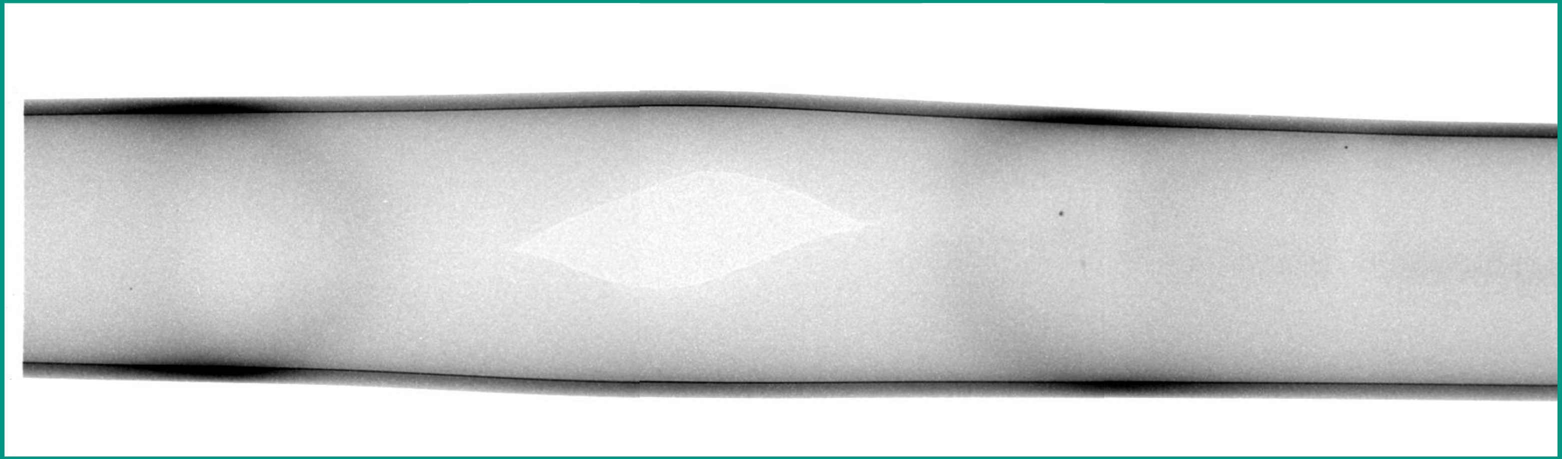
Karlsruhe Institute of Technology

The QUENCH Program at KIT

M. Grosse

KIT / Institute for Applied Materials / Program NUSAFE



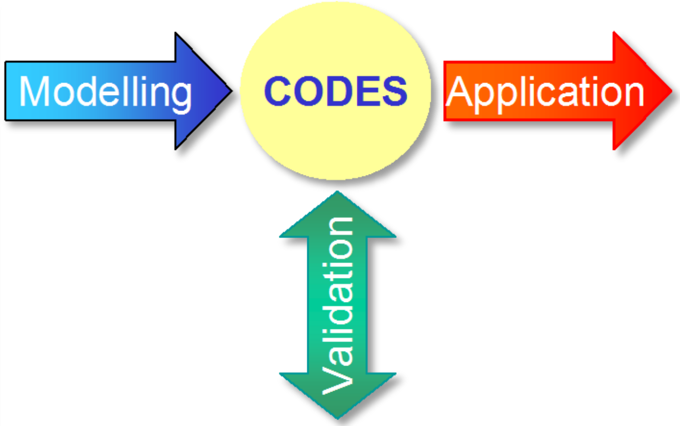
Outline

- Introduction
- The QUENCH facility
- Previous tests
- Main outcome
- Planned future tests

Introduction

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

Separate-effects tests



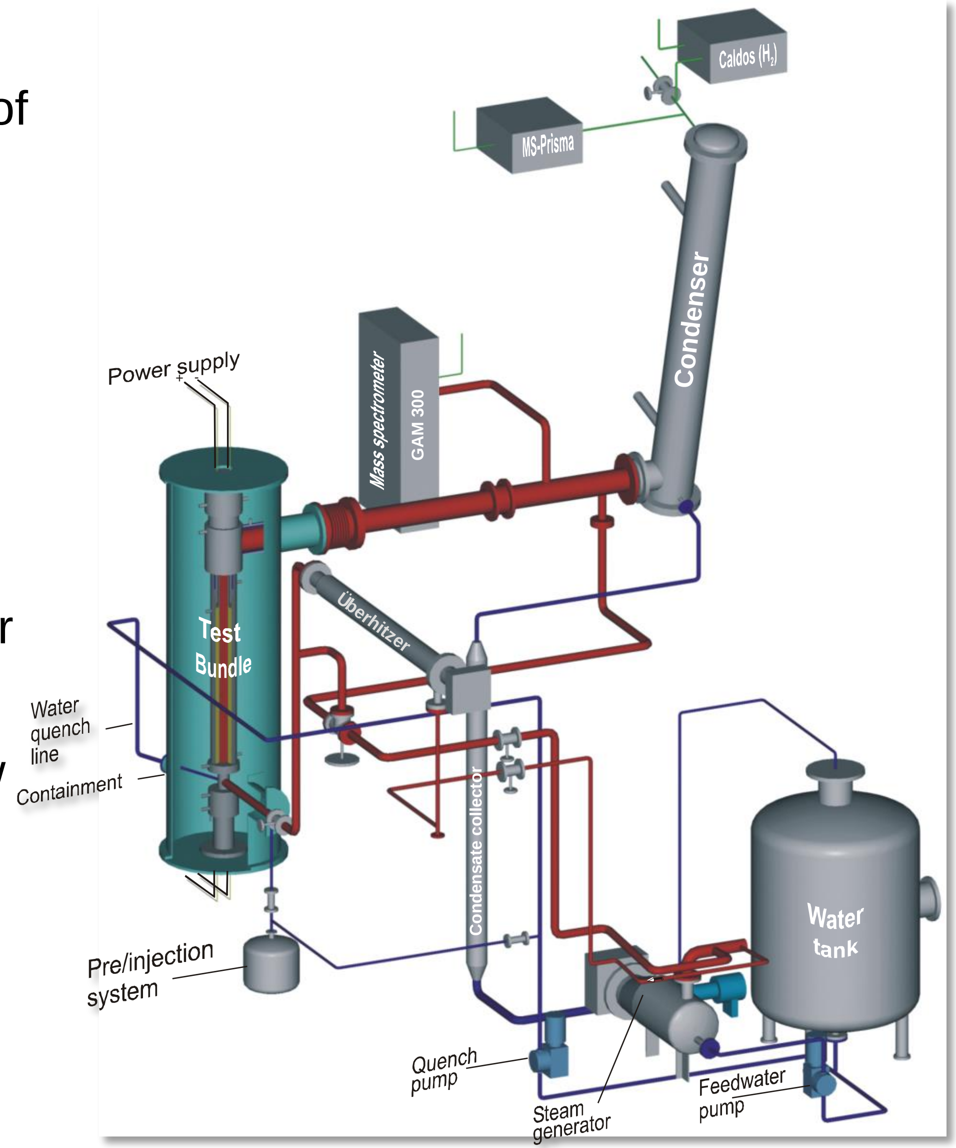
Bundle experiments

PWR fuel element

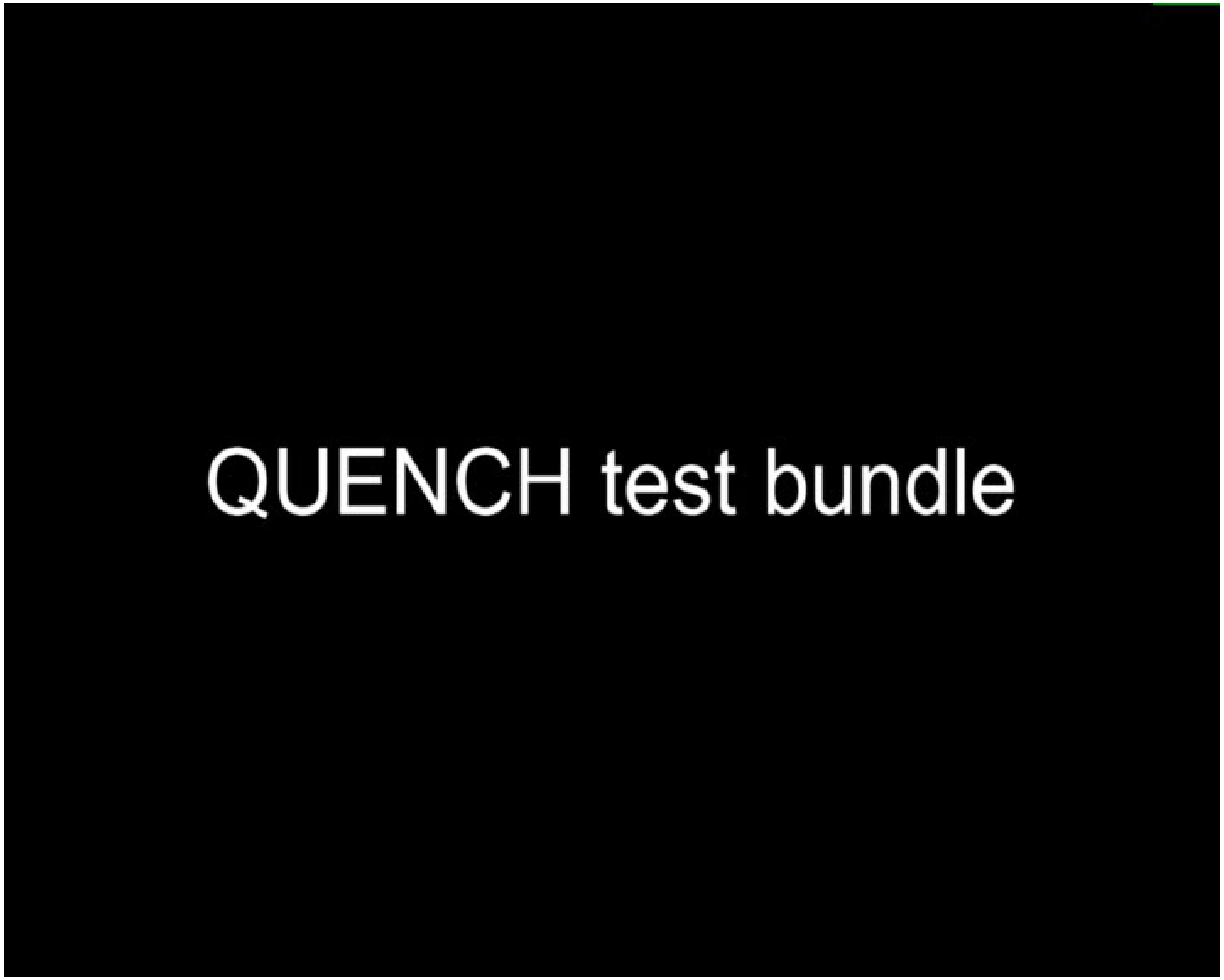
M. Steinbrück et al. given at QUENCH workshops

The QUENCH facility

- Bundle with 21-32 fuel rod simulators of ~2,5 m length
- Electrically heated: ~1 m; max 70 kW
- Fuel simulator: ZrO_2 pellets
- Quenching (from bottom or top) with water or saturated steam
- Off-gas analysis by mass spectrometer (H_2, steam …)
- Extensive instrumentation for T, p, flow rates, water level, etc.
- Removable corner rods during test
- Separately pressurized rods for LOCA tests

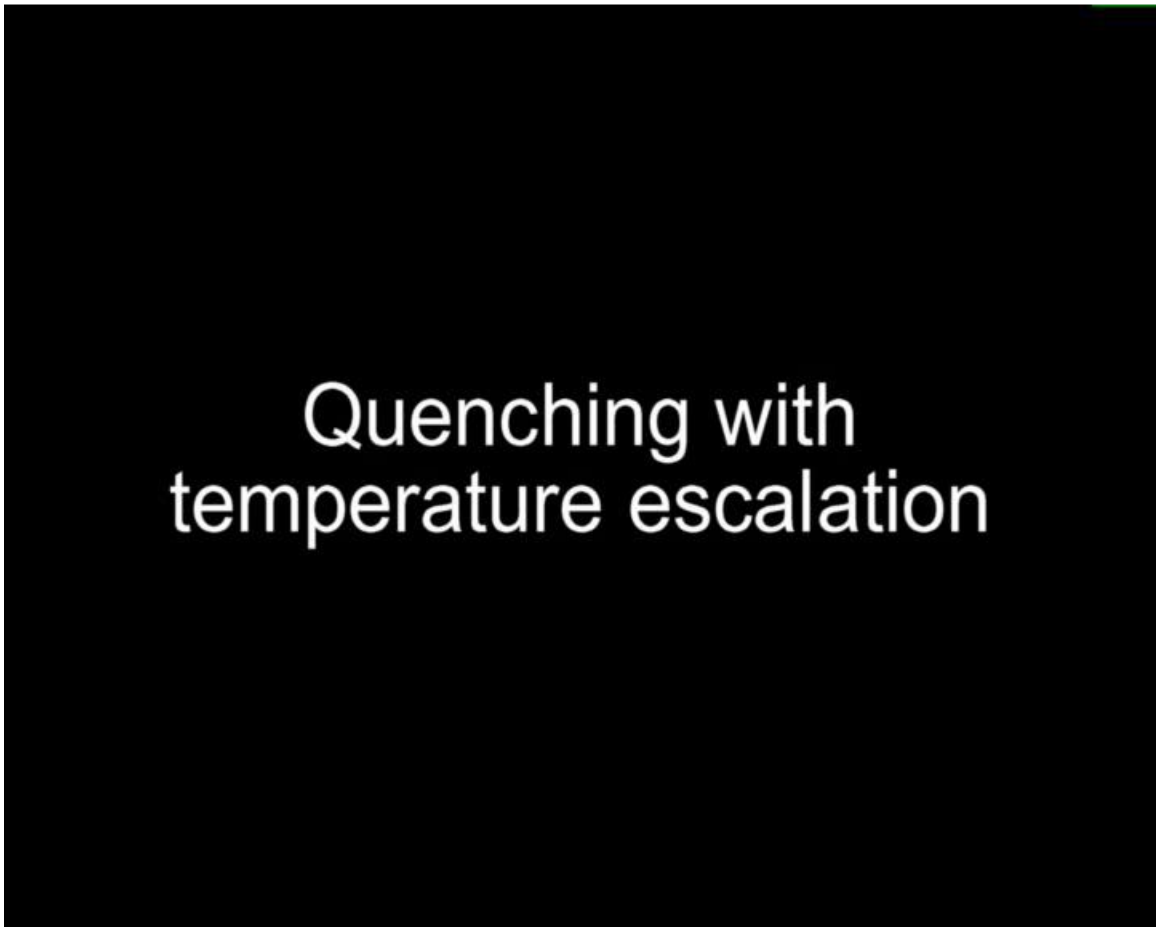


The QUENCH facility



The QUENCH facility

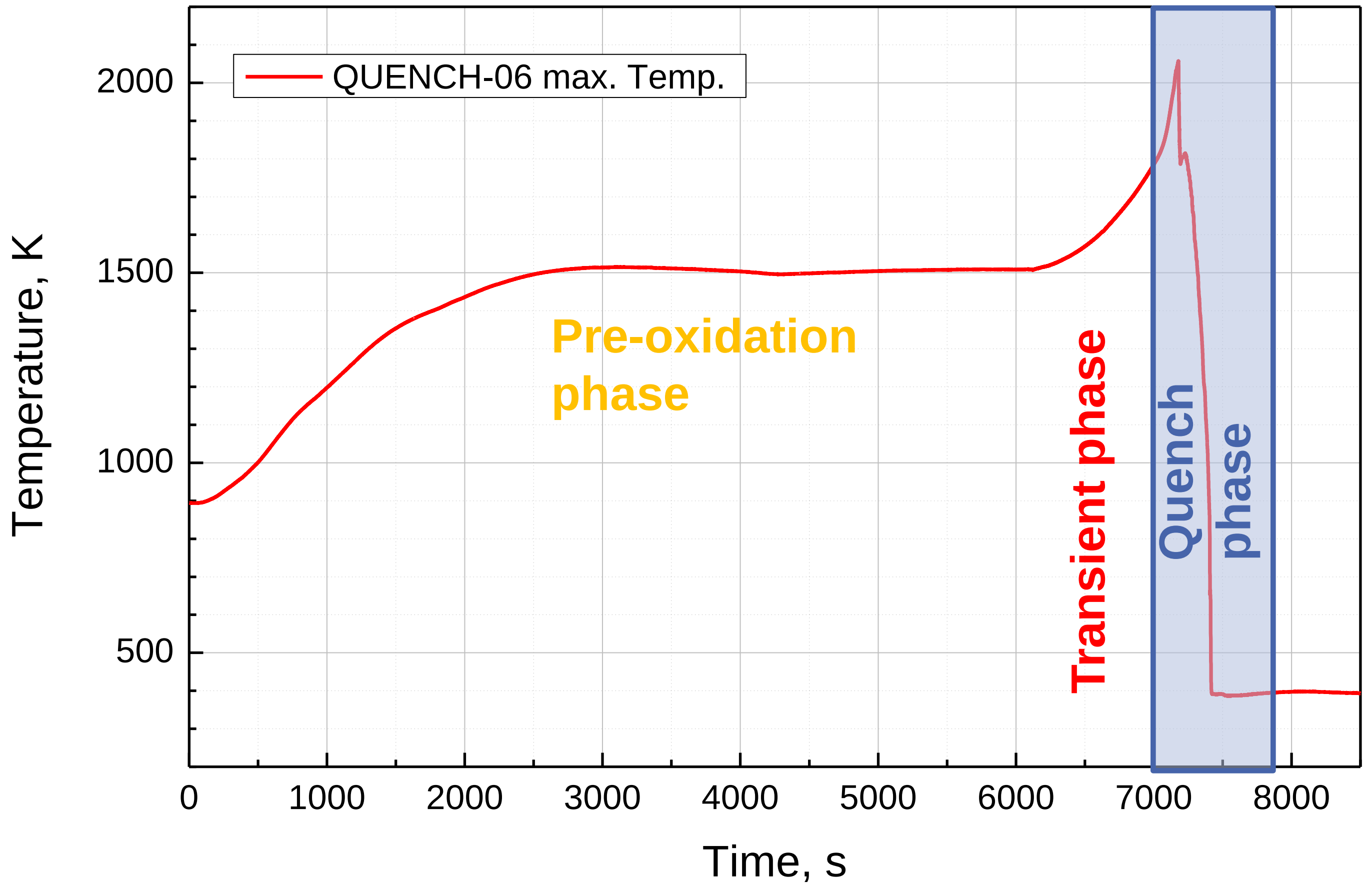
Unsufficient cooling



The QUENCH facility

sufficient cooling

Previous tests



Typical temperature scenario valid for QUENCH-6, -12, -14 and -15

Previous tests

- Different temperature scenarios: QUENCH-1 … -5, -11
  - Different pre-oxidation
  - Cool down by water quenching or in steam
  - Boil off
- Control rod behaviour: QUENCH-7 … -9, -13
  - B_4C or Ag-In-Cd
  - with or without control rod
  - with or without steam starvation phase
- Different cladding materials: QUENCH-6, -12, -14, -15
  - Zry-4, E110, M5™, ZIRLO®
- Air ingress: QUENCH-10, -16
  - Different pre-oxidation and T_{max}
- Debris bed formation: QUENCH-17
- LOCA: QUENCH-L0 … -L5, -3HT
  - Different materials: Zry-4, M5™, ZIRLO®, prehydrided M5™ and ZIRLO®
  - Different temperature scenarios

Main outcome

- For successful quenching a minimum water injection rate per fuel rod of 1 g/s is necessary. The hydrogen release is small (< 10 g H_2 in the QUENCH test). This is not a sufficient condition!
- Insufficient quenching occurs if the cladding melts (up to 400 g H_2 in the QUENCH test):
  - Not enough water is injected.
  - Temperatures at which quenching was initiated is too high.
  - Temporary steam starvation
  - Eutectic reactions between absorber material - steels – zirconium
  - Pronounced breakaway oxidation occurs over a large axial range
  - Air or steam/nitrogen oxidation
- Debris bed formed is very inhomogeneous
- During LOCA: Band shaped hydrogen enrichments non-perpendicular to the rod axis are formed if the temperatures exceed 1000°C

Planned future tests

More or less fixed tests will be performed until end of 2018

- Air ingress test in the framework of the China – EU program ALISA
- QUENCH test with BWR geometry and B_4C control blade in the framework of the EU SAFEST project
- QUENCH-FeCrAl in cooperation with ORNL

Further tests in discussion

- 2 .. 4 additional tests can be performed until end of 2020.
- QUENCH-LOCA test in cooperation with CEA
- QUENCH-SiC test in cooperation with Westinghouse
- Interest of Korean institutions?

Termination of the QUENCH-program at the end of 2020?

Summary and Conclusions

- The QUENCH facility is world-wide unique to simulate accidents at fuel rod bundle scale
- 17 severe accident and 7 design basis LOCA simulation tests were performed.
- Insufficient quenching is connected with high hydrogen release and temperature escalation. It occurs if :
  - Temperatures at which quenching was initiated is too high
  - Temporary steam starvation
  - Eutectic reactions between absorber material - steels – zirconium
  - Non-protective oxide layers are formed at the claddings
- During LOCA: Band shaped hydrogen enrichments non-perpendicular to the rod axis are formed if the temperatures exceed 1000°C

Thanks to the whole QUENCH team at KIT and to all teams cooperating in preparation and analyses of the test as well as in the post test examinations in particular the colleagues from PSI, GRS, EdF, CEA, IRSN, KFKI, RUB, IBRAE, AREVA, WESTINGHOUSE, TWEL, …

Thank you for your attention.

Questions?

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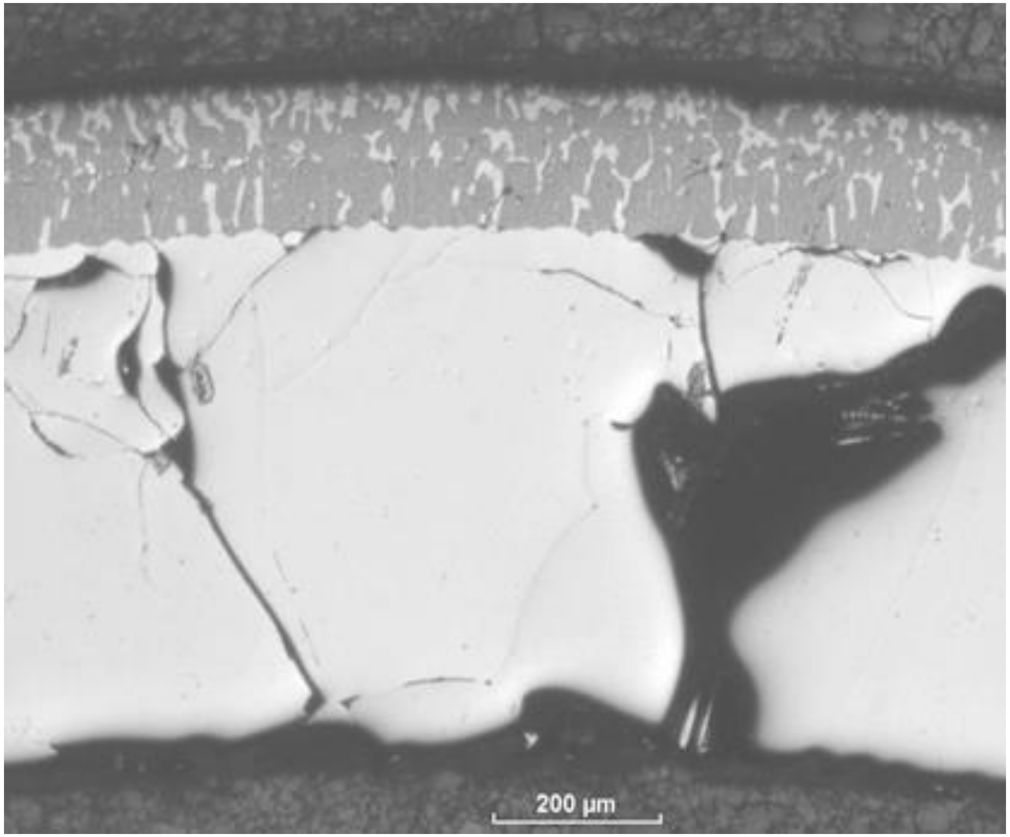
Temporary steam starvation



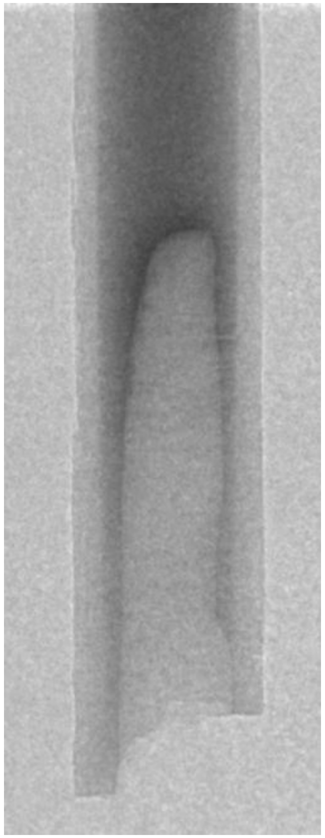
Formation of metallic islands in the oxide layer results in an enhanced oxidation.

Eutectic reactions between absorber material - steels – zirconium

Fe – B eutectic

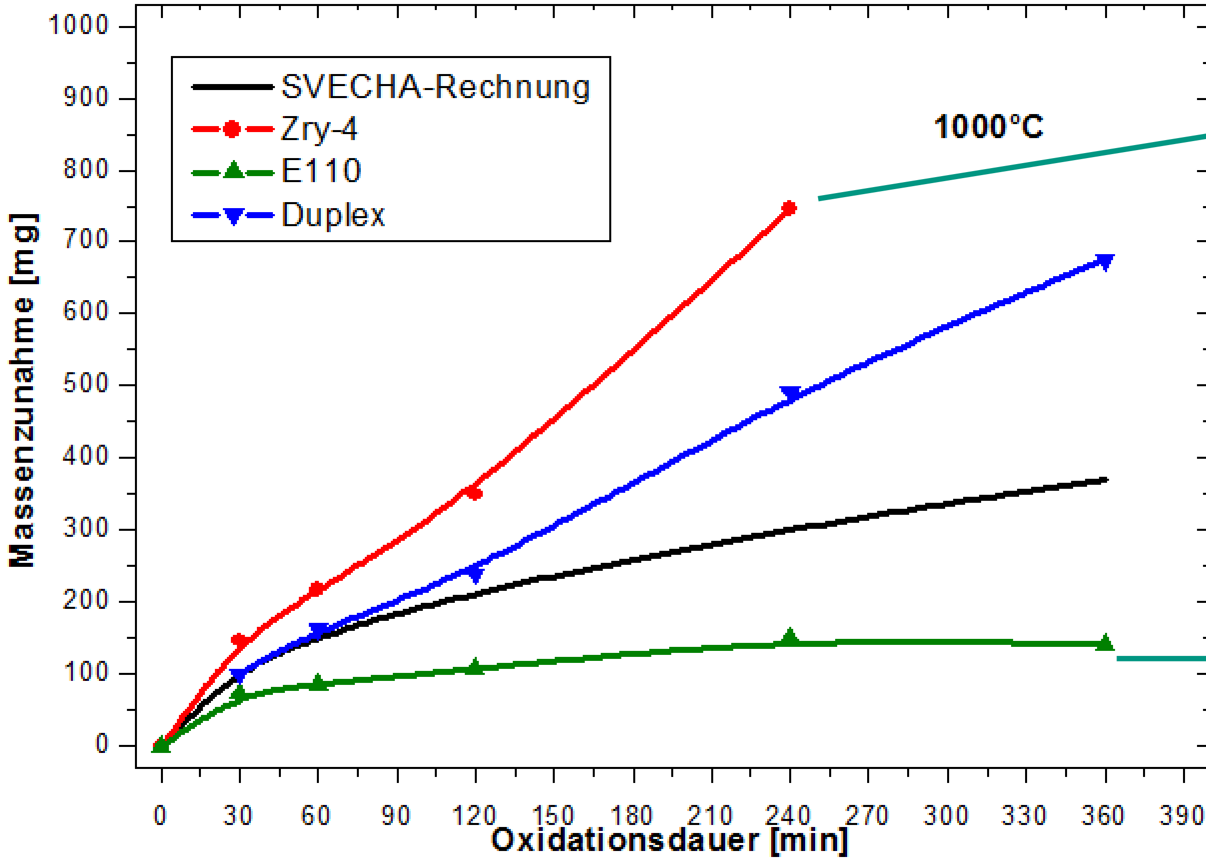
melting point at 1450 K

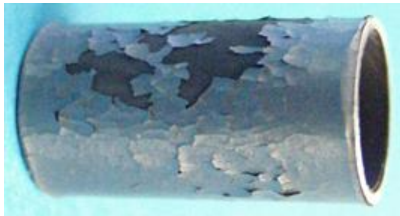
Fe – Zr eutectic, Melting points at 1610 K for Fe10%Zr and 1201 K for Zr_3Fe



H stabilices β-Zr with lower melting point (2128 K) than α-Zr (2248 K)

Pronounced breakaway oxidation occurs over a large axial range

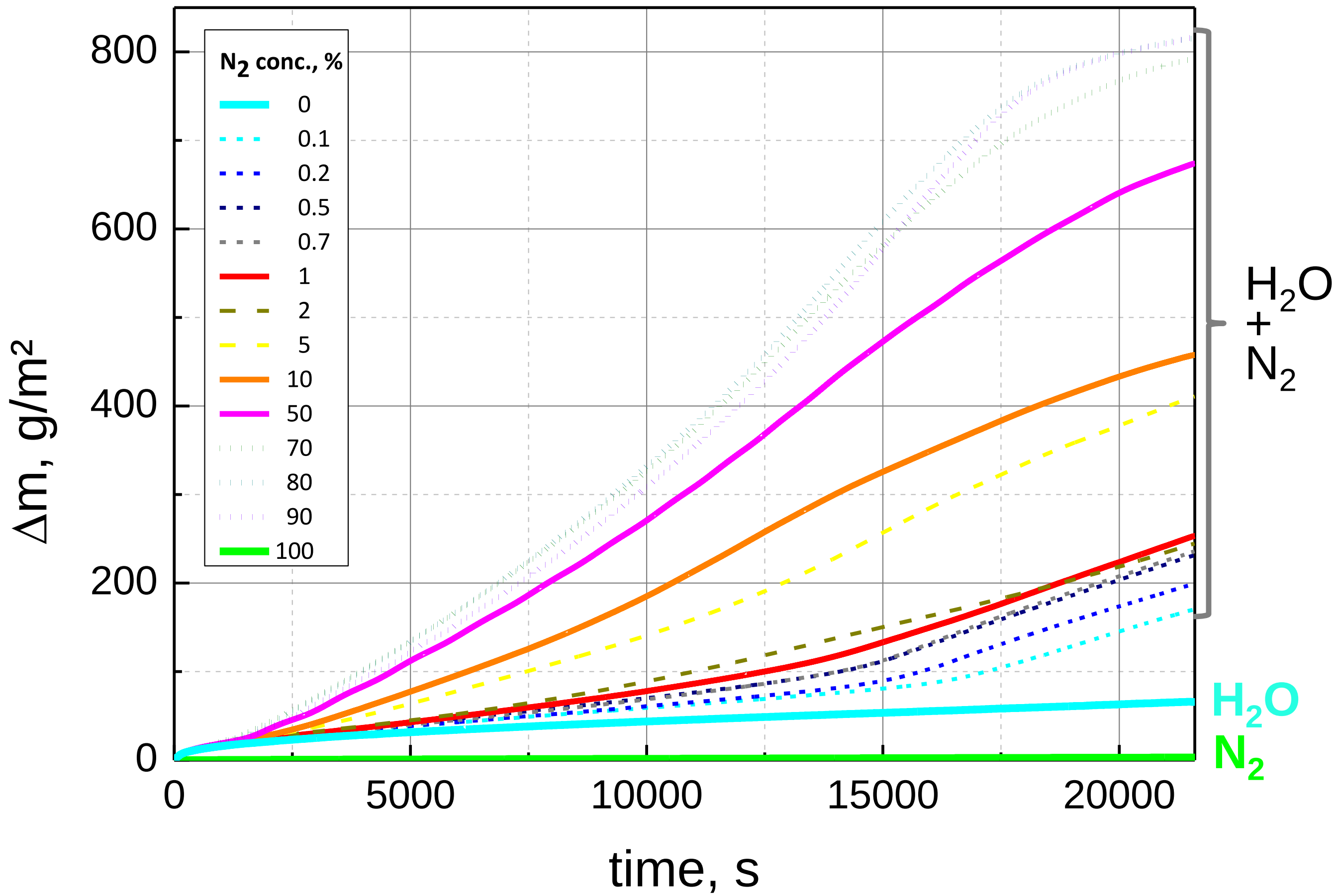




Breakaway oxide

Compact oxide

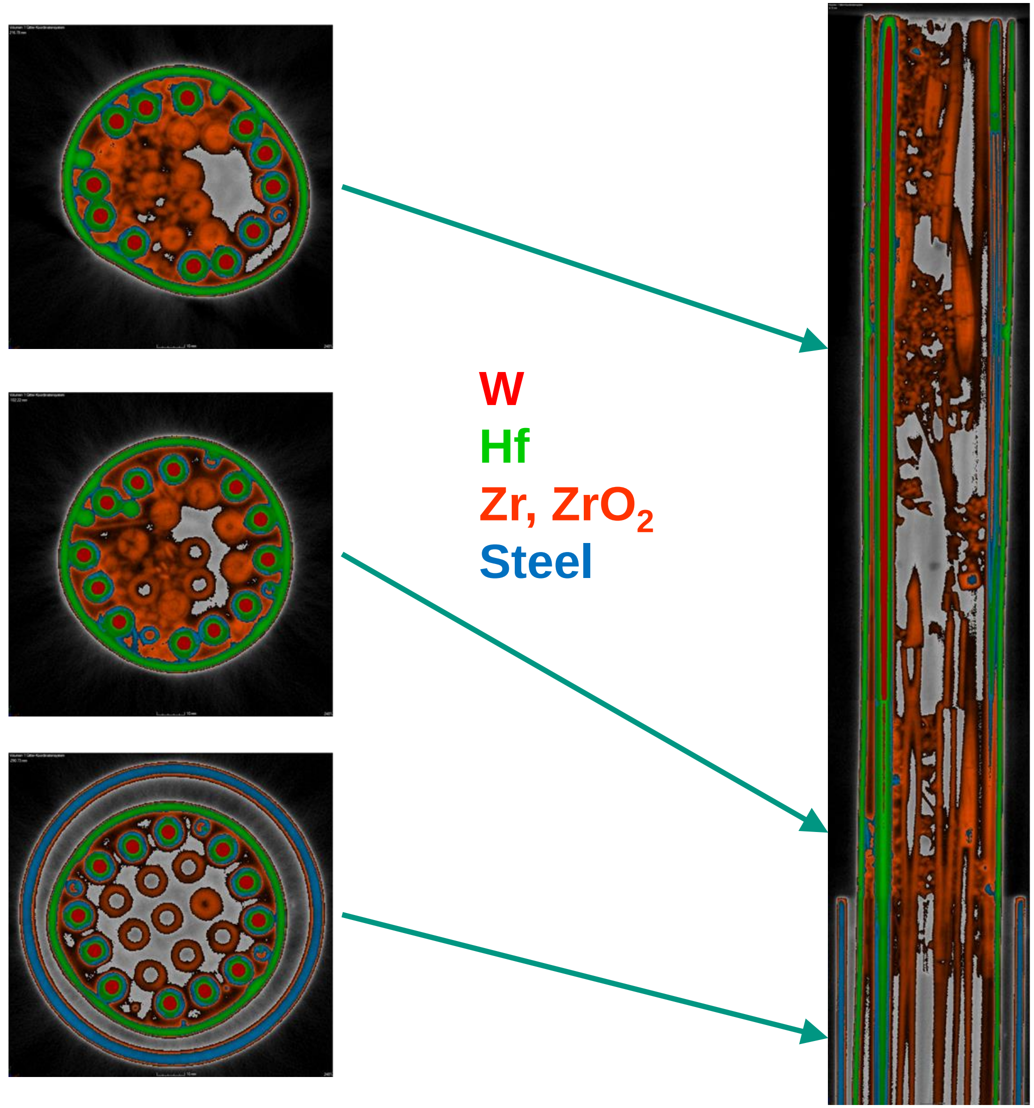
Air or steam/nitrogen oxidation



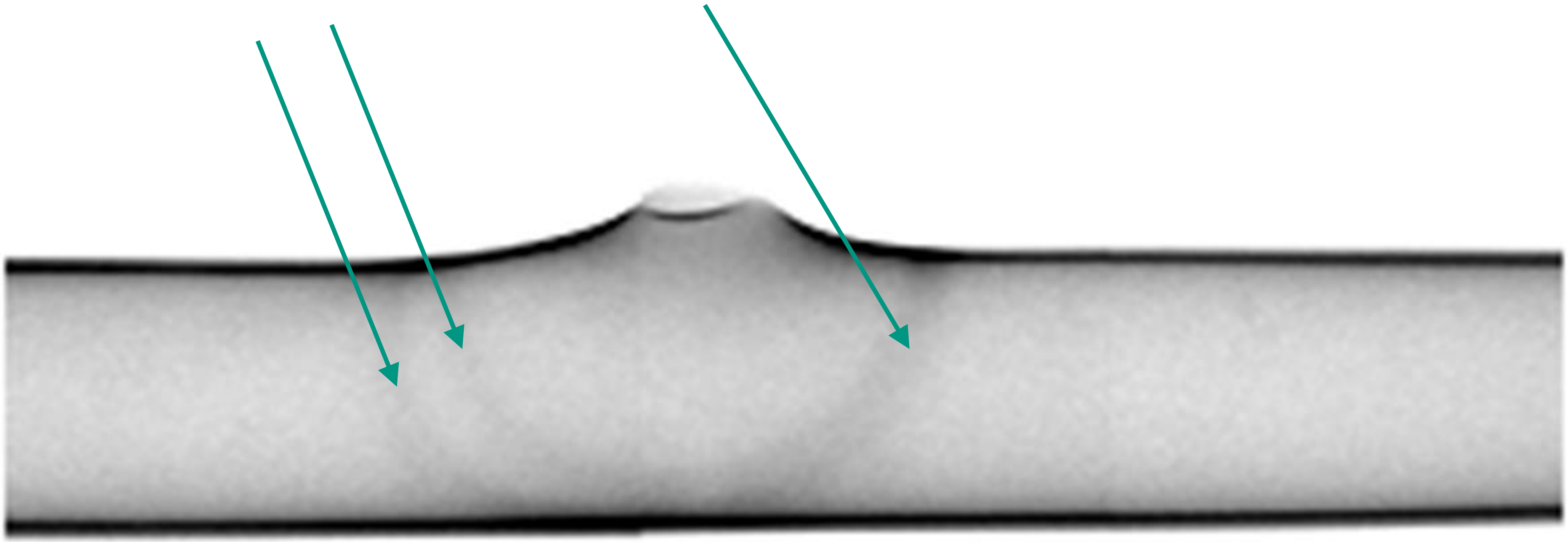
Strong effect of nitrogen on the oxidation kinetics

Debris bed formed is very inhomogeneous

Appearance of a debris bed formed after complete oxidation of the claddings



Band shaped hydrogen enrichments



QUENCH-L0, rod 06

Hydrogen enrichments only were found if the temperatures exceeded 1000°C