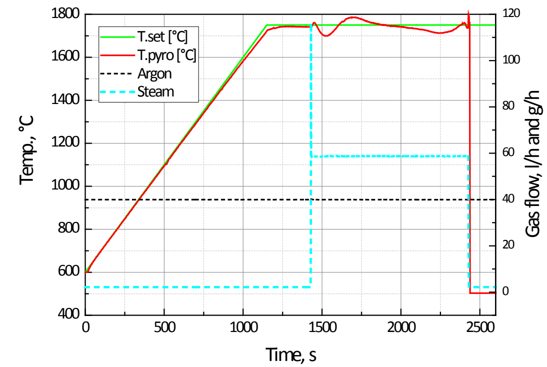


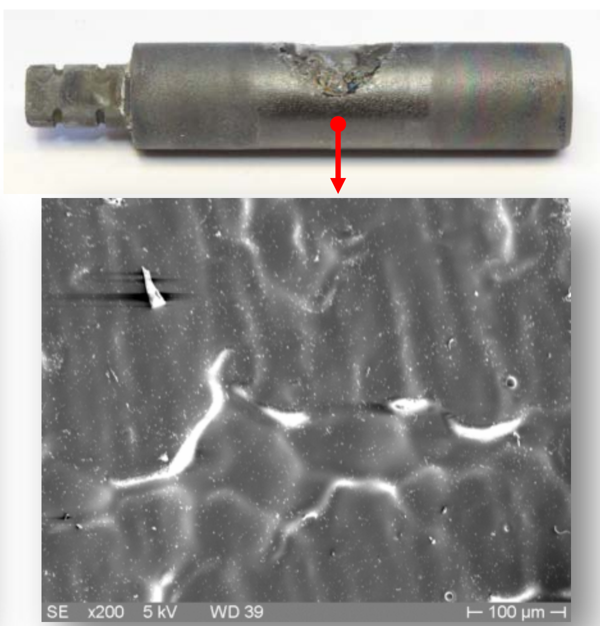


1 h @ 1700°C



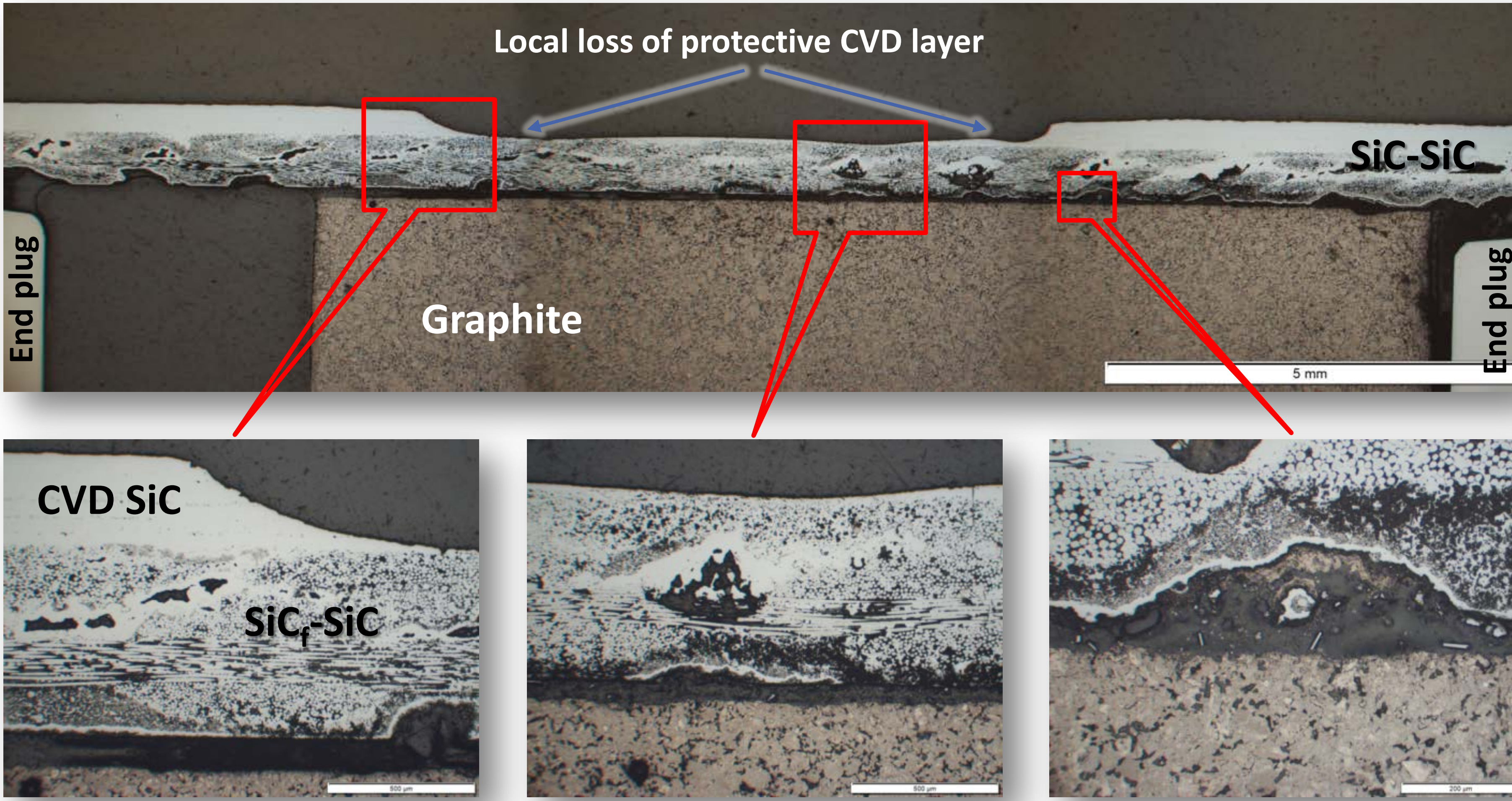
16 min @ 1750°C



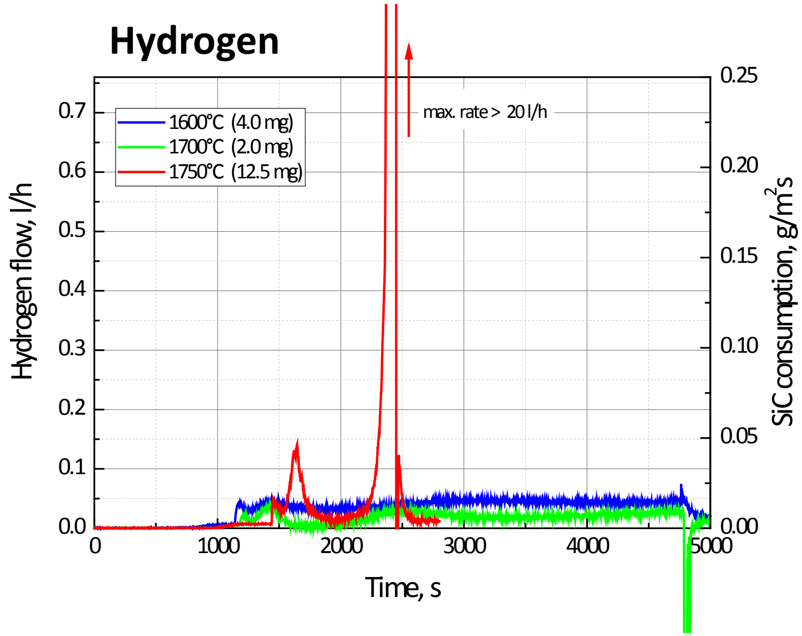


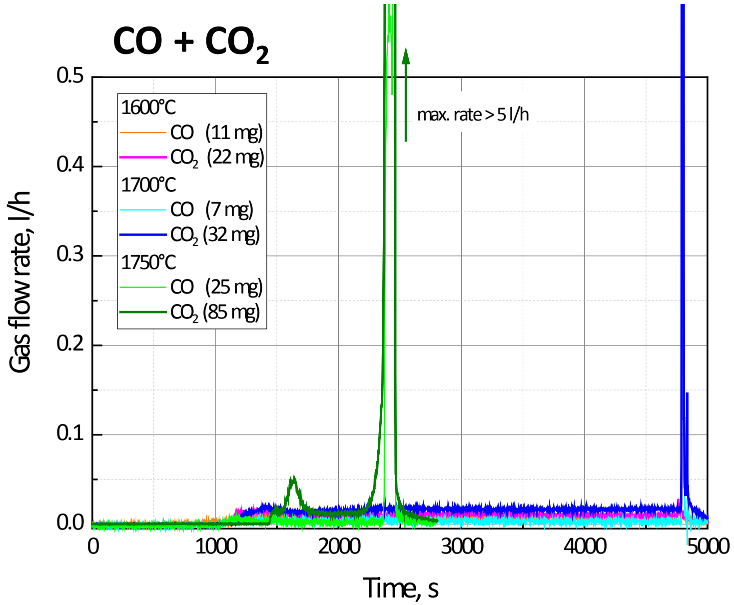
- SEM/EDX: all surfaces are covered with SiO_2

Isothermal tests: Micrographs of longitudinal cross section



Isothermal tests: Gas release





- Very limited oxidation of the SiC_f-SiC cladding at 1600 and 1700°C
- Local failure of the sample after 16 min at 1750°C resulting in strong gas release
- Failure mechanism not yet identified

QUENCH activities for Accident Tolerant Fuel Claddings

- PhD thesis
  - 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, final meeting 01/2018, follow-up program under discussion) as well as in the new TOPATF initiative
- Participation in the IAEA CRP on Accident Tolerant Fuel Concepts for Light Water Reactors (ACTOF)
- WP leader (coolant-cladding-fuel interaction) in the EC project IL TROVATORE in the framework of HORIZON2020
- Partner in the CARAT project lead by Westinghouse, USA

Modelling and code validation

- QUENCH bundle tests are part of validation matrices of most SFD code systems
- Pre-test calculations for QUENCH-18/-19/-20 by various organisations
- Post-test calculations for QUENCH-18 in the framework of the NUGENIA QUESA project by GRS, PSI, IBRAE, LEI, EdF and of QUENCH-19 by GRS
- QUENCH data were used in the frame of IAEA FUMAC project
- RELAP5/SCDAPSIM analyses of various QUENCH tests
- Separate-effects test data on air oxidation of Zr alloys are used by PSI, RUB, EdF, ISS and others for model development

Reporting

- QUENCH-LOCA: KIT Scientific Reports available online
- LOCA summary paper planned for ASTM Symp. Zr in Nucl. Ind. 2019
- Papers, book chapters and conference contributions (>15 Scopus references)
- Plenary talk at NUMAT 2018

1114 ZIRCONIUM IN THE NUCLEAR INDUSTRY: 18TH INTERNATIONAL SYMPOSIUM

STP 1597, 2018 / available online at www.astm.org / doi: 10.1520/STP159720160041

Mirco Grosse,[1] Martin Steinbrueck,[1] Burkhard Schillinger,[2] and Anders Kaestner[3]

In Situ Investigations of the Hydrogen Uptake of Zirconium Alloys during Steam Oxidation

Citation

Grosse, M., Steinbrueck, M., Schillinger, B., and Kaestner, A., "In Situ Investigations of the Hydrogen Uptake of Zirconium Alloys during Steam Oxidation," *Zirconium in the Nuclear Industry: 18th International Symposium, ASTM STP1597*, R. J. Comstock and A. T. Motta, Eds., ASTM International, West Conshohocken, PA, 2018, pp. 1114–1135, http://dx.doi.org/10.1520/STP159720160041[4]

ABSTRACT

The hydrogen uptake during steam oxidation of Zircaloy-4 and E110 was

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Influence of composition and heating schedules on compatibility of FeCrAl alloys with high-temperature steam

Chongchong Tang, Adrian Jianu, Martin Steinbrueck, Mirco Grosse, Alfons Weisenburger, Hans Juergen Seifert

HIGHLIGHTS

ARTICLE INFO

ABSTRACT

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Phenomenology of BWR fuel assembly degradation

Masaki Kurata, Marc Barrachin, Tim Haste, Martin Steinbrueck

HIGHLIGHTS

ARTICLE INFO

ABSTRACT

Contents

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Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

High-temperature interaction of oxygen-preloaded Zr1Nb alloy with nitrogen

Martin Steinbrück, Stefan Prestel, Uta Gerhards

ARTICLE INFO

ABSTRACT

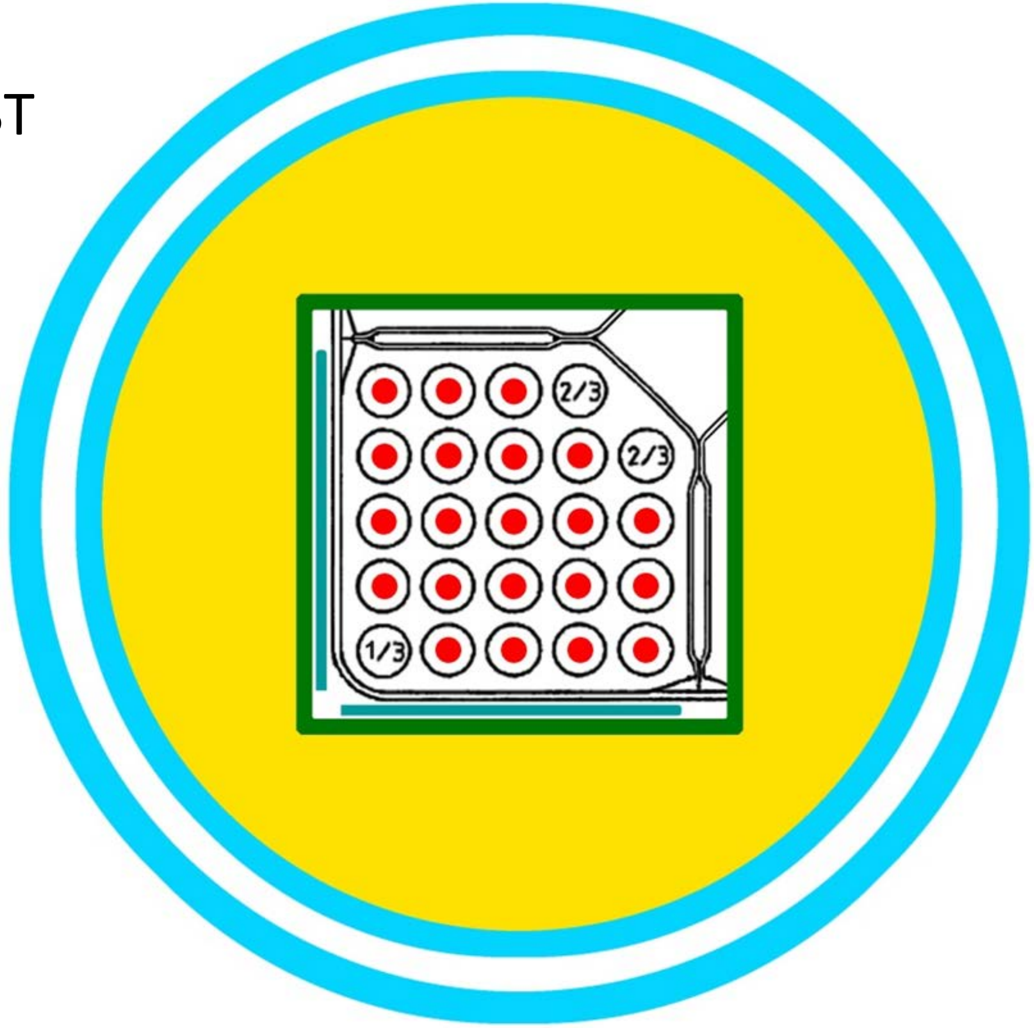
1. Introduction

Outlook 2019-2020

- BWR bundle test with in the framework of the EC SAFEST program beginning 2019
- Post-test examinations of QUENCH-18/-19/-20
- Discussion with various international partners on further bundle tests with ATF claddings
- SETs on various further topics with the focus on ATF cladding high temperature oxidation
- Activities on safety of long-term dry intermediate storage

BWR bundle test QUENCH-20

- Planned to be conducted beginning 2019 in the framework of the EC SAFEST program
- Proposed by Swedish regulatory body and supported by Westinghouse
- Square bundle cross section
- Including boron carbide absorber blades and water channels



Co-operations

KIT Karlsruhe Institute of Technology

Programs

- NUGENIA
- HORIZON 2020
- IAEA
- OECD-NEA

Bilateral

- PSI
- MTA EK
- IRSN, CEA, EdF
- RUB-LEE, IKE
- JRC
- GRS
- Westinghouse
- USNRC
- KONICOF
- NECSA, BAM, HMI
- NRA, JAEA
- ISS
- ORNL
- Various Chinese Organizations

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- Program NUSAFE and IAM institute's management for broad support of our activities
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- And last but not least the QUENCH team:
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Karlsruhe Institute of Technology

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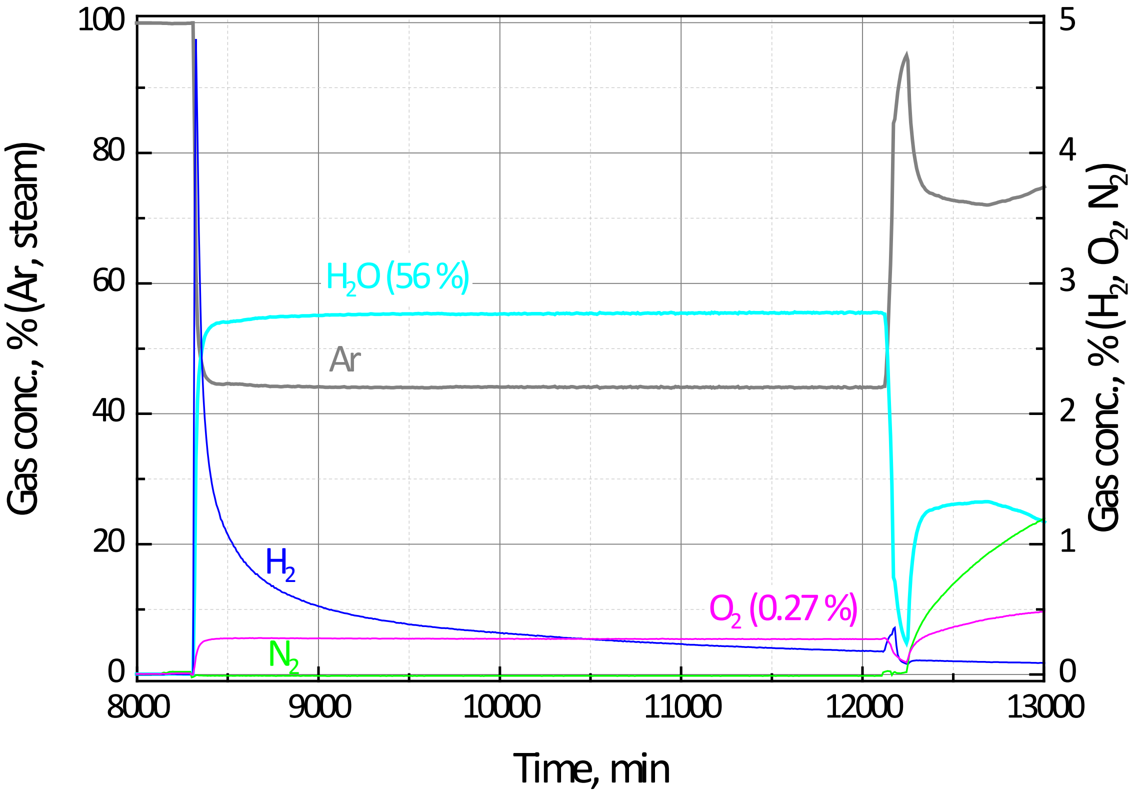
MS issue with O_2 signal in presence of steam

- Since July 2017 after change of filaments
- Small artificial O_2 signal (<1%) in presence of steam without any correlation to other signals (N_2, H_2)



Example:
Zry-4 oxidation in steam
at 1200°C