Karlsruhe Institute of Technology

Institute for Applied Materials

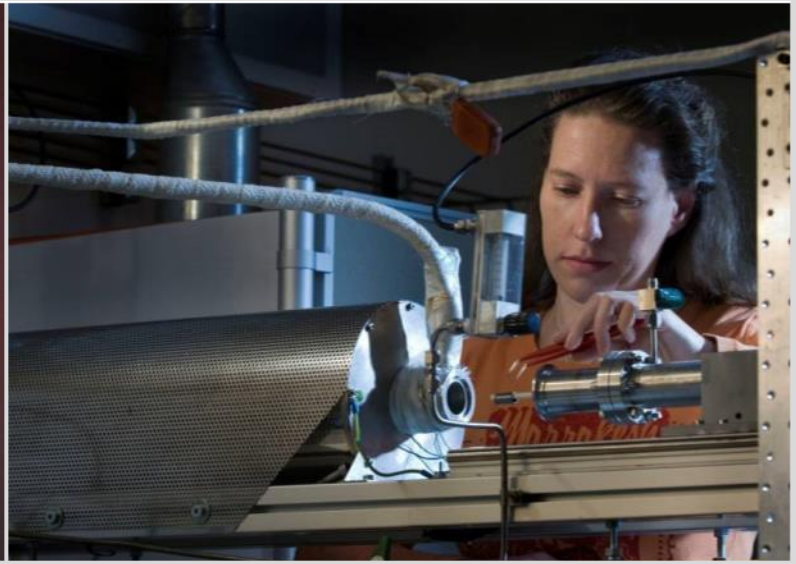
Update of KIT activities on ATF claddings

M. Steinbrück, M. Grosse, A. Jianu, A. Weisenburger, V. Avincola, S. Ahmad, C. Tang

Third Meeting of the Expert Group on ATF for LWRs (EGATFL)

3-5 March 2015, OECD-NEA Headquarters, Issy-les-Moulineaux, France

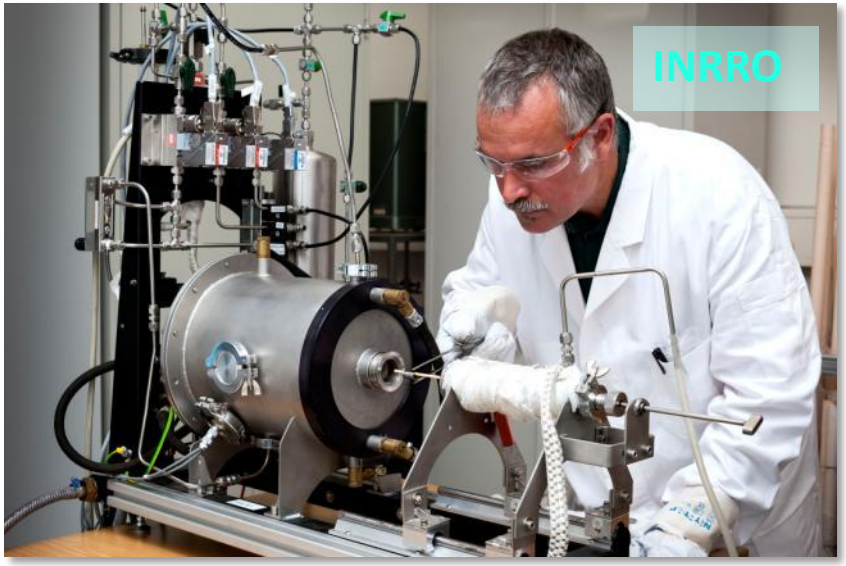
Institute for Applied Materials IAM-AWP & Program NUKLEAR

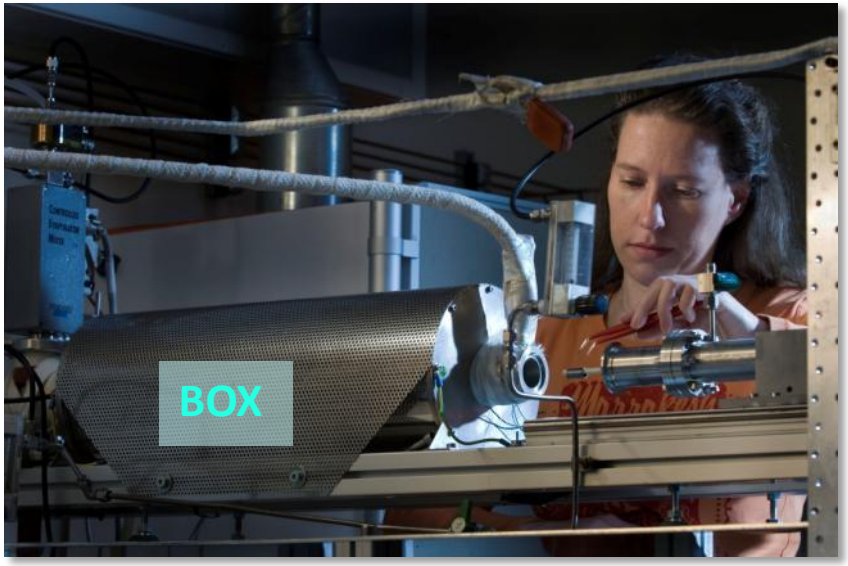


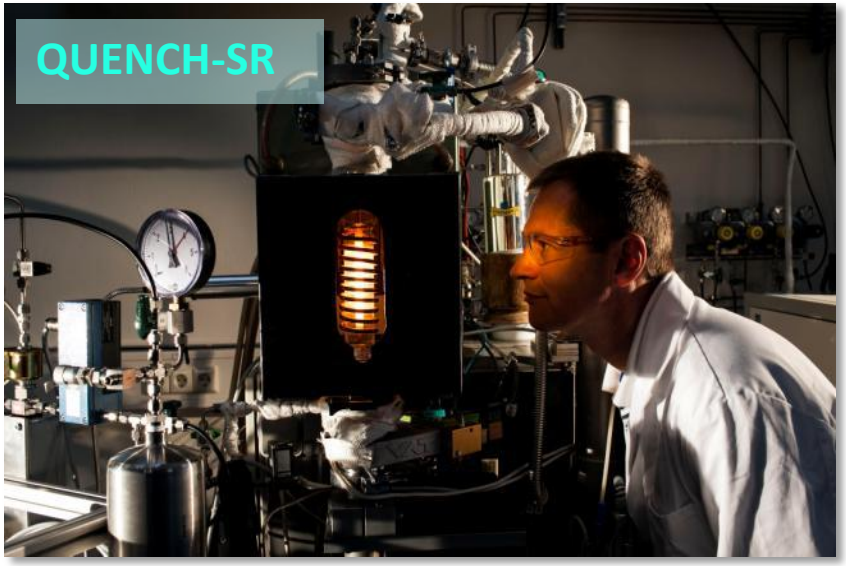
Outline

- Experimental infrastructure
- FeCrAl surface modification
- High-temperature oxidation of SiC materials and SiC-SiC joining
- High-temperature resistant coatings on Zry clads
- Large-scale bundle test with FeCrAl claddings

HT oxidation and materials interactions - Main setups



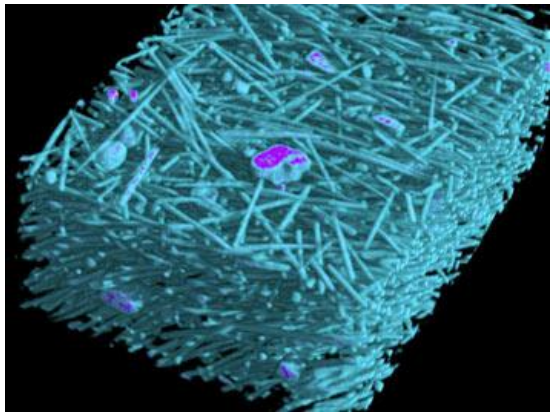




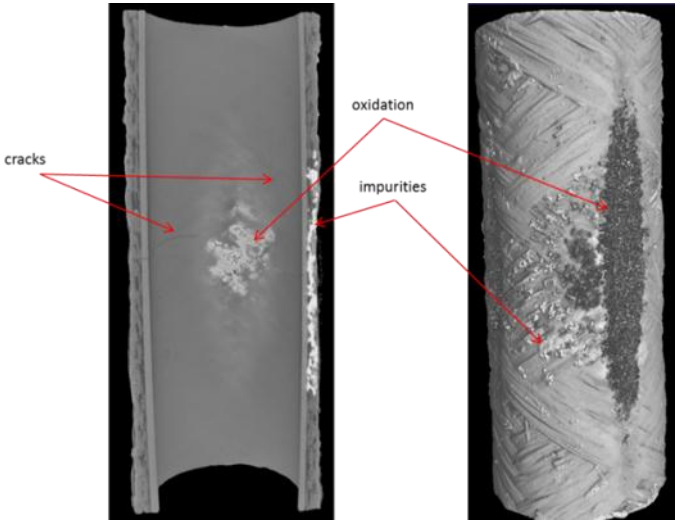
X-Ray and neutron radiography/tomography

GE phoenix v|tome|x s

- For 2D X-ray inspection and 3D computed tomography
- Max. sample size: 200 x 150 mm
- Resolution down to 1 µm



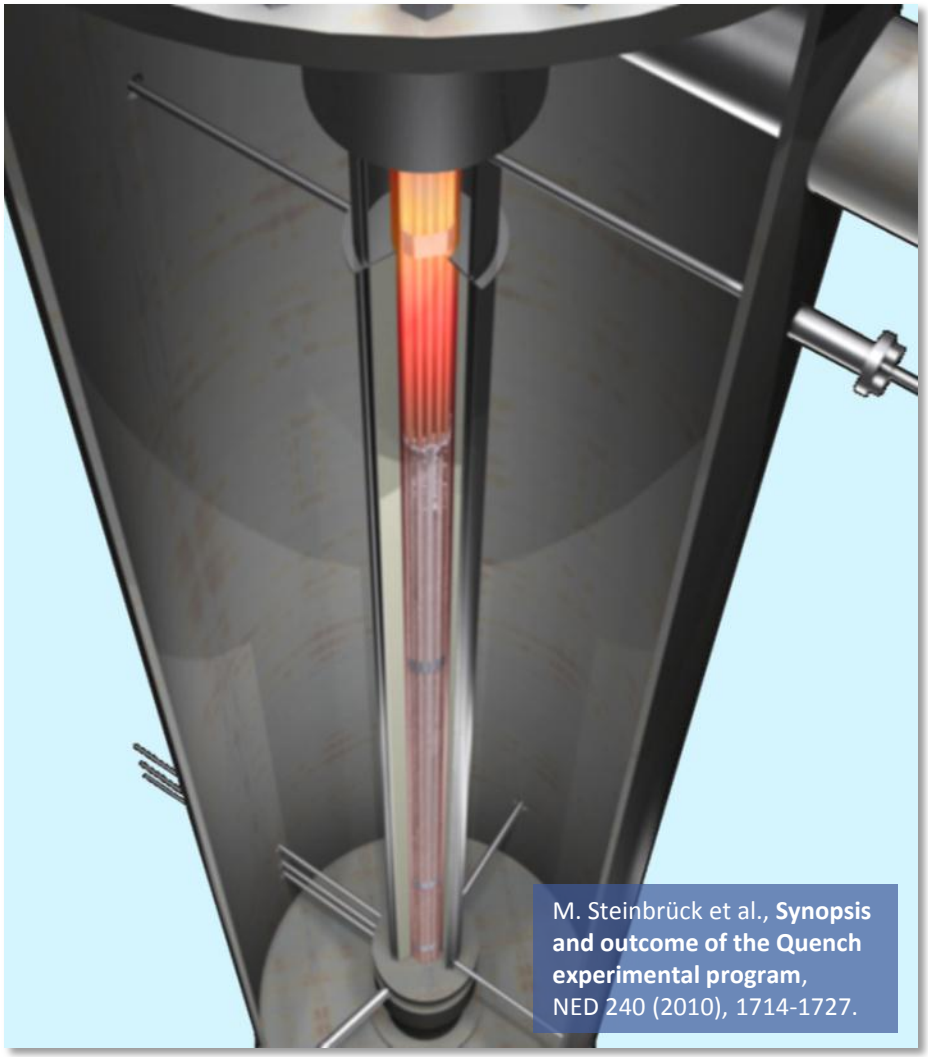
glass fiber-reinforced plastic



SiC/SiCf cladding

QUENCH Facility

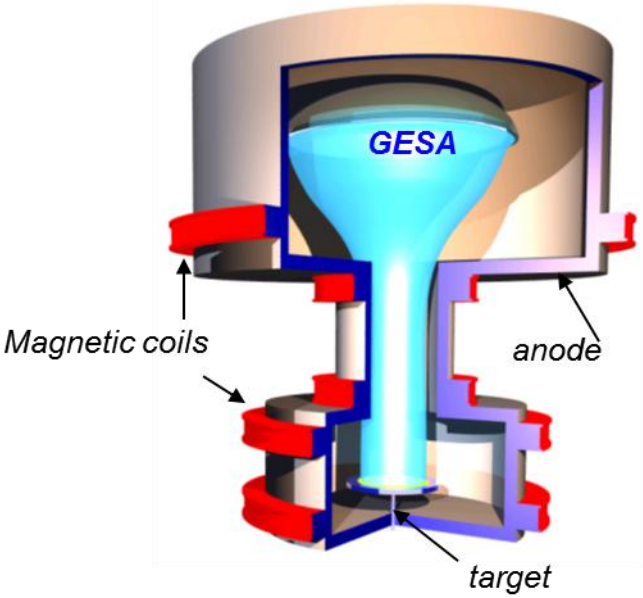
- Unique out-of-pile bundle facility to investigate reflood of an overheated reactor core
- 21-31 electrically heated fuel rod simulators; T up to >2000°C
- Extensive instrumentation for T, p, flow rates, level, etc.
- So far, 17 experiments on SA performed (1996-today)
  - Influence of pre-oxidation,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

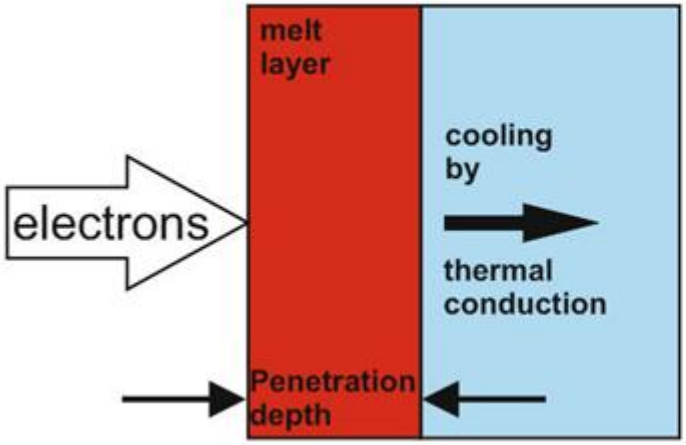


M. Steinbrück et al., **Synopsis and outcome of the Quench experimental program**, NED 240 (2010), 1714-1727.

Surface modification of materials using pulsed electron beams (GESA)

- Using intensive pulsed electron beams, energy can be deposited into surface layers of materials very efficiently and fast. Material surfaces are melted with a single pulse to a depth of up to 100 µm.
- Plates as well as tubes can be treated by GESA process.



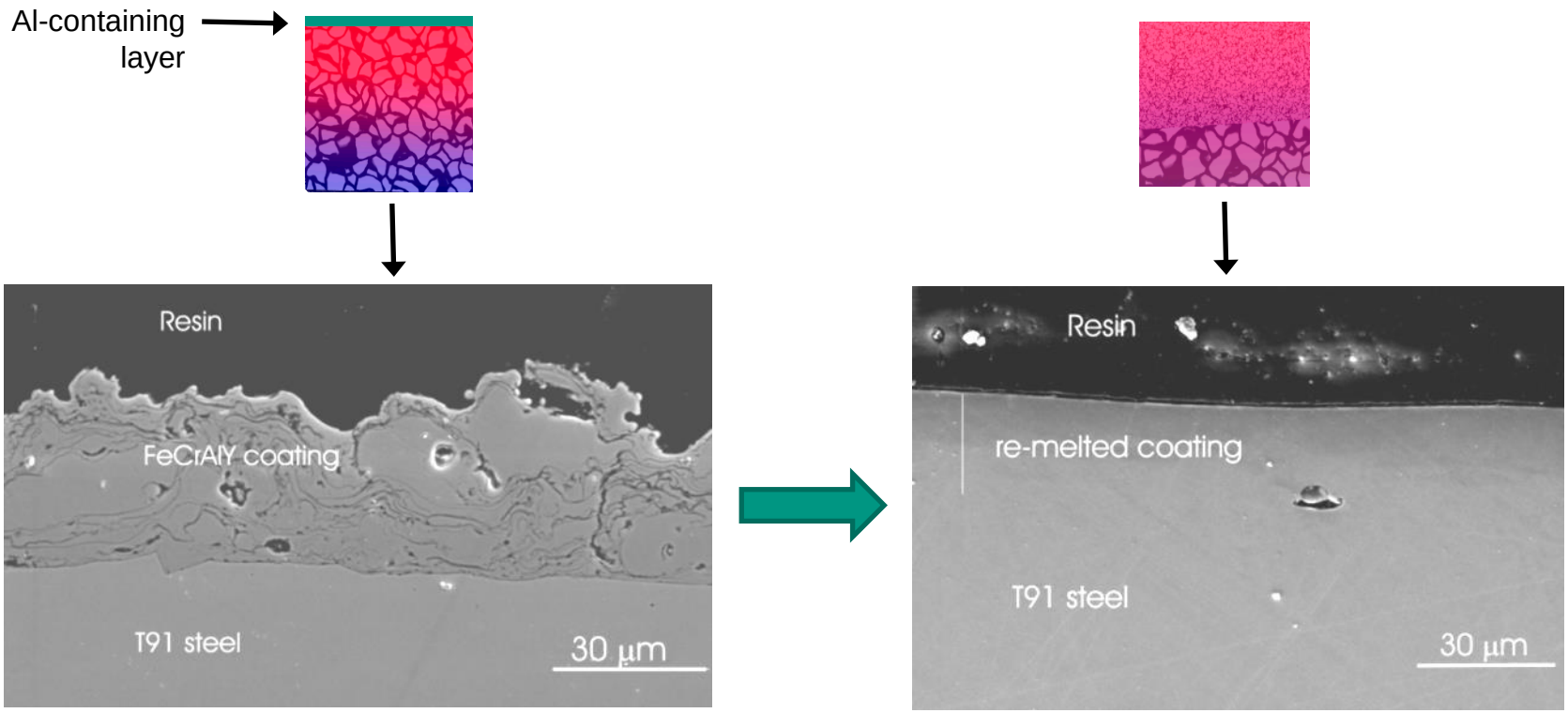


- Penetration depth of electrons: 10 - 100 µm
- 3 -20 J/cm^2 are necessary for melting
- Rapid cooling by thermal conduction into underlaying materials (10^7 -10^9 K/s)
- efficient energy coupling

G. Müller et al.
J. Nucl. Materials 278 (2000) 85-95

Fe-Cr-Al-based modified surface layer (GESA)

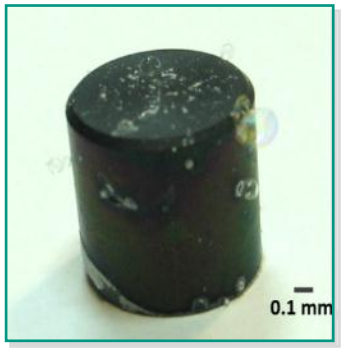
- Coating by plasma spraying
- Re-melting of the coating by intensive pulsed electron beam
- Additions of RE (reactive elements like Zr) to foster the formation of Al_2O_3



metallic bonding – pore removal – surface smoothening

High-temperature oxidation of SiC materials

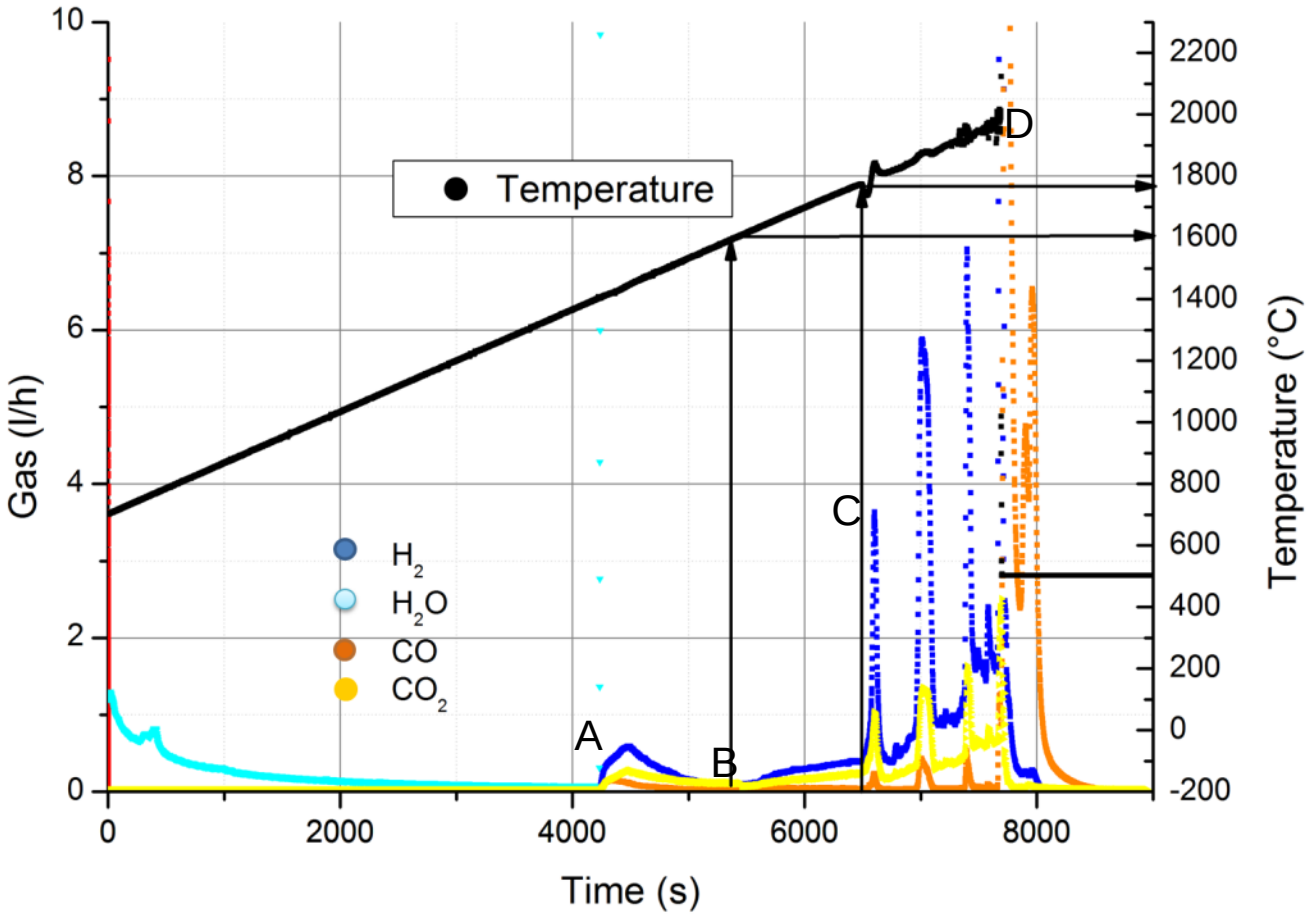
- PhD thesis "**Combined experimental and numerical investigation of accident tolerant nuclear fuel cladding materials in extreme conditions with a focus on silicon carbide**"



- Materials:
  - Commercial α-SiC cylindrical samples (ESK Ekasic F-plus)
  - SiC-SiC CMC cladding tubes provided by CEA and CTP
  - Zry with MAX coatings
- Atmospheres:
  - Argon-oxygen mixtures
  - Helium-impurities mixtures
  - Steam

- Experiments with final quench phase from up to 2000°C
- Will be completed soon

SiC oxidation in steam and quenching from 2000°C



A: Steam injection formation of SiO_2

B: Start of the phase with SiO_2 scale degradation from 1600°C

C: Strong increase of hydrogen production from 1750°C

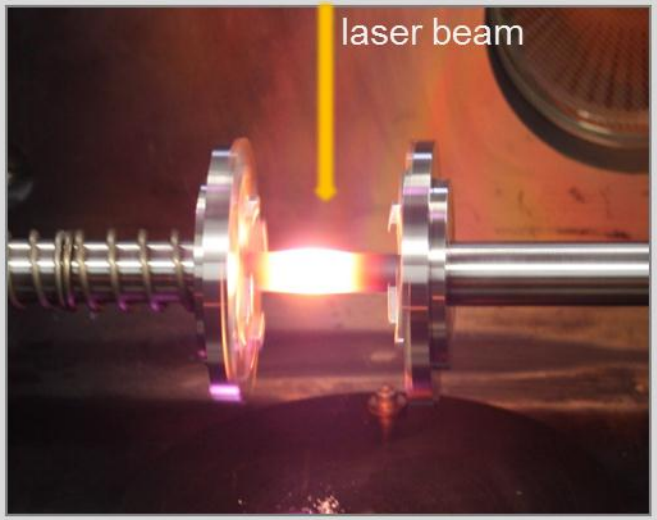
D: Cooldown phase

Sample: CTP triplex cladding

Laser-beam joining of SiC components

- PhD in cooperation with Technical University Dresden
- Rare earth alumino-silicate glasses are used as solder
- AlSiY, AlSiDy and AlSiHo glasses showed best wettability with SiC structures

SSiC- capsules
StarCeram S (H.C.Starck)
Ø: 12 mm, h: 16 mm

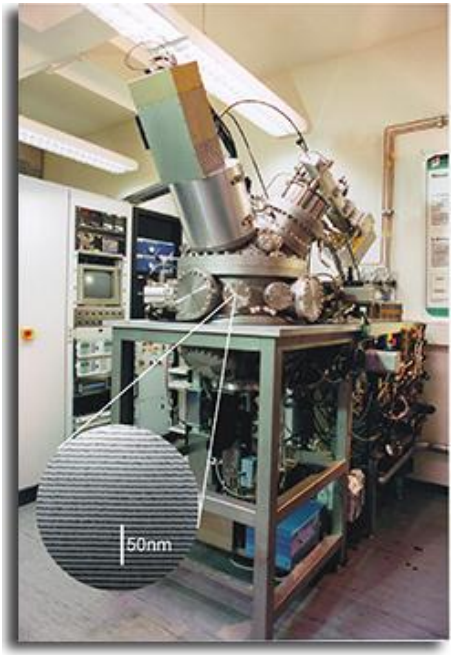


Joining process
(ambient or inert atmosphere)

joined capsules

HT resistant coating on Zr alloy cladding

- PhD supported by Chinese Scholarship Council (CSC)
- Objective: Development of coating with oxidation resistance in water steam up to 1500°C
- Literature study finished, selection process in progress
- First candidates: MAX phases (Ti_3AlC_2), Zr-Si(-C) system, and FeCrAl



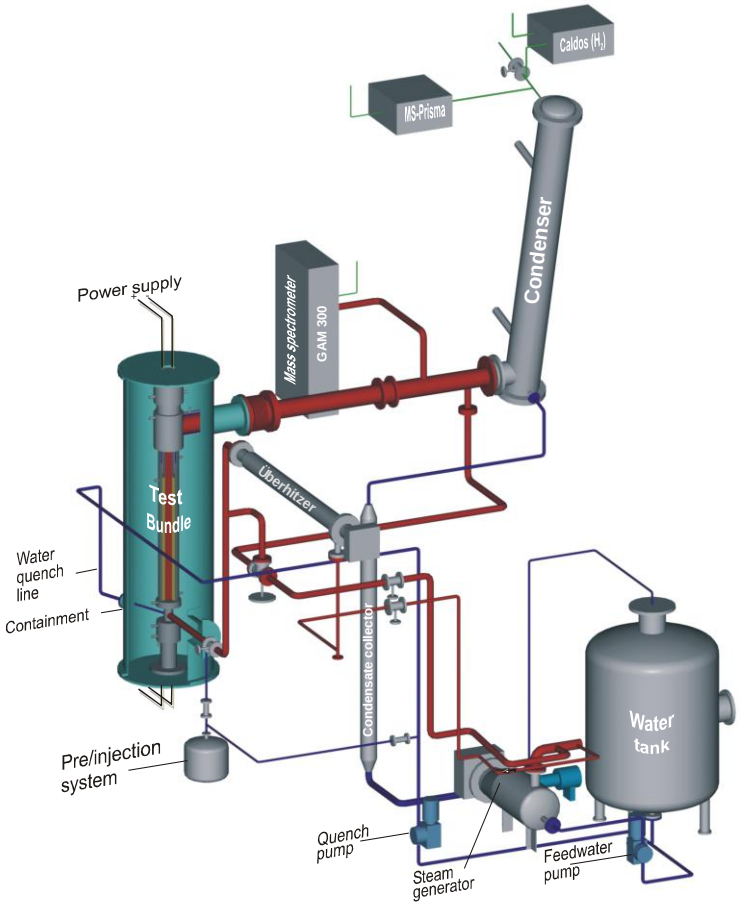
Hybrid coating facility

Coating facility HTC 625

Multi-functional PVD coating facility

Potential future KIT contributions to ATF research

- Separate-effects tests on high-temperature oxidation, quenching, joining, and mechanical behavior of AT claddings
- Development and optimization of HT resistant coatings on Zircaloys
- Bundle tests with prototypic LOCA and BDBA scenarios
  - Discussions with ORNL and Westinghouse on bundle test in QUENCH facility with FeCrAl cladding in progress



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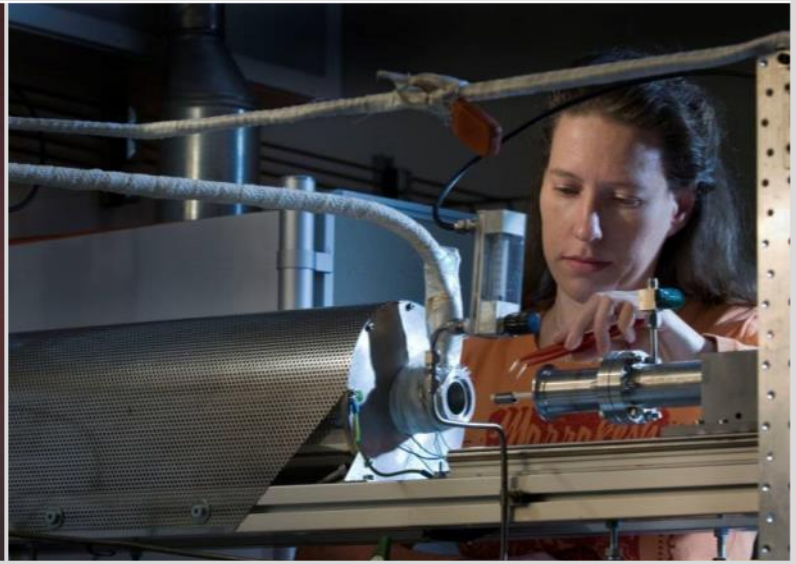
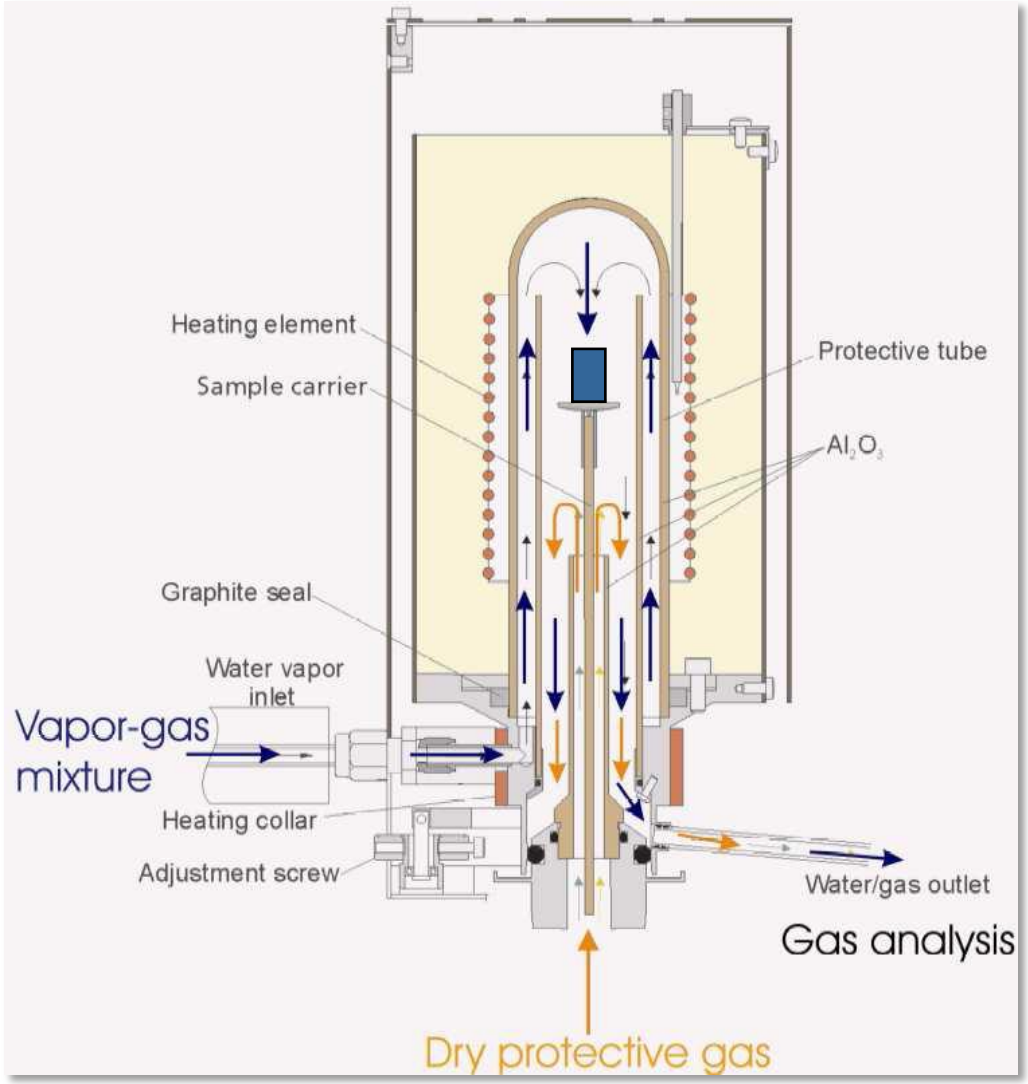
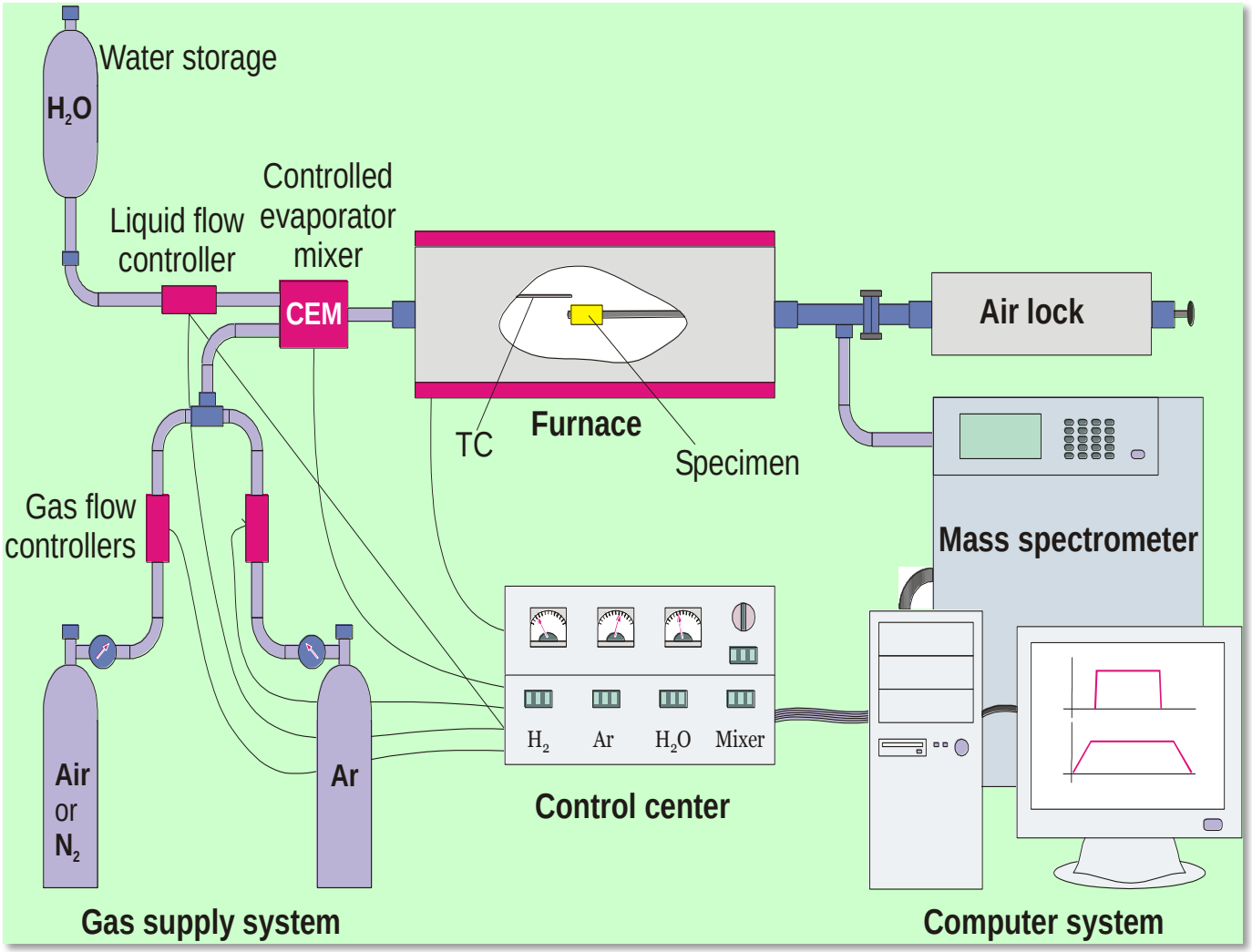


NETZSCH® steam furnace for TGA

- Up to 100% steam
- Up to 1250°C



BOX rig for investigation of materials at high temperatures (1700°C) in defined atmospheres



BOX Facility

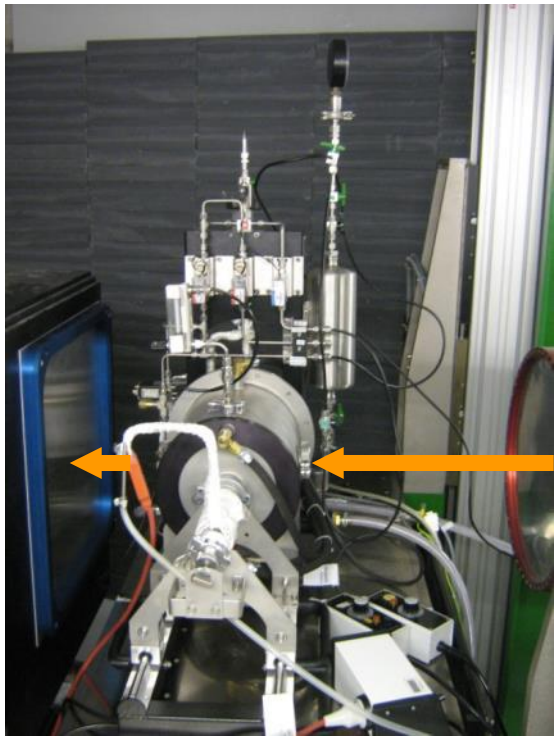
1700 °C

Oxidising, reducing atmosphere (incl. steam)

Specimens: 1-2 cm

MS coupling

In-situ NR investigation of hydrogen diffusion in Zry



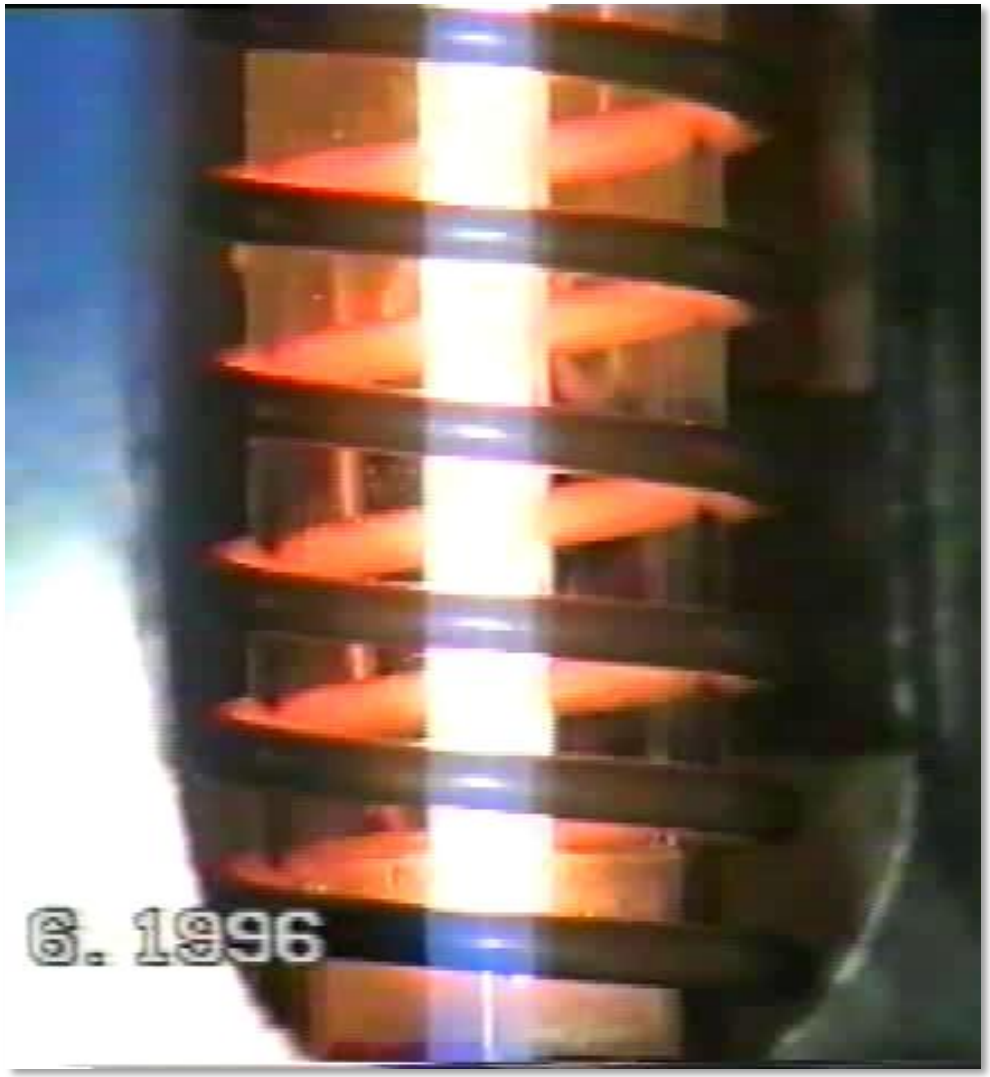
Example:

- Hydrogen diffusion into a Zry-4 cylinder
- Surface oxidized except one base
- Ø =12mm, l = 20 mm
- at 1100°C
- time ratio: 1:100

M. Grosse, 16th Intern. Symposium on Zirconium in the Nuclear Industry (ASTM)

Single-rod QUENCH tests

- 15-cm rods filled with ZrO_2 pellets
- Direct inductive heating till melting temperatures
- Video recording
- Mass spectrometer for analysis of hydrogen release



Reflood from 1400°C

SiC oxidation in steam and quenching from 2000°C